The evolution of groups & of galaxies therein

1) Evolution of groups

- 1a) How can we tell if a group is collapsing or virialized?
- 1b) How frequently do compact groups from?

2) Evolution of galaxies in groups

- 2a) How frequently do galaxies merge?
- 2b) Do we understand the morphology density relation?
- 2c) How far out should we see the effects of the group environment?

3) Internal kinematics of groups

- 3a) Which is the best estimator of the virial radius of a group?
- 3b) Can we constrain the mass profiles & orbits?
- 3c) What are the nature of the different classes of groups?

States of groups

10^{13} M_{sun} halos in cosmological simulations

friends-of-friends groups

stringy, z-space selection: contaminated by filaments
Moore, Frenk & White 93; Diaferio et al. 99

States of compact groups

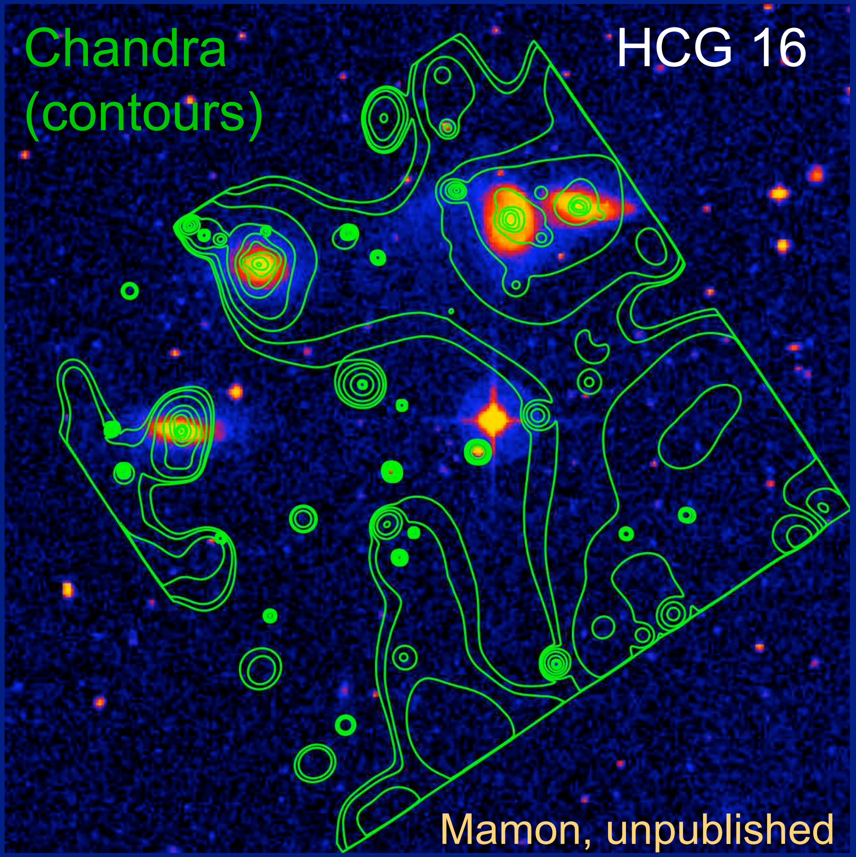
isolated virialized overdensities $\delta\rho/\rho \sim 10^5$

cores of virialized groups

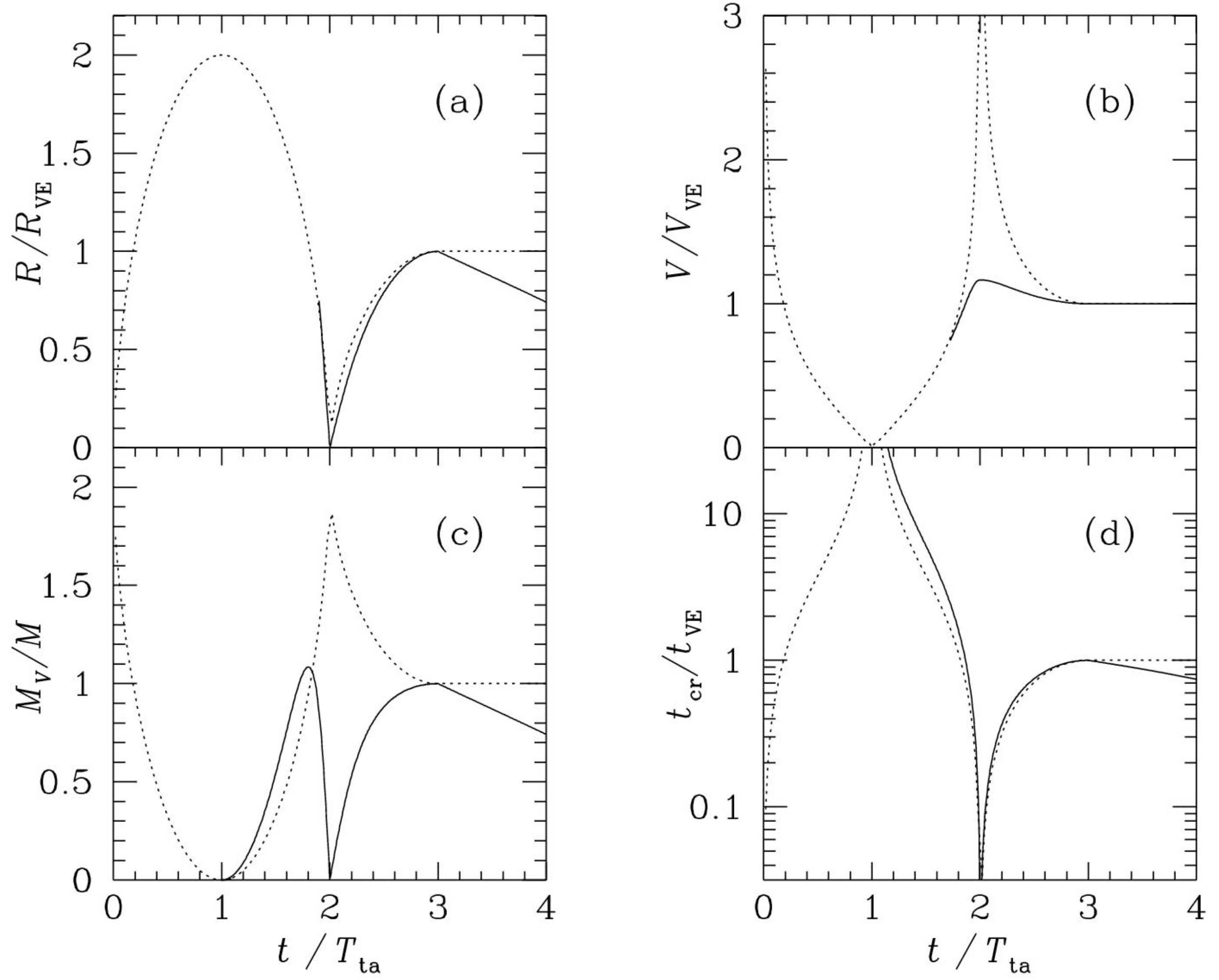
chance alignments of galaxies within:

loose groups Rose 77; Mamon 86
clusters Walke & Mamon 89
filaments Hernquist, Katz & Weinberg 95

Is a group collapsing or virialized?

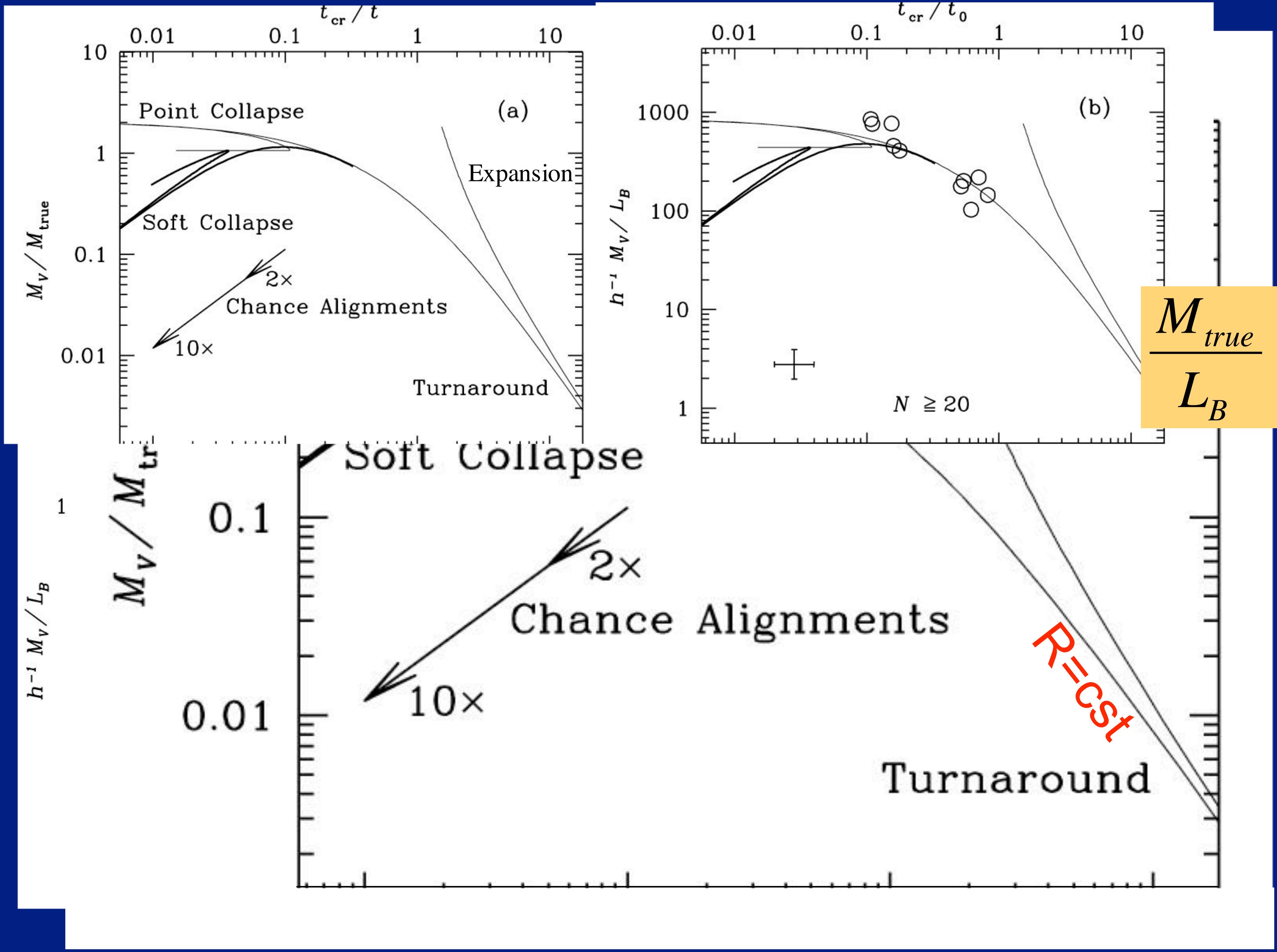


Departure from Hubble expansion



Mamon 93, astro-ph/9308032, 95 astro-ph/9511101

Fundamental track

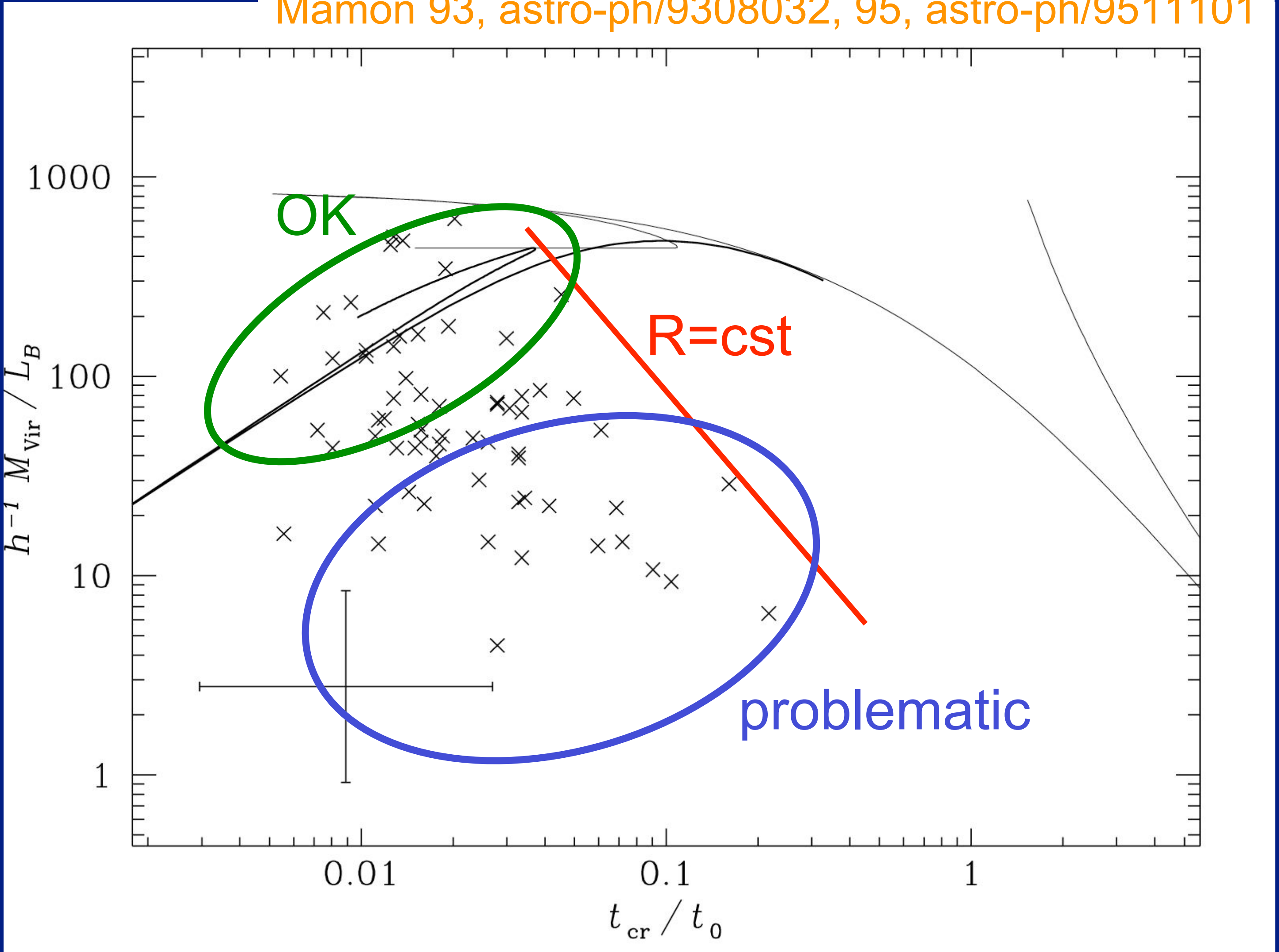


$$\frac{M_{true}}{L_B} = 440\,h$$

Mamon 93, astro-ph/9308032, 95, astro-ph/9511101

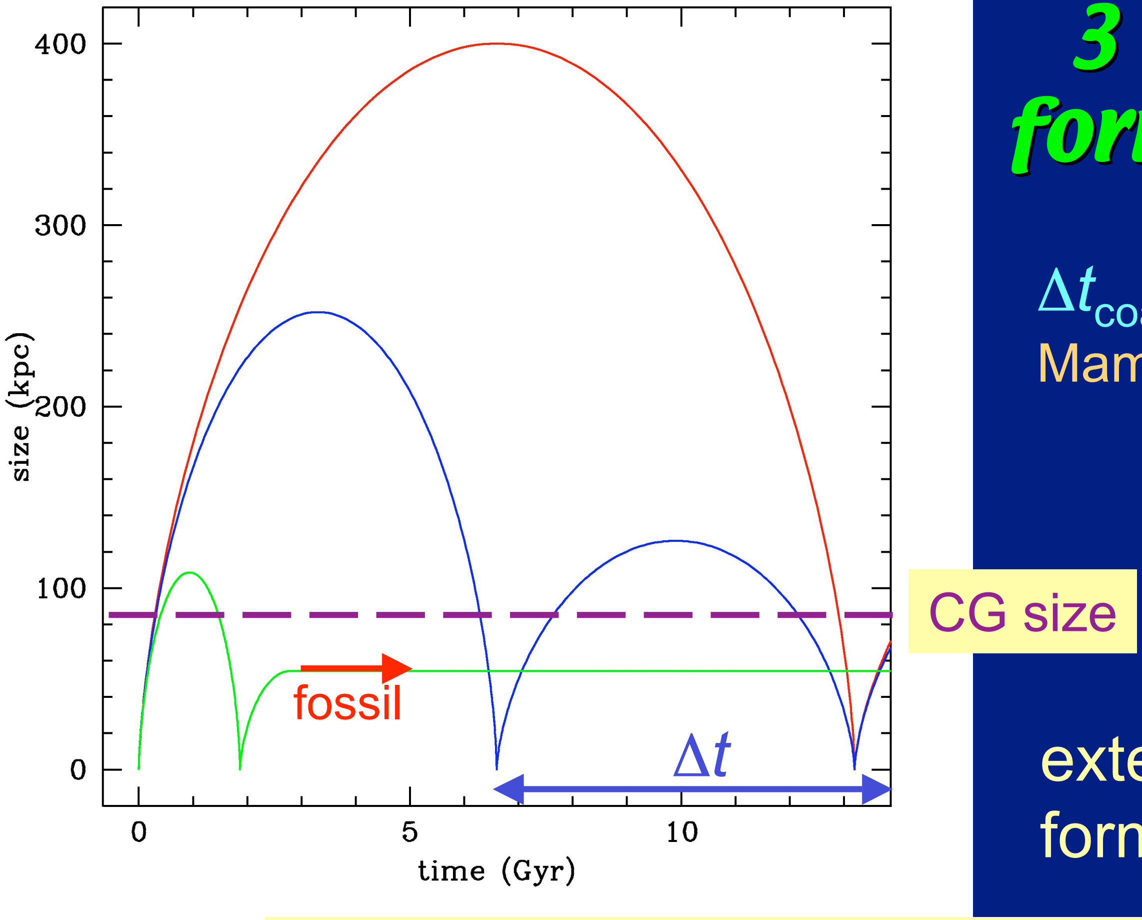
Hickson compact groups & fundamental track

Mamon 93, astro-ph/9308032, 95, astro-ph/9511101



How frequently do compact groups form?

3 compact group formation scenarios



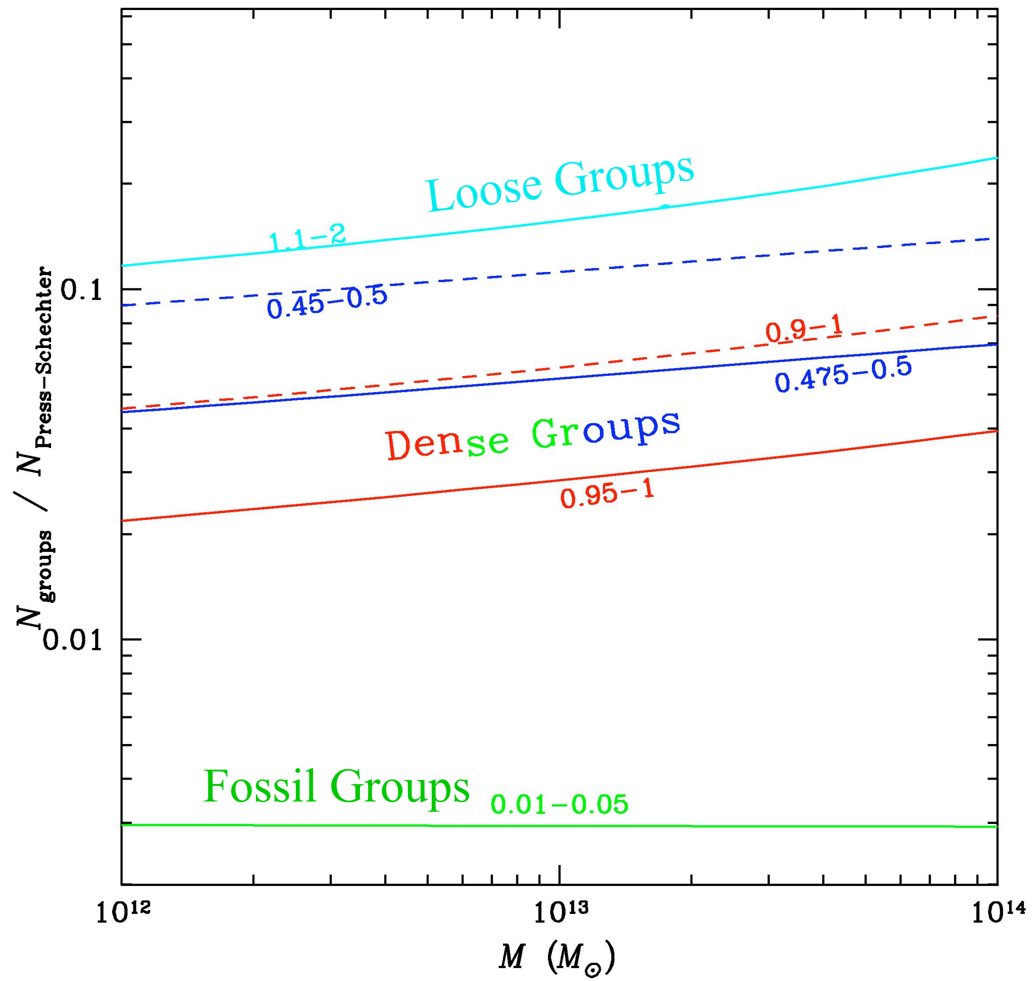
$\Delta t_{\rm coalescence}$~0.2-2 Gyr
Mamon 87

extended Press-Schechter formalism

$$N(M,t_0) = \int_{t_0-\Delta t}^{t_0} dt \int_{M/2}^{M} dM' \, \boxed{R_{\rm form}(M',t)} \, \boxed{P(M,t_0 \mid M',t)}$$

Kitayama & Suto 96 Lacey & Cole 93

Extended Press-Schechter estimates



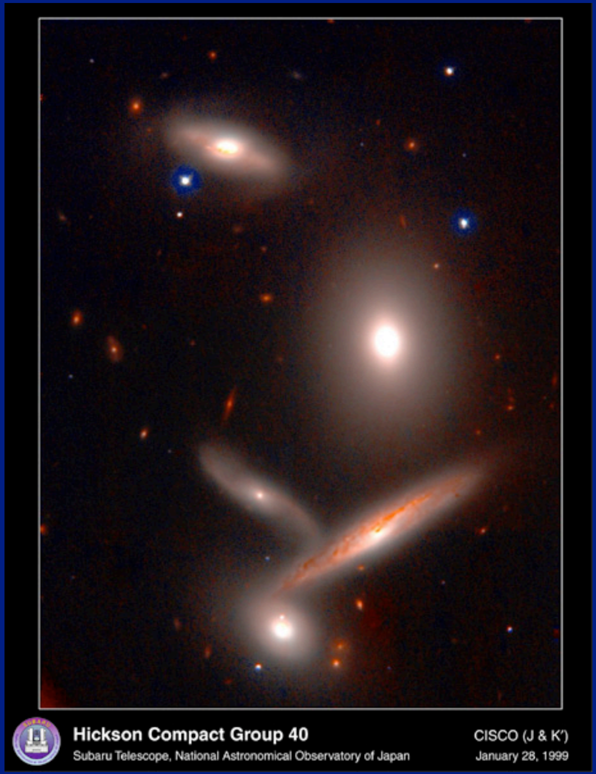
after Mamon 00, Turku, astro-ph/9909019

For 100 Virialized:

4	Compact
10	Loose
0.3	Fossil

collapsing groups are frequent enough to explain CGs!

Compact groups of galaxies



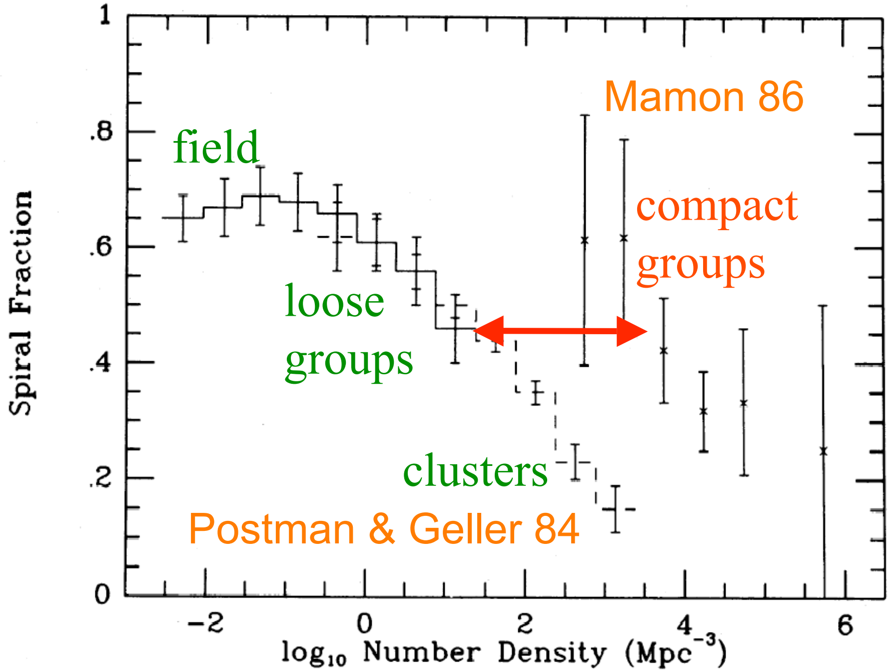
Hickson Compact Group 40
Subaru Telescope, National Astronomical Observatory of Japan
CISCO (J & K')
January 28, 1999

very high density & low velocity dispersion → direct mergers

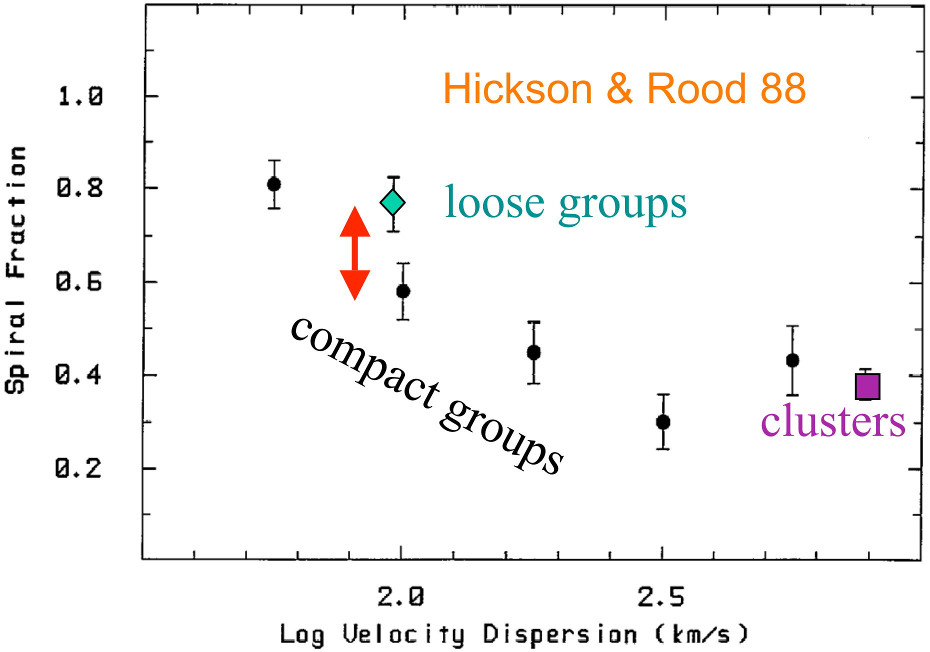
→ should be very elliptical-rich!

Galaxy morphologies

compact groups of galaxies are …



spiral-rich



spiral-poor

How frequently do galaxies merge in groups?

Mamon 00, astro-ph/9911333

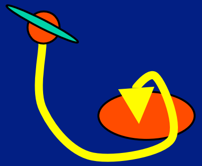
Theoretical rates of galaxy mergers, function of:

- environment
- galaxy mass
- position in group/cluster

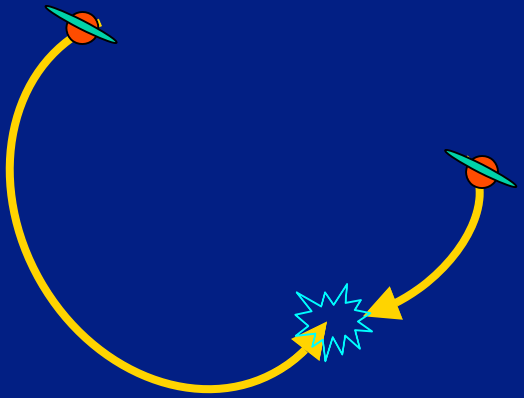
⇨ morphology-density relation

2 types of mergers

Mergers after orbital decay by dynamical friction



Direct mergers (« satellite-satellite »)



Direct merger rates

Mamon 92, ApJL,
00, astro-ph/9911333

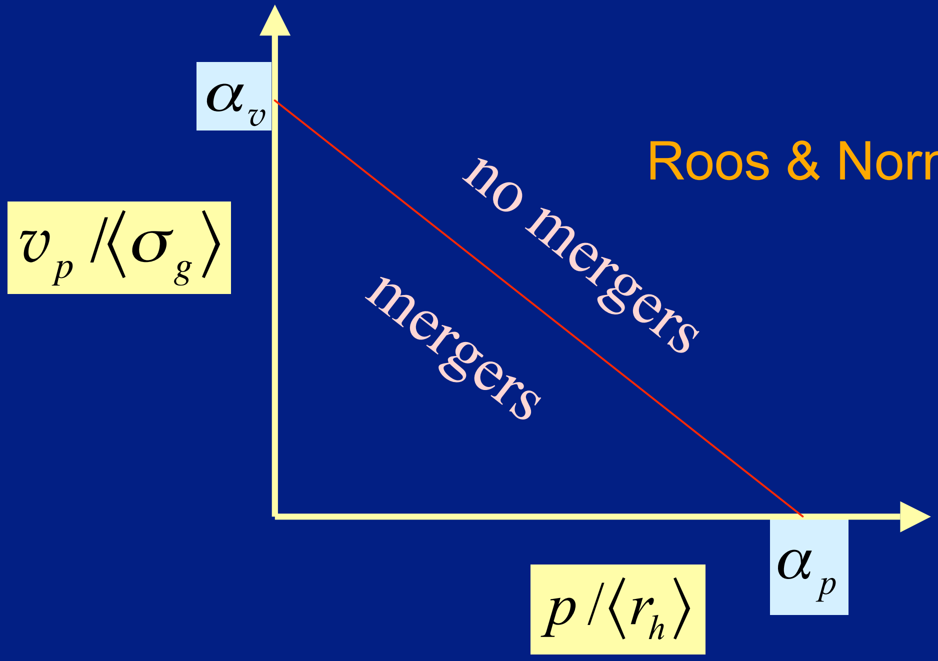
$$\frac{d^2N}{dt\,dV} = n^2 k$$

$$k = \langle v\Sigma(v)\rangle$$

rate

$$\Sigma(v) = \pi\, p_{\rm crit}^2(v)$$

x-section



Roos & Norman 79

$\alpha_p = 4$

$\alpha_v = 5.4$

rate ⇒ x-sec at apocenter

x-sec at pericenter ⇒ no gravitational focussing

Merger rate vs. environment

Roos & Norman 79 x-section (no grav. focussing)

$$k = 2\sqrt{\pi}\,\alpha_p \alpha_v r_h^2 \sigma_g K(\sigma_{\rm cl}/\sigma_g)$$

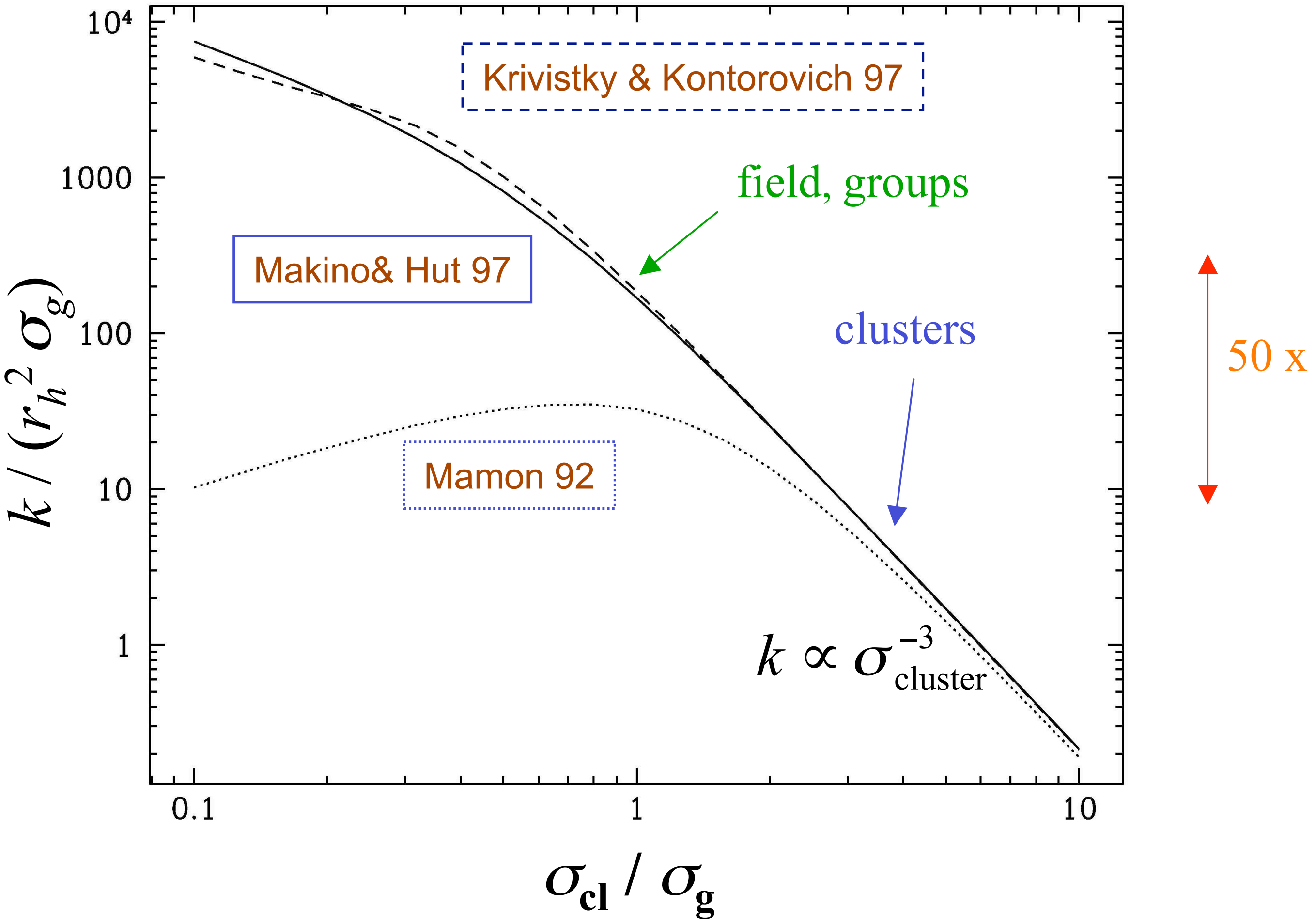
$$\sigma_{\rm cl} >> \sigma_g$$

$$\Downarrow$$

$$K \longrightarrow (\sigma_{\rm cl}/\sigma_g)^{-3}$$

$$\Downarrow$$

$$k \propto \frac{r_h^2 \sigma_g^4}{\sigma_{\rm cl}^3} \approx 8 \frac{G^2 m^2}{\sigma_{\rm cl}^3}$$



Mamon 92; Mak

Merger rate versus galaxy mass

Mamon 00, astro-ph/9911333

$$k(m,m) \propto \frac{r_g^2 \sigma_g^4}{\sigma_{\rm cl}^3} \quad \Rightarrow \quad k(m,\lambda m) \propto \frac{\langle r_g \rangle^2 \langle \sigma_g^2 \rangle^2}{\sigma_{\rm cl}^3}$$

cst mean density → $m \propto r^3 \propto v_{\rm circ}^3$

homology → $\sigma_v \propto v_{\rm circ} \propto m^{1/3}$

$$\Rightarrow \quad k(m,\lambda m) = \frac{8G^2m^2}{\sigma_{\rm cl}^3}\left(\frac{1+\lambda^{1/3}}{2}\right)^2\left(\frac{1+\lambda^{2/3}}{2}\right)^2$$

mean merger rate

$$\frac{dN}{dt} = n\bar{k}(m) = \int_{\lambda_{\rm min} m}^{\lambda_{\rm max} m} k(m,\lambda m)\frac{dn}{d(\lambda m)}\,d(\lambda m)$$

major mergers

$\lambda_{\rm min} = 1/3$ $\lambda_{\rm max} = 1$

or 1/5 Burkert 01

elliptical morphologies

minor mergers

$\lambda_{\rm min} = 0$ $\lambda_{\rm max} = 1/3$

destruction

$\lambda_{\rm min} = 1$ $\lambda_{\rm max} = \infty$

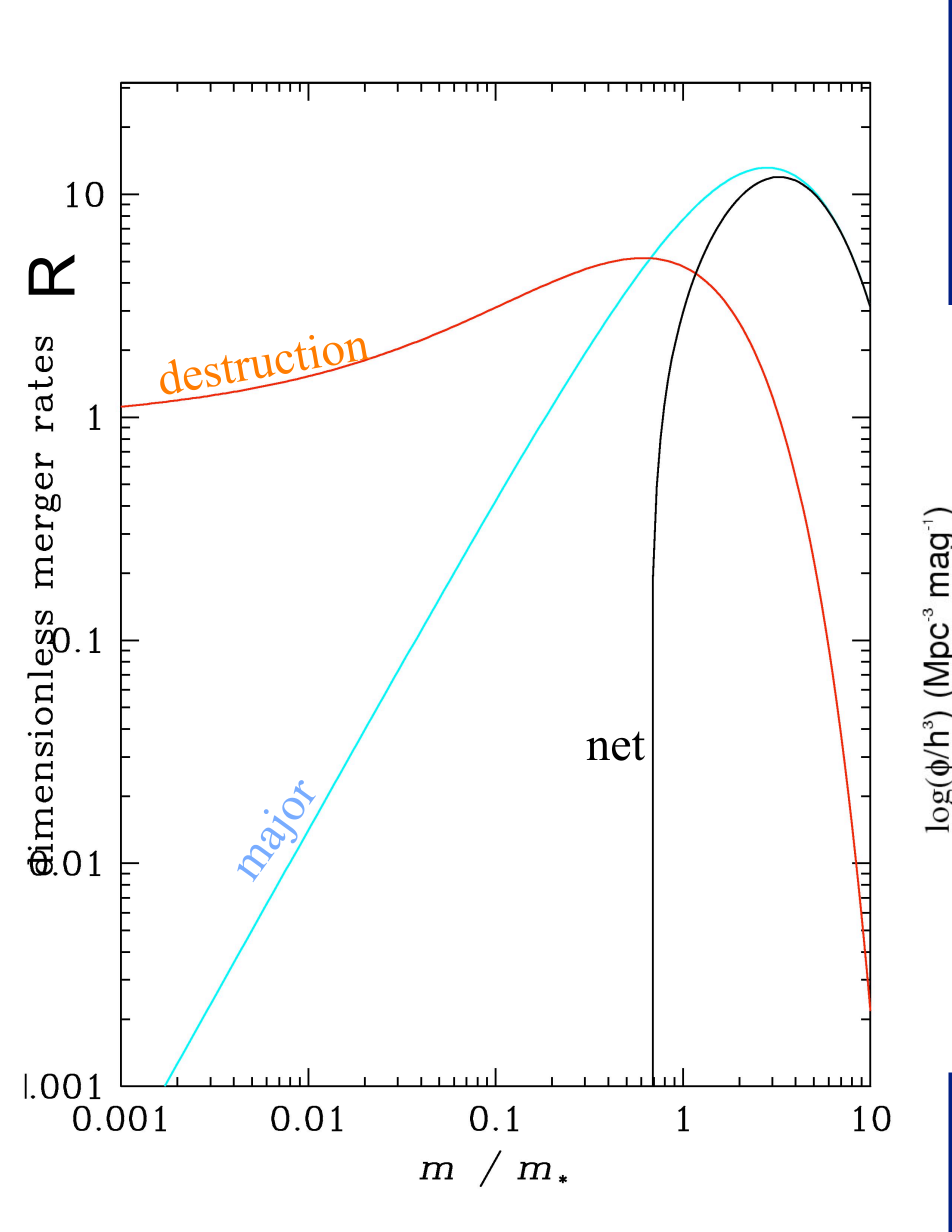
Schechter 76 mass function

$$\frac{dn}{dm} = \frac{n_*}{m_*}\left(\frac{m}{m_*}\right)^{-\alpha} \exp\left(-\frac{m}{m_*}\right)$$

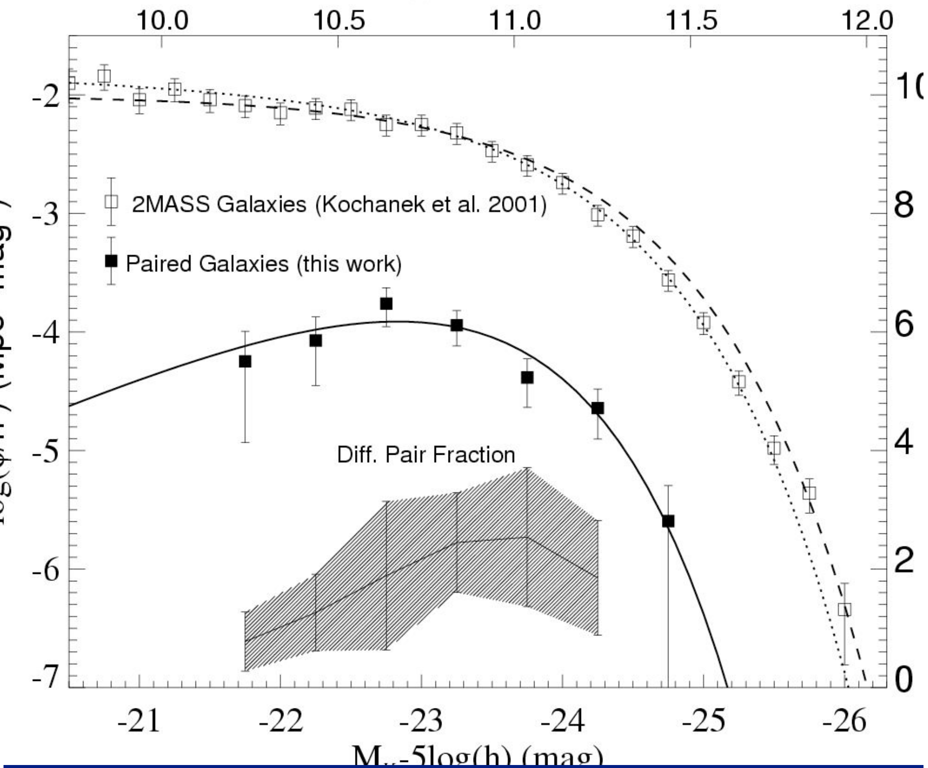
$$n\bar{k}(m) \approx 0.5\,\frac{G^2 n_* m_*^2}{\sigma_{\rm cl}^3}\,\mathcal{R}\,(m/m_*)$$

$$\mathcal{R}\,(x) = x^{3-\alpha} \sum_{j=0}^{6} {\rm Min}(j,7-j)\left[\Gamma(1+j/3-\alpha),\lambda_{\rm min}x) - \Gamma(1+j/3-\alpha),\lambda_{\rm max}x)\right]$$

Direct merger rate vs. mass



Xu, Sun & He 04



Merger rates versus galaxy position in group/cluster

x-secs → modulated by global tidal field

elongated galaxy orbits in clusters: $R_p / R_a \cong 0.2$ Ghigna et al. 98

stars in galaxy feel *tidal shock* Ostriker et al. 72

$$\Delta v \approx F_{\rm tide} \times \Delta t \approx \frac{GM(R_p)}{R_p^3}\, r \times \frac{R_p}{V_p}$$

$$r = r_t$$

$$E_{\rm shell} \approx -\frac{Gm(r_t)}{r_t} \approx \Delta E_{\rm shell} \approx \frac{1}{2}\left(\Delta v_{\rm tide}\right)^2$$

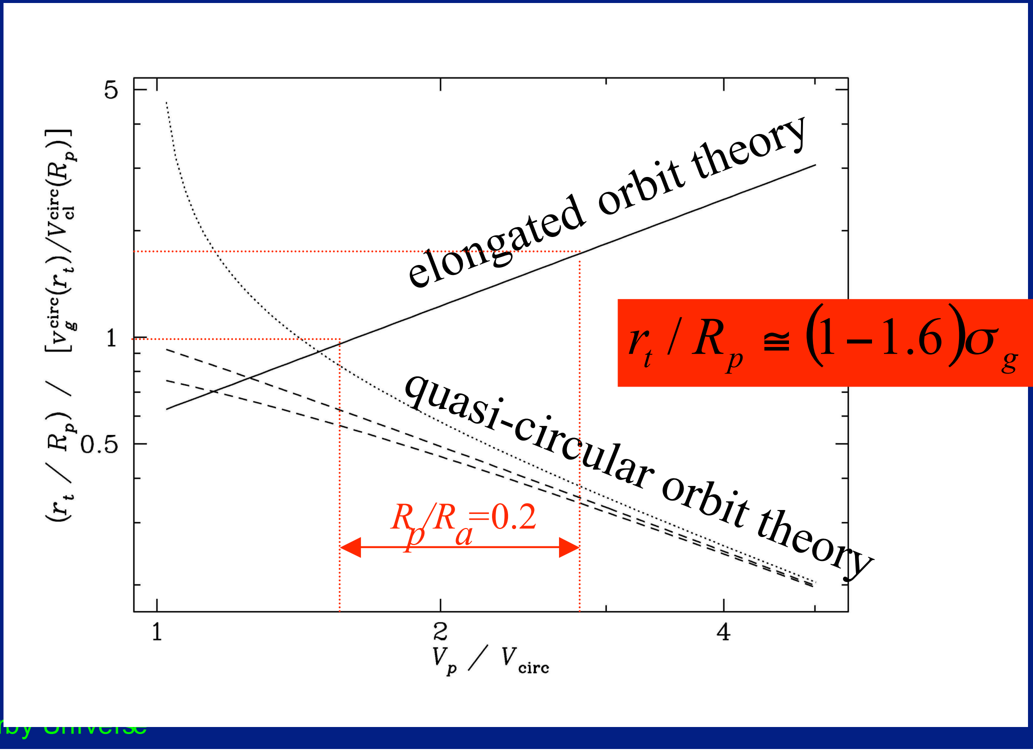
White 83

density criterion

$$\overline{\rho}_g(r_t) \approx \overline{\rho}_{\rm cl}(R_p)\left[\frac{V_{\rm circ}(R_p)}{V_p}\right]^2$$

↓ for all *ρ(r)*

$$\frac{r_t / R_p}{v_{\rm circ}(r_t)/V_{\rm circ}(R_p)} \cong \frac{V_p}{V_{\rm circ}(R_p)}$$



$$r_t / R_p \cong (1 - 1.6)\,\sigma_g / \sigma_{\rm cl}$$

Merger rates versus galaxy position in group/cluster

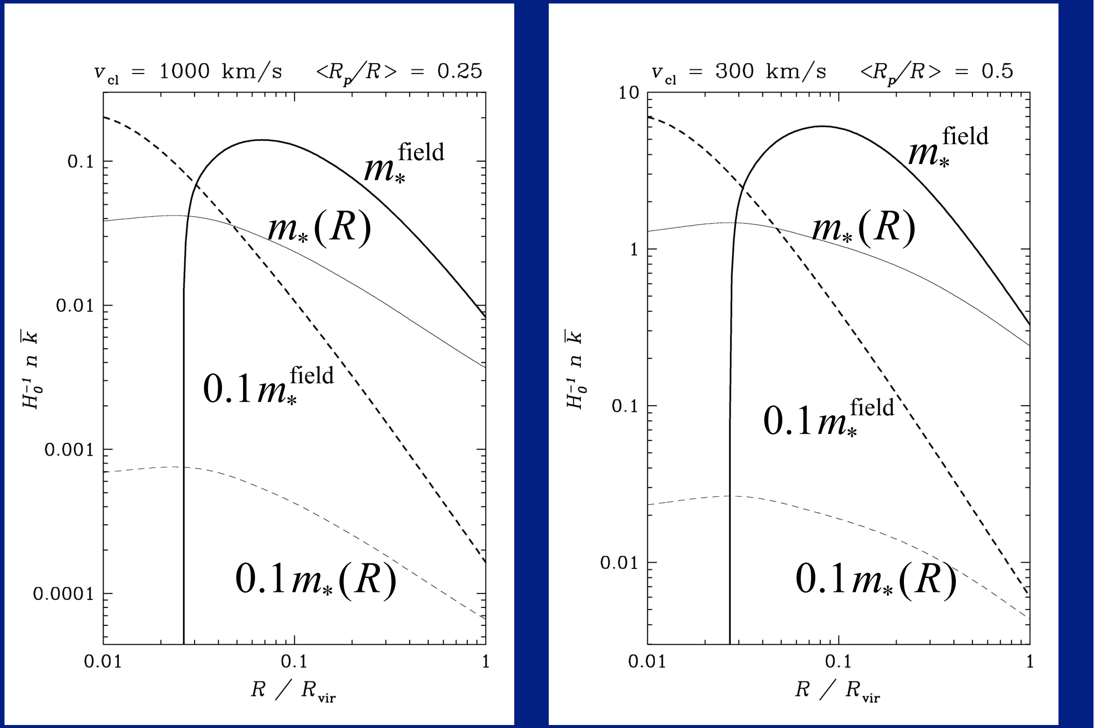
$$\mathsf{R} \equiv n\bar{k} \cong 0.5\,G^2 \left\langle \frac{n_* m_*^2}{\sigma_{\rm cl}^3} f(m/m_*) \right\rangle_{\rm orbit} \approx 0.5\,G^2 \frac{n_*(R)\, m_*^2(R)}{\sigma_{\rm cl}^3(R)} f\left[m/m_*(R)\right]$$

fraction of mass in galaxies at *R*

$$n_*(R) \propto \frac{\eta(R)\rho(R)}{m_*(R)} \propto \rho(R) = n_*^{\rm field} \frac{\rho(R)}{\rho_{\rm field}}$$

$$m_*(R) \approx m_*^{\rm field} \frac{M_{cl}(R_p)}{M_{cl}(R_{\rm vir})}$$

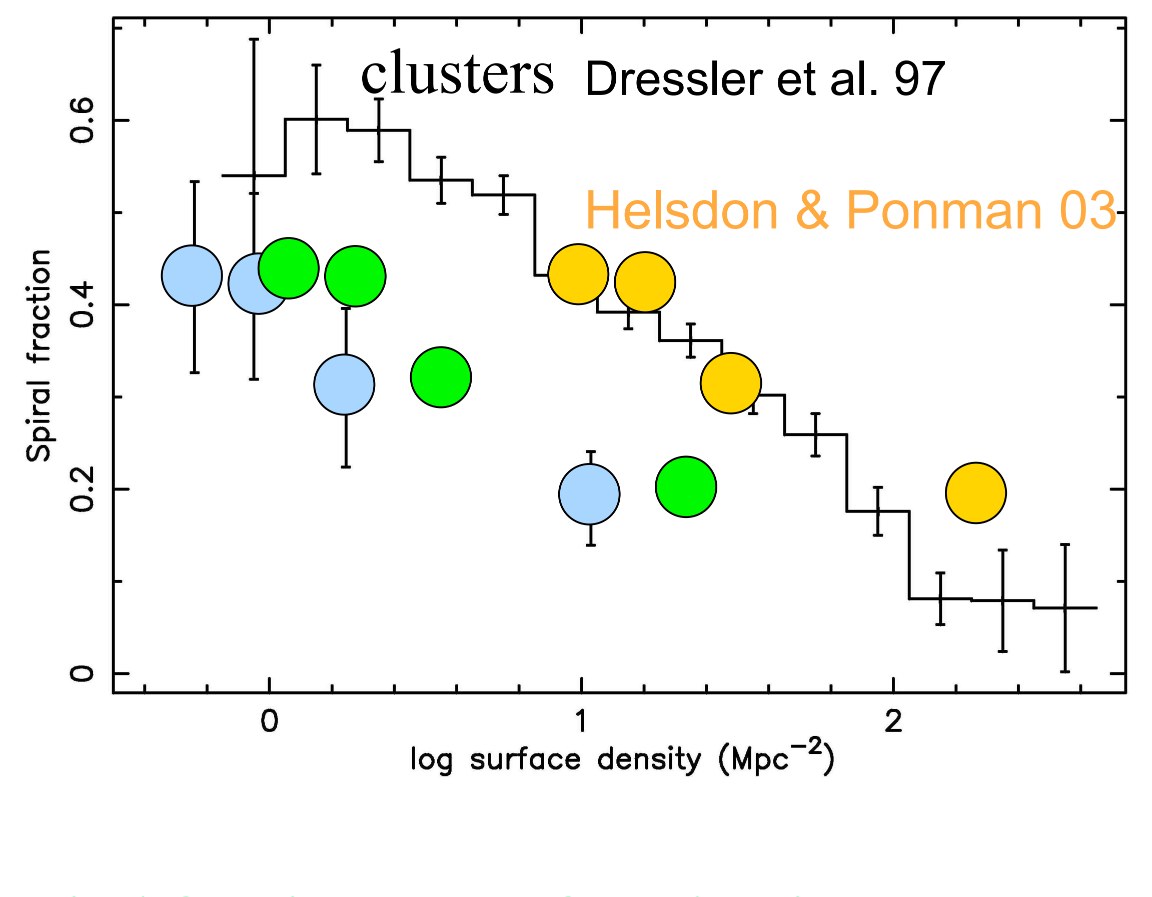
Rates of major mergers extrapolated to Hubble time



cluster

group

Do we understand the morphology-density relation in groups?



spiral fraction vs. surface density

corrected for projection $n \propto \Sigma / R \propto T^{-1/2}\,\Sigma$

corrected for projection and mergers

$$f_{\rm Spirals} = f(n\,k) = f\left(n/\sigma^{3}_{\rm cluster}\right) = f\left(T^{-2}\,\Sigma\right)$$

Origin of Helsdon & Ponman morphology-density relation in X-ray groups

can be understood if:

$$\frac{\text{merger rate in groups today}}{\text{merger rate in clusters today}} = \frac{\text{average merger rate in group progenitors}}{\text{average merger rate in cluster progenitors}}$$

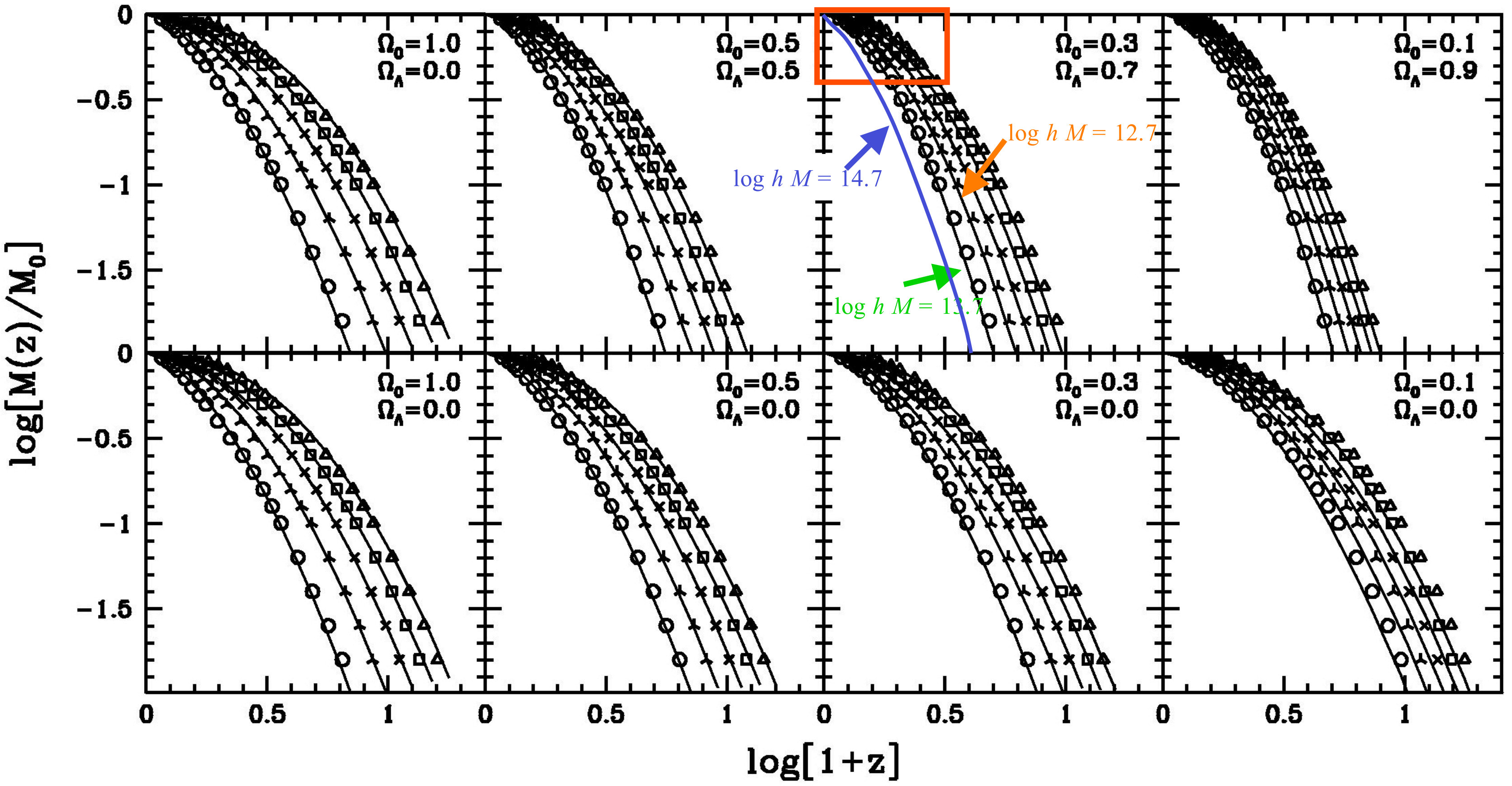
AND

little erasure of morph. segregation during group/group mergers

AND

$$\frac{\text{direct merger rate}}{\text{frictional merger rate}}$$ independent of mass

History of mass accretion



van den Bosch 02

mass accretion of today's groups ≈ mass accretion of today's clusters

Direct mergers vs dynamical friction

$$\tau_{\rm friction} \approx {\rm cst}\,\frac{v^3}{G^2\rho\, m \ln\Lambda}$$

Chandrasekhar 43

$$\tau_{\rm direct} \approx {\rm cst}\,\frac{\sigma_{\rm cl}^3}{G^2 n_* m_*^2}\,{\rm R}(m/m_*)$$

$$\frac{\tau_{\rm direct}}{\tau_{\rm friction}} = 8\pi\,\frac{\rho}{n_* m_*}\left(\frac{\sigma_v}{v_c}\right)^3 \frac{\ln[M(R)/m]}{{\rm R}(m/m_*)/(m/m_*)}$$

scales with group/cluster mass only logarithmically!

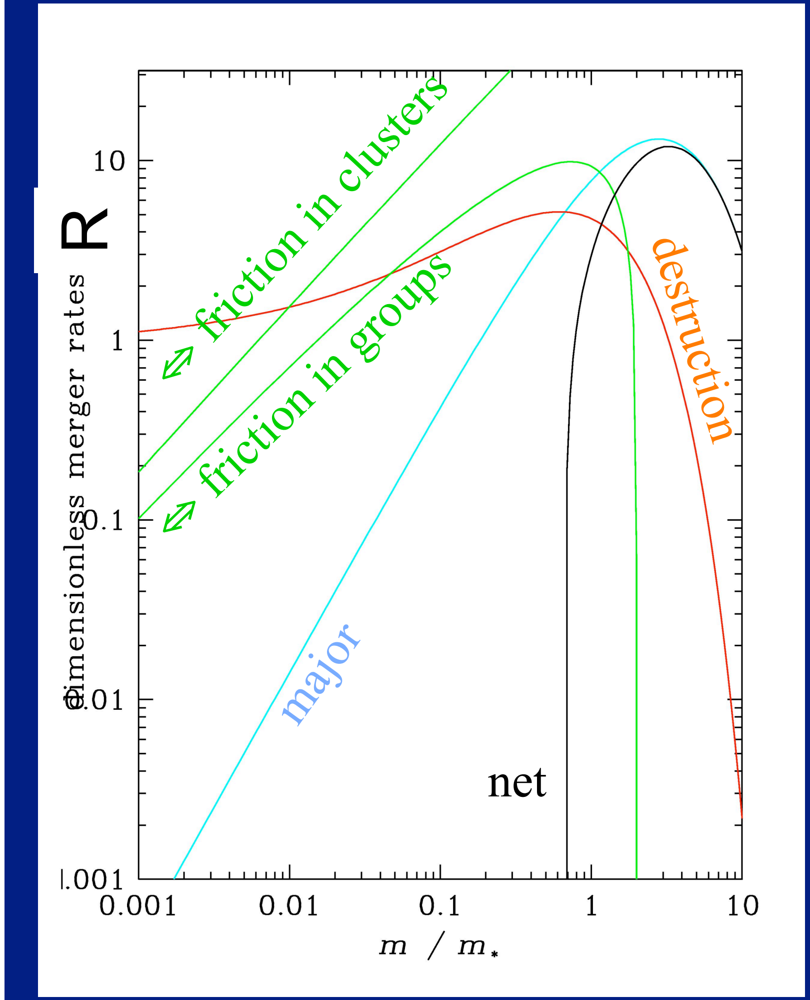
➡ Helsdon & Ponman X-ray group morphology-density relation understood!

Direct mergers vs dynamical friction (ctd)

$$\frac{\tau_{\rm direct}}{\tau_{\rm friction}} = 8\pi\,\Gamma(2-\alpha)\left(\frac{\sigma_{\rm cl}}{v_{\rm circ}}\right)^3 \frac{\ln\left[M(R)/m\right]}{\mathsf{R}\left(m/m_*\right)/\left(m/m_*\right)}$$

$$= \frac{\mathsf{R}_{\rm friction}\left(m/m_*\right)}{\mathsf{R}\left(m/m_*\right)}$$

Merger rates vs. mass



rich clusters:

$m < m_*/100$ ↓ destruction

$m > m_*/100$ ↓ orbital decay

poor groups:

$m < m_*/20$ ↓ destruction

in between ↓ orbital decay?

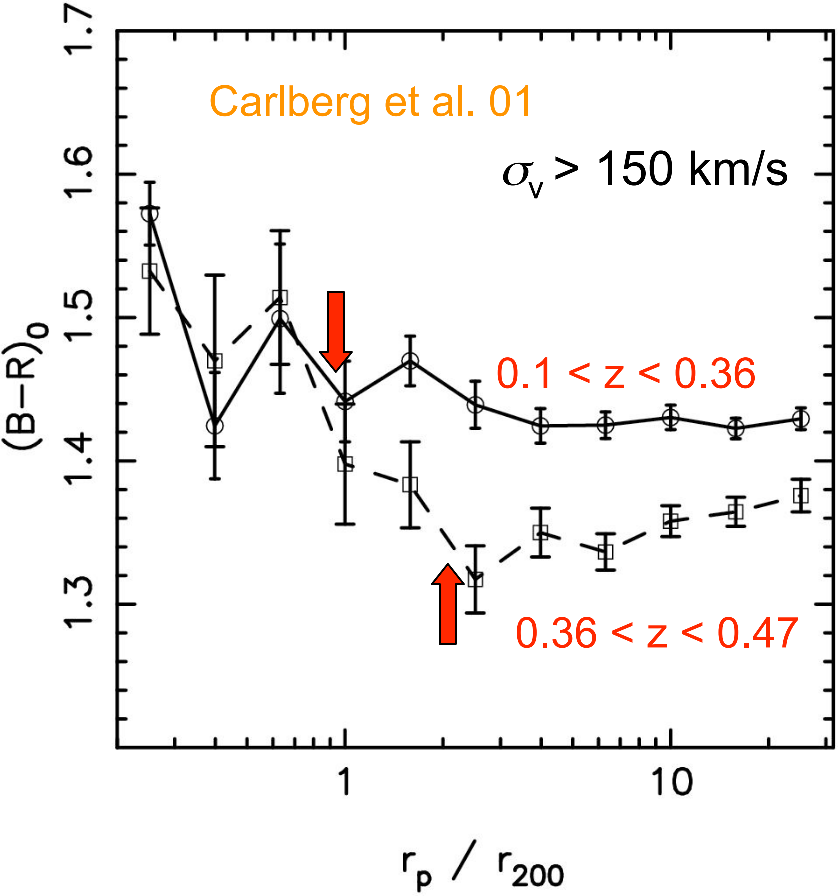
$m > m_*$ ↓ major merger

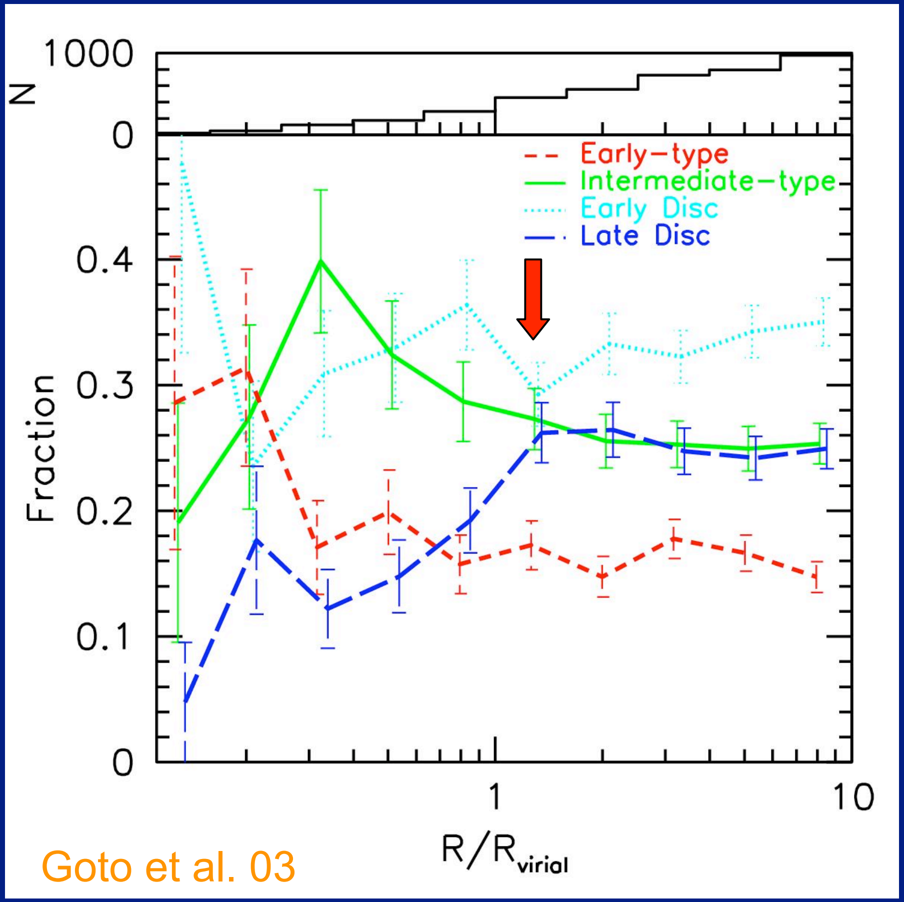
irregular potential: no well-defined center

How far does one see the effects of the group environment?

How far do galaxies bounce out of groups (and clusters)?

Observations vs. normalized radius


Carlberg et al. 01

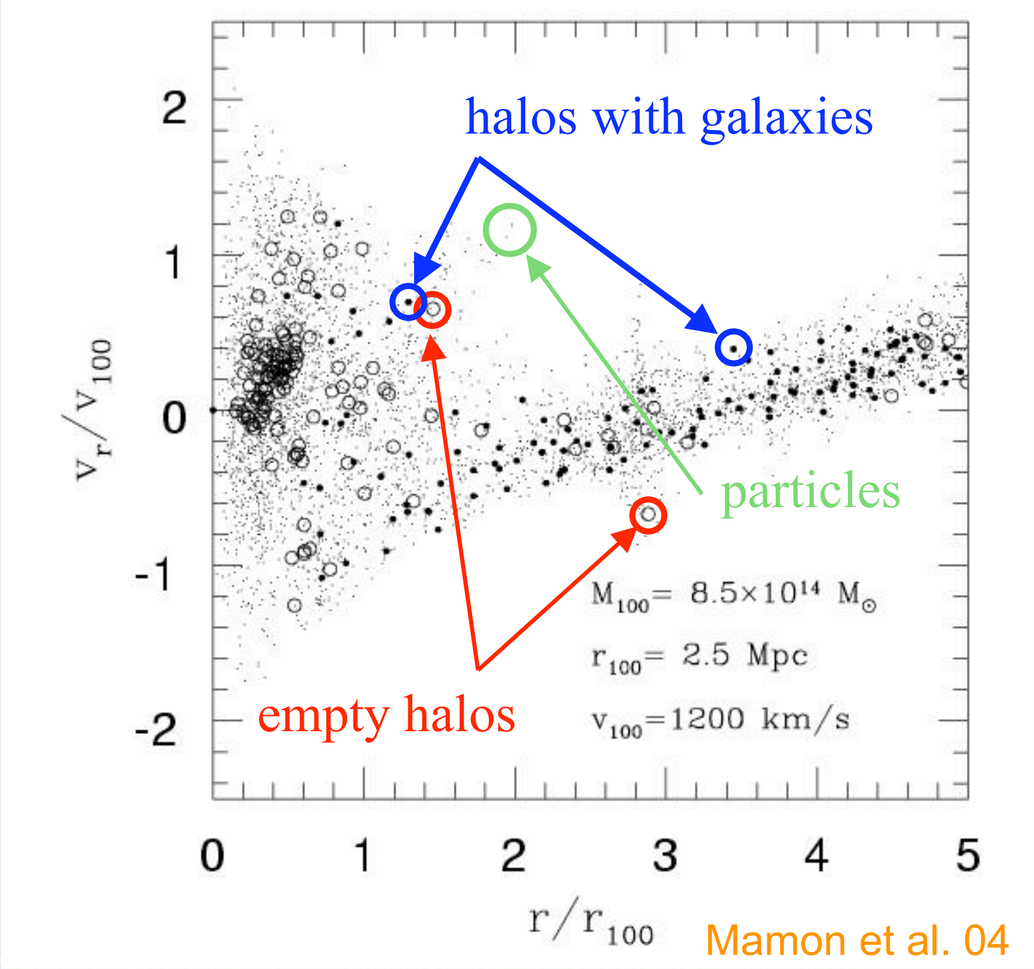

Goto et al. 03

change of colors
& morphological mix at 1-2 r_{200}

Predictions of rebound radius

inside rebound radius material is mixed ⇒ virialized?

$$\Rightarrow \quad r_{\text{rebound}} \approx r_{\text{vir}}$$



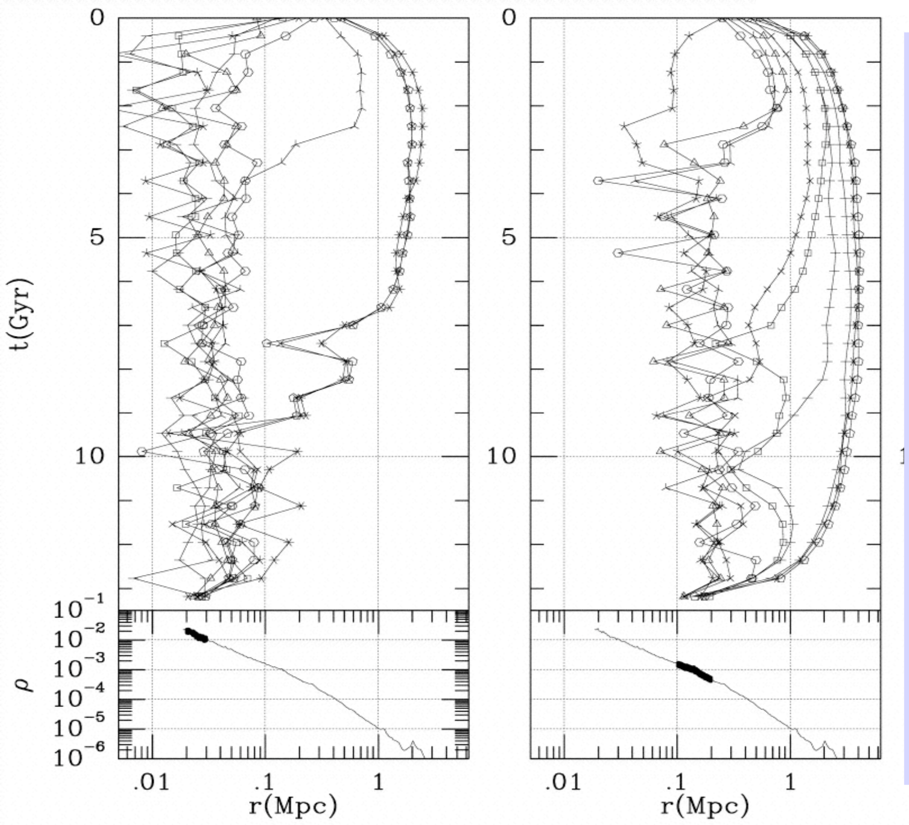
Mamon et al. 04

particles → 2.0 r_{100}

galaxies → 1.7 r_{100}

How far can galaxies bounce out of groups?

Fukushige & Makino 01



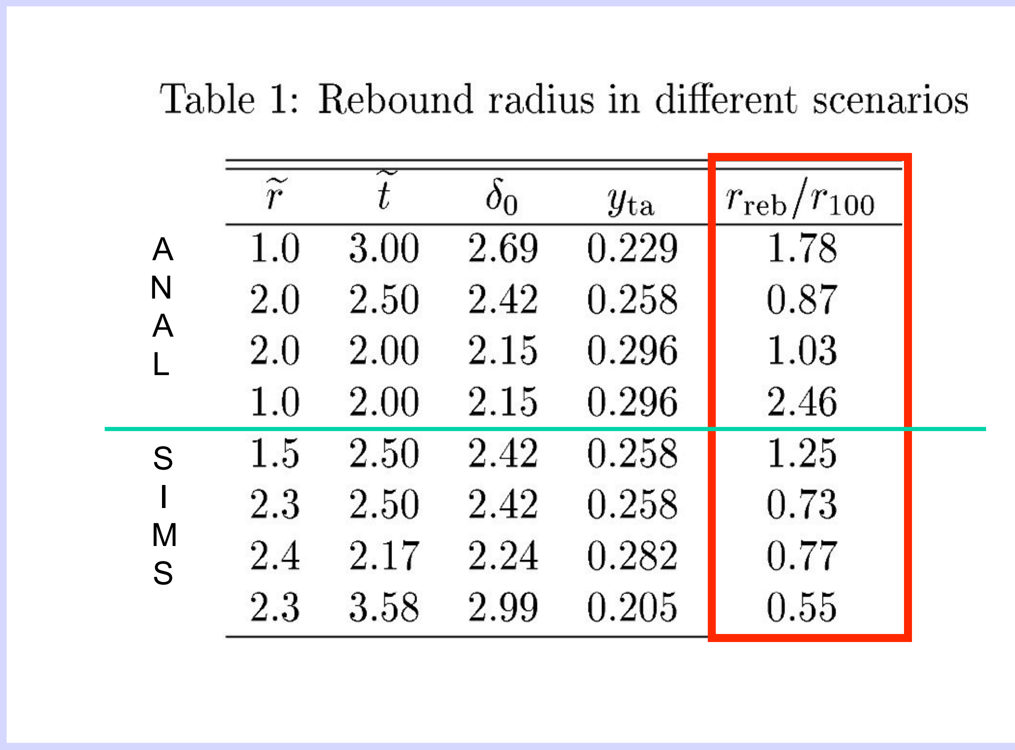


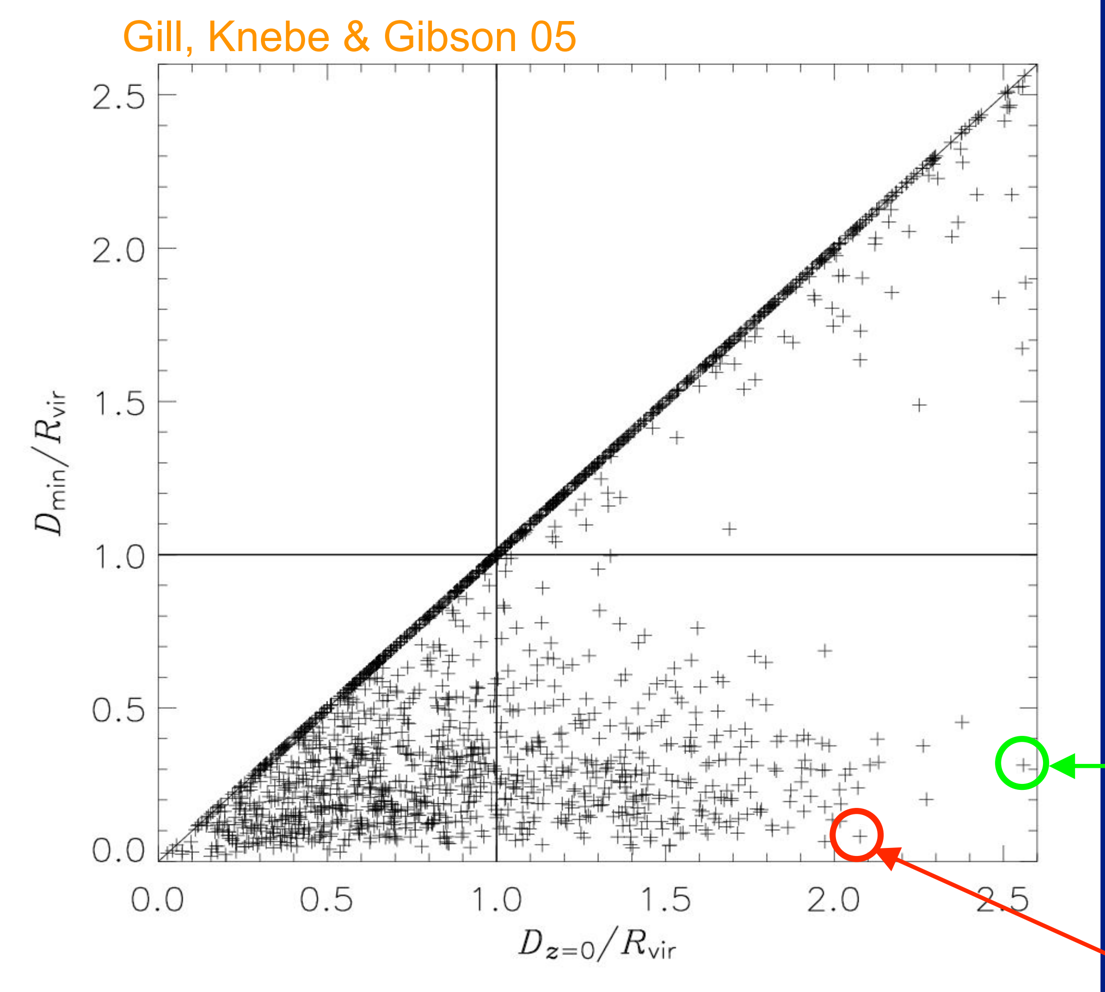
Table 1: Rebound radius in different scenarios

	$\tilde{r}$	$\tilde{t}$	δ_0	$y_{\rm ta}$	$r_{\rm reb}/r_{100}$
ANAL	1.0	3.00	2.69	0.229	1.78
	2.0	2.50	2.42	0.258	0.87
	2.0	2.00	2.15	0.296	1.03
	1.0	2.00	2.15	0.296	2.46
SIMS	1.5	2.50	2.42	0.258	1.25
	2.3	2.50	2.42	0.258	0.73
	2.4	2.17	2.24	0.282	0.77
	2.3	3.58	2.99	0.205	0.55

→ $r_{\rm rebound} = 1 \text{ to } 2.5\, r_{100}$

Mamon, Sanchis, Salvador-Solé & Solanes 04

Following orbits...



$r_{reb} = 2.6\ r_{100}$

penetrating subhalo

$r_{reb} = 2.1\ r_{100}$

deeply penetrating subhalo

Group internal kinematics

ongoing …

with Andrea Biviano (*Trieste*)
& Trevor Ponman (*Birmingham*)

Data

GEMS: groups pointed at with X-ray telescopes:
→ group centers, temperatures
→ classes:

G = group emission
H = galaxy « halo » emission
U = undetected

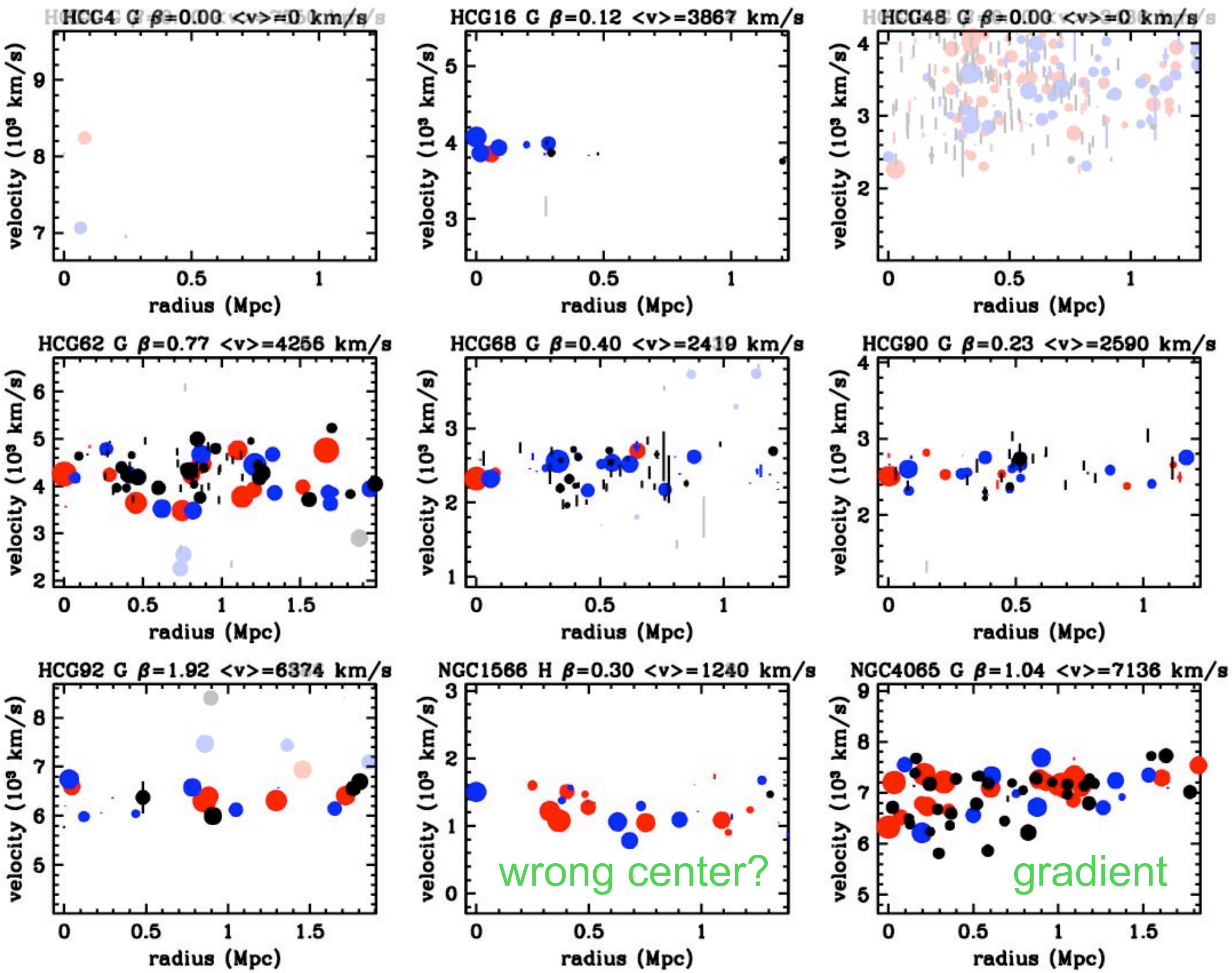
NED: incl. *SDSS-DR4*, *6dFGS-DR2*

$\theta < 2\ \theta_{vir}$ from Max(σ_v,300 km/s)
$|v-v_{group}| < 3$ Max(σ_v,300 km/s)

→ galaxy velocities (& errors), morphological types

2MASS: galaxy K-band magnitudes

Interloper removal



wrong center?

gradient

Which is the best method to estimate the virial radius?

from group velocity dispersion

→ pure NFW
$$\boxed{\frac{h_{70}\,r_\Delta}{1\mathrm{Mpc}} \approx \sqrt{\frac{200}{\Delta}}\,\frac{\sigma_v}{490\,\mathrm{km/s}}}$$
« sigvnfw »

→ cosmological M-σ_v « Borgani »

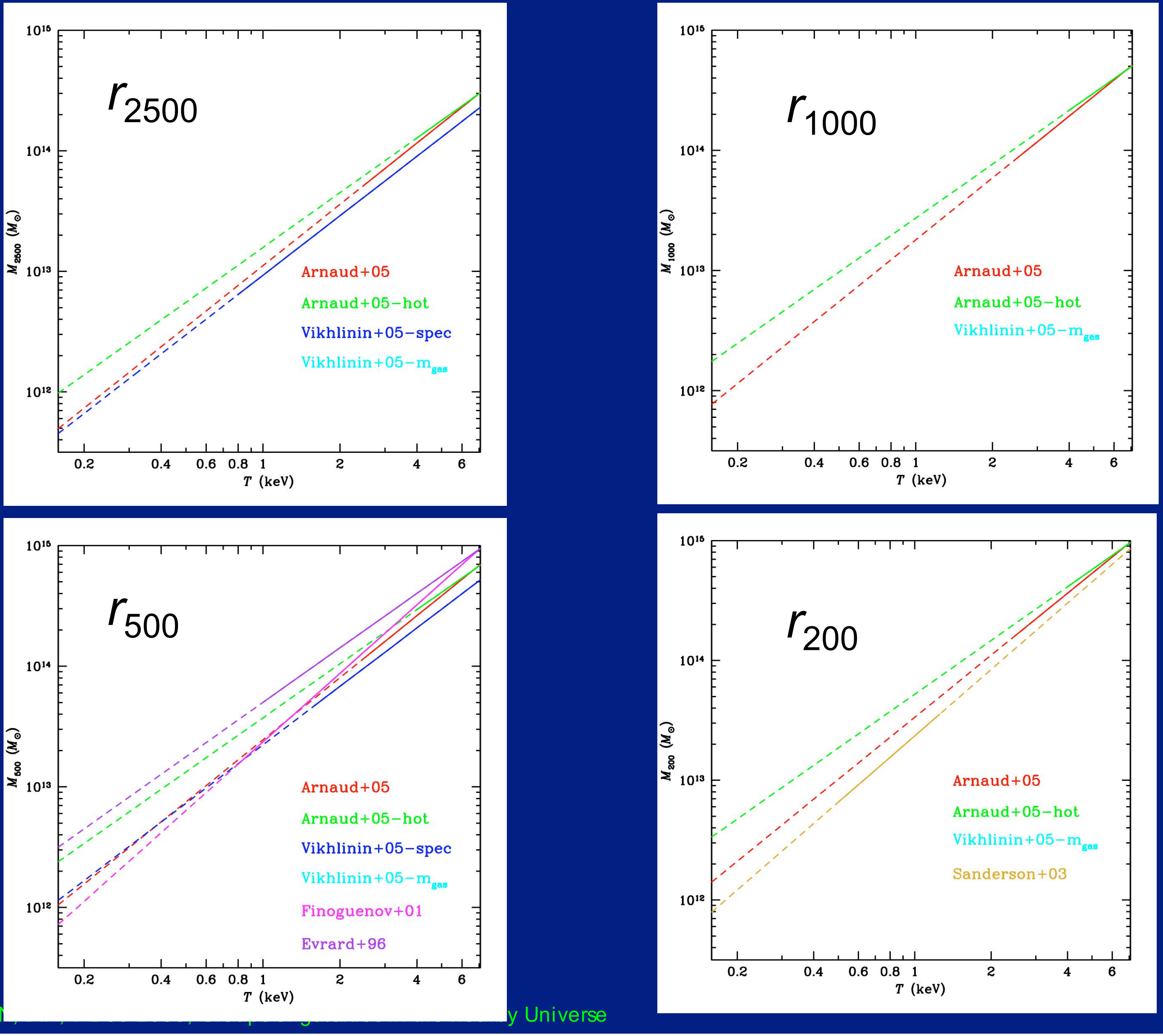
from temperature
$$\boxed{\frac{h_{70}\,r_\Delta}{1\mathrm{Mpc}} \approx \sqrt[3]{\frac{200}{\Delta}\,\frac{h_{70}\,M_\Delta}{1.14\times 10^{14}\,M_{\mathrm{sun}}}}}$$

M_Δ from *M*-*T* relation

from *K*-luminosity Lin, Mohr & Stanford 03

corrected for incompleteness
calibrated on *M*-*T* relation of Finoguenov et al. 01

Mass - temperature relations



Computing line-of-sight velocity dispersion profiles

from data:

stack groups:, normalize radii to $r_{\rm vir}$ & velocities to $v_{\rm vir}$

unweighted or weighted

equal number of galaxies / radial bin

(omitting central galaxy)

Prugniel & Simien 97

from (NFW) model: $\beta = 0$:

$$I(R)\,\sigma^2_{\rm los}(R) = 2G\int_R^\infty \frac{\sqrt{r^2-R^2}}{r^2}\,\nu(r)\,M(r)\,dr$$

E/S0s in clusters: *Coma* Lokas & Mamon 03; *ENACS* Biviano & Katgert 04

for some simple $\beta(r)$

$$I(R)\,\sigma^2_{\rm los}(R) = 2G\int_R^\infty \boxed{K(r,R)}\,\nu(r)\,M(r)\,dr$$

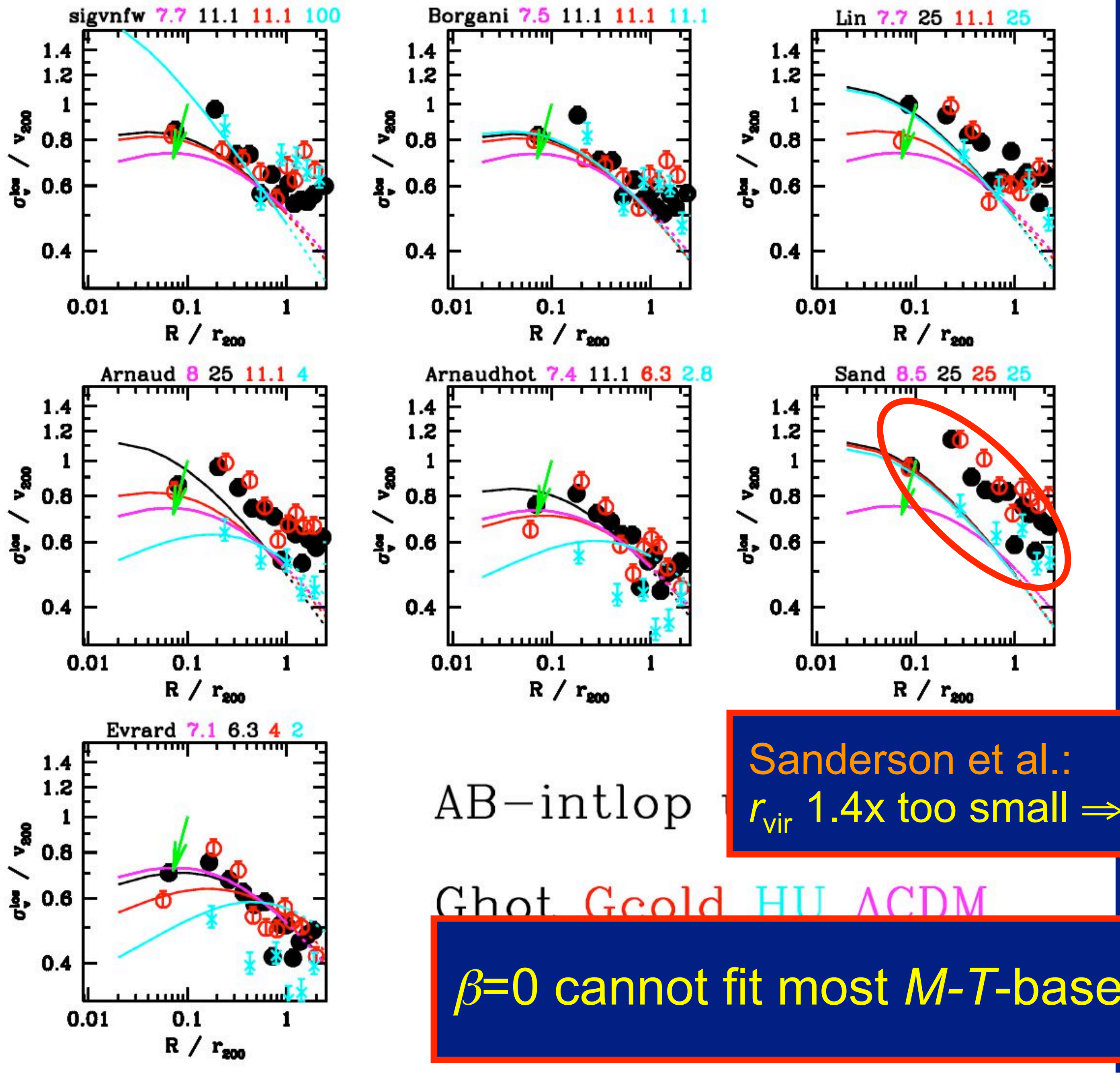
Mamon & Łokas 05b

$$\text{e.g.}\ \beta = \frac{1}{2}\,\frac{r}{r+a}$$

Mamon & Łokas 05b

tracer density ∝ mass density or fit separately $\nu(r)$ & $\rho_{\rm tot}(r)$

Line-of-sight velocity dispersion profiles of groups



Rvir ↑ x1.4

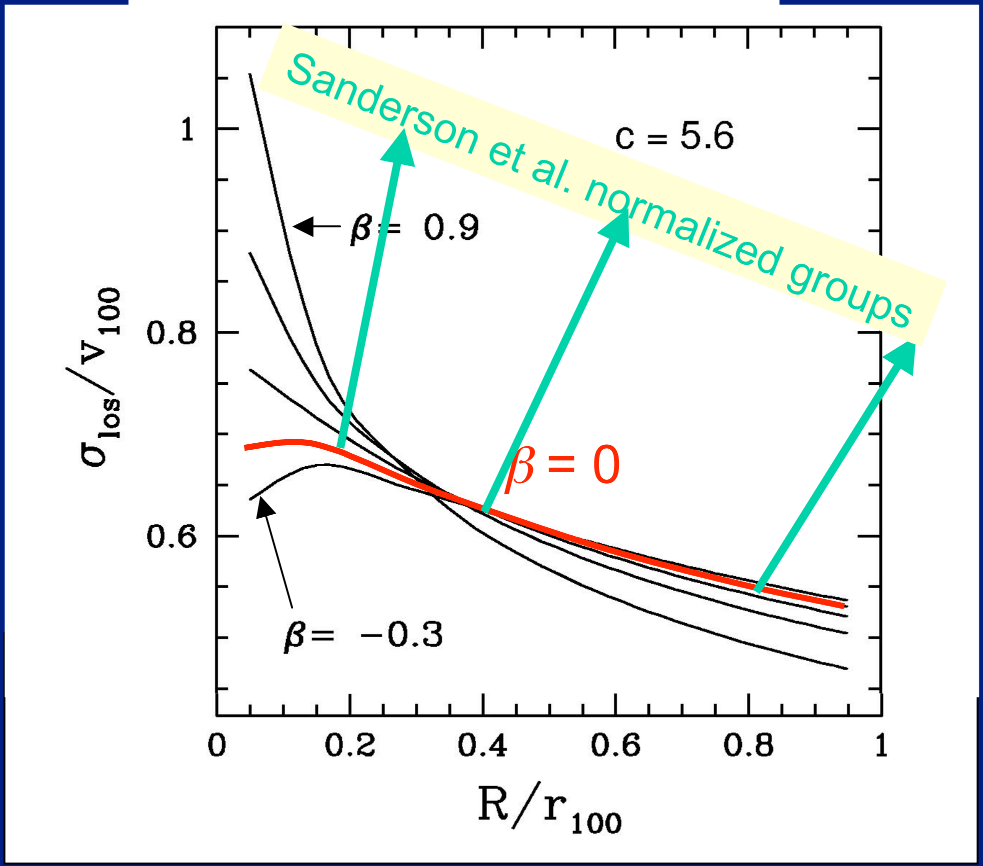
G_{hot}: T>0.82 keV
G_{cold}: T<0.82keV

Sanderson et al.:
r_{vir} 1.4x too small ⇒ M_{vir} 3x too small

β=0 cannot fit most M-T-based r_{vir}'s!

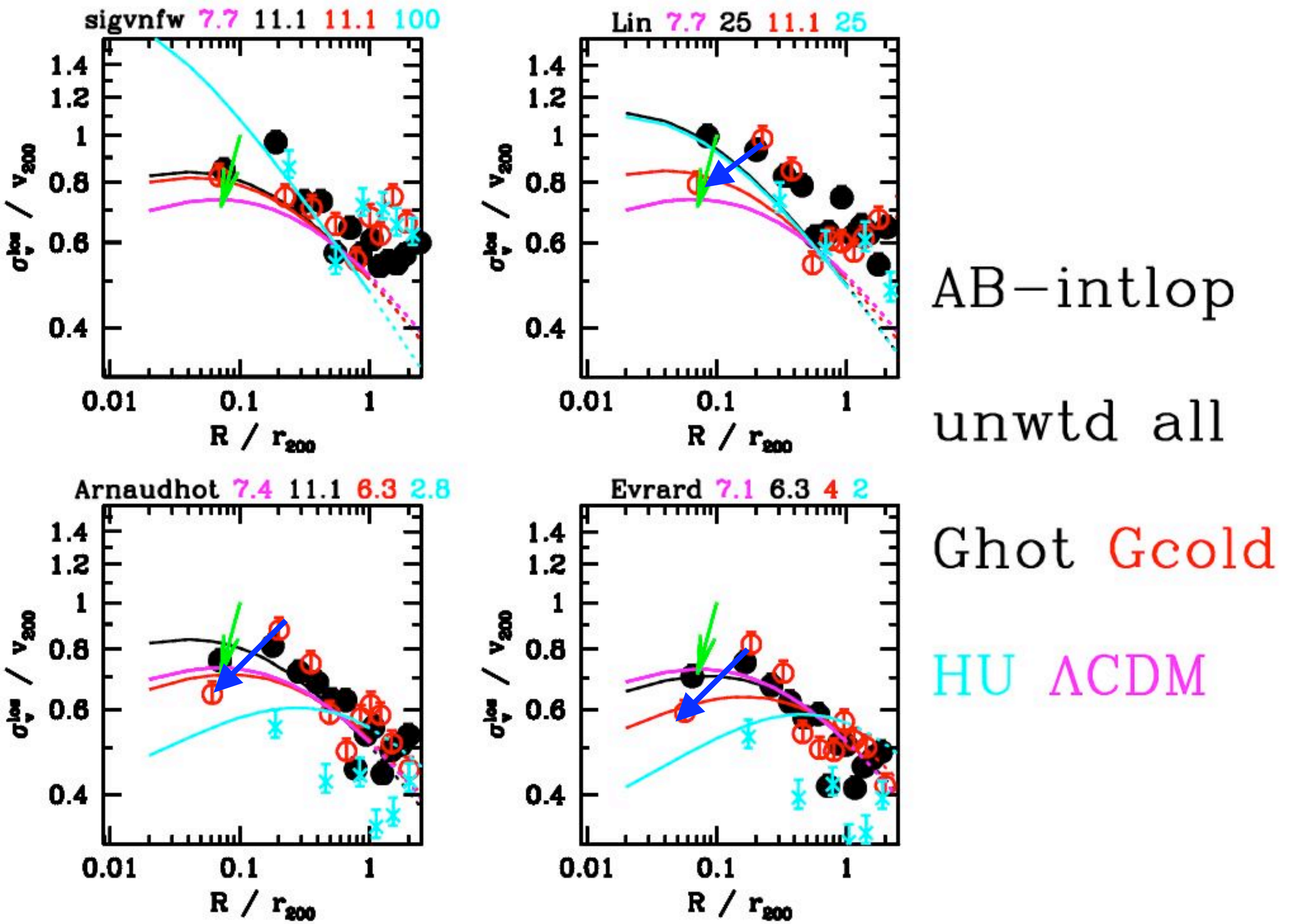
Do different anisotropy help the extreme M-T based r_{vir}'s?

Sanchis, Łokas & Mamon 04



→ No!

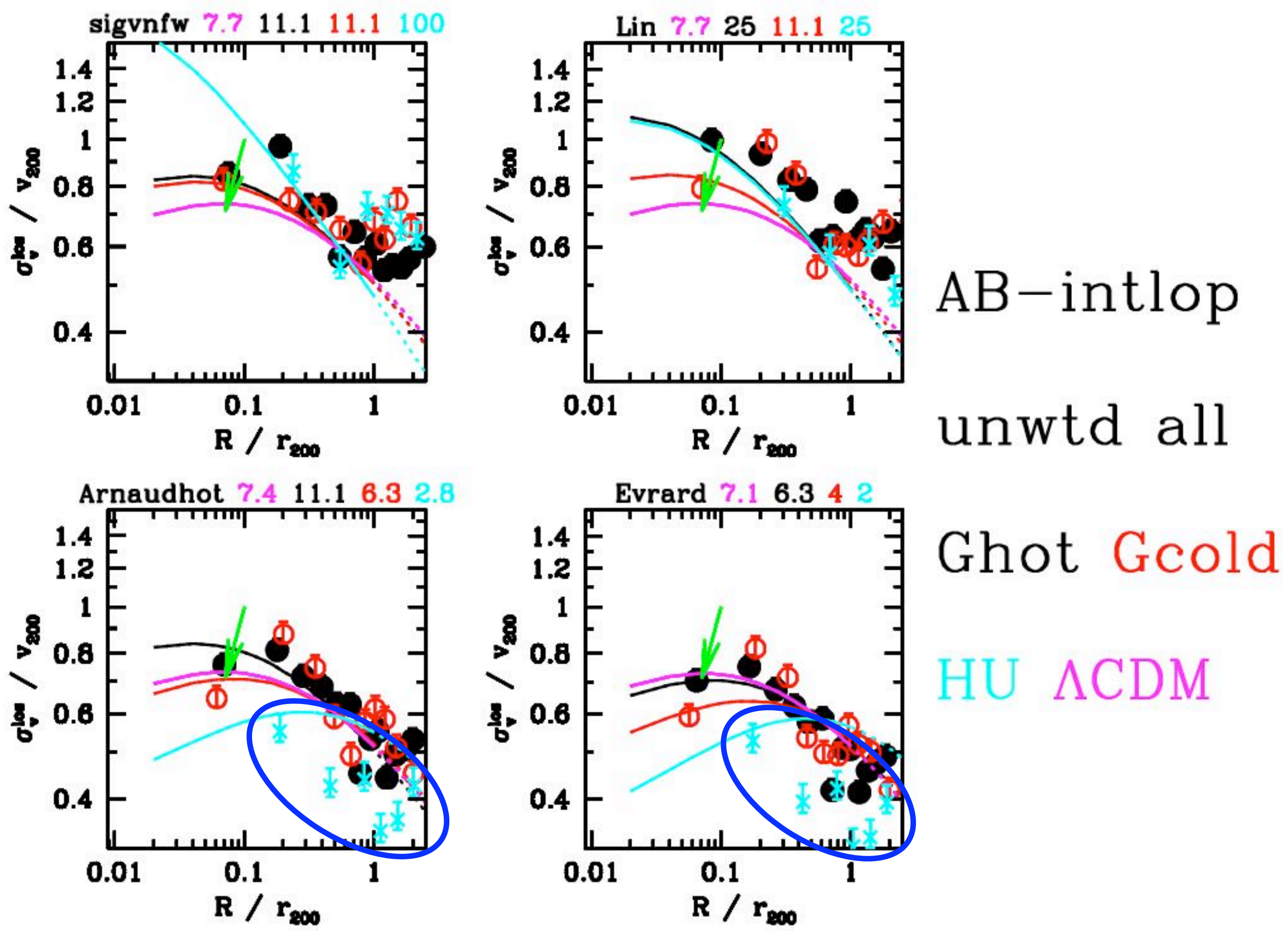
Hot vs cold G groups



cold G groups: dispersion drop near center?

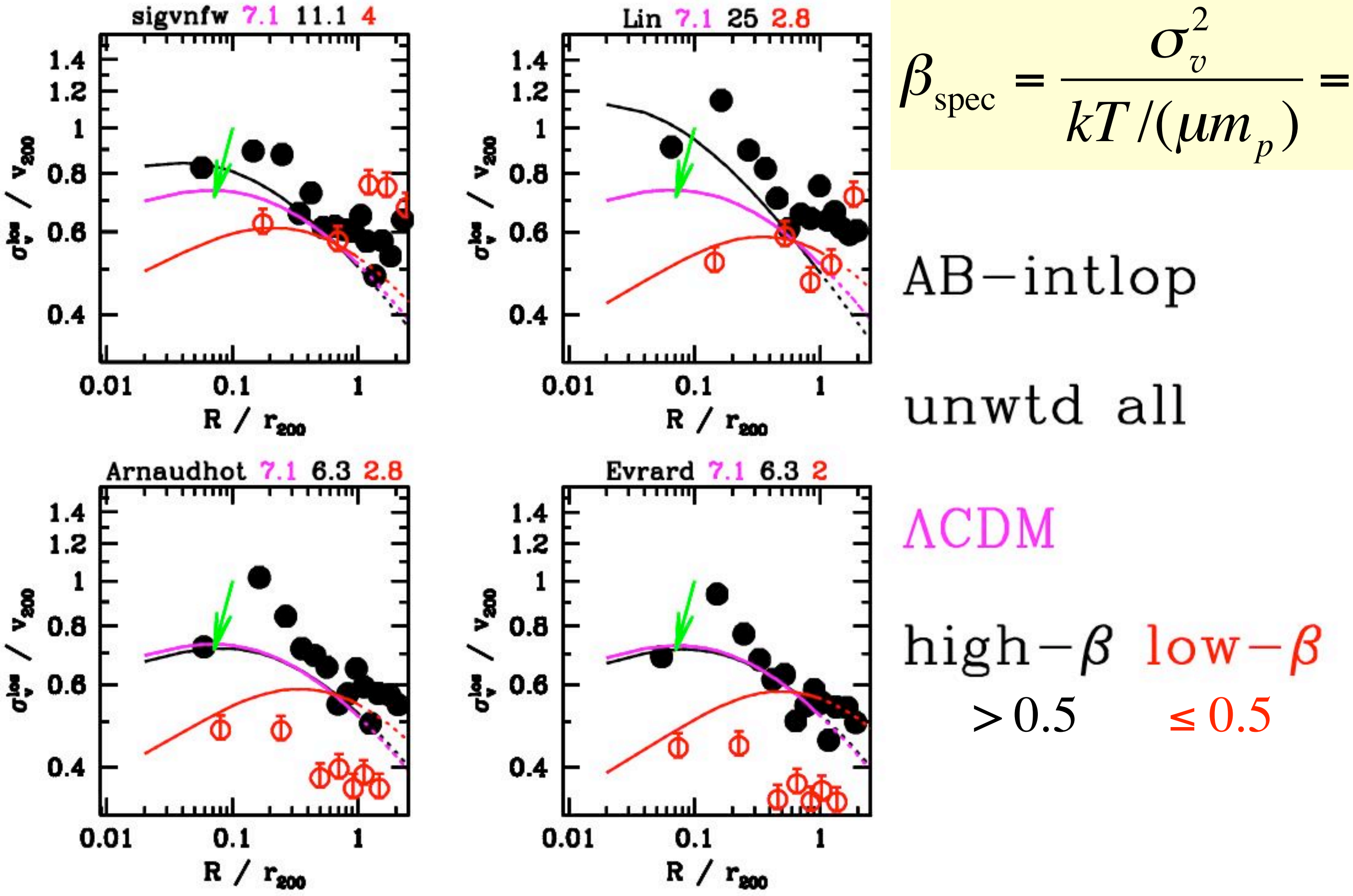
energy dissipation in coalescing compact cores?

Temperature of H groups



Temperature of central galaxy of H groups
overestimates T_{group} by factor 2

High vs low β_{spec} groups

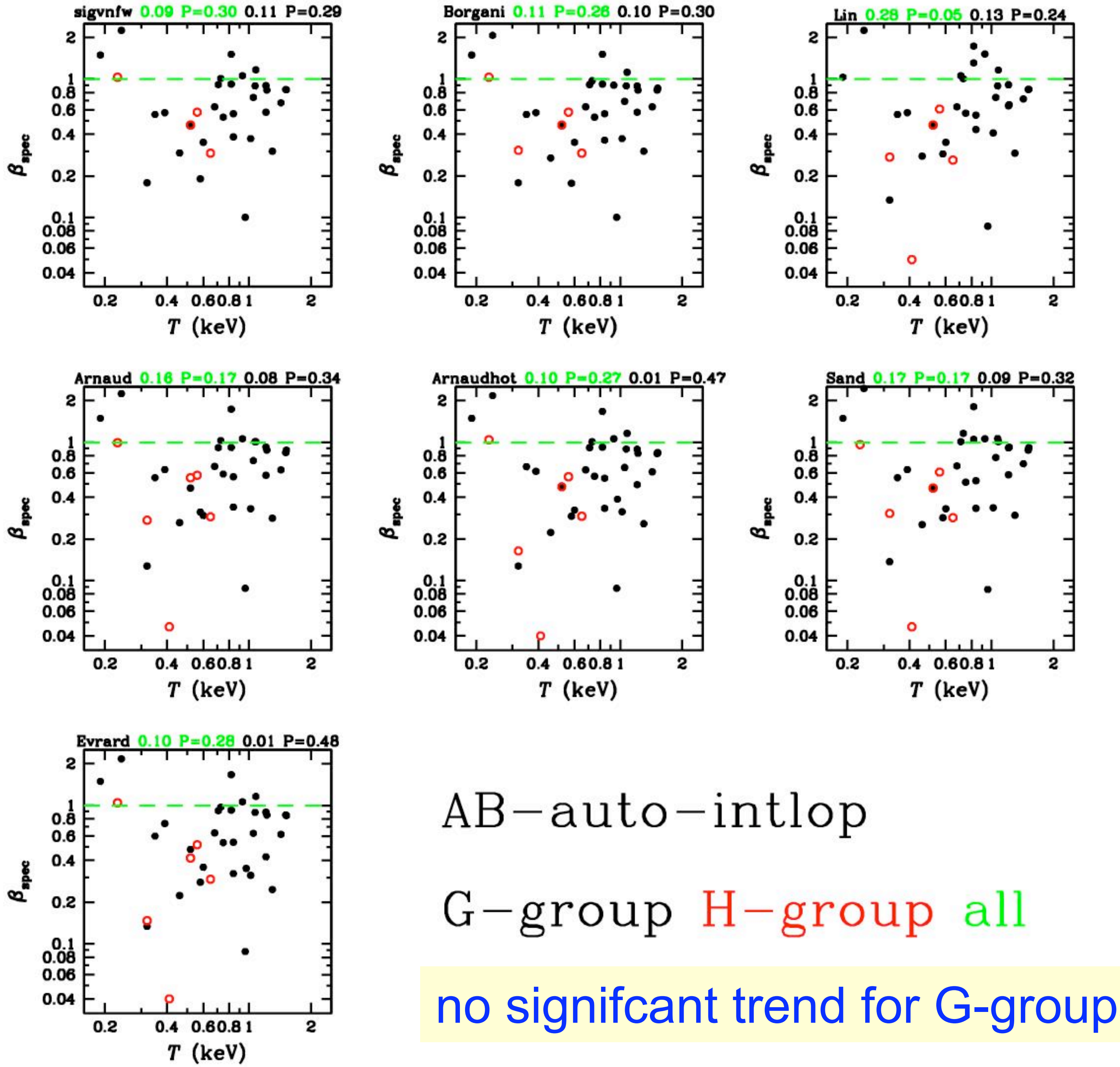


$$\beta_{\rm spec} = \frac{\sigma_v^2}{kT/(\mu m_p)} = \frac{\left(\sigma_v / 406\,{\rm km/s}\right)^2}{T/1\,{\rm keV}}$$

Girardi et al. 03

low-β dispersions stacked by T-based r_{vir} → too low
⇒ low β caused by high (x2.5) T!!

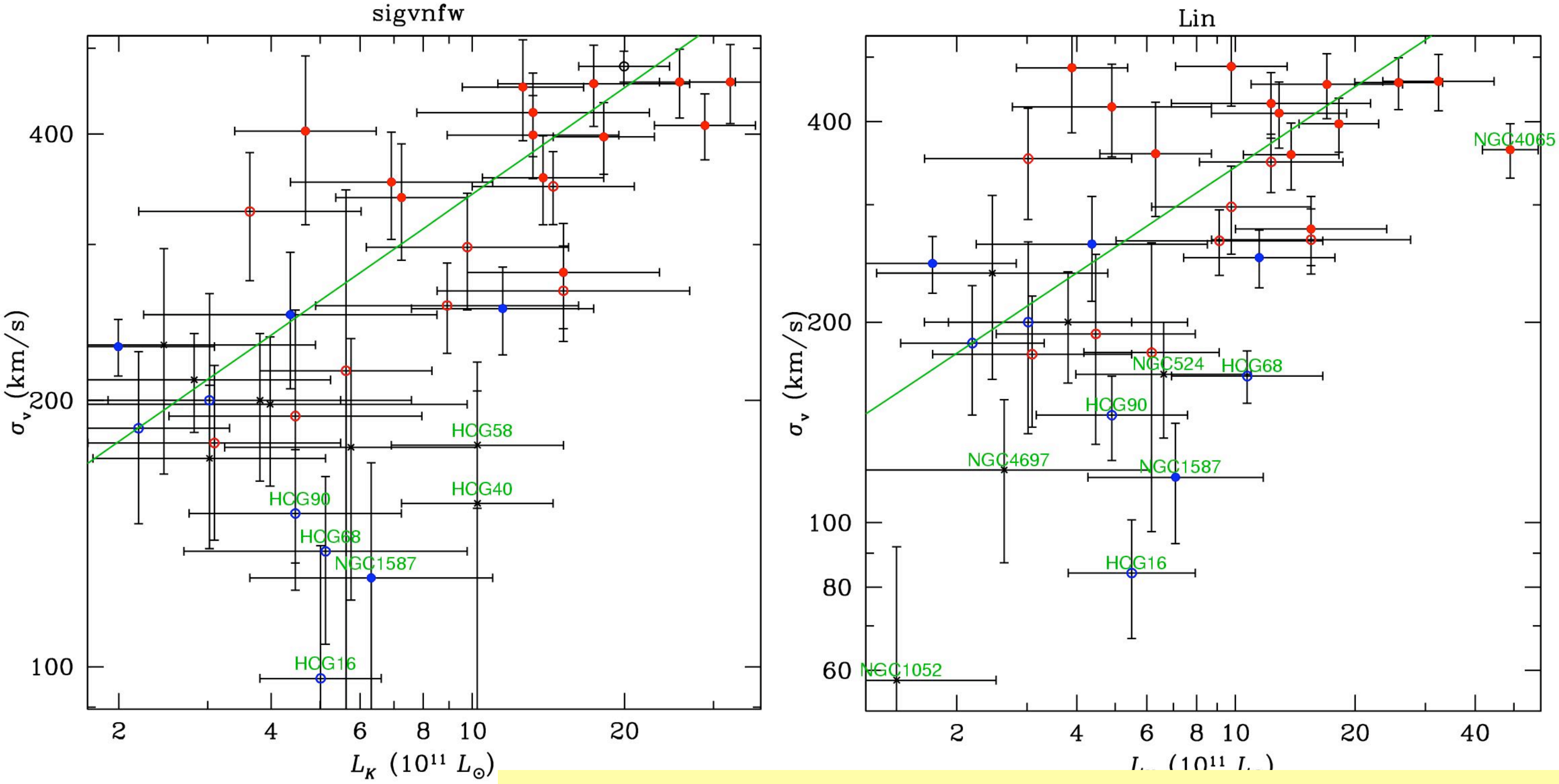
low β → less concentrated mass (or circular orbits?)



no signifcant trend for G-groups!

Stellar mass - velocity dispersion

hi-β		low-β
●	**G**roup em.	●
○	**H**alo em.	○
×	**U**ndetected	×

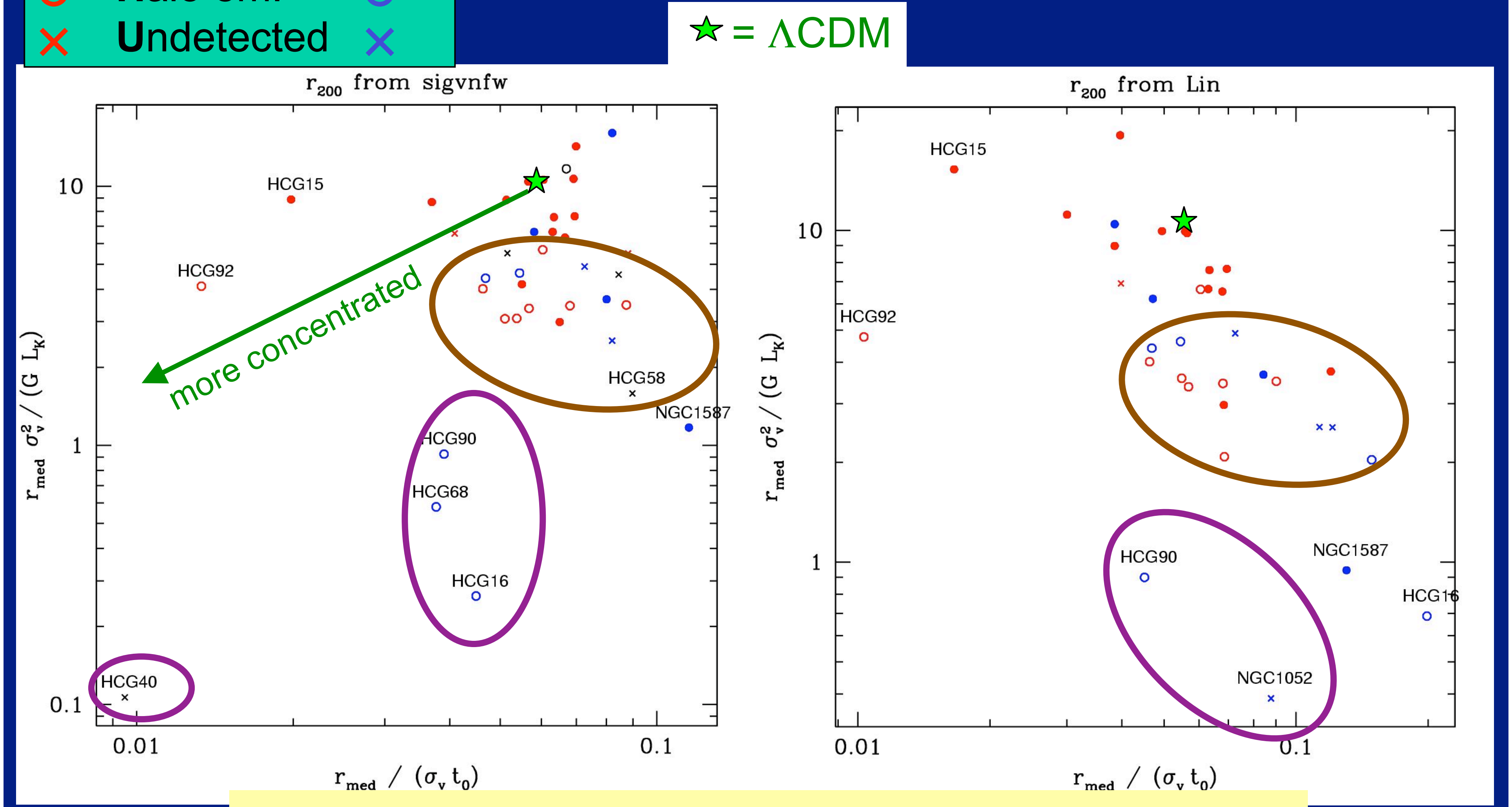


strong outliers have no X-ray detected group emission

most low β G groups have normal velocity dispersion

Fundamental track

hi-β		low-β
●	Group em.	●
○	Halo em.	○
×	Undetected	×



outliers have no X-ray detected group emission

undetected (H+U) groups less concentrated

Conclusions

CGs form at fast enough rate to replenish fossilized ones

Massive galaxies in groups suffer more direct than frictional mergers

Morphology-density relation difference between
X-ray groups and clusters is as expected from mergers

Group environment felt out to ~ 2 r_{200}

No break in M-T relation

Low T groups may show energy dissipation near center

Low β groups caused by high T & much less concentrated
(or in circular orbits) → recent group-group mergers

Outliers in L_K-σ_v & fundamental track:
coalescing or chance alignments?