Virialized Groups
& Compact Groups of Galaxies

nearest compact group of galaxies (around M60 in Virgo) SDSS

Virialized Groups
& Compact Groups of Galaxies

with

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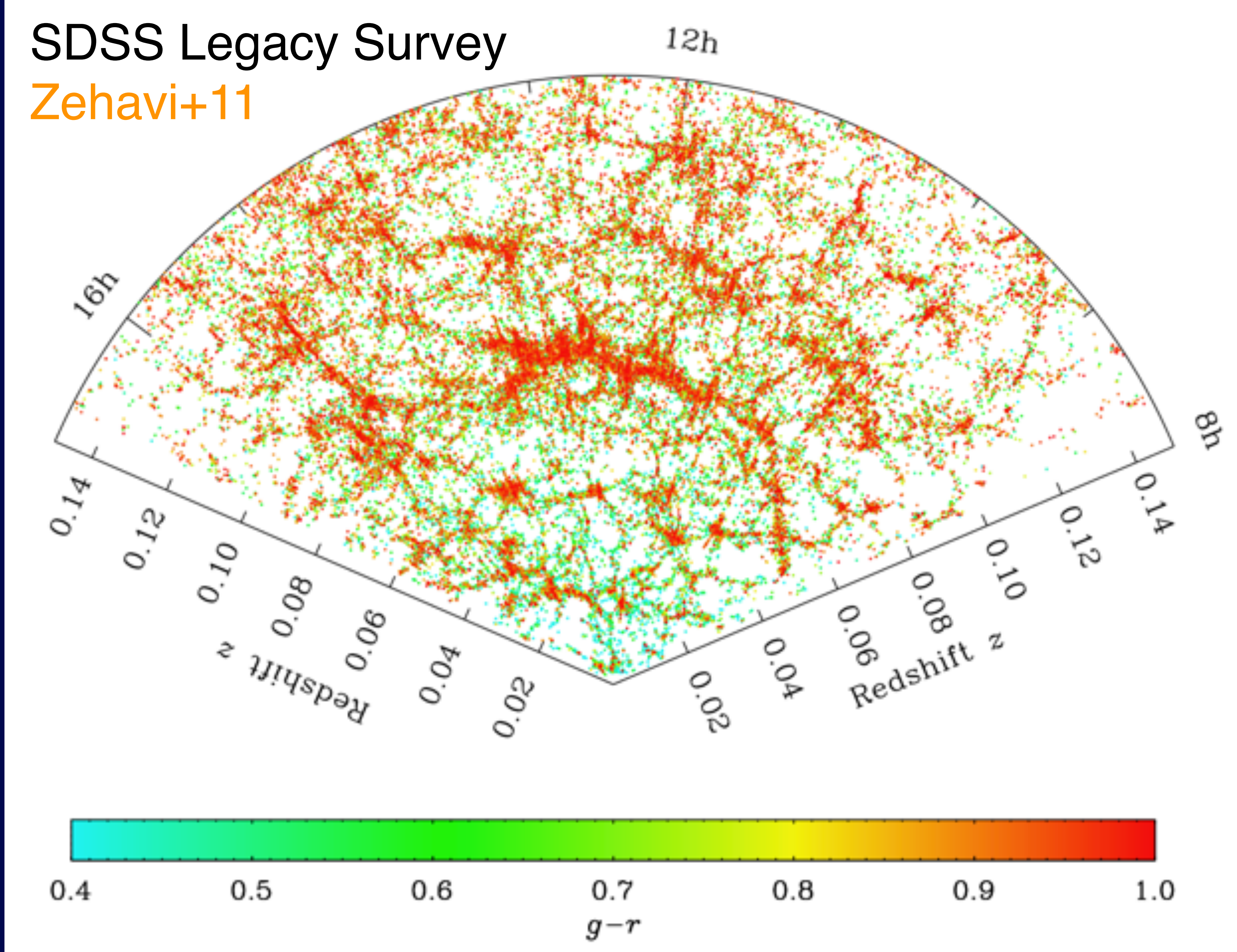
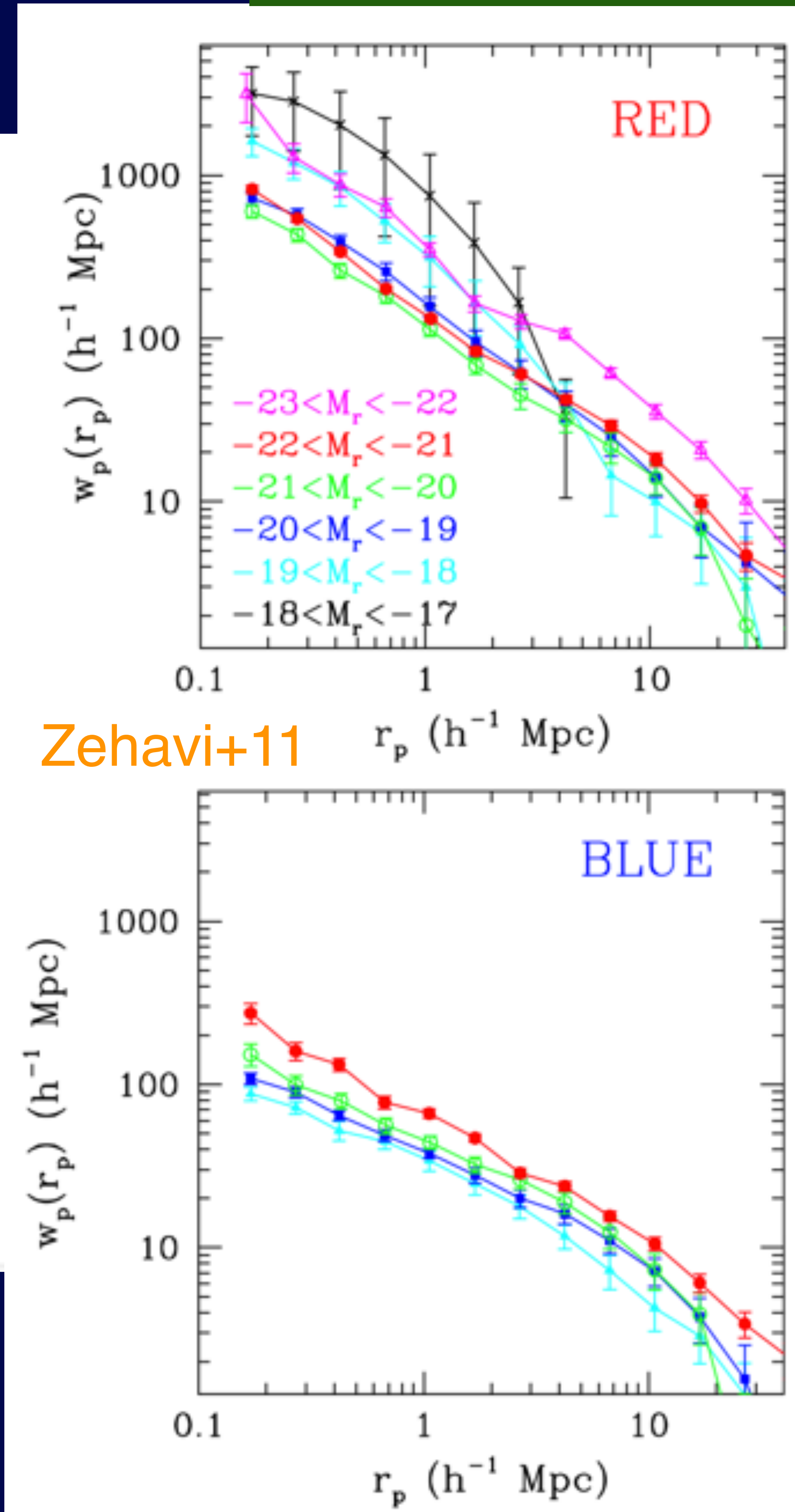
Galaxies cluster on small scale: especially red ones

Galaxy 2-point correlation functions

SDSS Legacy Survey

Zehavi+11





Zehavi+11

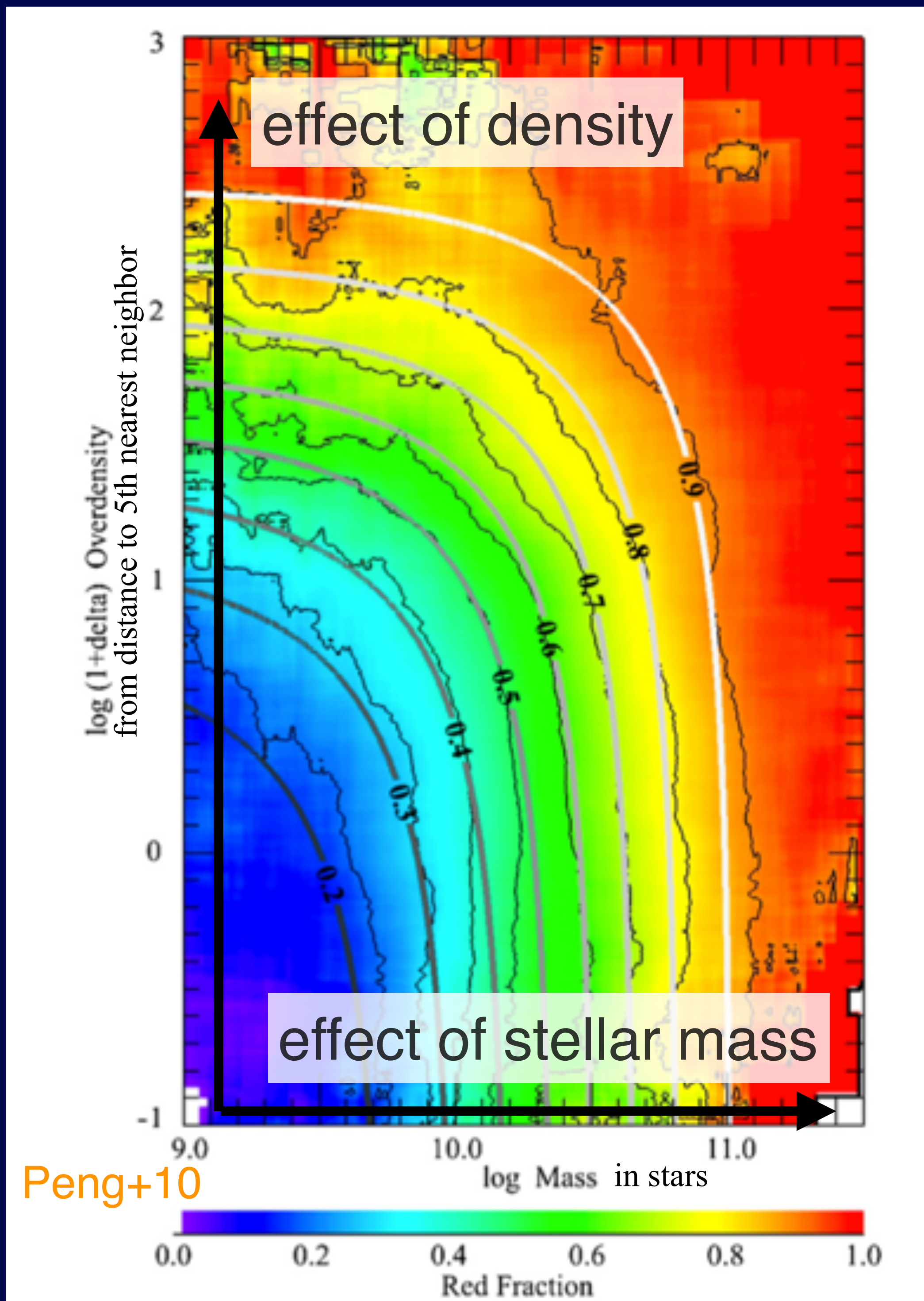
Motivations

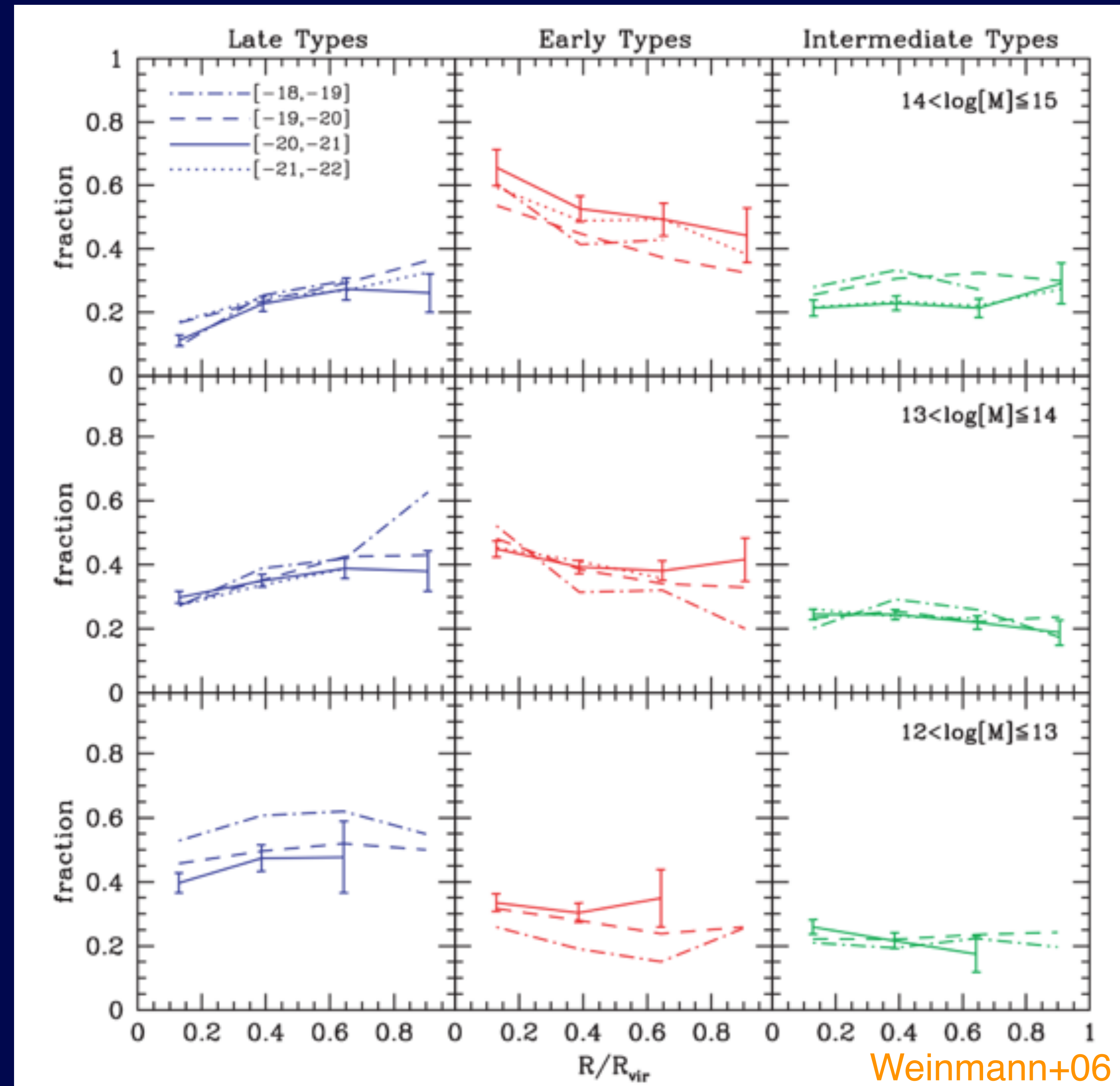
~50% of galaxies in groups log $M/M_\odot$ = 12 to 14,
5% in clusters, log $M/M_\odot$ = 14 to 15.5

Groups (& Clusters) =

- Laboratories for gas astrophysics on large scales
  infall, bubbles from AGN & SNe, shocks, …
- Laboratories for environmental effects on galaxies
  tidal stripping, ram pressure stripping, mergers, harassment, …
- Probes of Dark Matter
  normalization, concentration, galaxy orbits, …
- Cosmographic tools
  Ω_m, σ_8, dark energy (w_0, w_a), …

Effects of galaxy environment on red galaxy fraction





Peng+10: red fraction boosted at hi density (for lo $M_{\rm stars}$) or hi $M_{\rm stars}$ (at lo density)

Weinmann+06: red fraction boosted at hi group mass & for innermost satellites (even at hi $M_{\rm stars}$!)

Defining the environment

- N^{th} nearest neighbor

  → mixes global and local environment!

- Friends of Friends (FoF) Turner & Gott 77; Huchra & Geller 82; Berlind+06

  → filamentary groups Moore, Frenk & White 93

- FoF + X rays

- Bayesian NFW profiles... Yang+07; Domínguez-Romero+12

- Compact groups $N \geqslant 4$ within 3 mags Hickson 82; Hickson+92; McConnachie+09; Díaz-Giménez+12

How are galaxies affected by their environment?

Global environment: group mass

Local environment: galaxy position within $r_{\rm vir}$ $\quad \frac{\delta\rho}{\rho_{\rm cri}} = 200$

↓

SSFR, morphologies, metallicity, presence of AGN, etc.

Large-mass galaxies: fraction of high SSFR

* not affected by environment (5th nearest neighbor) Peng+10
* slightly affected by local environment

Weinmann+06; von der Linden+10

Poor measure of environment can blur environmental effects!

How are galaxies affected by their environment?

Global environment: group mass

Local environment: galaxy position within $r_{\rm vir}$ $\frac{\delta\rho}{\rho_{\rm cri}} = 200$

↓

SSFR, morphologies, metallicity, presence of AGN, etc.

Compact group environment: isolated & $\frac{\delta\rho}{\rho} > 10^5$

⇒ ideal laboratories for galaxy interactions & mergers?
quenched or tidally triggered star formation?

Defining a Compact Group

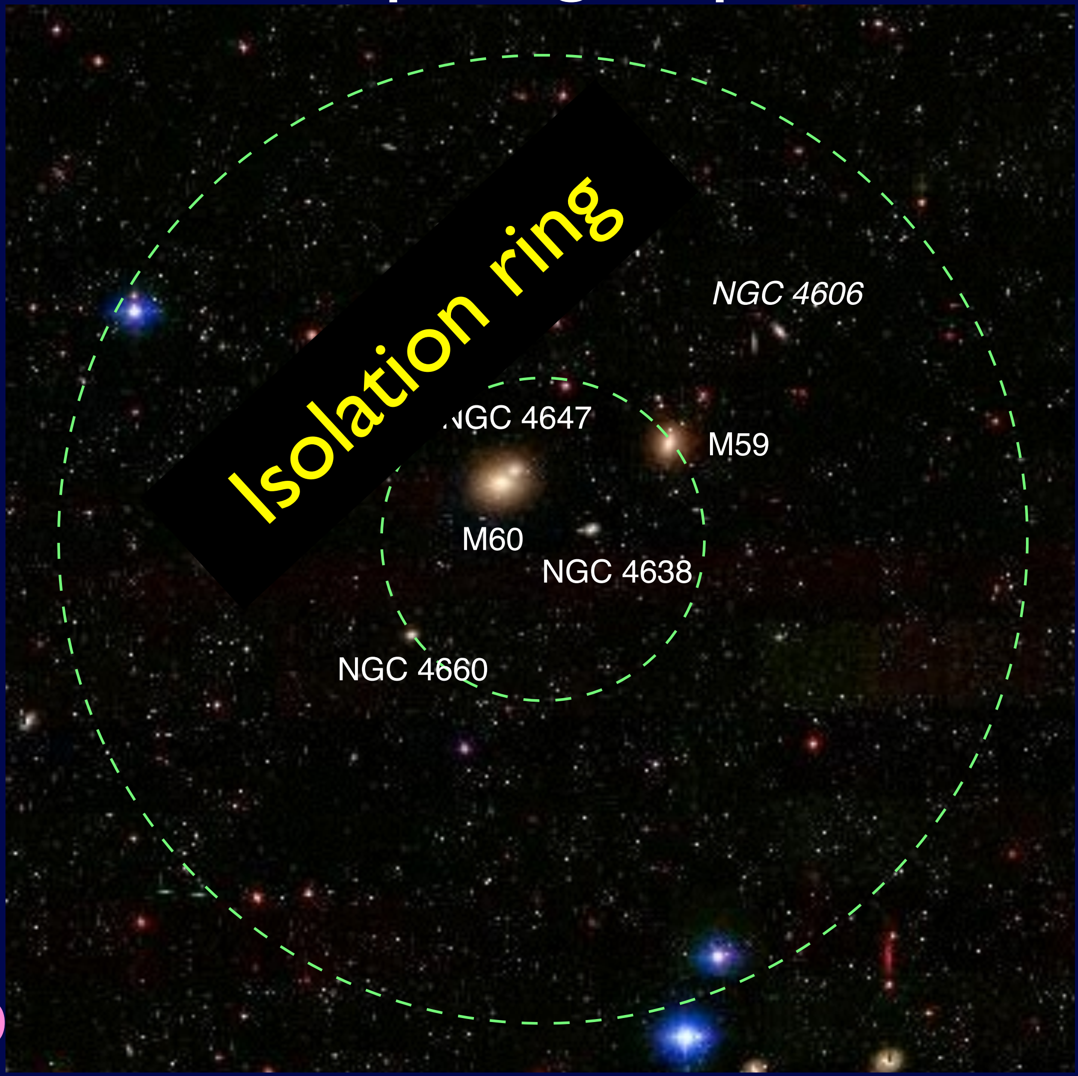
Hickson 82

- Compact: $\mu_R < 26$
- Rich: $N \geq 4$ within R_1, R_1+3
- Isolated: empty ring within R_1, R_1+3

100 HCGs

brightest magnitude in group

Nearest compact group Mamon 08



Hickson et al. 92

Accordant velocities: $| v - \langle v \rangle | < 1000$ km/s

67 (not 92) HCGs with $N \geq 4$ accordant velocities

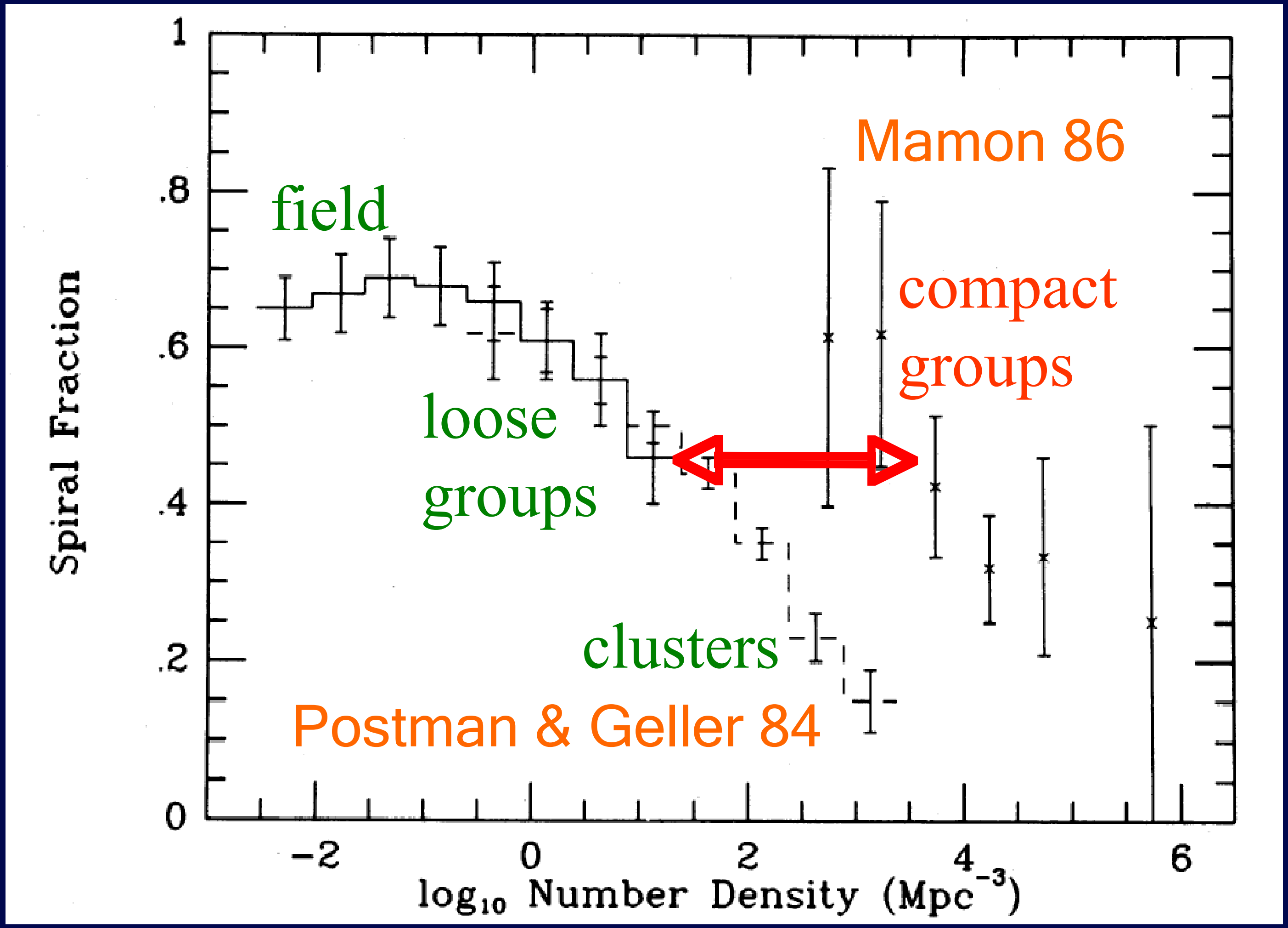
Are most compact groups chance alignments of galaxies?

Mamon 86, 87

- Dense groups transform rapidly into fossil groups (mergers → magnitude gap), while HCGs have no magnitude gaps
- Dense groups rapidly develop luminosity segregation, while HCGs show none
- Chance alignments are frequent in N-body simulated normal groups & predicted analytically Walke & Mamon 89
- HCGs do not obey universal morphology-density relation

Galaxy morphologies in Hickson Compact Groups

morphology-density relation: offset from typical environments



but even stronger correlation with CG velocity dispersion

Hickson & Rood 88

Five questions on z≈0 groups

1) Can we build a much better *group finder* than the optimal FoF?
hope to find stronger environmental effects

2) Is there a *complete* compact group sample?
vs. HCG Hickson 82; Hickson+92

3) How do CG galaxies relate to CG *environment*?
morphology – density – velocity dispersion – …

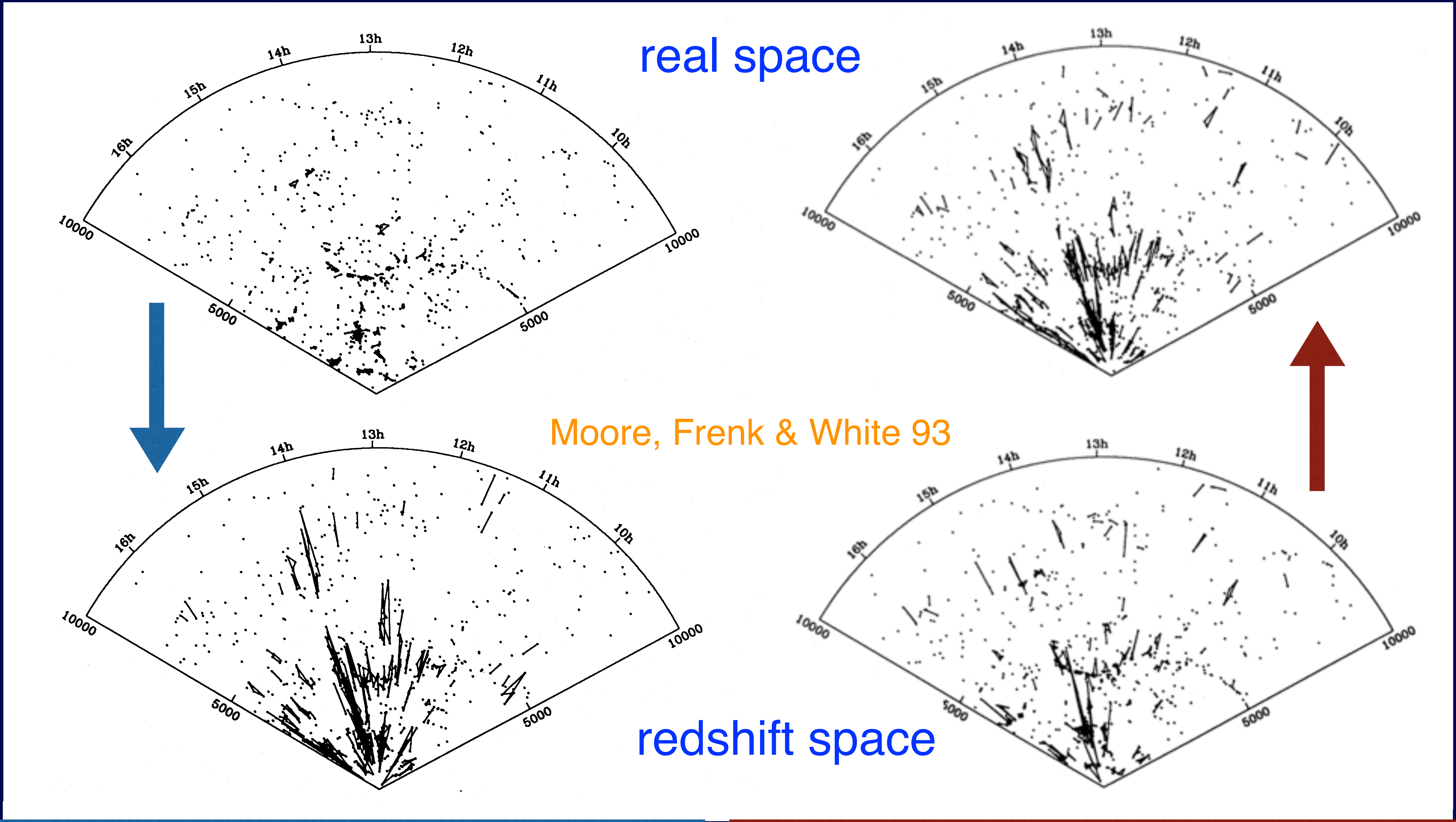
4) What is the *nature* of compact groups?
chance alignments of galaxies vs physically dense

5) How do compact groups *assemble*?
early collapse? late arrival of 4th galaxy?
slow contraction of core of virialized group?

1) Can we build a much better group finder than the optimal FoF?

Manuel DUARTE

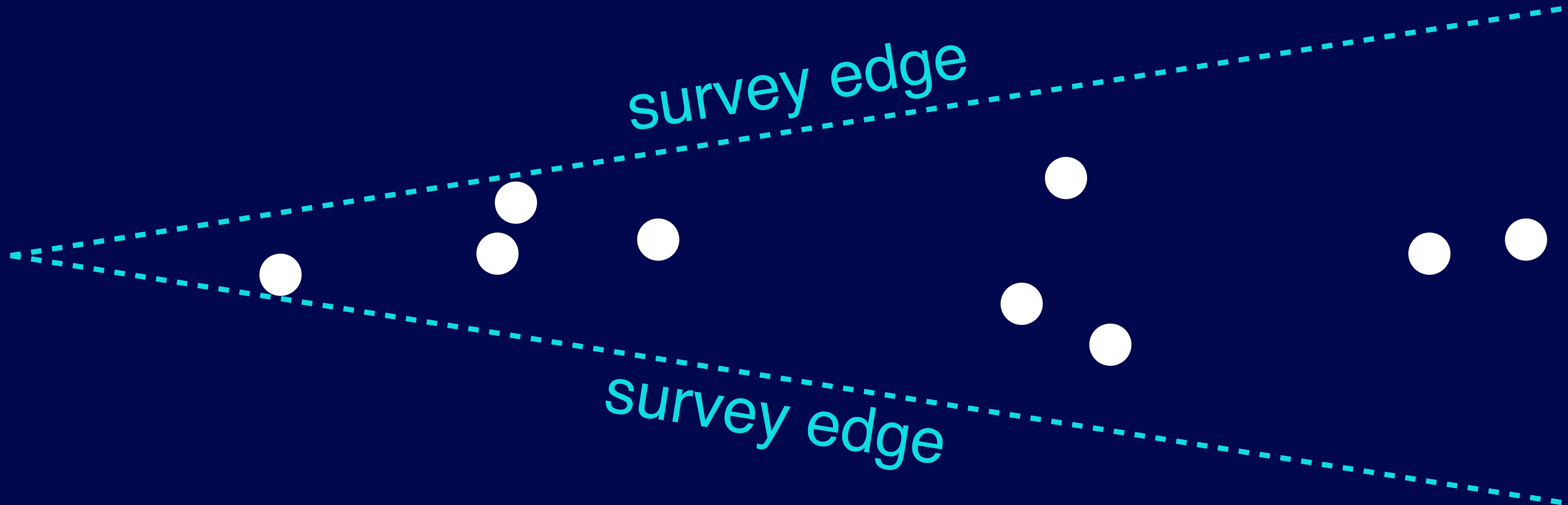
How to extract real-space groups from redshift-space data?



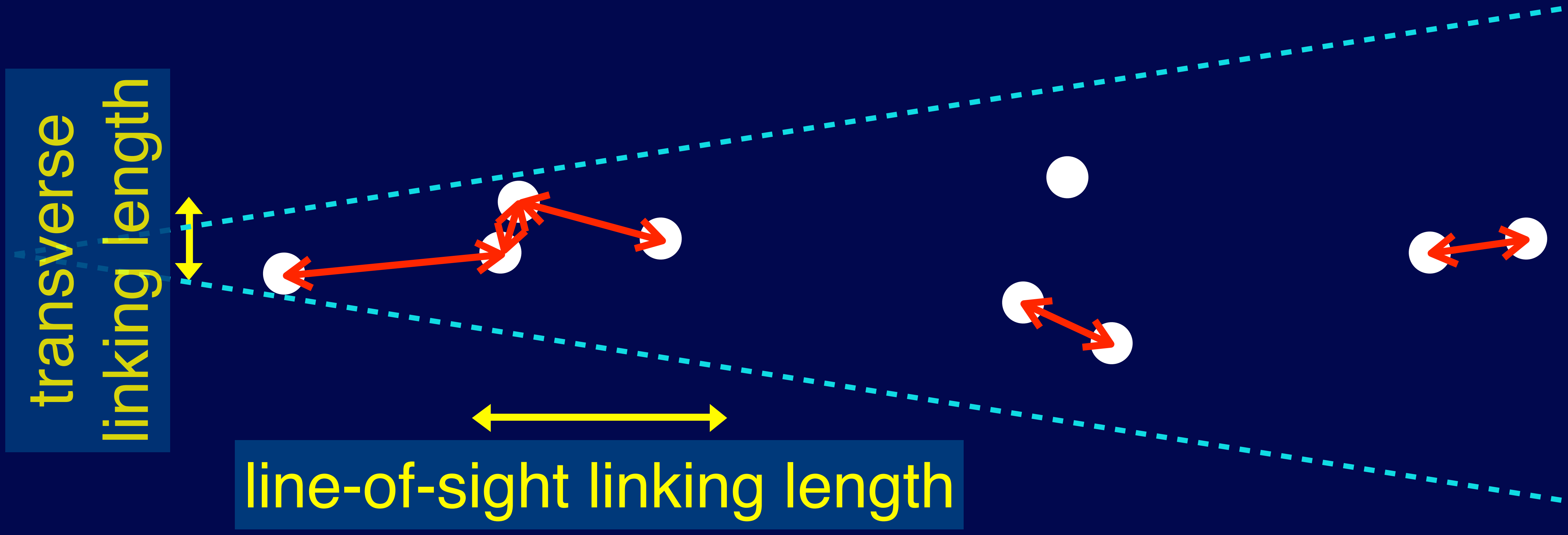
Real space groups = elongated in redshift space

Redshift space groups = elongated in real space!

Friends of Friends (FoF)

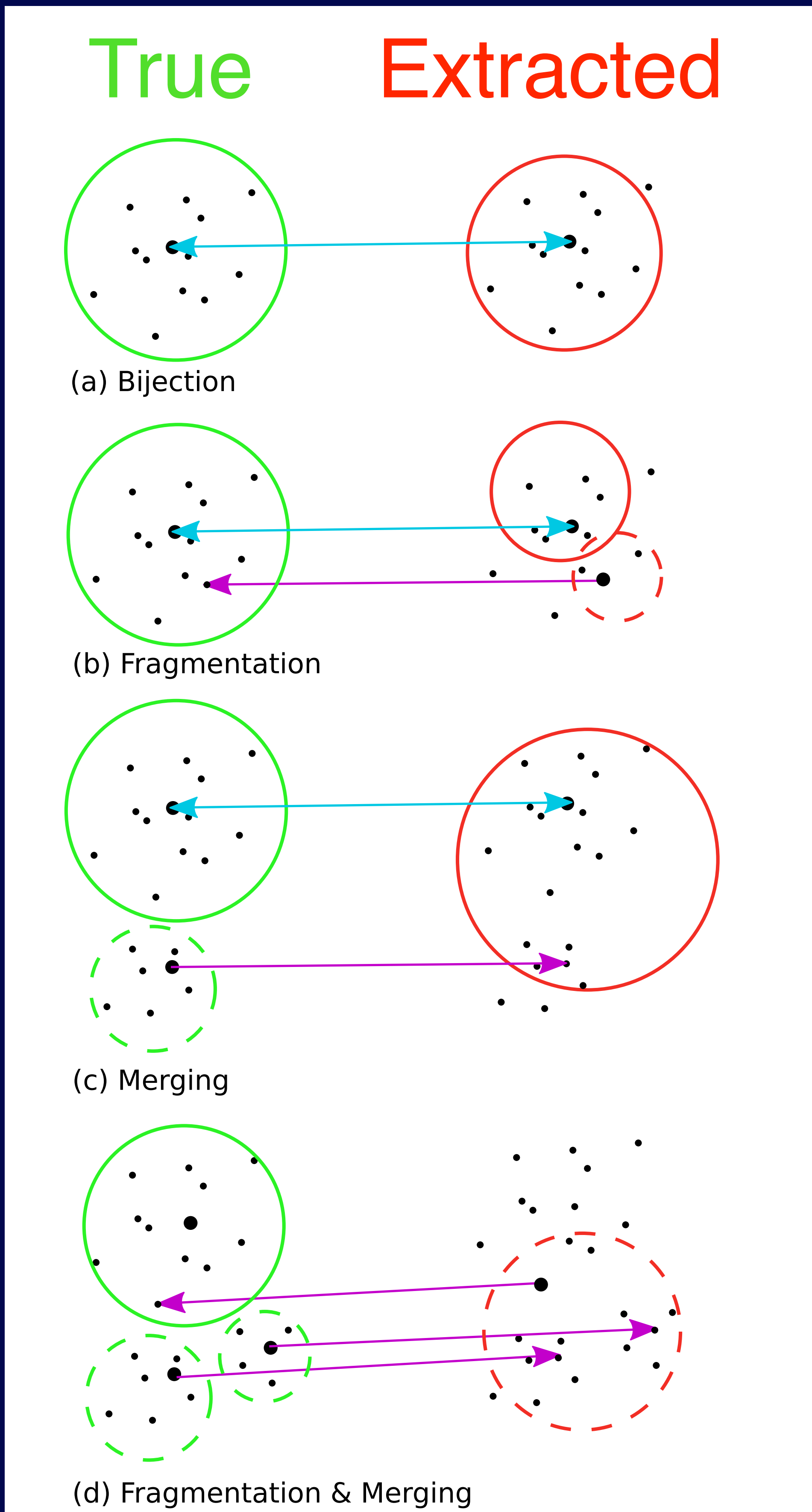


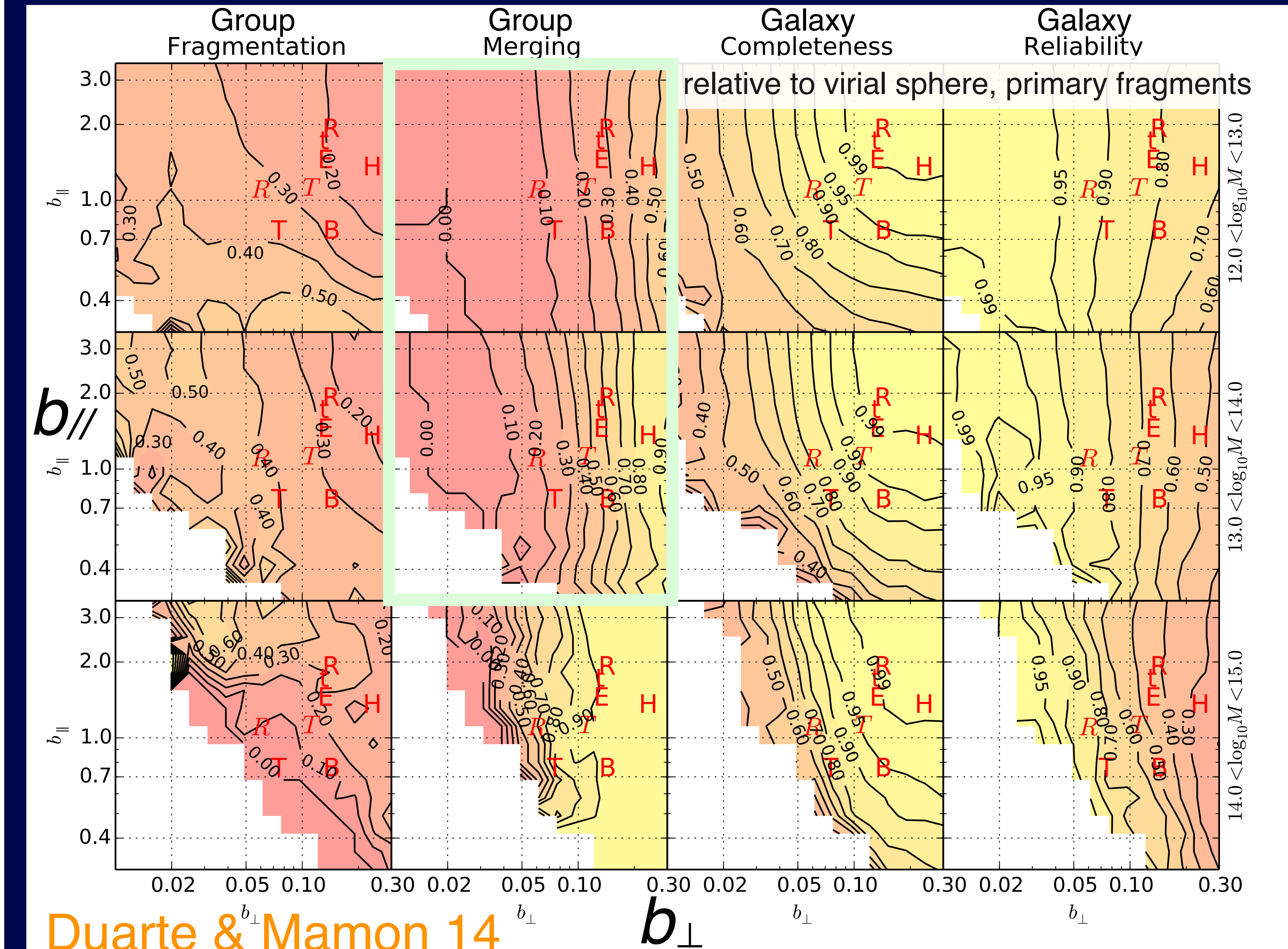
Friends of Friends (FoF)



Dimensionless linking lengths in terms of mean nearest neighbor separation: $b = \mathrm{LL}/\langle n(z)\rangle^{-1/3}$

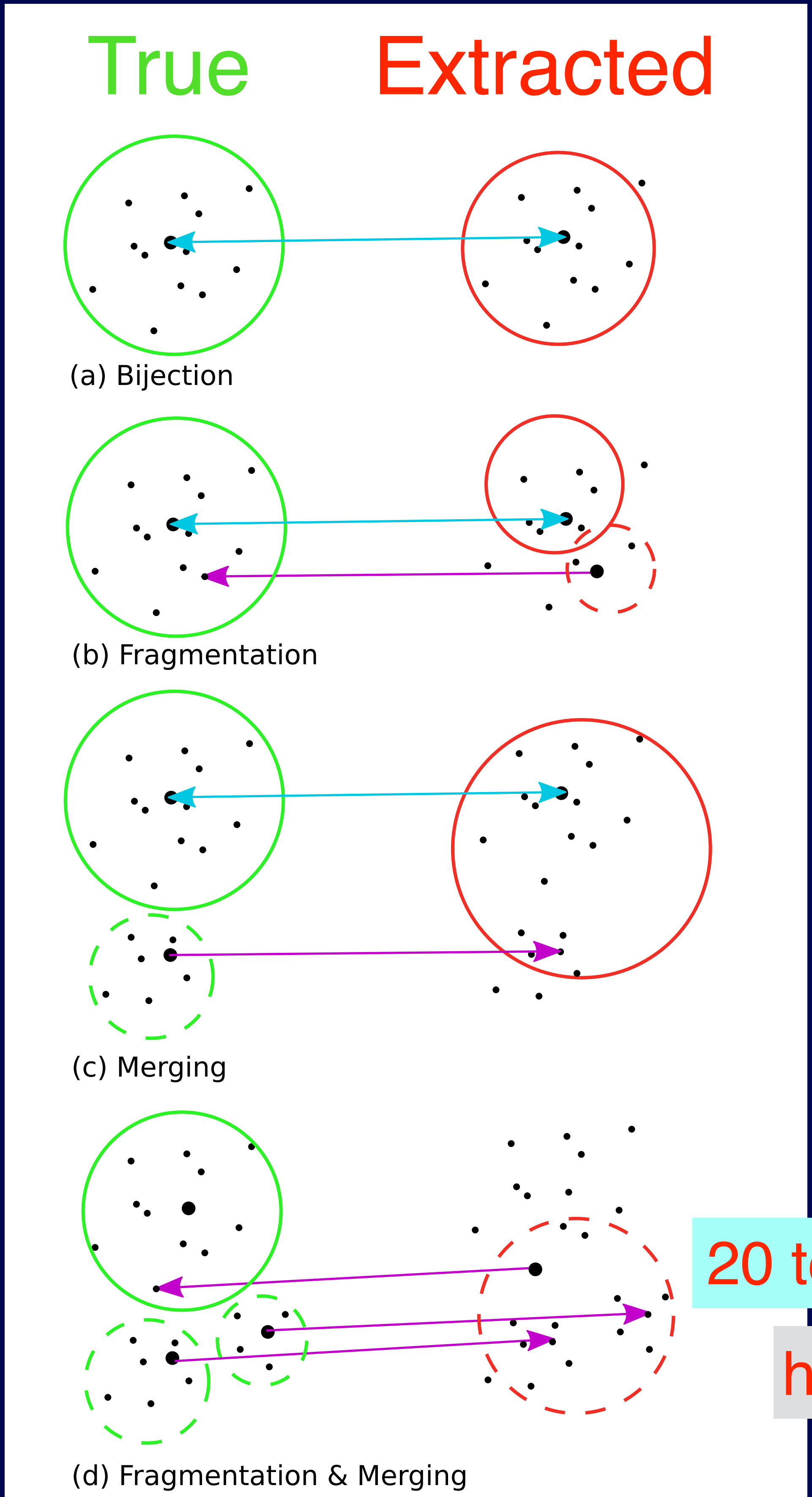
Friends of Friends Optimization (N⩾3)

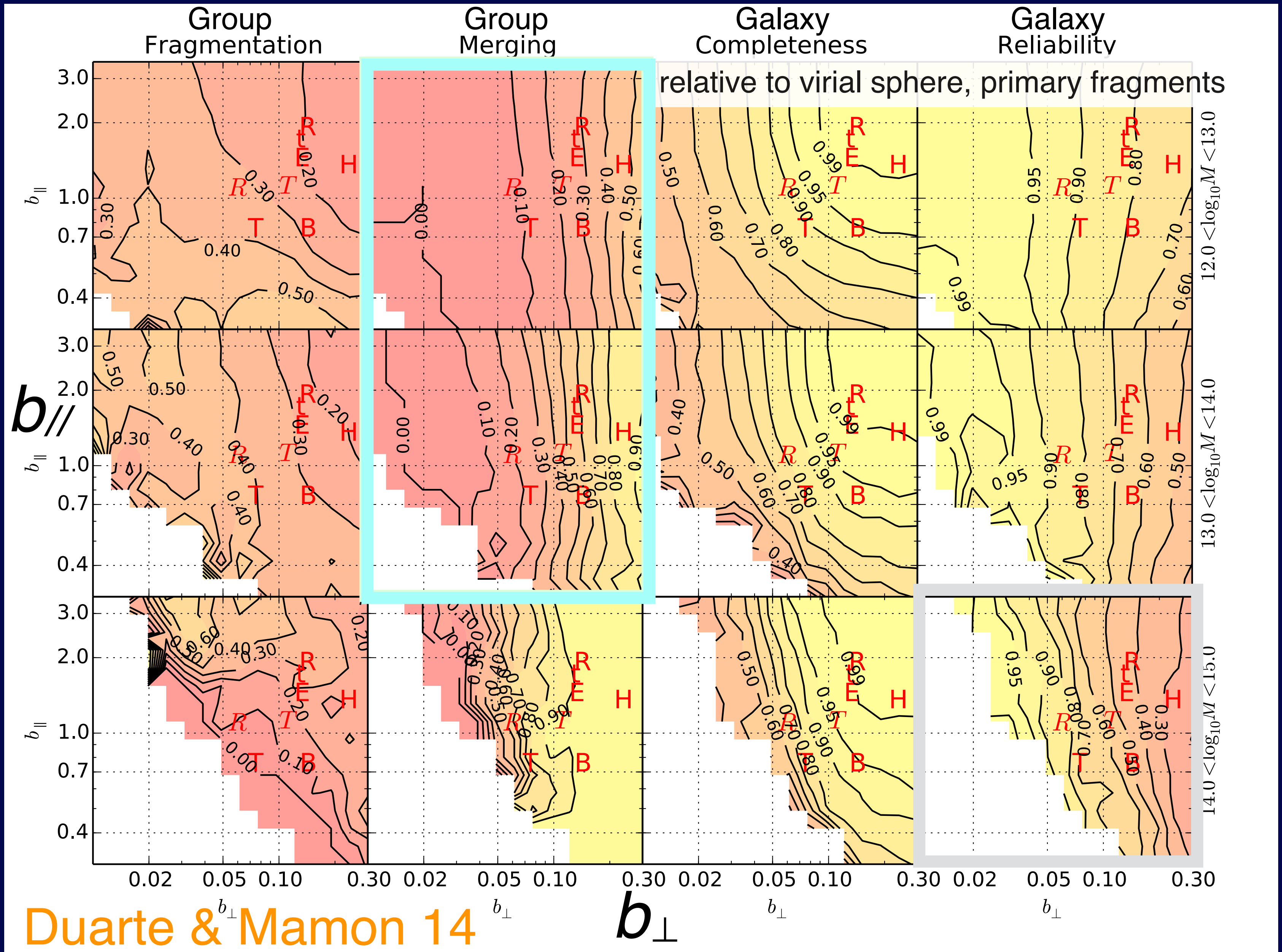




20 to 40% of lo & interm $M_{\rm est}$ groups = mergers!

Friends of Friends Optimization (N⩾3)





20 to 40% of lo & interm $M_{\rm est}$ groups = mergers!

20 to 40% of lo & interm $M_{\rm est}$ groups = 2ndary fragments!

hi $b_\perp$ (Huchra-Geller 82) → hi $M_{\rm est}$ groups 25% reliable

Optimal FoF linking lengths

Duarte & Mamon 14

- Group fragmentation
- Group merging
- Galaxy completeness
- Galaxy reliability
- Group mass bias
- Group mass inefficiency (scatter)

→ depends on scientific goal

Environmental effects	$b_\perp \simeq 0.07$ $b_{//} \simeq 1.1$	also Robotham+11
Cosmography	$b_\perp \simeq 0.07$ $b_{//} \simeq 2.5$	
Individual groups	$b_\perp \simeq 0.07$ $b_{//} \simeq 5$	

Yang et al.'s Bayesian group finder

Yang, Mo & van den Bosch 04; Yang+07
Domínguez Romero, García Lambas & Muriel 12

Density in *Projected Phase Space* (projected radius R, LOS velocity v_z)

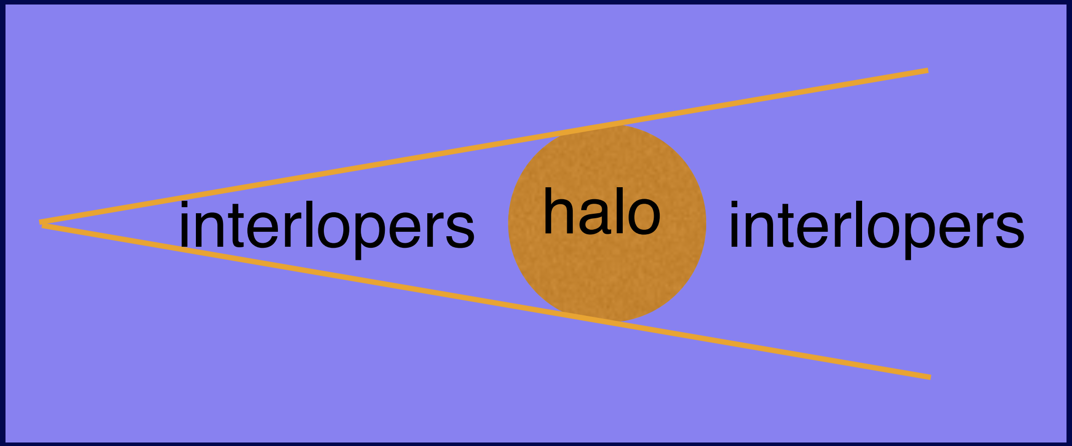
$$g(R, v_z) = \Sigma_{\rm NFW}(R)\,\exp\left(-\frac{v_z^2}{2\,\sigma_{\rm LOS}^2}\right) > 10\,\frac{c\,\rho_{\rm Univ}}{H_0}$$

group masses (hence $R_{\rm vir}$) from:
- luminosities (1st pass)
- Abundance Matching on group luminosities (next passes)

weaknesses

- LOS velocity dispersion should be convex in log-log (not cst)
- LOS velocity distributions not Maxwellian (outer radial vel. anisotropy)
- ad hoc threshold for membership (10)
- imprecise correction for lum. incompleteness (for SDSS flux-limited sample)
- hard group assignment is unstable

MAGGIE: *Models & Algorithms for* *Galaxy Groups, Interlopers & Environment*



Mamon & Duarte 14b in prep.

- $g_{\rm ilop}$ measured in cosmo' simulations — Mamon, Biviano & Murante 10
- more realistic $g_{\rm halo}$ from ΛCDM 3D model with anisotropic velocities

probabilistic group assignment

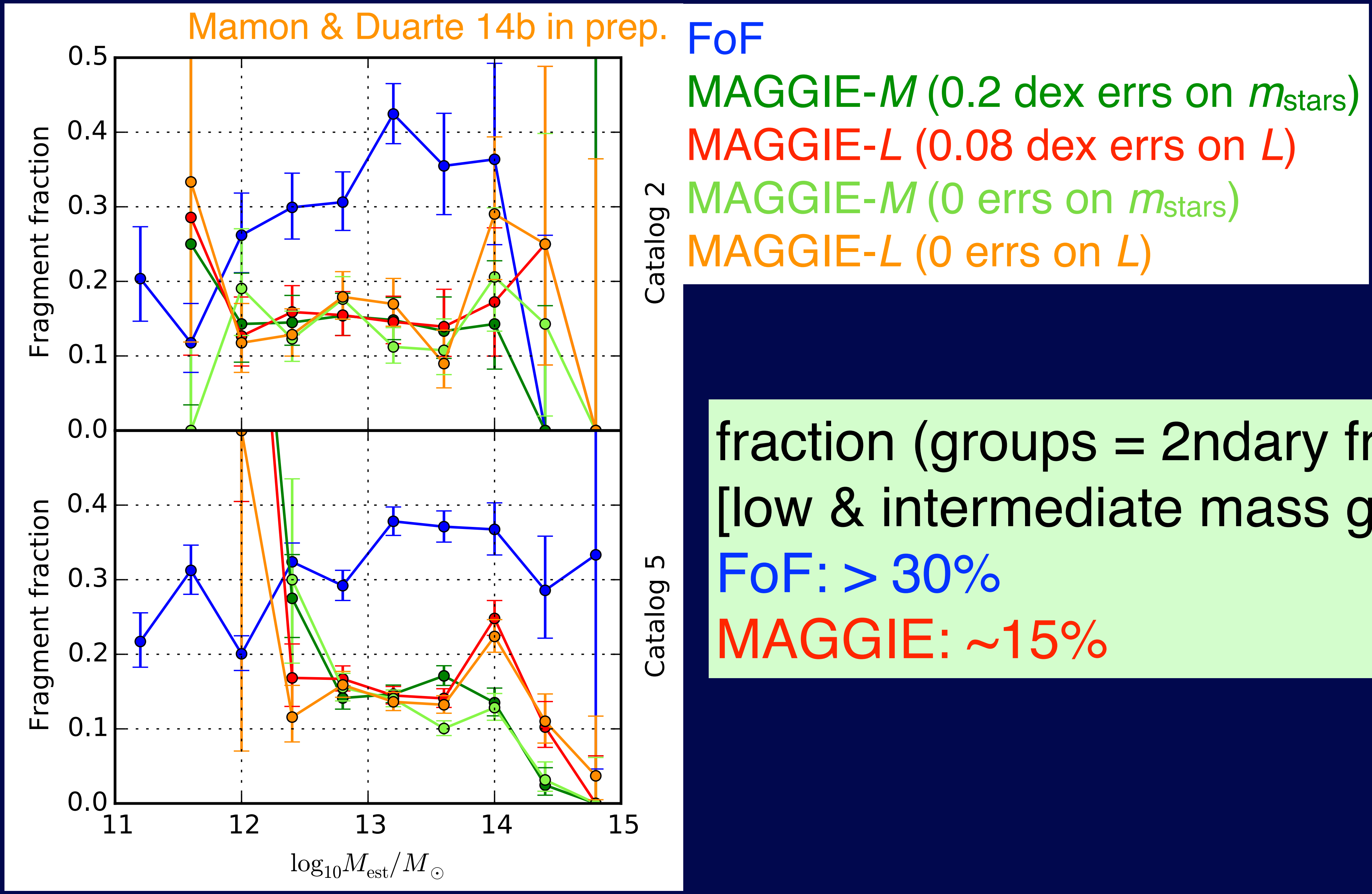
$$P(R, v_z) = \frac{g_{\rm halo}(R, v_z)}{g_{\rm halo}(R, v_z) + g_{\rm ilop}(R, v_z)}$$

- groups extracted from distance- & luminosity-complete subsamples
- group properties = sums weighted by probabilities

Tests: Fragmentation

build mocks adding errors on luminosities & stellar masses

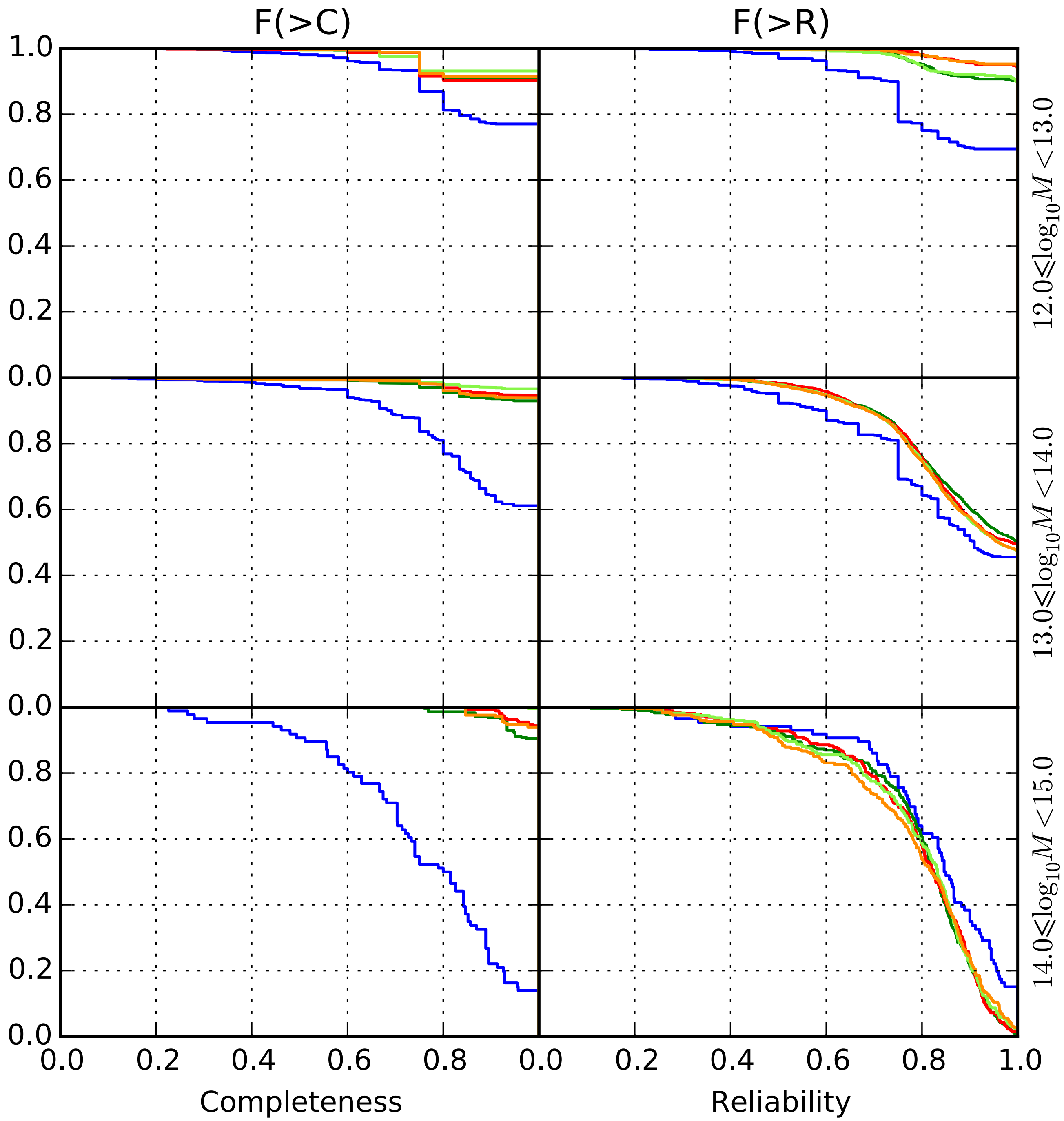
fraction of extracted groups = secondary fragments of true groups



fraction (groups = 2ndary fragments)
[low & intermediate mass groups]
FoF: > 30%
MAGGIE: ~15%

MAGGIE has much less fragmentation for log $M_{\rm est}/M_\odot$ > 12.3

Tests: Galaxy completeness & reliability

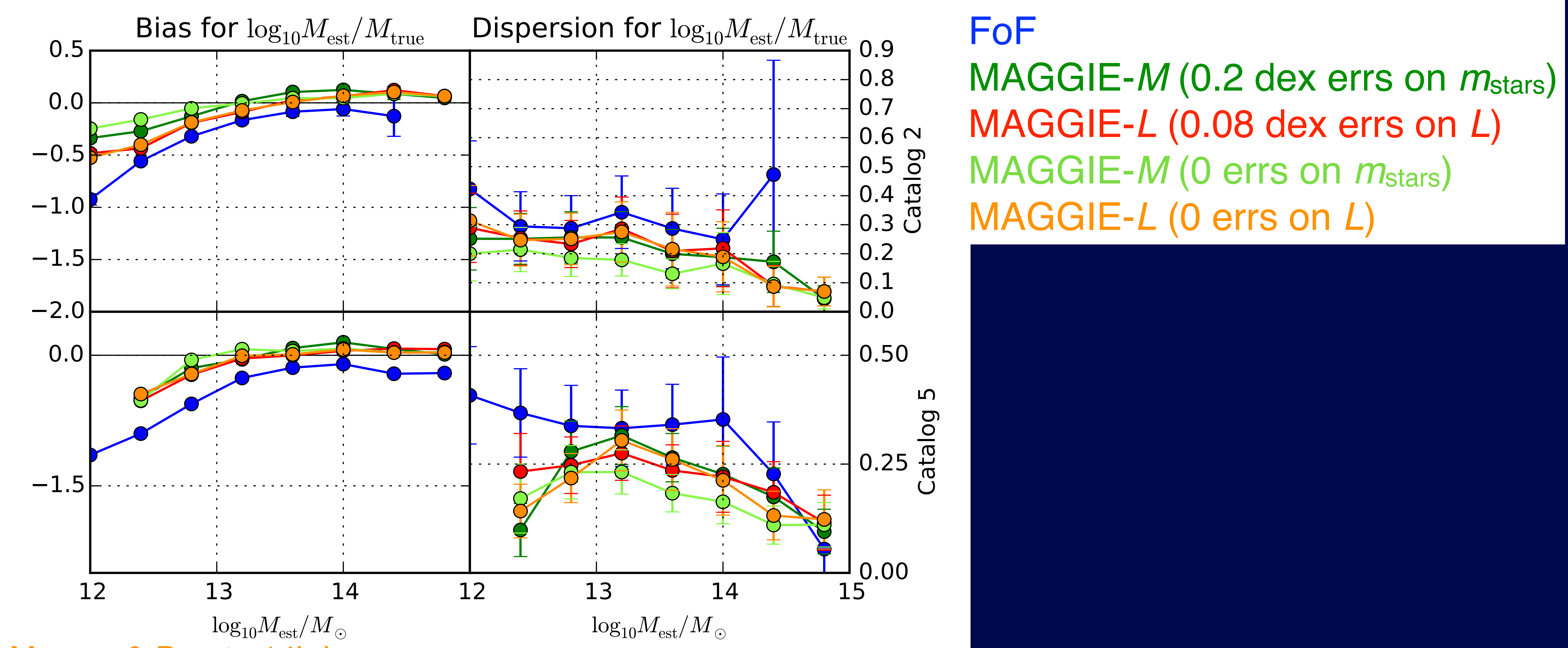


FoF
MAGGIE-*M* (0.2 dex errs on $m_{\rm stars}$)
MAGGIE-*L* (0.08 dex errs on *L*)
MAGGIE-*M* (0 errs on $m_{\rm stars}$)
MAGGIE-*L* (0 errs on *L*)

Mamon & Duarte 14b in prep.

MAGGIE is much more complete
MAGGIE is more reliable, except at high mass

Group total mass accuracy



Mamon & Duarte 14b in prep.

mass accuracy (log $M_{\rm est} < 14.5$):

FoF (with Virial Theorem): > 0.3 dex & biased low

MAGGIE: ~ 0.22 dex & unbiased

FoF vs MAGGIE-M vs MAGGIE-L:

Mamon & Duarte 14b in prep.

	Test	Weight	12–13			13–14			14–15		
			$\log M_{\rm est}/M_\odot$								
			FoF	MM	ML	FoF	MM	ML	FoF	MM	ML
fragmentation	F	4	1	4	4	0	4	4	1	4	4
completeness	C	2	1	2	2	0	2	2	0	2	2
reliability	R	3	0	3	2	1	2	2	3	1	0
total mass bias	μ_M	2	1	2	2	1	2	2	1	2	2
total mass inefficiency	σ_M	3	1	3	3	1	3	3	1	3	2
luminosity bias	μ_L	1	1	0	0	1	0	0	0	1	1
luminosity inefficiency	σ_L	2	1	1	1	0	2	2	1	1	1
stellar mass bias	μ_m	1	1	0	0	1	0	0	0	1	1
stellar mass ineff'y	σ_m	2	1	1	1	0	2	2	0	1	1
	Total	20	8	**16**	15	5	**17**	**17**	7	**16**	14

MAGGIE-M performs best
(in all mass ranges)!

2) Is there a complete compact group sample?

Euge DÍAZ-GIMÉNEZ

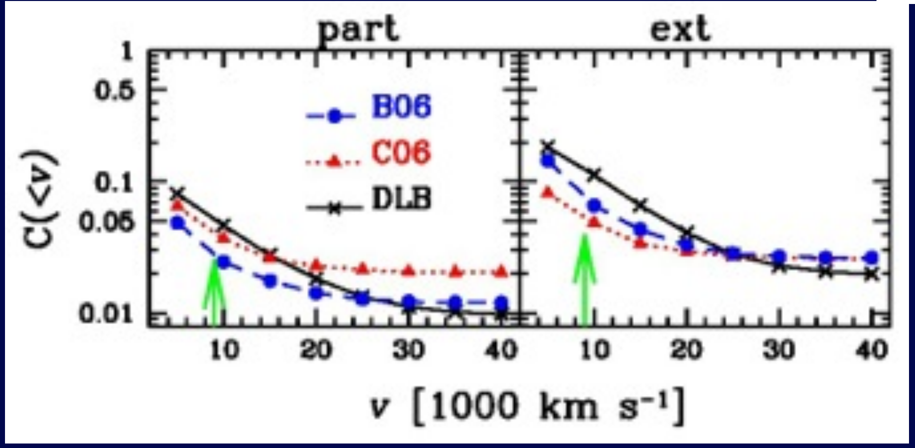
HCG only 10% complete:
missing groups dominated by 1 galaxy

Prandoni, Iovino & MacGillivray 94	auto-selection on photo plates
Díaz-Giménez & Mamon 10	SAMs

Incompleteness and biases in HCG sample

Díaz-Giménez & Mamon 10

completeness of HCG relative to mock



Incompleteness and biases in HCG sample

Díaz-Giménez & Mamon 10

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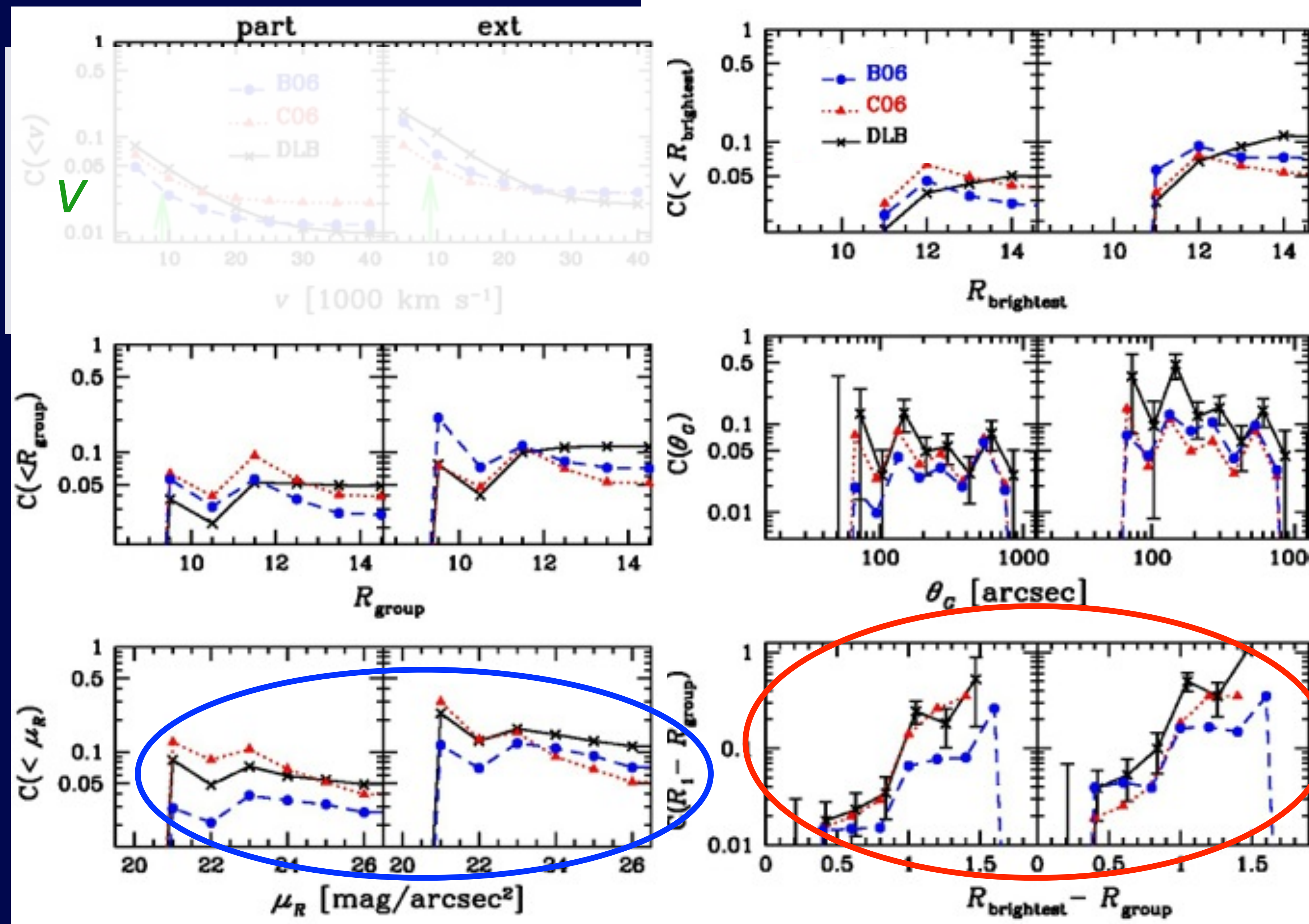


number density
of mock CGs
= 12x that of HCGs

Hickson missed CGs:

- lower surface brightness — Walke & Mamon 89
- with dominant brightest galaxy — Prandoni, Iovino & McGillivray 94

New Compact Group catalogue

Díaz-Giménez, GM et al. 12, MNRAS

Selected from 2MASS

- Compact: $\mu_K < 23.6$
- Rich: $N \geq 4$ within K_1, K_1+3
- Isolated: empty ring $R \leftrightarrow 3R$, within K_1, K_1+3
- Flux limit: $K_1 < K_{\text{lim-2MASS}} - 3 = 10.57$

Filtered after visual checks

231 2MCGs

144 with *full* redshift info

85 with ≥ 4 accordant velocities

78 “v2MCGs” w ≥ 4 accordant vels & cz > 3000 km/s

2MCG vs HCG & others

more accordant-velocity CGs
than Hickson CG catalog
although 10x less deep!

SDSS CGs McConnachie+09

→ 54 CGs with $r < 17.77$, ⩾ 4 accordant redshifts

→ only 19 CGs with $r < 17.77$, *all* z's available & ⩾ 4 accordant

more with SDSS-DR7 velocities, but only 15 with $r_1 < 14.77$

v2MCG = Only CG catalog showing strong & significant signs of:

* bright-end magnitude gap ⇒*mergers*

** luminosity segregation*

Bright-end of luminosity function

on absolute magnitudes ...

$$T_1 = \frac{\sigma(M_1)}{\langle M_2 - M_1 \rangle}$$

$$T_2 = \frac{1}{\sqrt{0.677}} \frac{\sigma(M_2 - M_1)}{\langle M_2 - M_1 \rangle}$$

$T_1>1$ & $T_2>1$ for normal luminosity function(s)

Tremaine & Richstone 77

HCG: $T_1=1.16$ Mamon 86

Dense Group N-body simulations: $T_1<0.8$ & $T_2<0.8$ Mamon 87

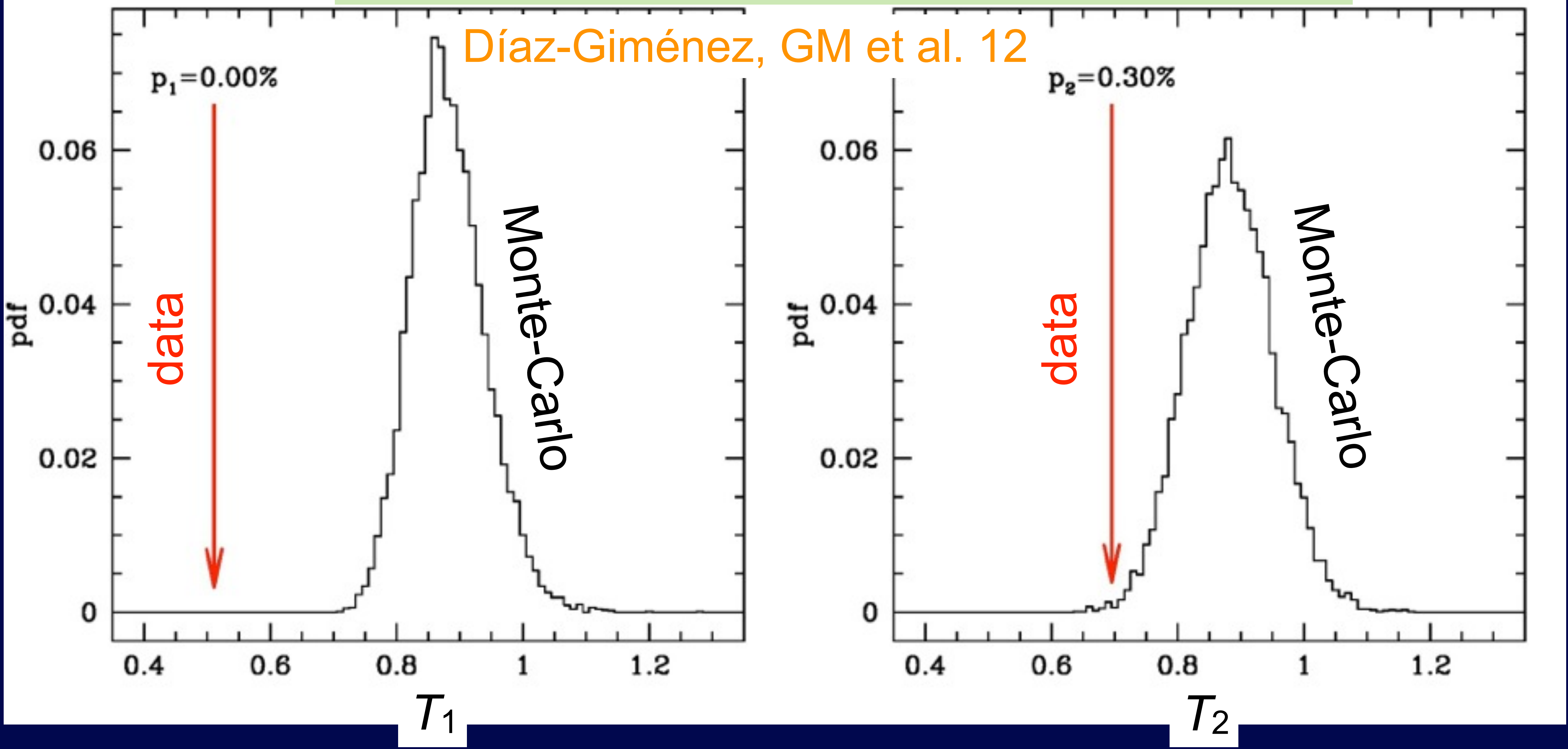
mergers build 1st-ranked galaxy at expense of 2nd-ranked

Tremaine-Richstone statistics on new CG sample

78 v2MCGs: T_1=0.51±0.06 & T_2=0.70±0.06

SAM v2MCGs: T_1=0.46±0.02 & T_2=0.59±0.02

Díaz-Giménez, GM et al. 12



2MCGs = 1st CG sample with signs of mergers in bright end of LF

it's the completeness, stupid!

Luminosity segregation

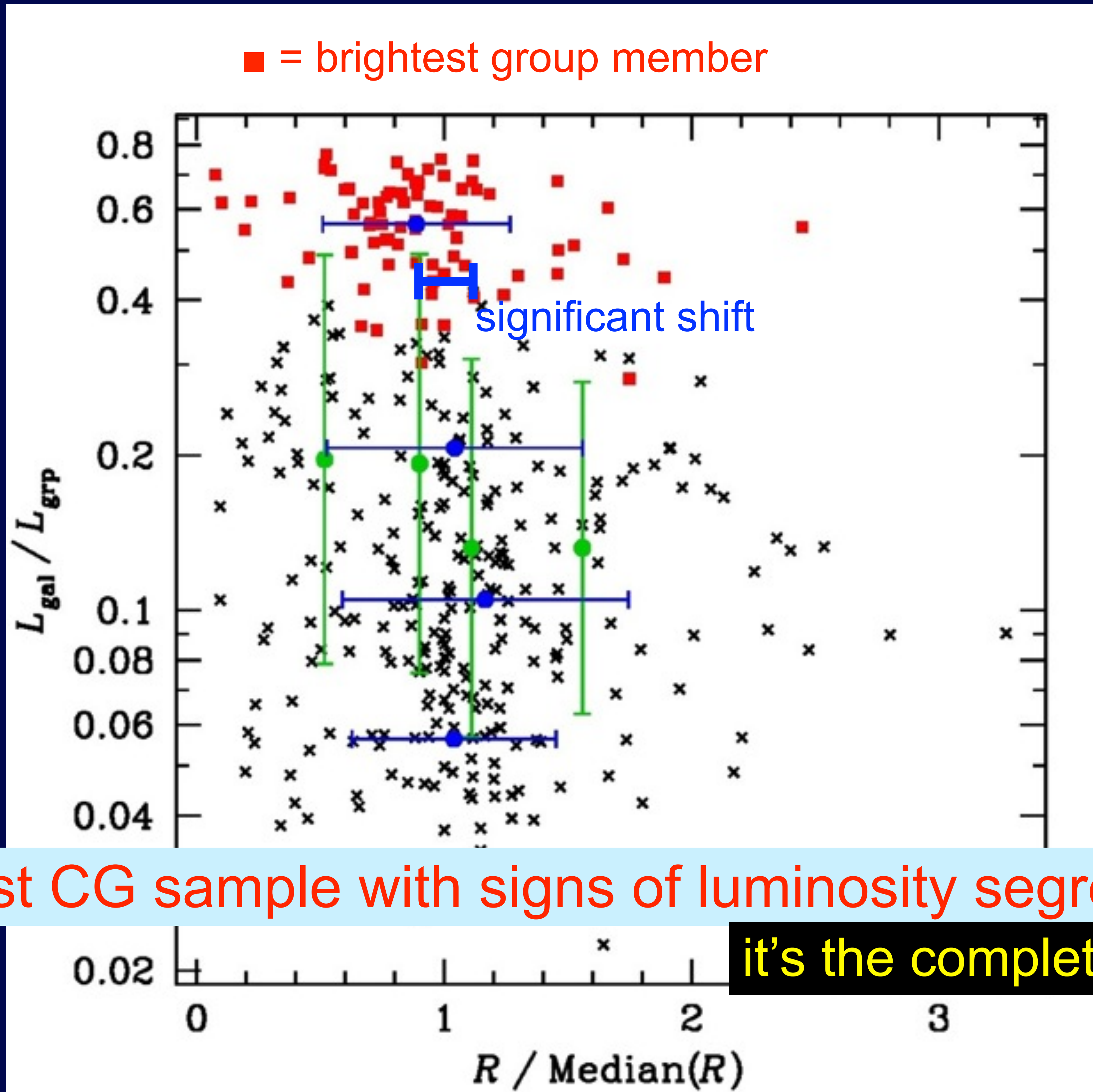
(x_i) distance to centroid / median distance
vs.
luminosity / group luminosity
Spearman rank correlation & KS on x_1 vs x_2

All group catalogs: *no L-segregation* HCG: Mamon 86

Dense Group simulations: *rapid L-segregation* Mamon 87

dynamical friction & 2-body relaxation → most massive at center

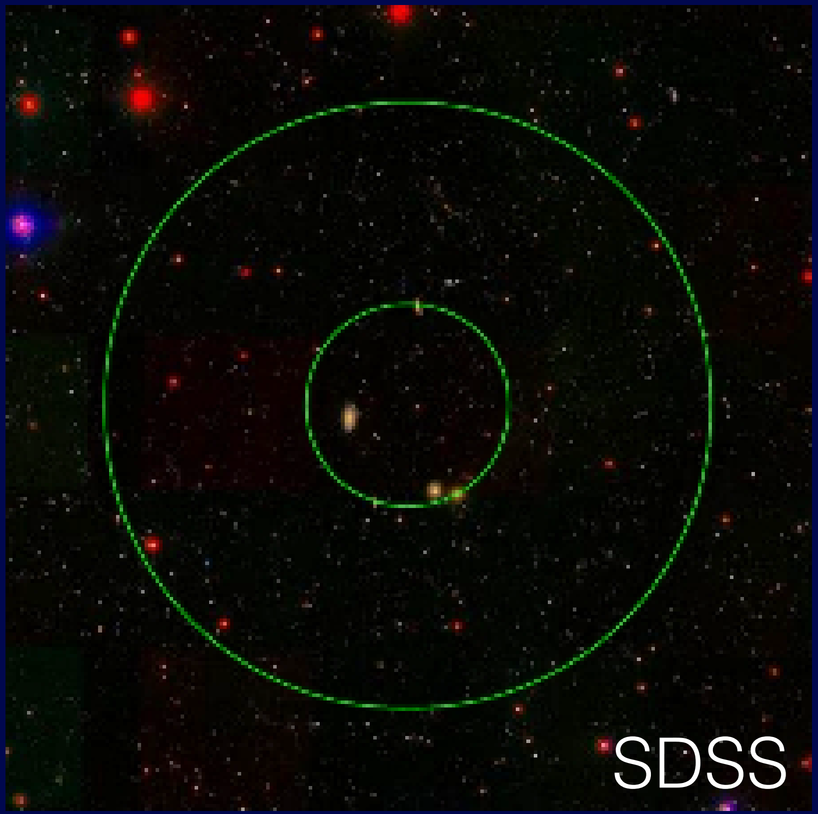
Luminosity segregation



2MCGs = 1st CG sample with signs of luminosity segregation

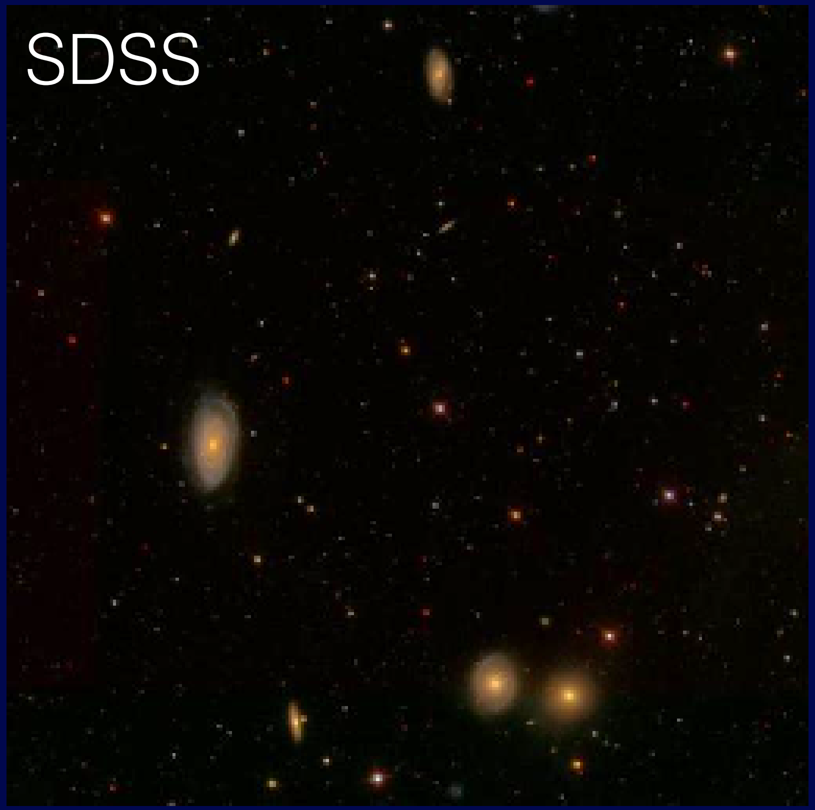
it's the completeness, stupid!

2MCG compact groups

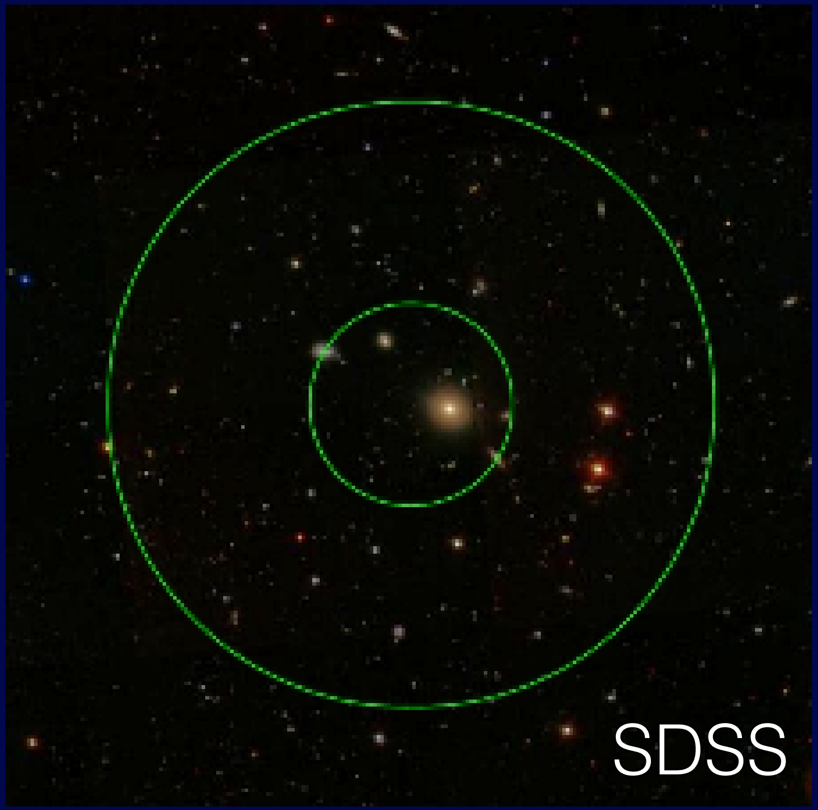


2MCG85

zoom in →

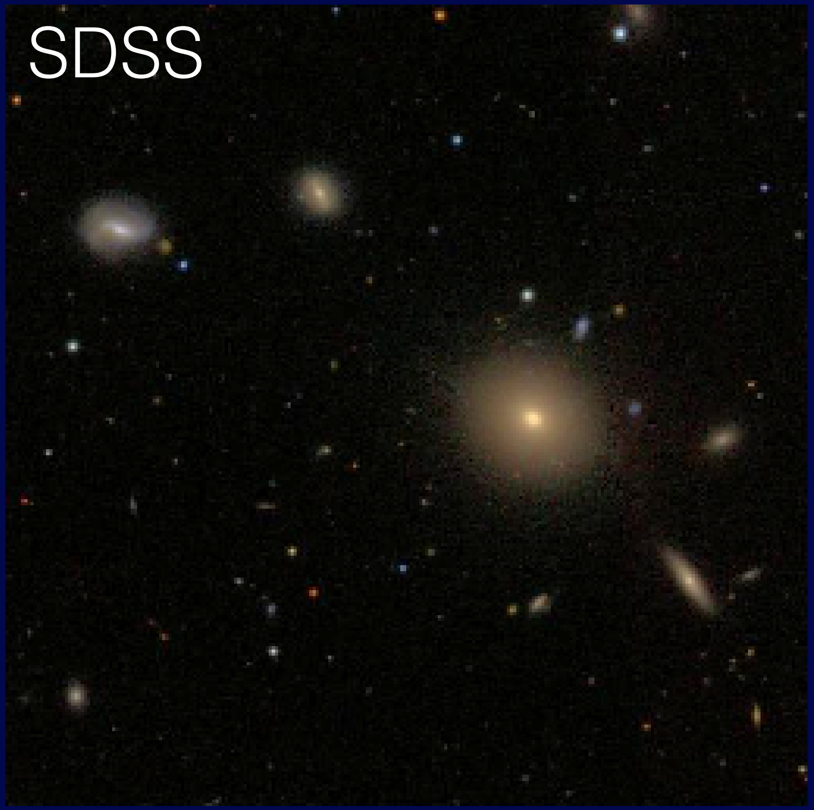


non-Dominated



2MCG52

zoom in →



Dominated

3) How do CG galaxies relate to the CG environment?

Mathieu BOZZIO

Morphological correlations in 2MCGs

Spearman rank tests	spiral fraction			elliptical fraction		
	N	corr.	prob not by	*N*	corr	prob not by
ALL						
density	47	–0.20	0.91	47	0.12	0.78
velocity dispersion	47	–0.22	0.93	47	0.20	0.91
spiral density	46	–0.12	0.79	47	–0.10	0.75
elliptical density	47	–0.47	0.999	35	0.36	0.98
crossing time	47	0.31	0.98	47	0.31	0.98

M. BOZZIO

morphologies not correlated with density nor velocity dispersion!
but with *density of ellipticals* and with *mass density* (crossing time)

Morphological correlations in 2MCGs

Spearman rank tests	spiral fraction			elliptical fraction		
	N	corr.	prob not by	*N*	corr	prob not by
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density	47	–0.20	0.91	47	0.12	0.78
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elliptical density	47	–0.47	0.999	35	0.36	0.98
crossing time	47	0.31	0.98	47	0.31	0.98
Dom						
density	23	0.33	0.94	23	0.18	0.79
velocity dispersion	23	0.18	0.80	23	–0.09	0.66
spiral density	23	–0.26	0.88	23	0.01	0.51
elliptical density	23	–0.40	0.97	16	0.08	0.62
crossing time	23	0.01	0.51	23	–0.02	0.54
Non-Dom						
density	24	–0.03	0.56	24	–0.02	0.53
velocity dispersion	24	–0.68	0.999	24	0.37	0.96
spiral density	23	0.19	0.81	24	–0.27	0.90
elliptical density	24	–0.48	0.99	19	0.51	0.99
crossing time	24	0.73	0.9997	24	–0.32	0.93

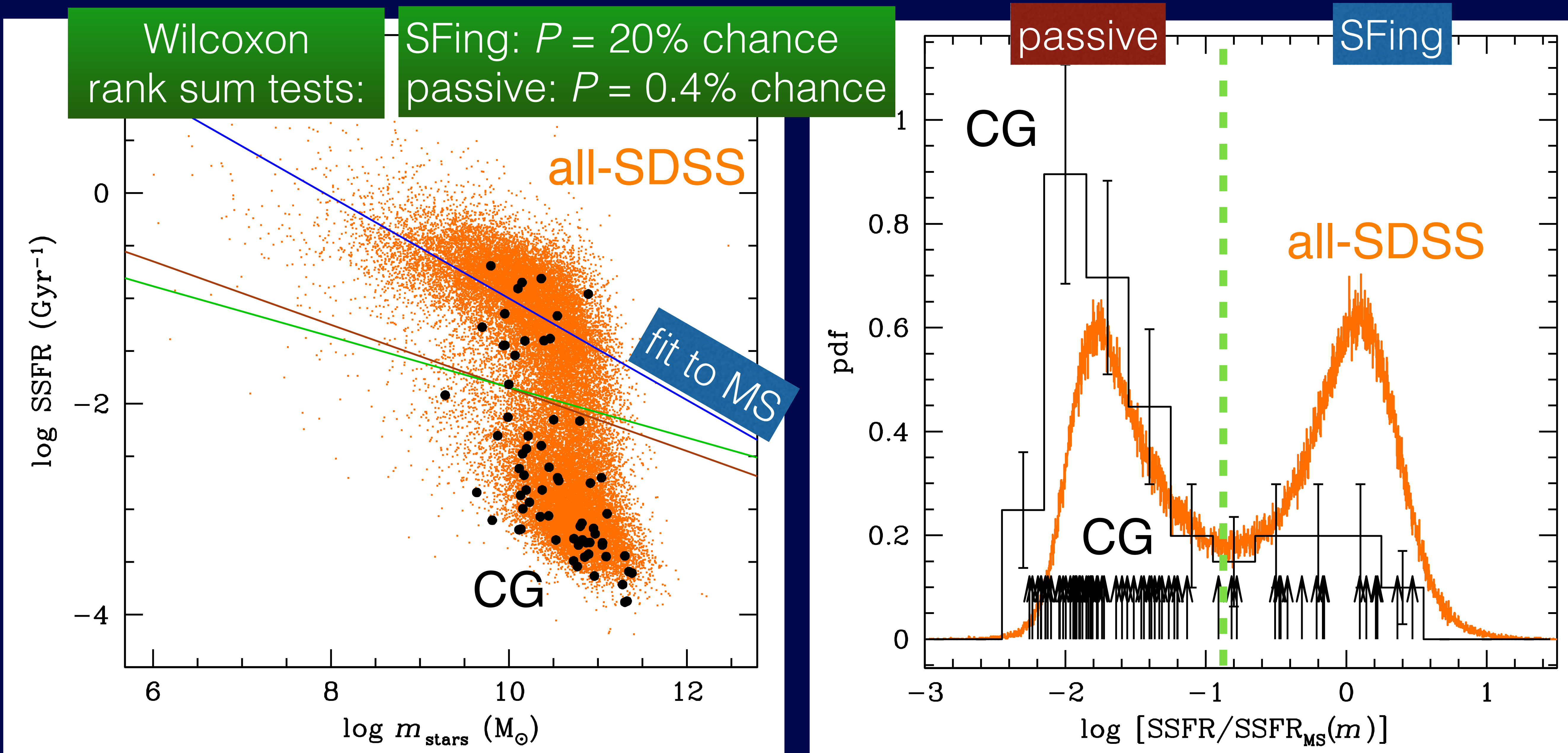
f_S vs σ_v correlation only in non-Dom CGs!

M. BOZZIO

Are 2MCG galaxies bursty or anemic?

Wilcoxon rank sum tests:

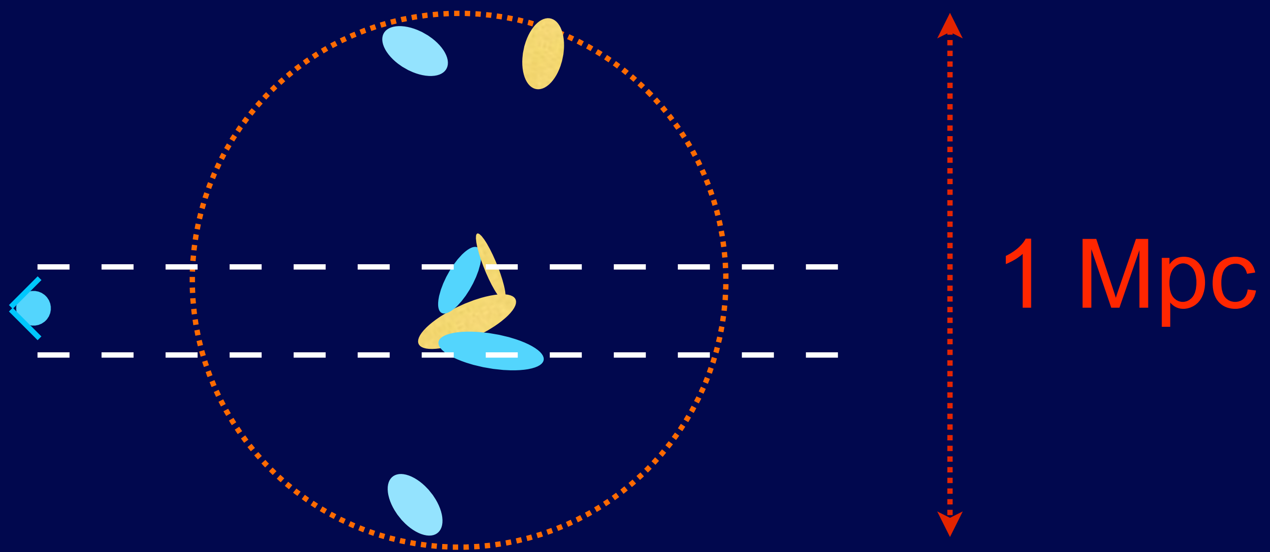
SFing: P = 20% chance
passive: P = 0.4% chance



SFing CG galaxies not bursty/anemic on average
passive CG galaxies more passive than average!

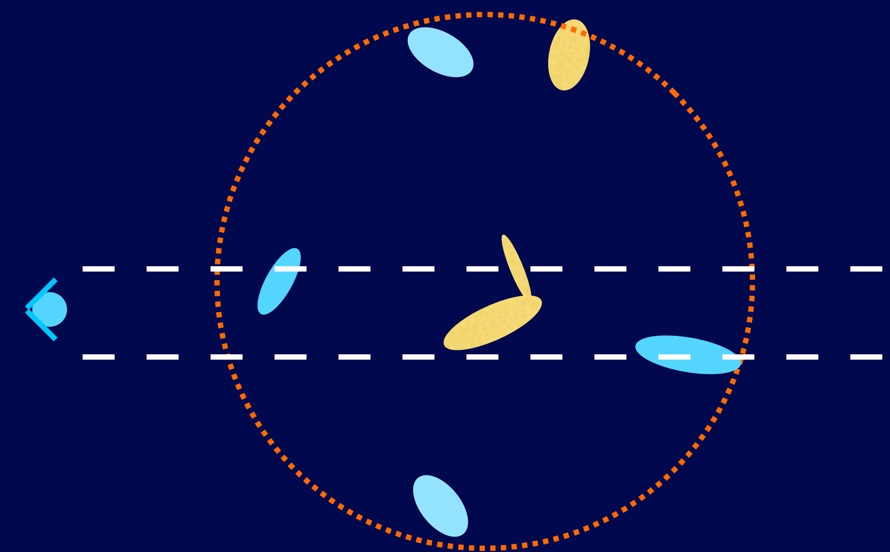
but satellite ages indep of M_{group} at given (not low) m Gallazzi in prep.

4) What is the nature of compact groups?



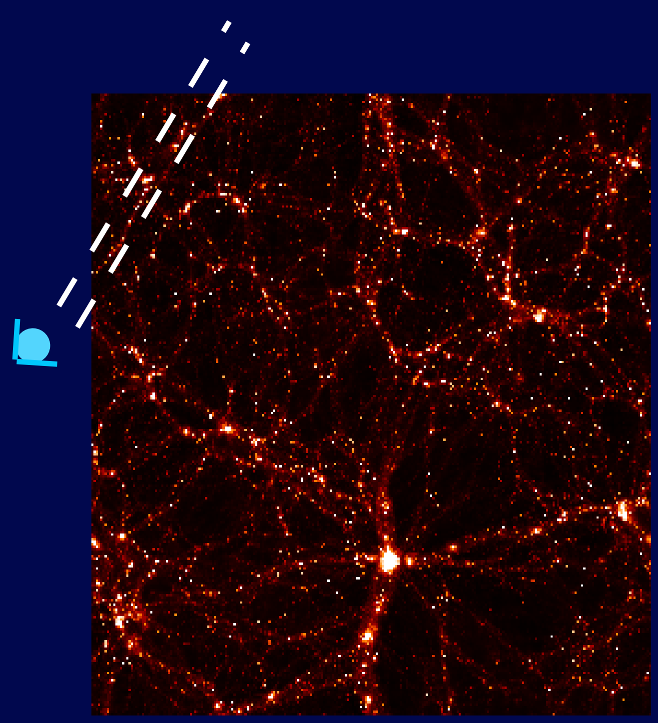
physically dense

Hickson & Rood 88



chance alignment
within virialized group (CAVG)

Rose 77; Mamon 86, 87;
Walke & Mamon 89



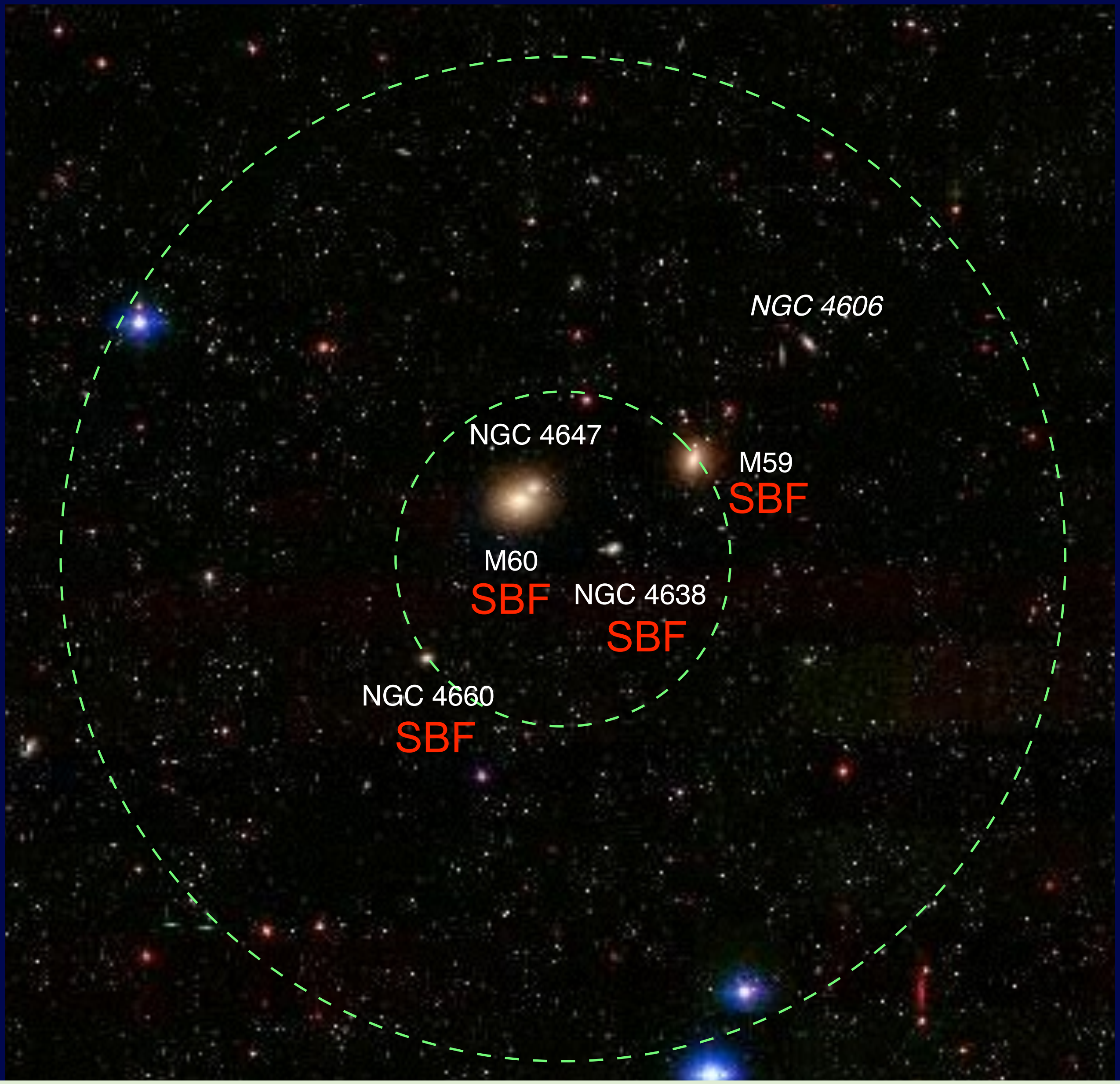
chance alignment
within filament (CAF)

Hernquist, Katz & Weinberg 95

Δv = 1000 km/s ⇒ CGs up to 20/h Mpc long!

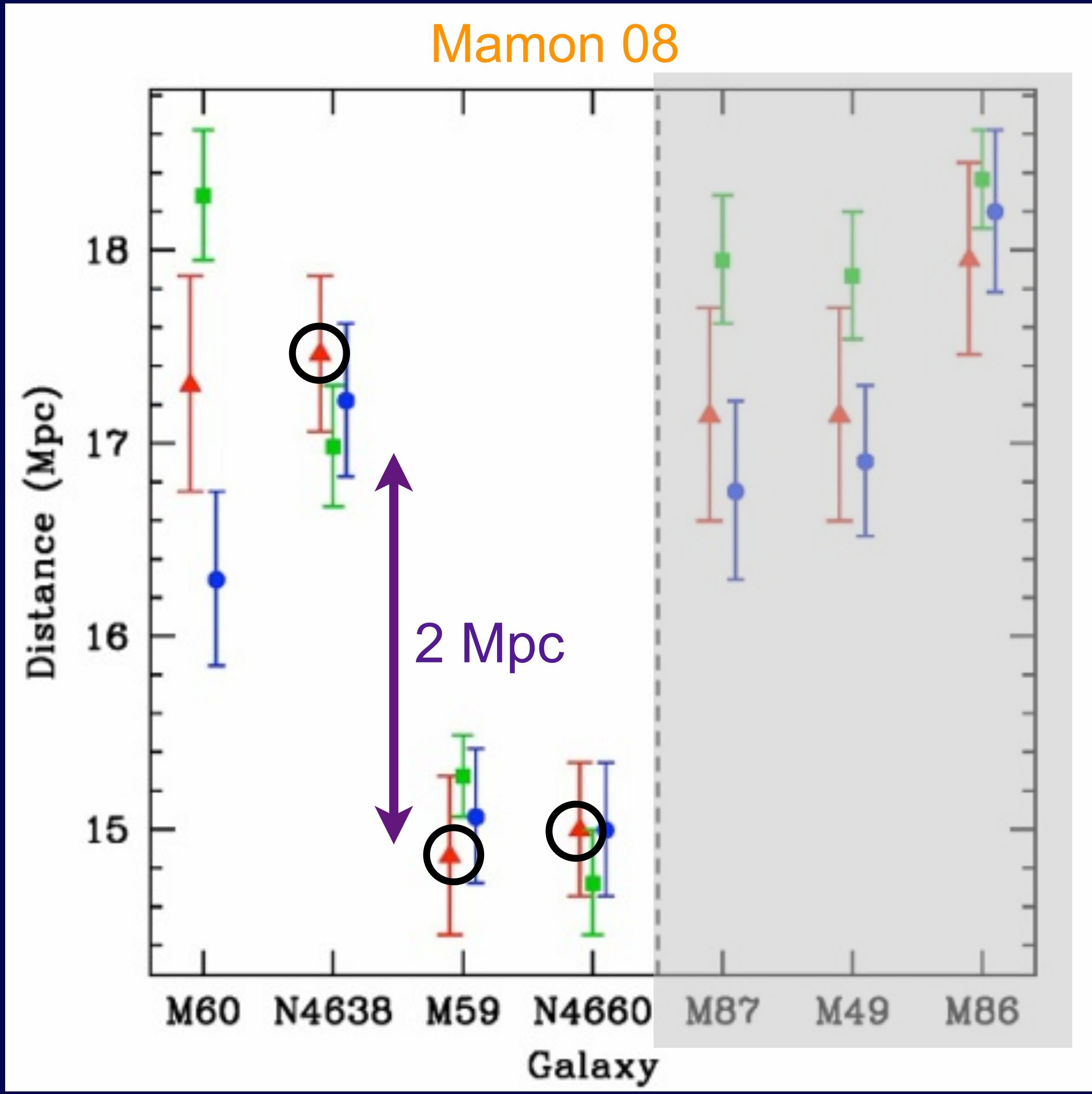
A direct test of the nature of a CG

closest CG: in Virgo Mamon 89



SBF = Surface Brightness Fluctuation (accurate distance estimator)

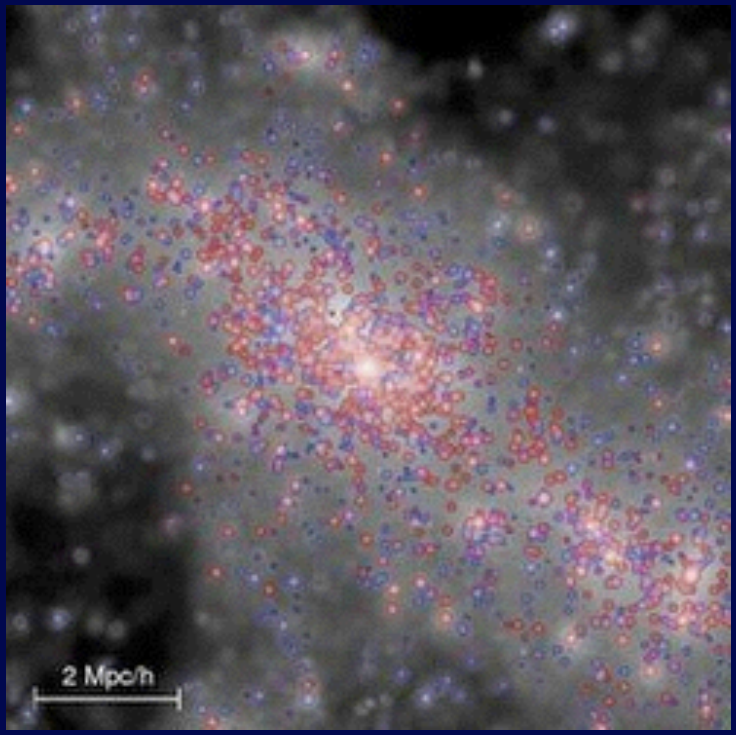
Mei+07



Virgo cluster CG = chance alignment!

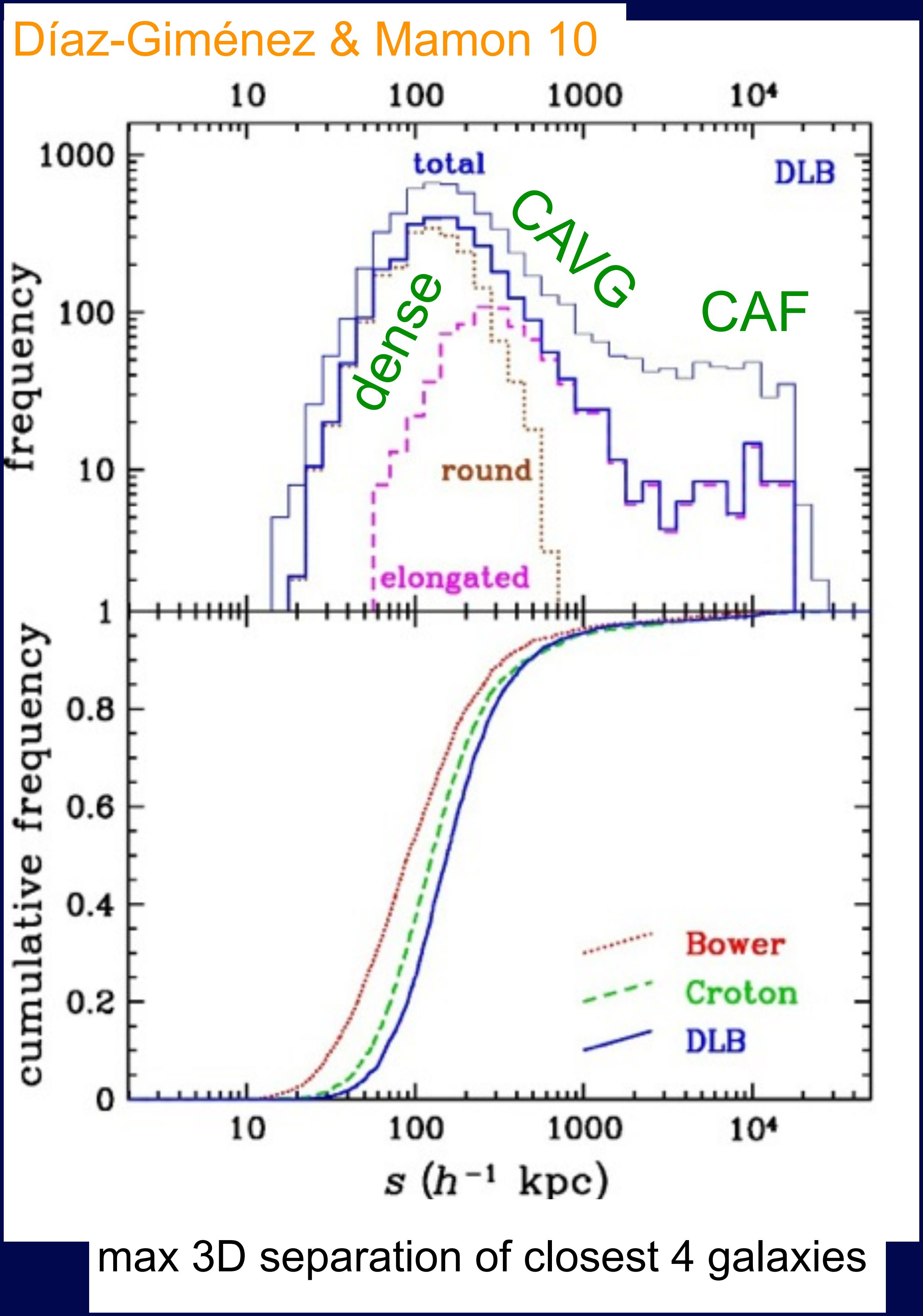
The nature of CGs from simulations

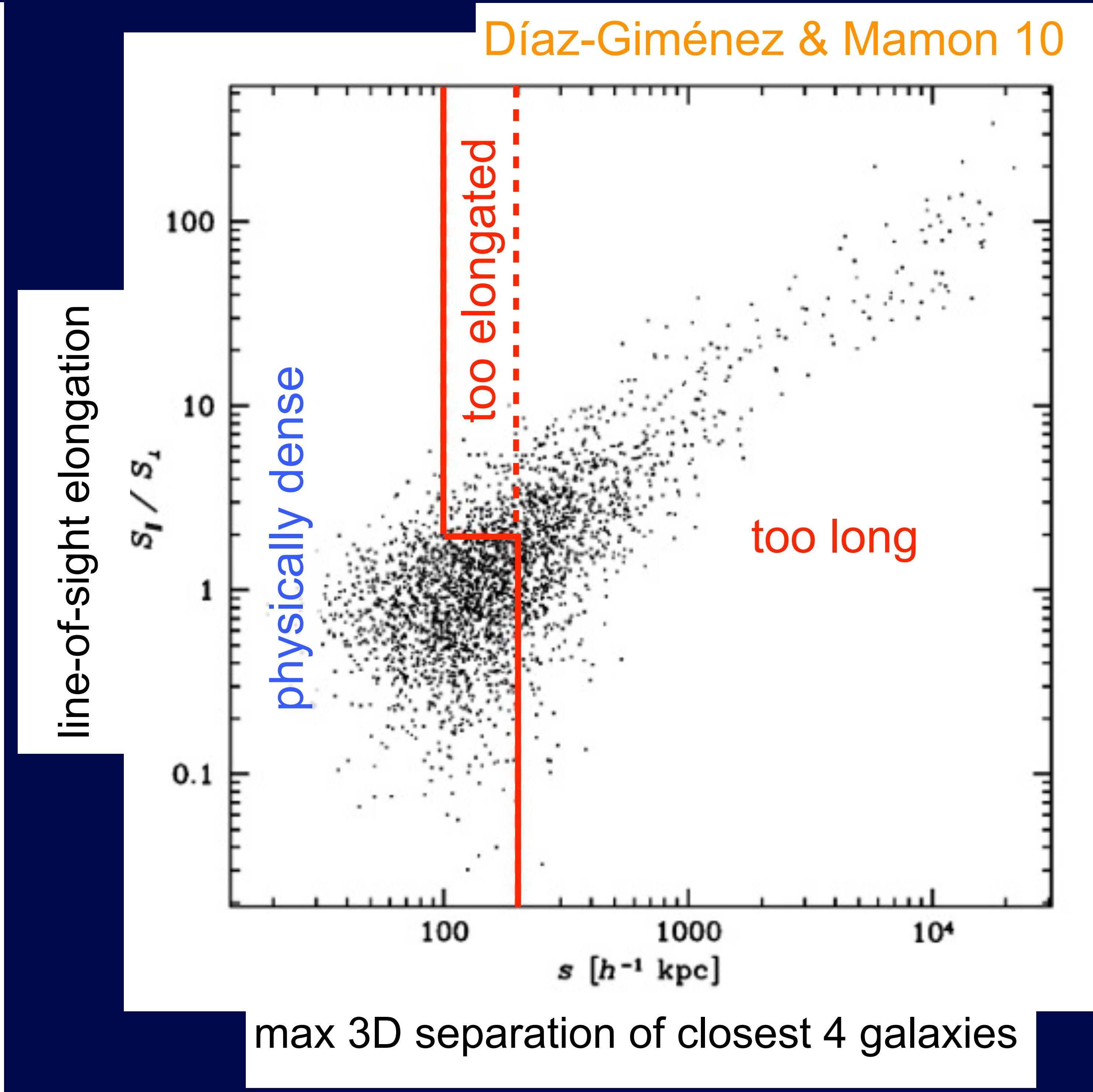
Díaz-Giménez & Mamon 10



- Millennium dark matter simulation: 10G particles!
- 3 different galaxy formation codes: 7M galaxies
  Croton et al. 06 $M_R < -17.4$
  Bower et al. 06
  De Lucia & Blaizot 07
- mock samples in redshift space: 1M galaxies
  $R < 17.44$
- *mock projected CGs*: 12k *mpCGs*
- *mock velocity-accordant CGs*: 7k *mvCGs*

Mock CGs: what is a dense group?





What fraction of mock CGs are physically dense?

Díaz-Giménez & Mamon 10; Díaz-Giménez, GM+12

max 3D sep = 80/h kpc

DM simulation	SAM	physically dense	Reference
8-body SAM (!)	Mamon 87	40%	Mamon 86, 87

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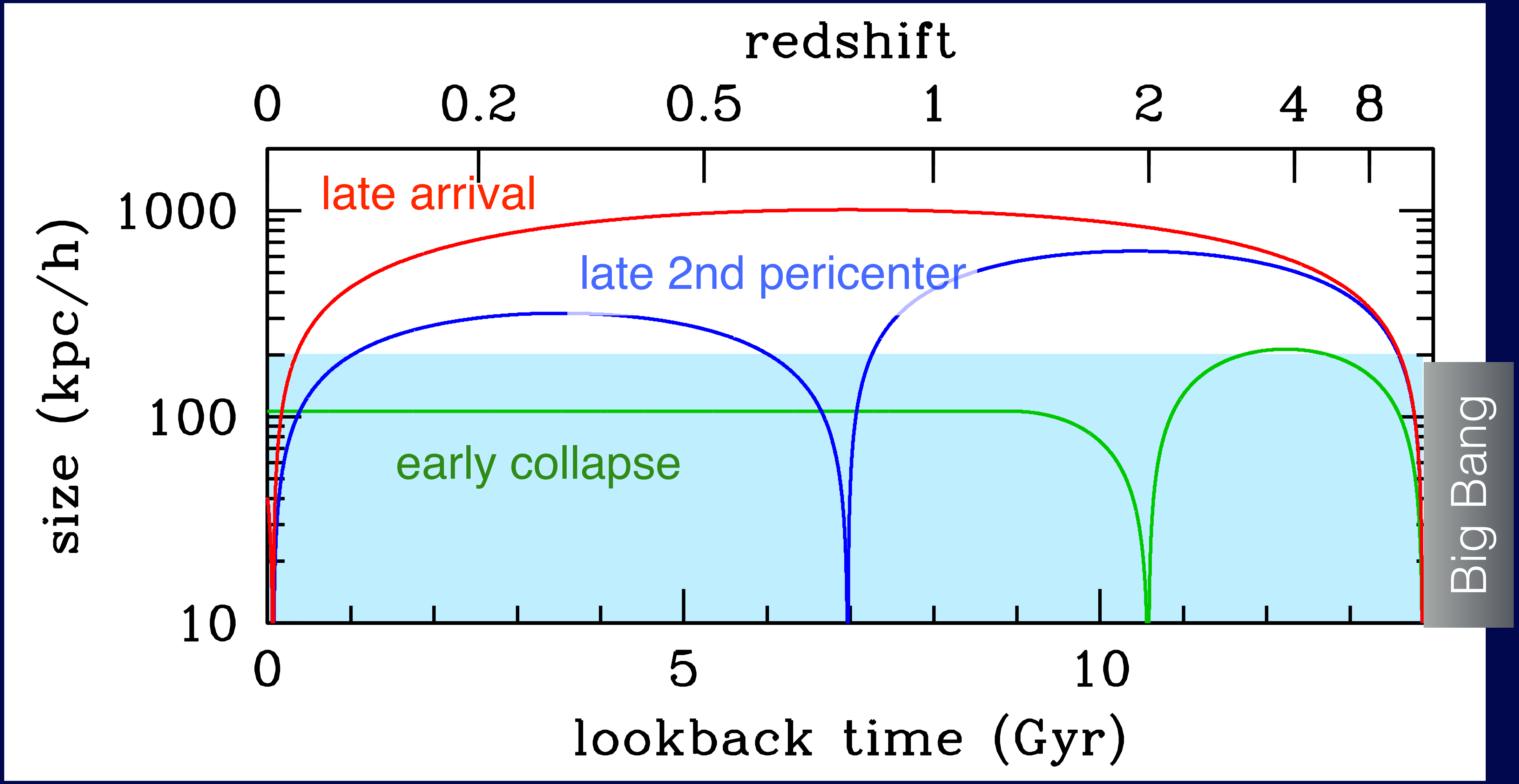
DM simulation	SAM	physically dense	Reference
8-body SAM (!)	Mamon 87	40%	Mamon 86, 87
MS	Bower et al. 06	77%	DíazG & GM 10
MS	Croton et al. 06	73%	DíazG & GM 10
MS	De Lucia & Blaizot 07	58%	DíazG & GM 10
MS-II	Guo et al. 11	69%	DíazG+12
MS	Guo et al. 11	56%	DG+ in prep
MS	Henriques et al. 12	53%	DG+ in prep

1/2 to 2/3 CGs physically dense (90% within virialized groups)
1/3 to 1/2 chance alignments (80% within virialized groups)

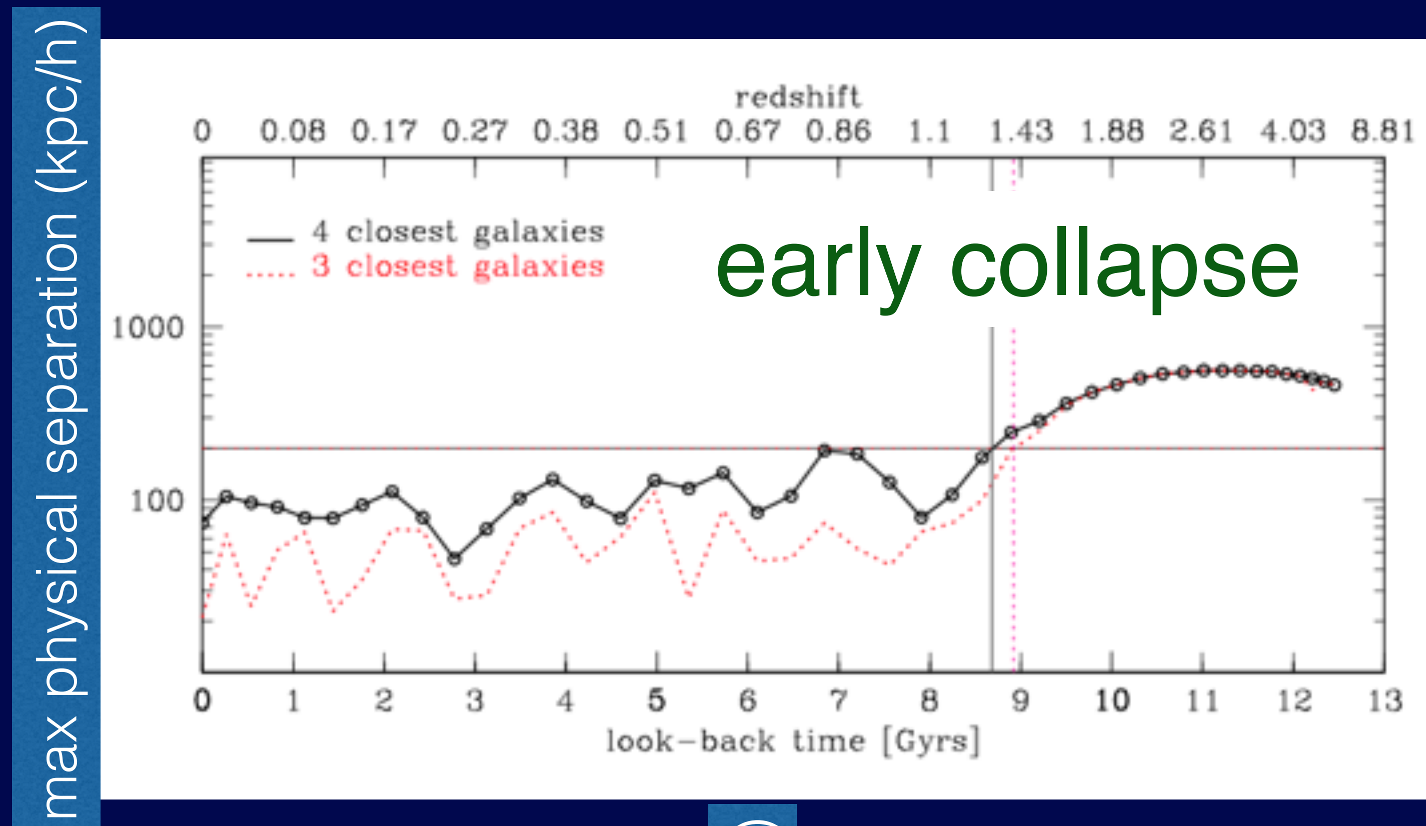
5) How do (physically dense) Compact Groups *assemble* their galaxies?

toy model



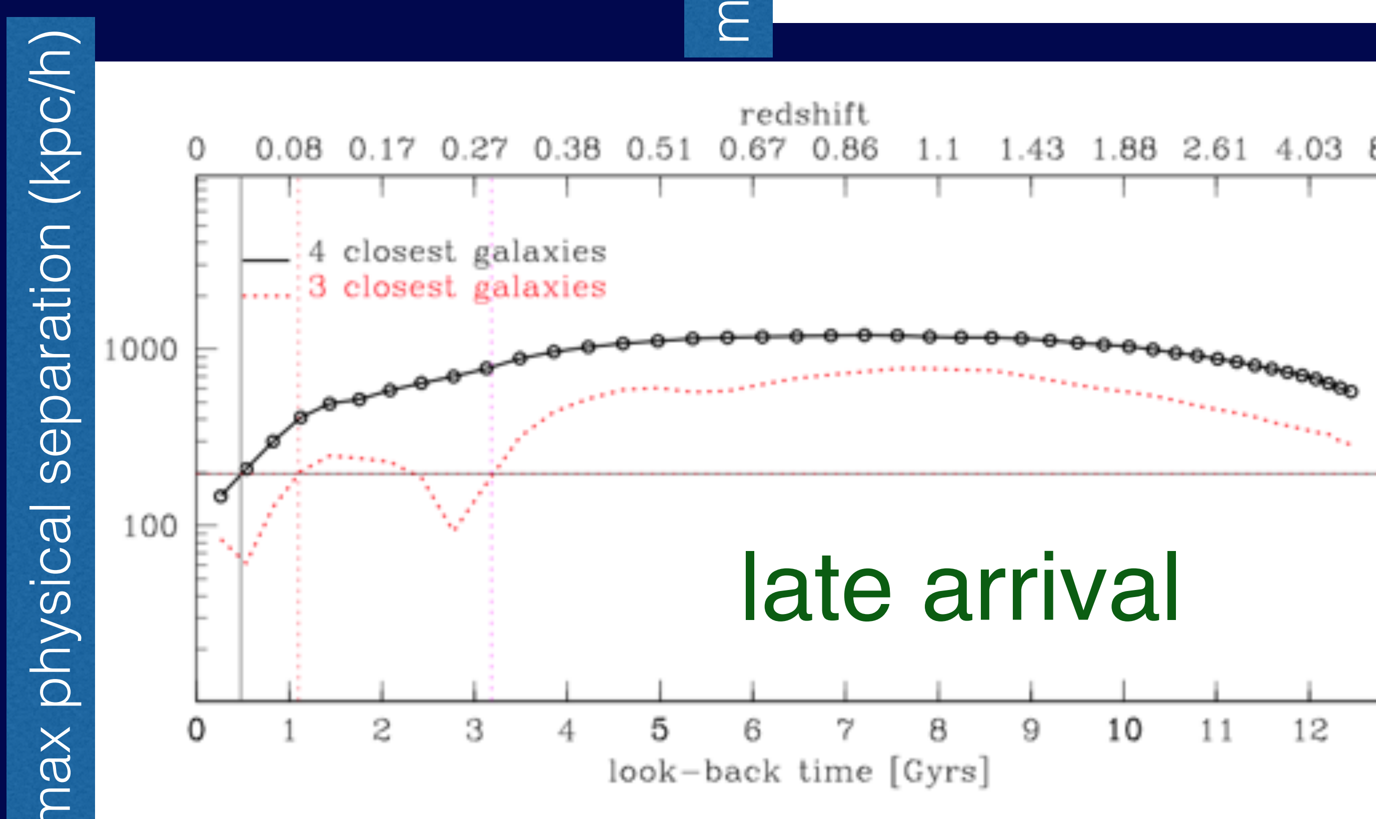
CG assembly in Henriques+12 SAM

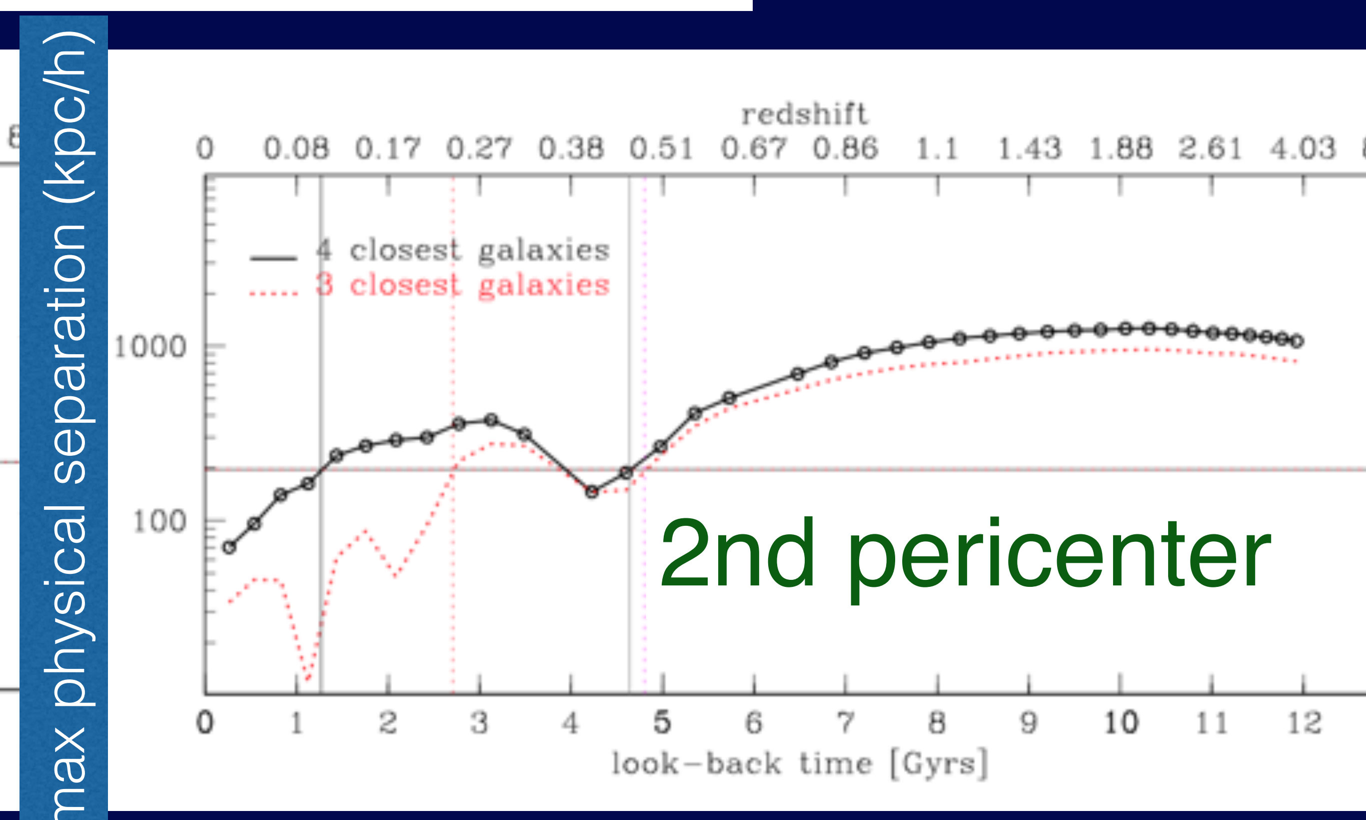
follow back in time main progenitors of physically dense z=0 CGs



Euge DÍAZ-GIMÉNEZ

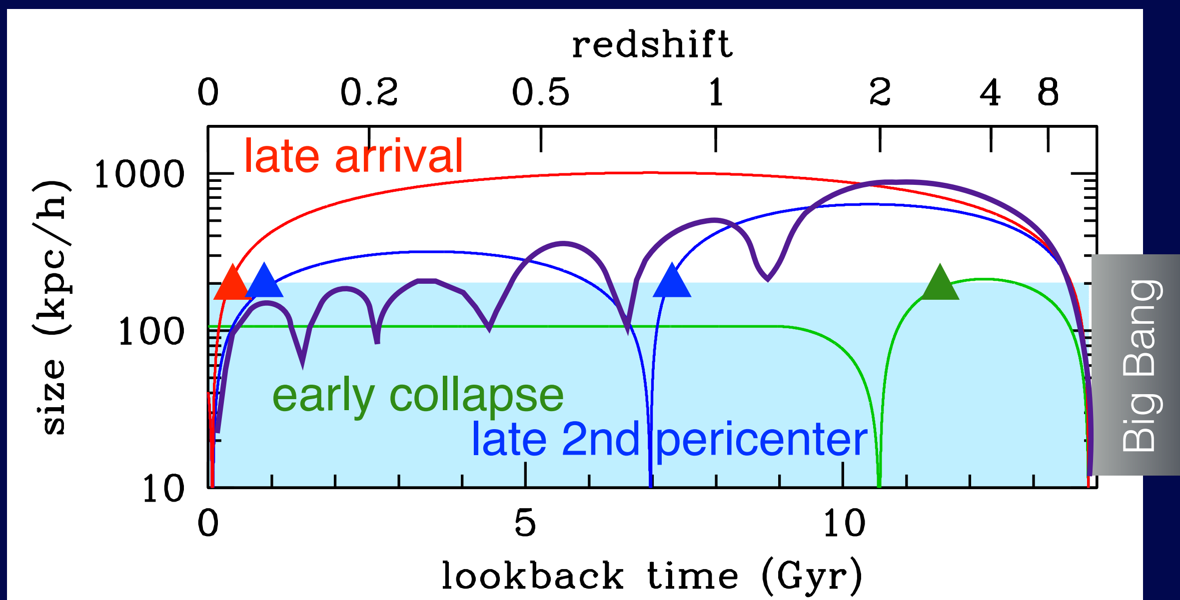
Ariel ZANDIVAREZ

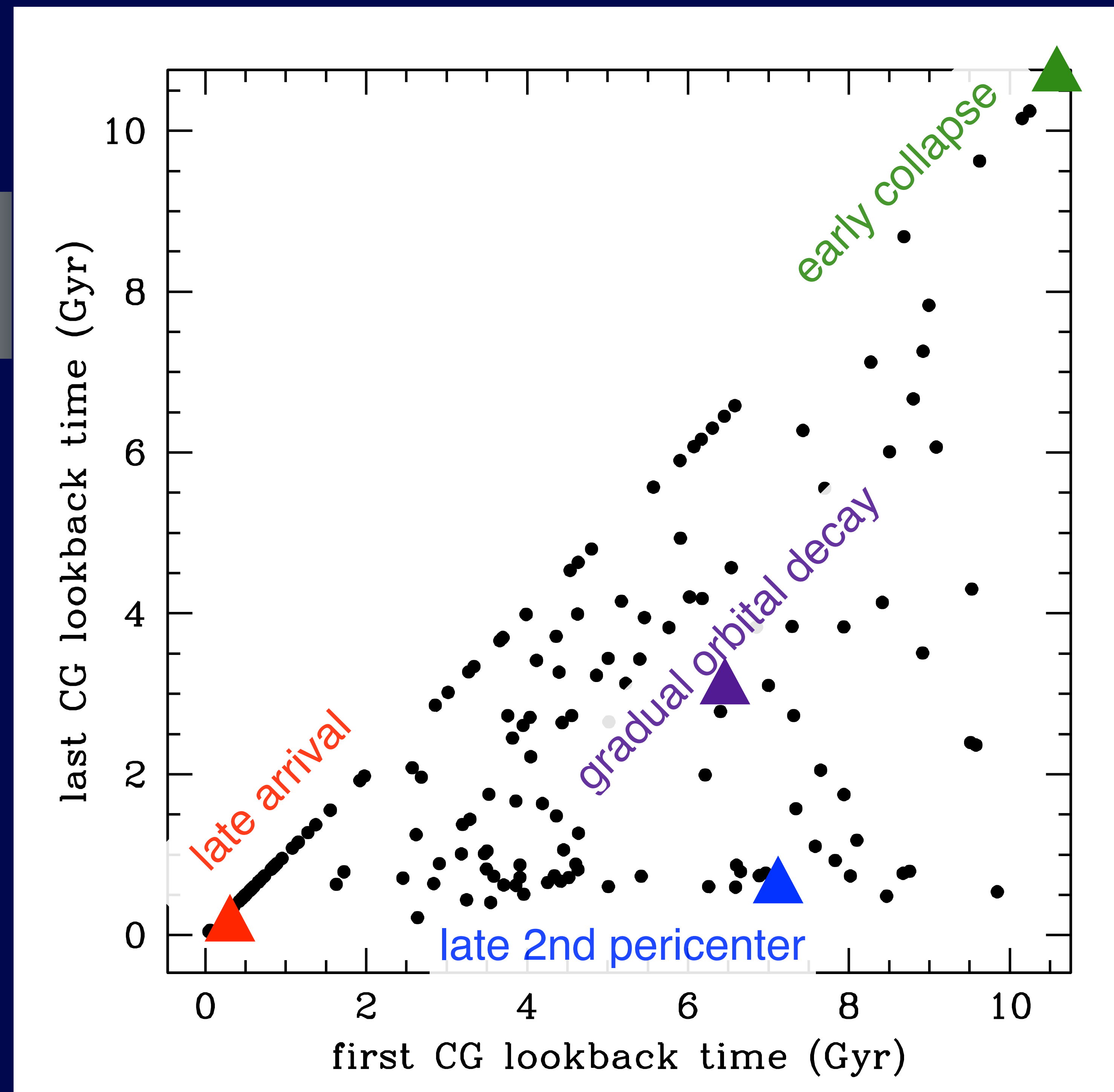




CG assembly history statistics

stats on 4 closest galaxies:
first & last entry within 200 kpc/*h* (after 1st apocenter)





<3% early collapse
1/4 late arrival
1/4 late 2nd pericenter
1/2 gradual orbital decay

Summary

1) Can we build much *better group finder* than optimal FoF?

MAGGIE (bayesian & probabilistic) beats optimal FoF!

2) Is there a *complete* compact group sample?

2MCG: 80 accordant velocity CGs, complete velocity sampling,
1st CG catalog w magnitude gap (mergers) & *L*-segregation

3) How do CG galaxies relate to CG *environment*?

morphological fractions ↔ density of ellipticals, crossing time
SSFRs of SFGs = normal; SSFRs of passive: anemic!

4) What is the *nature* of compact groups?

40±10% chance alignments, mostly within virialized groups

5) How do (physically dense) compact groups *assemble*?

1/2 by orbital decay, most others on late arrival of 4th galaxy

Perspectives

- Environmental effects on SDSS & GAMA galaxies
  $= f(M_{\rm group}, m_{\rm stars}, R/R_{\rm vir}, v_{\rm LOS}/\sigma_{\rm v}, \text{color})$ & vs. group finder

- Improve MAGGIE: treat red & blue galaxies differently

- Adapt MAGGIE to Euclid

- Mass / orbit modeling (DM concentration, velocity anisotropy) vs. group finder

- CG galaxy properties vs. group properties & split sats /centrals

- CG properties vs assembly history