ALHAMBRA
SURVEY

Accurate merger fractions by PDF analysis of photometric close pairs

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A. J. Cenarro, J. Varela, K. Viironen, A. Molino, N. Benítez,
& the ALHAMBRA collaboration

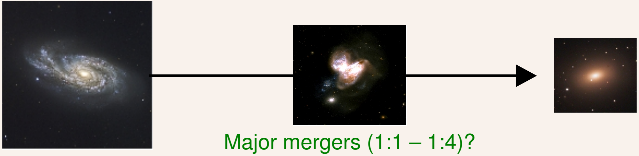
[ArXiv: 1409.1142]

CEFCA

Centro de Estudios de Física del Cosmos de Aragón

EGEE / 19th September 2014 / Bologna

Mergers and galaxy evolution



Major mergers (1:1 – 1:4)?

Toomre 77; Naab+06; Rothberg+06ab,10; Hopkins+09

$z = 0$ $z = 1$ $z = 2$

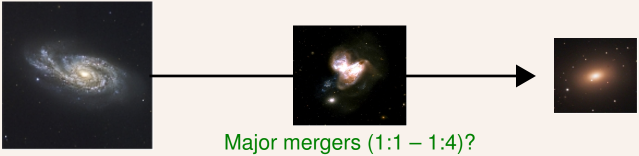
$\times 2$ $\times 2$

Major and minor mergers?

Trujillo+06,07; Buitrago+08; Naab+09, van Dokkum+10; Cassata+13

The knowledge of the merger fraction and its dependence on stellar mass and colour is needed to constrain the merger track (Nipoti, Naab, Eliche-Moral, Pawlik, Patton, Man, etc.)

Mergers and galaxy evolution



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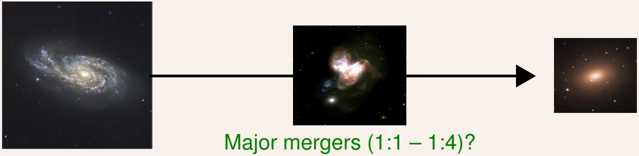

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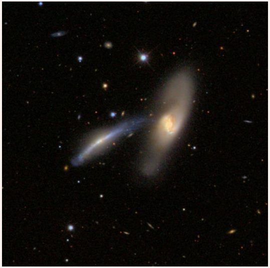
Close pairs in photometric samples



Two close galaxies in the sky plane, $r_p^{min} \leq r_p \leq r_p^{max}$, and in redshift space, $\Delta v \leq 500$ km s^{-1} (e.g., Patton+00).

$f_m = N_p / N_1$

N_1: number of central galaxies,

N_p: number of central galaxies with a close companion.

With photometric redshifts we...

(i) apply a correction to avoid projection effects (e.g., Rawat+08; Mármol-Queraltó+12; Xu+12; etc.),

(ii) assume a Gaussian probability distribution function (PDF) to weight the close pairs (e.g., CLSJ+10).

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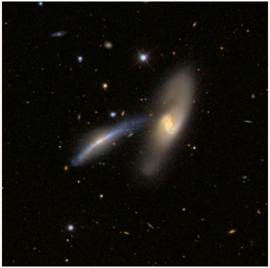

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The above methodologies have several shortcomings:

- The PDFs are usually non-Gaussian, and they assume either Gaussian or flat distributions.
- The luminosities and the stellar masses of the sources are also a function of z, and they assume the values at the best photometric redshift.
- A red galaxy can have two co–existing solutions: either an old, massive galaxy or a dusty, star-forming galaxy.

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Close pairs in photometric samples

Our goal is to improve the estimation of the merger fraction with photometric redshifts by using all the information encoded in the probability distribution functions (PDFs) of ALHAMBRA.

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The ALHAMBRA survey

Advanced, **L**arge, **H**omogeneous **A**rea, **M**edium–**B**and **R**edshift **A**stronomical survey (Moles+08, alhambrasurvey.com)

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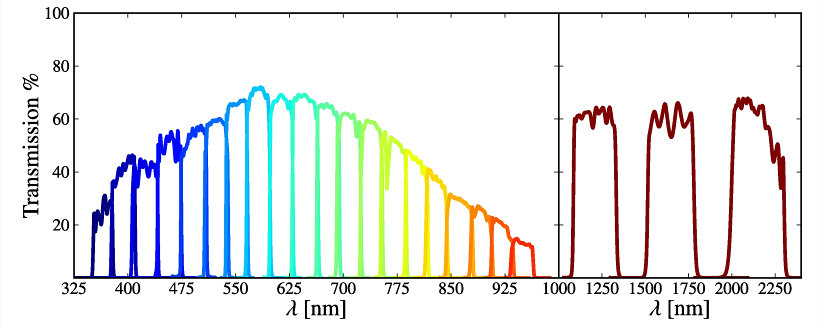

20 contiguous, non-overlapping medium-band ($\sim$ 30 nm) filters in the optical + 3 near-infrared filters (J, H, K_s).
Limiting magnitude of $\sim$ 23.5 (AB 5σ, $3''$ aperture).

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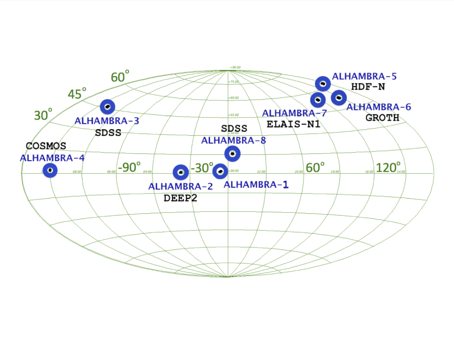
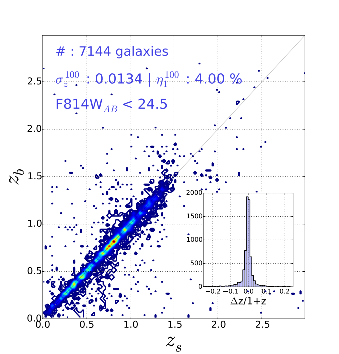


Field name	Overlapping survey	area (deg^2)
ALHAMBRA-2	DEEP2	0.377
ALHAMBRA-3	SDSS	0.404
ALHAMBRA-4	COSMOS	0.203
ALHAMBRA-5	GOODS-N	0.216
ALHAMBRA-6	AEGIS	0.400
ALHAMBRA-7	ELAIS-N1	0.406
ALHAMBRA-8	SDSS	0.375
Total		2.38

7 independent fields to defeat (and study!) the cosmic variance (CLSJ+14a, Man's talk) with a total high-quality area of 2.38 deg^2.

The ALHAMBRA survey

Advanced, **L**arge, **H**omogeneous **A**rea, **M**edium–**B**and **Redshift Astronomical** survey (Moles+08, alhambrasurvey.com)



$\Delta z/(1+z) = 0.013$ at $I \leq 24.5$ (Molino+14).

The probability distribution function (PDF) of each galaxy.

The ALHAMBRA survey

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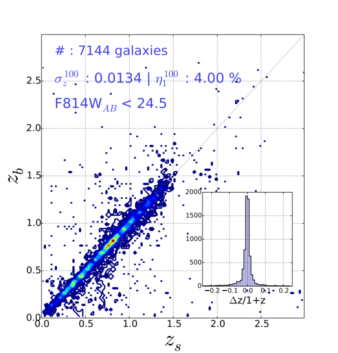

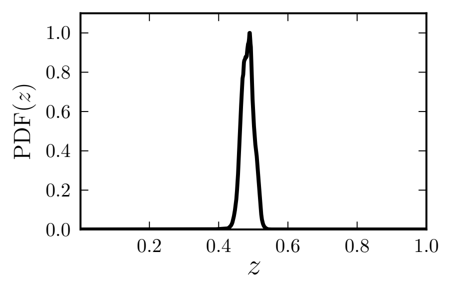

Probability of a galaxy of being located at redshift z

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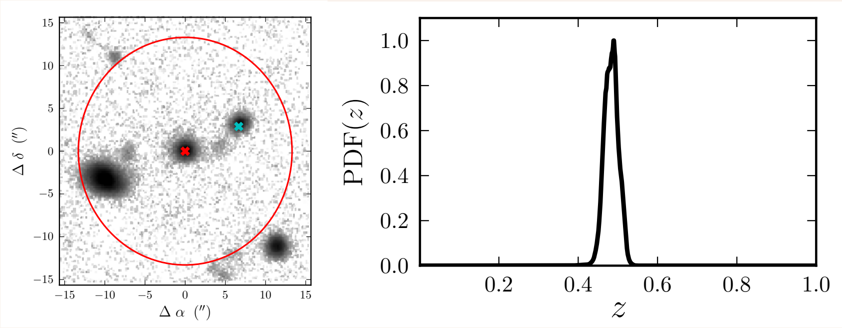
The PDF as a superior descriptor

ALHAMBRA SURVEY

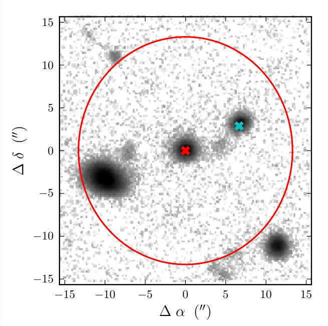


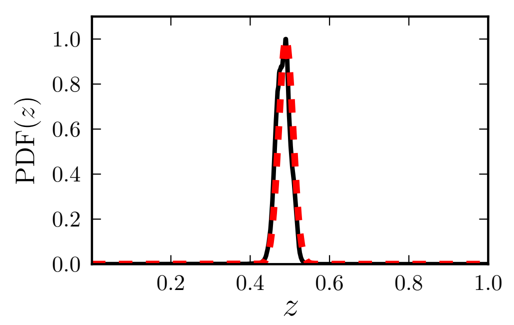
Central galaxy: The Gaussian approximation is $z_p = 0.490 \pm 0.018$.

Nice job!!

The PDF as a superior descriptor

ALHAMBRA SURVEY





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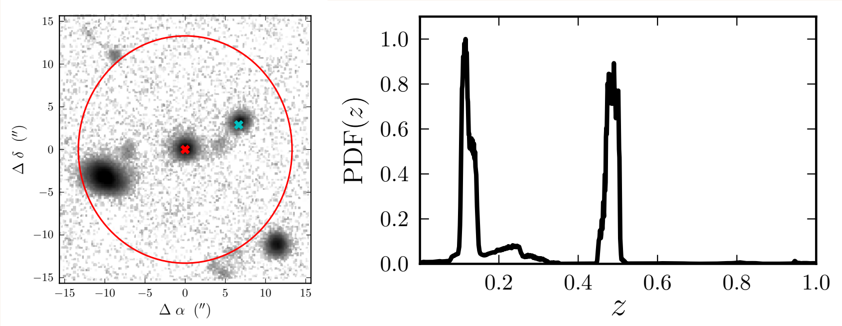
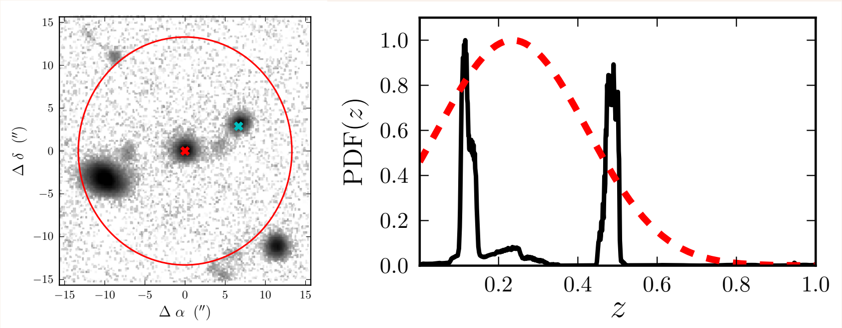


Companion galaxy: The Gaussian approximation is $z_p = 0.235 \pm 0.188$.

You know nothing!!

The PDF as a superior descriptor

ALHAMBRA SURVEY



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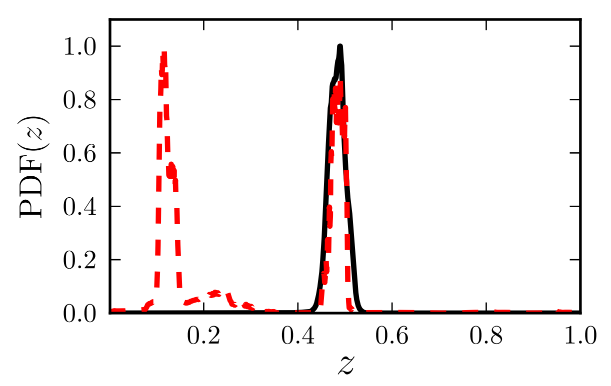
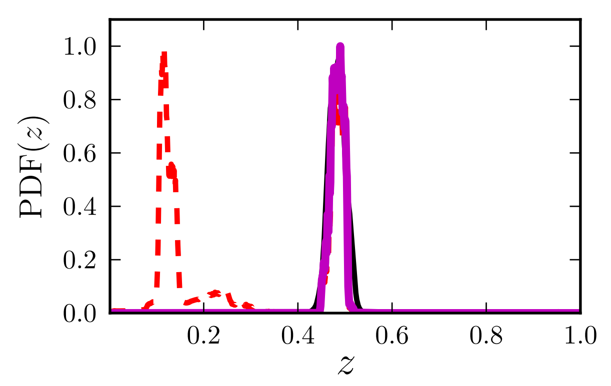
Close galaxies in redshift space: $\mathcal{Z}(z)$

ALHAMBRA SURVEY



Probability of being at the same redshift: $\mathcal{Z}(z) = PDF_1(z) \times PDF_2(z)$.
However, this provides the wrong normalisation!

Close galaxies in redshift space: $\mathcal{Z}(z)$



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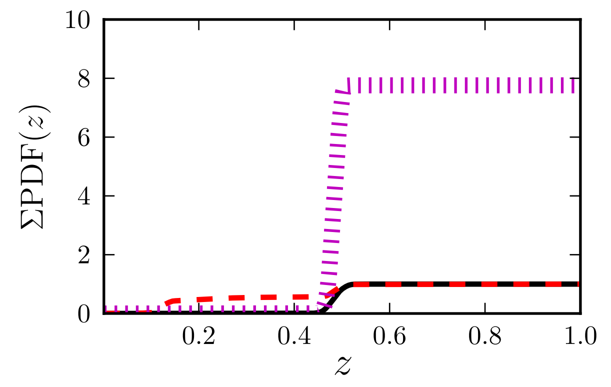

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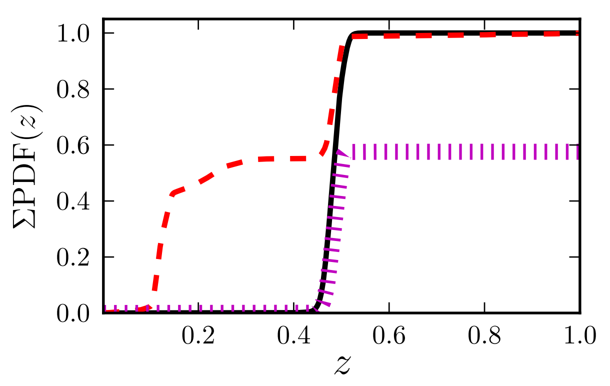
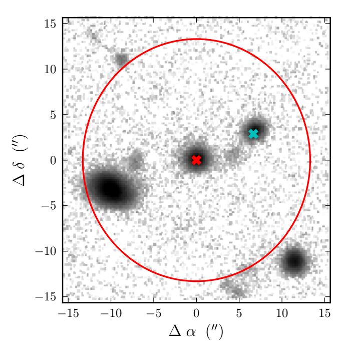


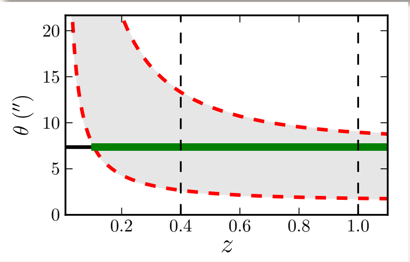
Probability of being at the same z: $\mathcal{Z}(z) = \frac{2 \times PDF_1(z) \times PDF_2(z)}{PDF_1(z) + PDF_2(z)}$.

We normalise to the number of pairs (two galaxies) at each redshift. In this case, $\int \mathcal{Z}\,\mathrm{d}z = 0.58$ pairs.

The angular mask: $\mathcal{M}^{\theta}(z)$

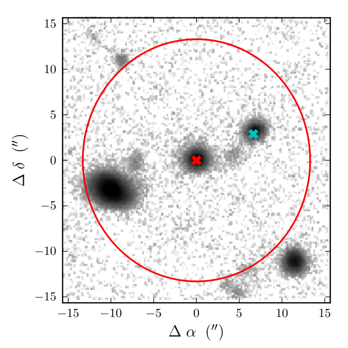


$10h^{-1}$ kpc $\leq r_p \leq 50h^{-1}$ kpc

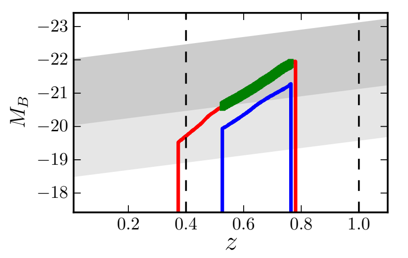


In addition to $\mathcal{Z}(z)$, we deffine two masks.
The **angular mask** $\mathcal{M}^{\theta}(z) = 1$ where the system fulfills the r_p condition, and 0 otherwise.

The pair selection mask: $\mathcal{M}^{\rm pair}(z)$



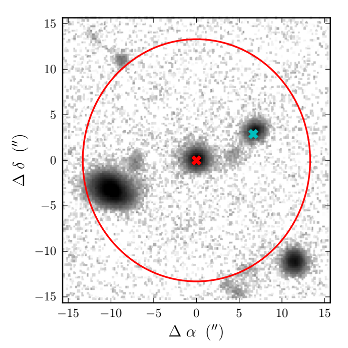
$$M_{B,1} \leq -20.0 - 1.1z$$
$$M_{B,2} \leq -18.5 - 1.1z$$



In addition to $\mathcal{Z}(z)$, we deffine two masks.
The **pair selection mask** $\mathcal{M}^{\rm pair}(z) = 1$ where the system fulfills the selection and the luminosity ratio constrain, and 0 otherwise.

The **pair probability function** is $PPF(z) = \mathcal{Z}(z) \times \mathcal{M}^{\theta}(z) \times \mathcal{M}^{\rm pair}(z)$

The pair selection mask: $\mathcal{M}^{\rm pair}(z)$



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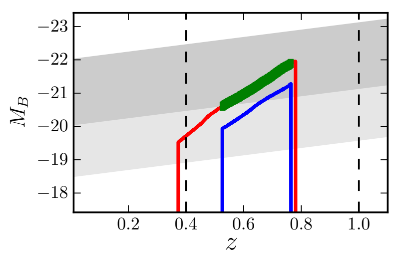

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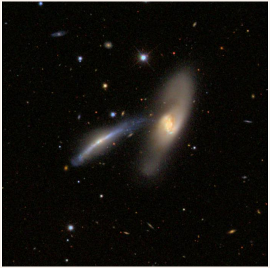
Robust estimation of $f_{\rm m}$ in ALHAMBRA



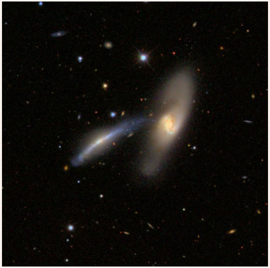
Two close galaxies in the sky plane, $r_{\rm p}^{\rm min} \leq r_{\rm p} \leq r_{\rm p}^{\rm max}$, and in redshift space, $PPF(z)$.

$$f_{\rm m} = \frac{N_{\rm p}}{N_1} = \frac{\sum_k \int PPF_k\,{\rm d}z}{\sum_i \int PDF_i\,{\rm d}z},$$

N_1: number of central galaxies,
$N_{\rm p}$: number of close pairs.

7 ALHAMBRA fields ⇒
48 sub-fields (chips) ⇒
48 measurements of $f_{\rm m}$ ⇒
$f_{\rm m}$ distribution ⇒
ALHAMBRA merger fraction
(CLSJ+14a)

Robust estimation of f_m in ALHAMBRA



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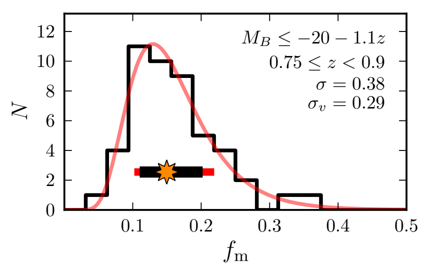
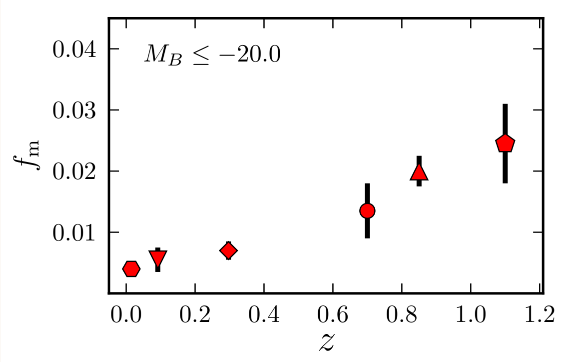


The merger fraction in M_B samples

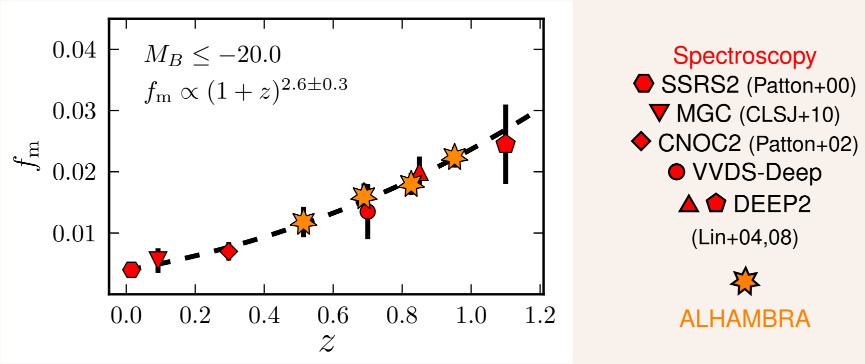


Spectroscopy
SSRS2 (Patton+00)
MGC (CLSJ+10)
CNOC2 (Patton+02)
VVDS-Deep
DEEP2
(Lin+04,08)

ALHAMBRA

Merger fraction of galaxies with $M_B \leq -20$.
Excellent agreement with spectroscopic surveys!
The merger fraction evolves as:
$f_m = (0.39 \pm 0.07) \times (1+z)^{2.6\pm0.3}$ %

The merger fraction in M_B samples



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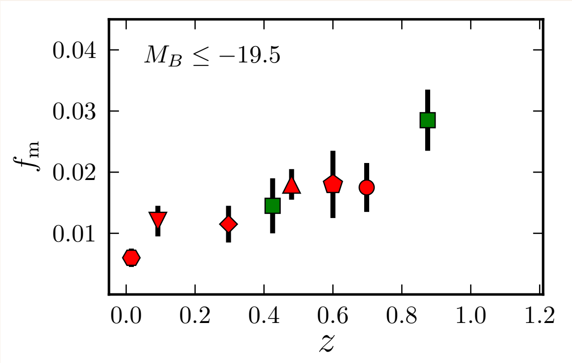


Spectroscopy

SSRS2 (Patton+00)

MGC (CLSJ+10)

CNOC2 (Patton+02)

VVDS-Deep

DEEP2

(Lin+04,08)

Spectroscopy + photometry

GOODS-S (CLSJ+10)

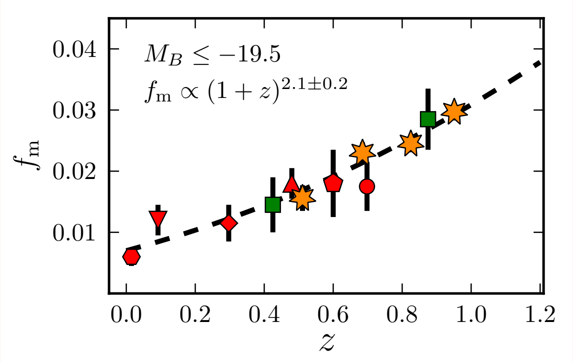
ALHAMBRA

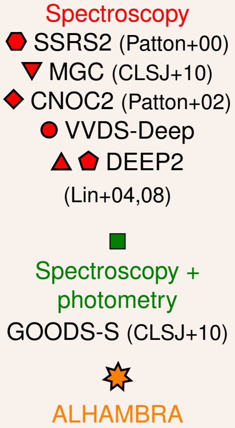
Merger fraction of galaxies with $M_B \leq -19.5$.

The merger fraction evolves as:

$f_m = (0.70 \pm 0.09) \times (1 + z)^{2.1 \pm 0.2}$ %

The merger fraction in M_B samples





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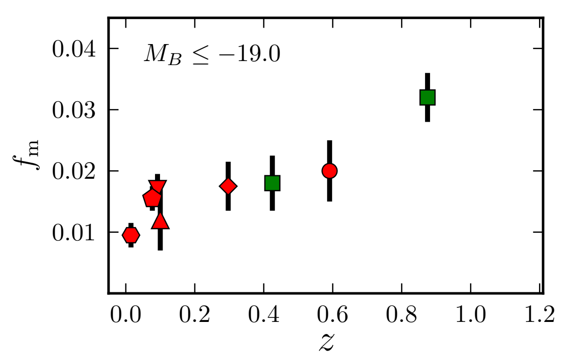

Spectroscopy

SSRS2 (Patton+00)

MGC (CLSJ+10)

CNOC2 (Patton+02)

VVDS-Deep

DEEP2 (Lin+04,08)

Spectroscopy + photometry GOODS-S (CLSJ+10)

ALHAMBRA

Merger fraction of galaxies with $M_B \leq -19.0$.

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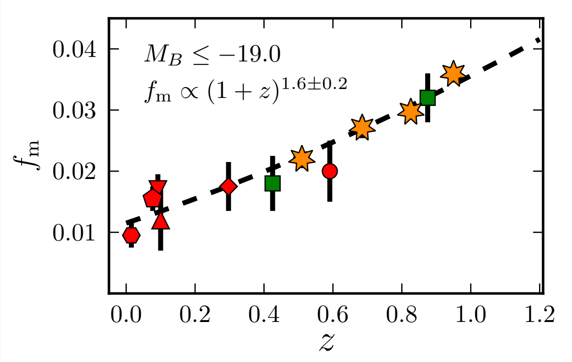
$f_m = (1.15 \pm 0.10) \times (1+z)^{1.6 \pm 0.2}$ %

The merger fraction in M_B samples



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MGC (CLSJ+10)
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Spectroscopy + photometry
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ALHAMBRA

Merger fraction of galaxies with $M_B \leq -19.0$.
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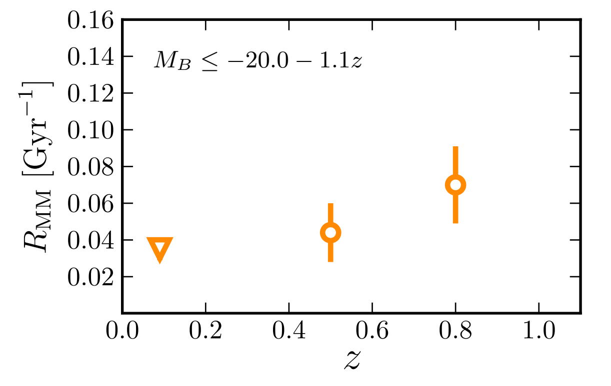
The major merger rate $R_{\rm MM}$

ALHAMBRA SURVEY



VVDS-Deep (CLSJ+11)

MGC (CLSJ+11)

ALHAMBRA

Major ($\Delta M_B < 1.5$) merger rate of $M_B \leq -20 - 1.1z$ galaxies.

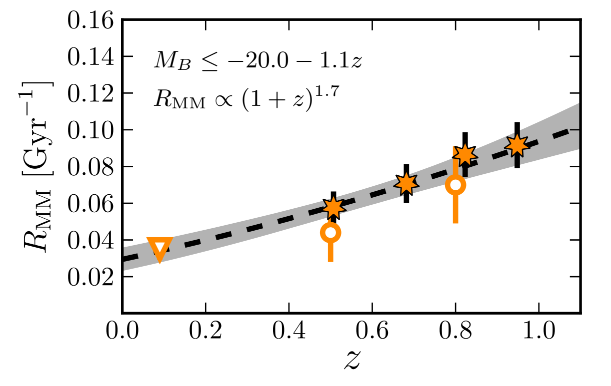
$R_{\rm MM} = f_{\rm MM}\, T_{\rm MM}^{-1}$ Gyr^{-1}

As previously, good agreement with the VVDS-Deep and MGC:

$R_{\rm MM} = (0.029 \pm 0.001) \times (1 + z)^{1.7 \pm 0.4}$ Gyr^{-1}

The major merger rate R_{MM}

ALHAMBRA SURVEY



VVDS-Deep (CLSJ+11)

MGC (CLSJ+11)

ALHAMBRA

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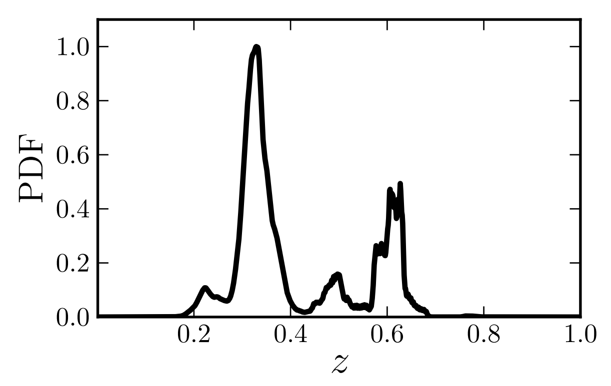
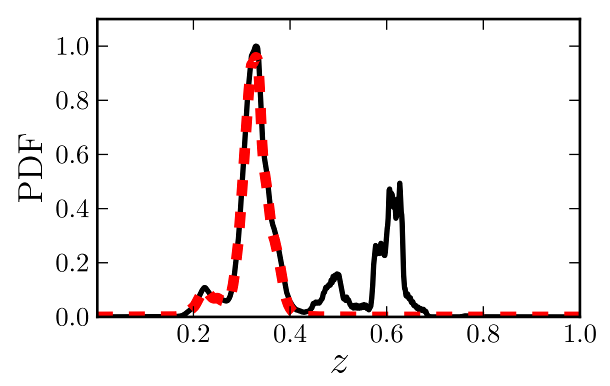
Red and blue galaxies from the PDF

ALHAMBRA SURVEY



The PDF has extra information about the spectral type of the source.
The E/S0 templates define "red galaxies", and the S/Starburst templates define "blue galaxies".
We can deal *statistically* with red and blue sub–samples.

Red and blue galaxies from the PDF



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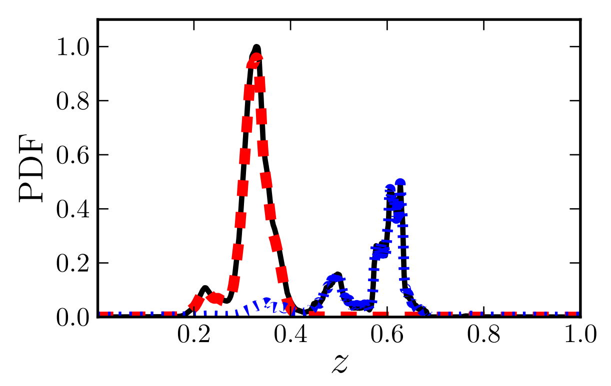

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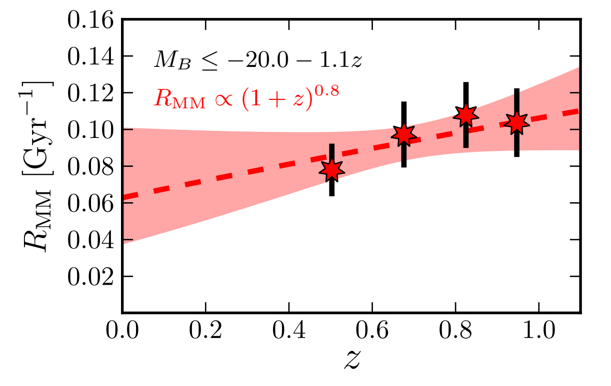
The major merger rate $R_{\rm MM}$ vs colour

ALHAMBRA SURVEY



ALHAMBRA
E/S0 templates

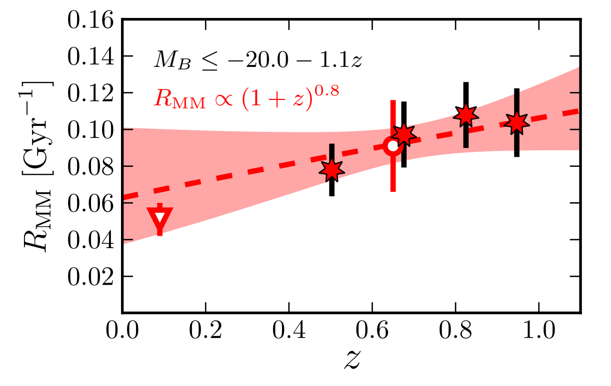
○ VVDS-Deep
$NUV - r \geq 4.25$
(CLSJ+11)

▽ MGC
$u - r \geq 2.1$

The E/S0 templates define "red galaxies", and the S/Starburst templates define "blue galaxies".

$$R_{\rm MM}^{\rm red} = (0.047 \pm 0.008) \times (1+z)^{1.3\pm0.4}\ {\rm Gyr}^{-1}$$

The major merger rate R_{MM} vs colour



ALHAMBRA
E/S0 templates

VVDS-Deep
$NUV - r \geq 4.25$
(CLSJ+11)

MGC
$u - r \geq 2.1$

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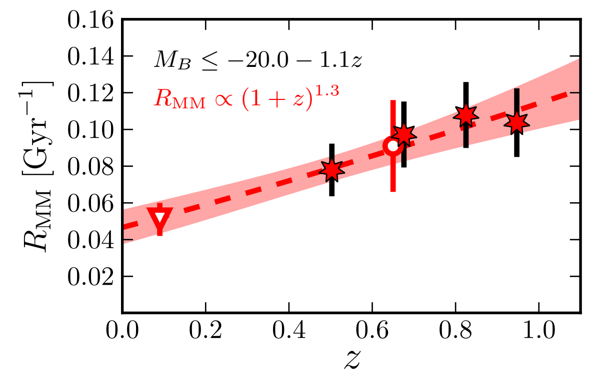
$$R_{MM}^{red} = (0.047 \pm 0.008) \times (1+z)^{1.3 \pm 0.4} \text{ Gyr}^{-1}$$

The major merger rate R_{MM} vs colour

ALHAMBRA SURVEY



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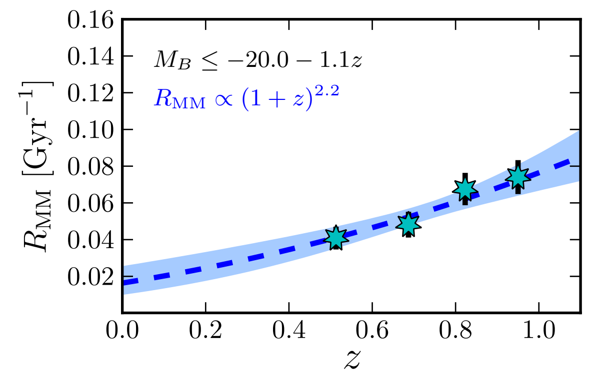
The major merger rate R_{MM} vs colour



ALHAMBRA
S/Starburst templates

○ VVDS-Deep
$NUV - r < 4.25$
(CLSJ+11)

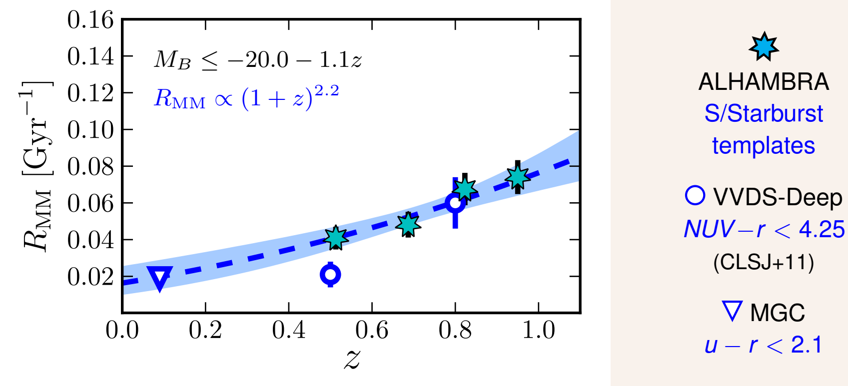
▽ MGC
$u - r < 2.1$

The E/S0 templates define "red galaxies", and the S/Starburst templates define "blue galaxies".

$R_{MM}^{blue} = (0.012 \pm 0.003) \times (1+z)^{2.7 \pm 0.5}$ Gyr^{-1}

The major merger rate R_{MM} vs colour

ALHAMBRA SURVEY



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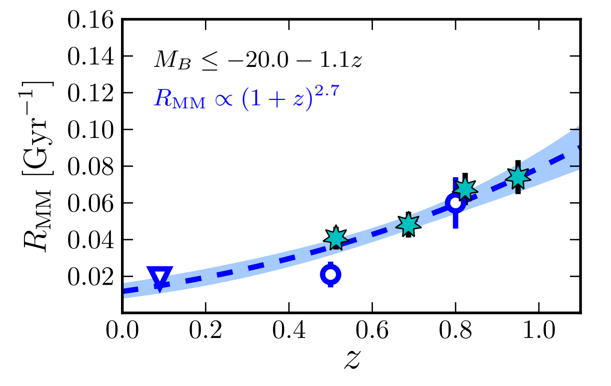
$$R_{MM}^{blue} = (0.012 \pm 0.003) \times (1+z)^{2.7 \pm 0.5}\ \text{Gyr}^{-1}$$

The major merger rate R_{MM} vs colour



ALHAMBRA
S/Starburst templates

VVDS-Deep
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(CLSJ+11)

MGC
$u - r < 2.1$

The E/S0 templates define "red galaxies", and the S/Starburst templates define "blue galaxies".

$$R_{MM}^{blue} = (0.012 \pm 0.003) \times (1+z)^{2.7 \pm 0.5} \text{ Gyr}^{-1}$$

Summary, conclusions, and future work

1. We have improved the methodology to compute the merger fraction $f_{\rm m}$ with photometric redshifts. The new method...
   - uses the full PDF information provided by BPZ.
   - applies consistent selections/conditions as a function of z.
   - deals statistically with “red” and “blue” templates.
2. We have applied the new method to the 48 ALHAMBRA sub-fields to estimate $f_{\rm m}$.
3. The merger fractions and rates from ALHAMBRA are in excellent agreement with those from spectroscopic surveys.

The next step is to include the stellar mass in the analysis.
We will apply this technique to estimate the merger fraction and the density field in the **J-PAS photometric survey**.

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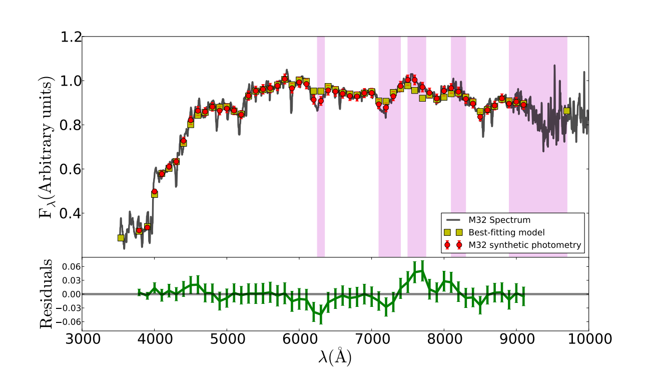
J-PAS: A next generation photometric survey

J-PAS : Javalambre - Physics of the accelerated universe Astrophysical Survey (Benítez et al. 2014 [ArXiv:1403.5237])



J-PAS (j-pas.org) will map ~8000 deg^2 of the northern sky with 54 narrow-band filters (~14 nm) + 2 medium-bands.
Photo–zs with $\Delta z/(1+z) \sim 0.3\%$ (~ 1000 km s^{-1} at $z = 0.1$)

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Thanks for your attention!!