Satellites around massive galaxies since z~2

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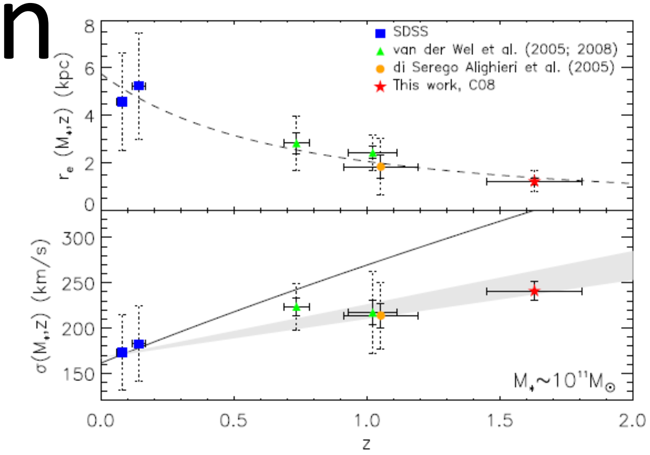
Abstract

- z~1までにmassive galaxiesのうち~30%が1:100のペア、z~2までに~15%が1:10のペアを伴っている。（観測事実）
- Spheroid-likeの方がDisk-likeよりもsatelliteを多い割合(~2-3倍)で持っている。（観測事実）
- Spheroid-likeはz~2までに~2回の1:3のminor mergerを経験している。
- 一方、Disk-likeは~1回。（理論予想）

1.Introduction



- Significant size evolution;
  - > Major merger ?
  - > Minor merger ?
  - > Puffing-up ?
- Results only from the path of galaxies… e.g.,
  - 1. a progressive build-up of the envelope (Hopkins et al. 2009)
  - 2. a mild decrease in the velocity dispersion (Cenarro & Trujillo 2009)
  - 3. no correlation between the size evolution and the age of the stellar population (Trujillo, Ferreras & de La Rosa 2011)

1.Introduction

- More direct way…
  - > find the fraction of galaxies with satellites and how they change with cosmic time.

1.Introduction

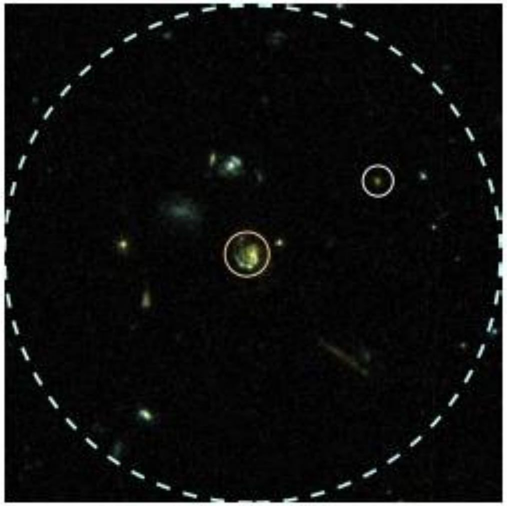
- Previous works;
- The fraction of the satellite galaxies in the local universe : ~12% (Chen et al. 2008)
  - > in good agreement with ΛCDM simulation (e.g., Boylan-Kolchin et al. 2010)
- Nierenberg et al. (2011) at z~1

  - > but 1/10 < M_{sat} < 1, z~1 and M_{star}< $10^{11} M_{\odot}$.

1.Introduction

- This work;

z<1	1/100 < M_{sat} < 1	$10^{11}\ M_{\odot}\ <\ M_{star}$
z<2	1/10 < M_{sat} <1	$10^{11}\ M_{\odot}\ <\ M_{star}$



2.Data

- z<2, 831 massive galaxies by Palomar Obs(200-inch).
- Chabrier IMF.
- Sersic n catalog by Trujillo et al. 2007

- For satellites,
- Rainbow Cosmological Data base (Barro et al.2011)
- $10^8 < M_{sat} < 10^{12}\ M_{\odot}$, z<2.2 ~55,000 objects.

3.Criteria

0<z<2	$0.1 < M_{sat}/M_{star} < 1$
0<z<1	$0.01 < M_{sat}/M_{star} < 1$

- Δz, $R_{search} < 100kpc$
  - > Gravitational bound, background contamination.

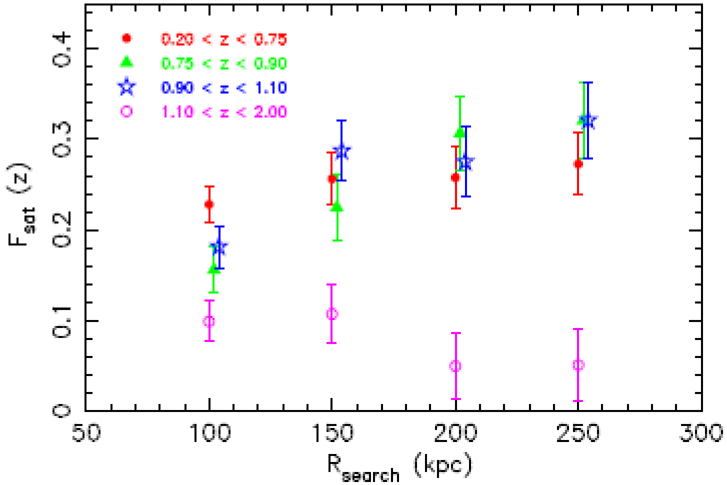
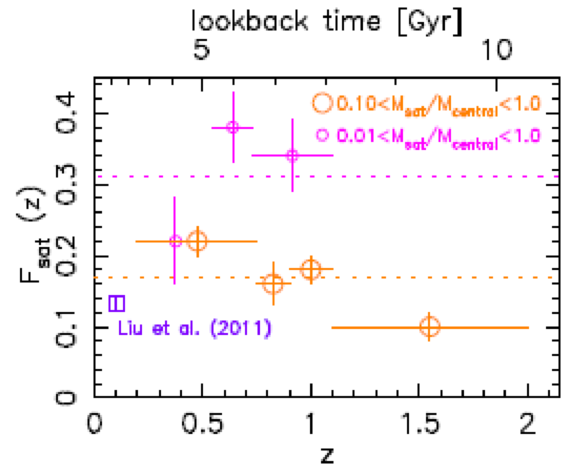
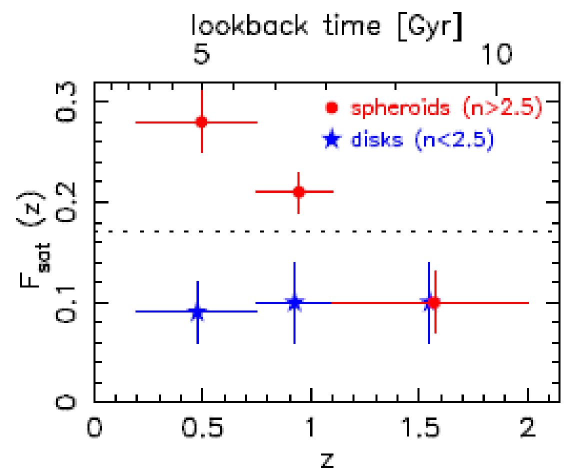


Figure 3. Fraction of massive galaxies having satellites within different projected radial distances (search radius, R_{search}) in the mass range $0.1 < M_{sat}/M_{central} < 1.0$ for the different redshift bins studied in this work.

4.Results

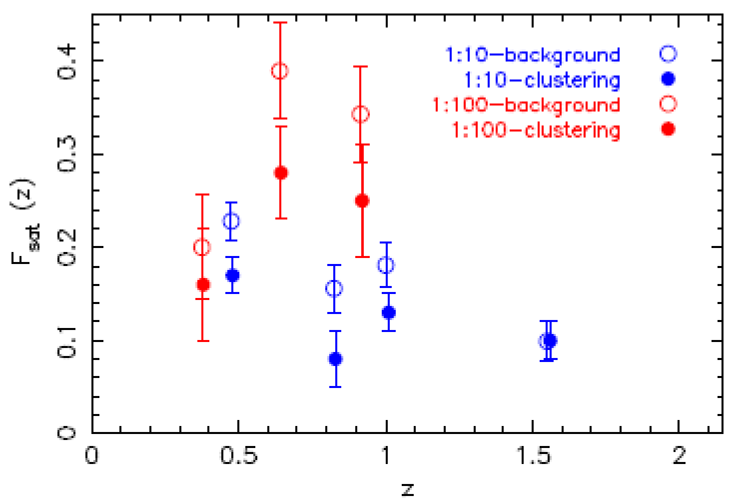
- “Constant” for 0<z<2 ($\sim 17 \pm 3\%$)
  - > consistent with z=0.
- “relatively constant”
  for 0<z<1 ($\sim 31 \pm 6\%$)





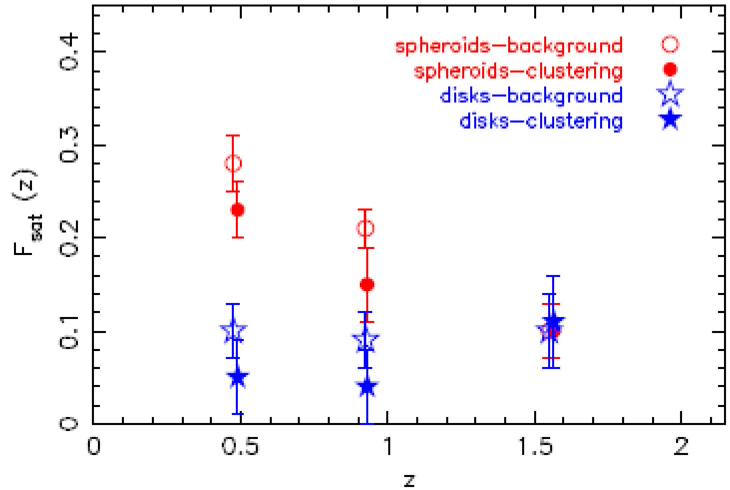
Discussion and Conclusion

- Constant F_{sat} since z~2.
  - > ~15% for $M_{sat} > 10^{10} M_{\odot}$, ~30% for $M_{sat} > 10^{9} M_{\odot}$.



Discussion and Conclusion; Hint ?

- F_{sat} for Spheroid-like > F_{sat} for Disk-like at z<1.1 (a factor of ~2).
  - > the different size growth for those two types (dramatic size growth for Spheroid since z~3).
- Or, clustering effect?



Discussion and Conclusion; Estimation of the Number of Mergers

- $N_m = T(z)F_{sat}/\tau_m$
- τ_m~1.5 Gyr at z~2 (e.g. Lotz et al. 2011)
  - > 1:3 merger would be ~ 1 for Disk (~2 for Spheroid). (see Fig.4 right.)
  - > 1:6 merger would be ~ 2 since z~1.

Discussion and Conclusion; Previous works

- Massive galaxies ($> 10^{11} M_{\odot}$) experience $N_m = (1.1 \pm 0.2)/\tau_m$ minor mergers over z=1.7-3.0 (Bluck et al. 2012).
  - > $N_m = (4.5 \pm 2.9)/\tau_m$ for 0<z<3.
  - > at high-z, F_{merge} is higher.
  - > still unnegligible error…
- Comparison with cosmological simulations (e.g., Naab et al. 2009; Oser et al.2012).

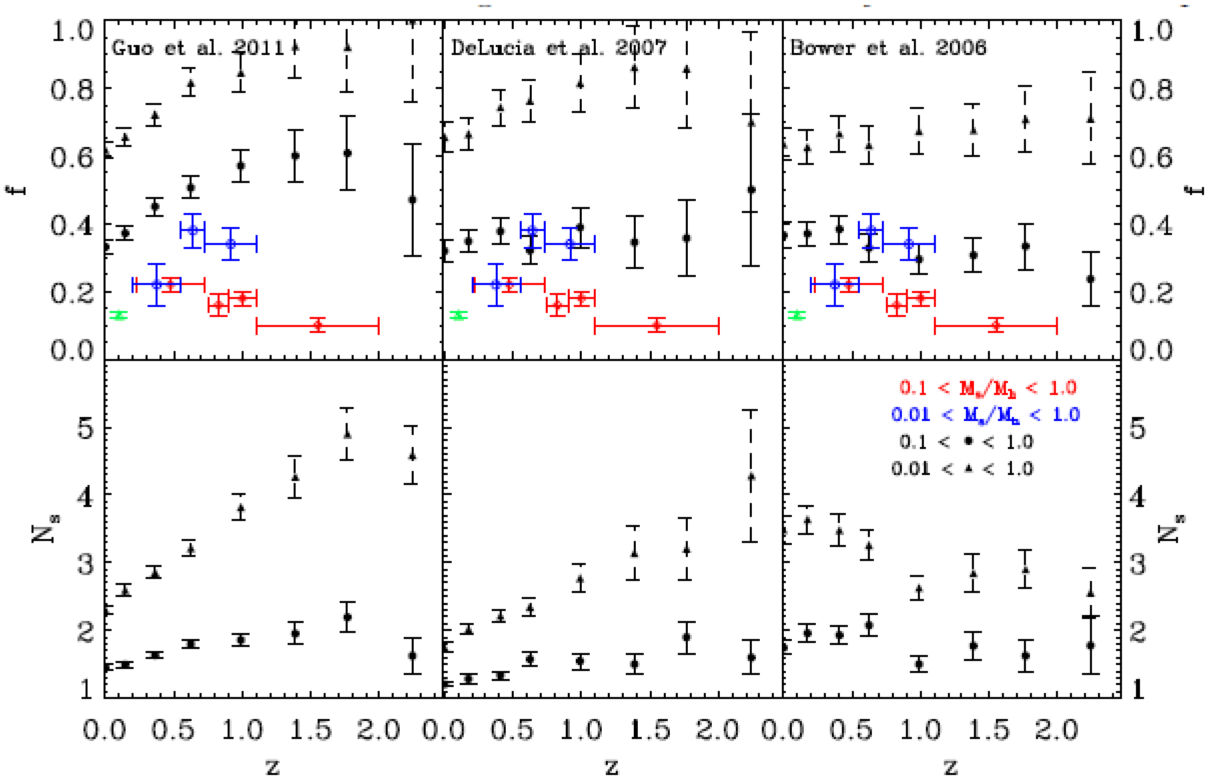


Figure 5. Columns stand for the results of three galaxy catalogs based on different semi-analytical models. For each model, and from top to bottom, are shown the fraction of massive galaxies that have at least one satellite within a sphere of 100 kpc radius and a projected distance smaller than 100 kpc, and the average number of satellites per massive galaxy when they have one of such objects around. The full circles (triangle) stand for the satellites with stellar mass ratios of $0.1<M_s/M_h<1$ ($0.01<M_s/M_h<1$). The error bars represent one standard deviation. The observational data from Mármol-Queraltó et al. (2012) are overplotted as red (blue) open circles (diamonds) for mass ratios of $0.1<M_s/M_h<1.0$ ($0.01<M_s/M_h<1$). The local observational reference (z=0.1) from Liu et al. (2011) for the fraction of massive galaxies with satellites with mass ratios of $0.1<M_s/M_h<1$ is plotted as a green open triangle, no data are available for smaller satellites. Figure taken from Quilis & Trujillo (2012).

Trujillo et al. 2012

Redshift range	$N_{central}$ (N with spec z)	F_{obs}	S_{simul}	$S_{cluster}$	F_{sat}	$F_{cluster}$
All galaxies						
$0.10 < M_{sat}/M_{central} < 1.00$						
$0.20 < z < 0.75$	197 (130)	0.29	0.09 ± 0.02	0.15 ± 0.02	0.22 ± 0.02	0.17 ± 0.02
$0.75 < z < 0.90$	129 (76)	0.24	0.10 ± 0.03	0.17 ± 0.03	0.16 ± 0.03	0.08 ± 0.03
$0.90 < z < 1.10$	142 (99)	0.25	0.08 ± 0.02	0.13 ± 0.03	0.18 ± 0.02	0.13 ± 0.02
$1.10 < z < 2.00$	161 (55)	0.18	0.09 ± 0.02	0.09 ± 0.03	0.10 ± 0.02	0.10 ± 0.02
$0.01 < M_{sat}/M_{central} < 1.00$						
$0.20 < z < 0.55$	51 (40)	0.37	0.20 ± 0.06	0.24 ± 0.06	0.22 ± 0.06	0.16 ± 0.06
$0.55 < z < 0.73$	70 (42)	0.53	0.24 ± 0.05	0.36 ± 0.05	0.38 ± 0.05	0.28 ± 0.05
$0.73 < z < 1.10$	73 (53)	0.52	0.27 ± 0.05	0.36 ± 0.06	0.34 ± 0.05	0.25 ± 0.06
Spheroid – like (n > 2.5) galaxies						
$0.10 < M_{sat}/M_{central} < 1.00$						
$0.20 < z < 0.75$	137	0.34	0.09 ± 0.03	0.16 ± 0.03	0.28 ± 0.03	0.23 ± 0.03
$0.75 < z < 1.10$	176	0.27	0.08 ± 0.02	0.14 ± 0.04	0.21 ± 0.02	0.15 ± 0.04
$1.10 < z < 2.00$	85	0.18	0.08 ± 0.03	0.08 ± 0.03	0.10 ± 0.03	0.10 ± 0.03
Disk – like (n < 2.5) galaxies						
$0.10 < M_{sat}/M_{central} < 1.00$						
$0.20 < z < 0.75$	60	0.18	0.10 ± 0.03	0.15 ± 0.04	0.09 ± 0.03	0.05 ± 0.04
$0.75 < z < 1.10$	95	0.19	0.09 ± 0.03	0.16 ± 0.04	0.10 ± 0.04	0.04 ± 0.04
$1.10 < z < 2.00$	76	0.18	0.09 ± 0.04	0.09 ± 0.05	0.10 ± 0.04	0.11 ± 0.05