Probability functions for unbiased statistical estimations in multi-filter surveys: the luminosity function

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A. F. Soto, A. J. Cenarro, J. Varela, L. A. Díaz-García,
& the ALHAMBRA collaboration

CEFCA

Centro de Estudios de Física del Cosmos de Aragón (Spain)

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The challenge of next generation surveys

Most of our knowledge about the evolution of galaxies is based on galaxy distributions ϕ from surveys.

J-PAS (Benítez+14) : 8500deg^2 with 56 narrow-band filters ($NB \lesssim 22.5$) for 0.3% photo$-z$ ($R \sim 50$). **2017**. j-pas.org

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LSST (Ivezić+08) : 18000deg^2 with 6 broad-band filters ($BB \lesssim 26$) for 3% photo$-z$ and time domain. **2023**. www.lsst.org

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LSST Large Synoptic Survey Telescope

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$$\delta^2_\phi = \delta^2_{\rm stat} + \delta^2_{\rm CV} + \delta^2_{\rm sys}$$

The importance of the posterior

What is the "**real**" redshift distribution $N(z)$ or the "**real**" luminosity function $\Phi(z, M_B)$ in a photometric survey?

With the best z_p

$$N(z_s) = \int N(z_p)\, P(z_s|z_p)\, \mathrm{d}z_p$$

(De)convolution process.
z_s are needed!! (Sheth+10)

With the posterior probability

$$N(z_s) = \sum_i \mathrm{PDF}_i(z)$$

Addition process of Probability Distribution Functions (PDFs)

Only photometry!! (Sheth+10)

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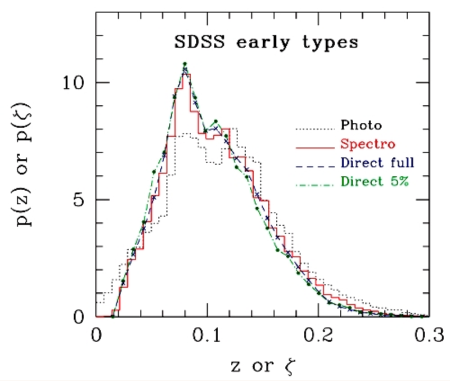

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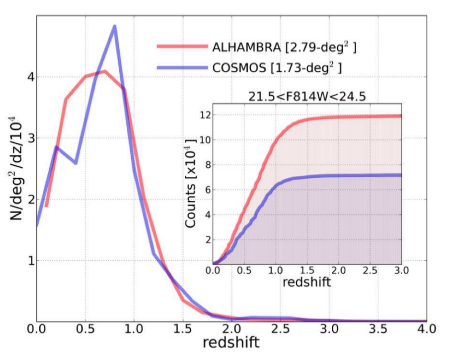
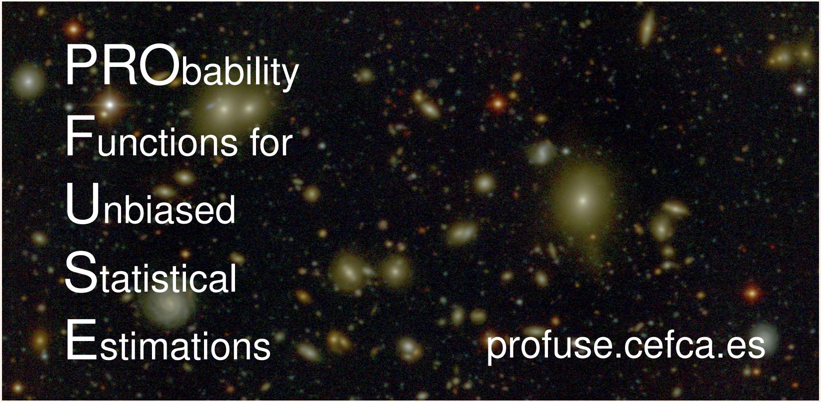


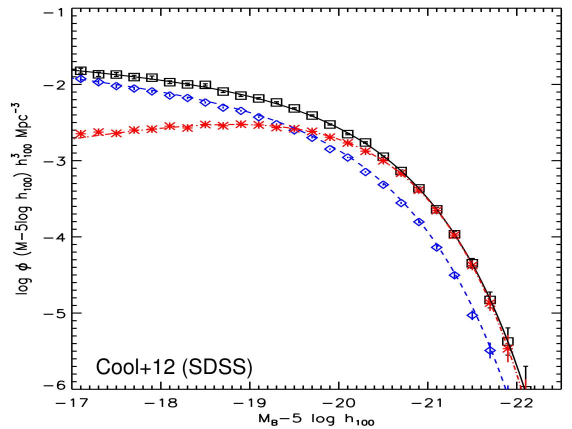
Molino+14

The PROFUSE project



in multi-filter surveys such as
COMBO-17, COSMOS30, ALHAMBRA, SHARDS, (completed)
PAU, J-PLUS, (on-going)
J-PAS, **Euclid**, and **LSST** (coming soon)

The luminosity function $\Phi\,(M_B)$



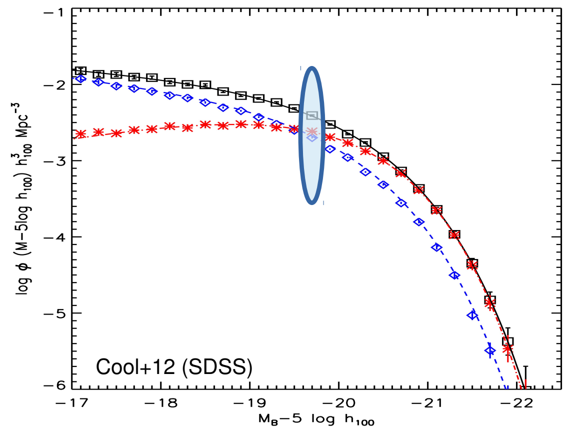
M_B^*
Characteristic luminosity

ϕ^*
Normalisation

α
Faint-end slope

To improve our knowledge about $\Phi\,(z, M_B)$, we need **(1)** an accurate and unbiased photometric LF estimator, and **(2)** a multi-filter photometric survey to apply it.

The luminosity function $\Phi(M_B)$



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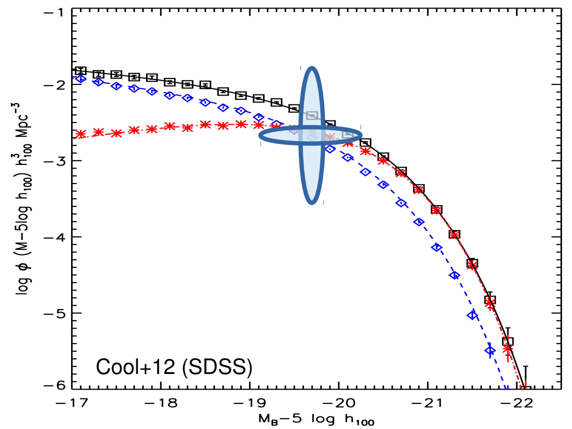
ALHAMBRA SURVEY



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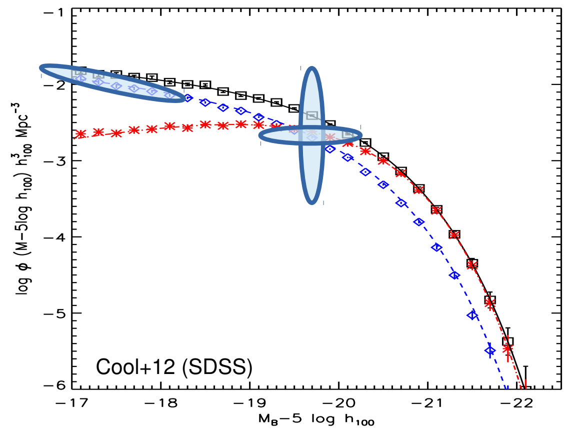

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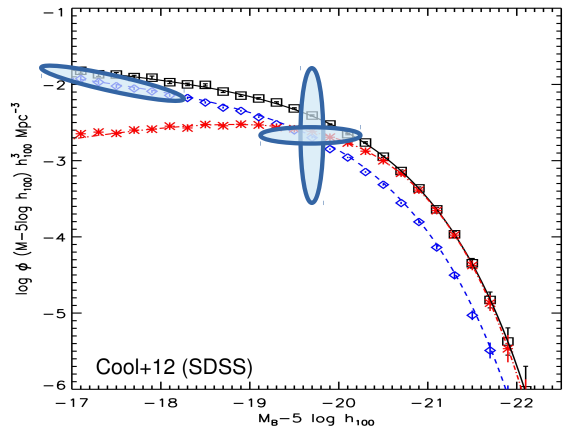
To improve our knowledge about $\Phi(z, M_B)$, we need **(1)** an accurate and unbiased photometric LF estimator, and **(2)** a multi-filter photometric survey to apply it.

The luminosity function Φ (M_B)



M_B^*
Characteristic luminosity

ϕ^*
Normalisation

α
Faint-end slope

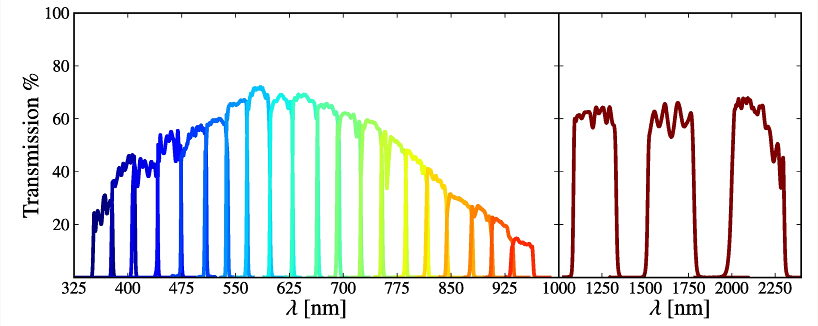
To improve our knowledge about Φ (z, M_B), we need **(1)** an accurate and unbiased photometric LF estimator, and **(2)** a multi-filter photometric survey to apply it.

The ALHAMBRA survey

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

The ALHAMBRA survey

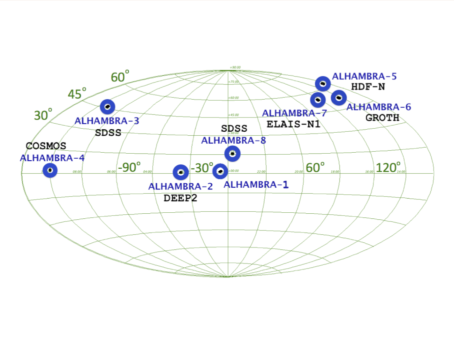
Advanced, Large, Homogeneous Area, Medium–Band Redshift Astronomical survey (Moles+08, alhambrasurvey.com)



20 contiguous, non-overlapping medium-band ($\sim$ 300Å) optical filters + 3 NIR filters (J, H, K_s).
Limiting magnitude of $\sim$ 24.0 (AB 5σ, $3''$ aperture).

The ALHAMBRA survey

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



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		2.381

7 independent fields to defeat (and study!) the cosmic variance (López-Sanjuan+14,15b) with a total high-quality area of 2.38 deg^2.

The ALHAMBRA survey

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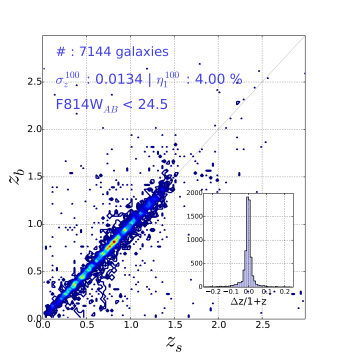

300k galaxies with $\Delta z/(1+z) = 0.012$ at $I \leq 24$ (Molino+14).
The PDF of each galaxy from BPZ2 (Benítez00).

The ALHAMBRA survey

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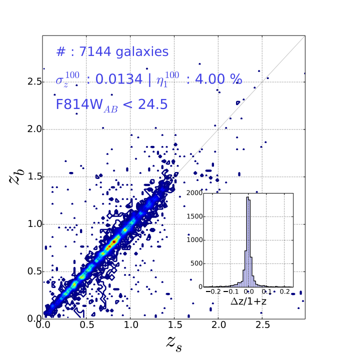

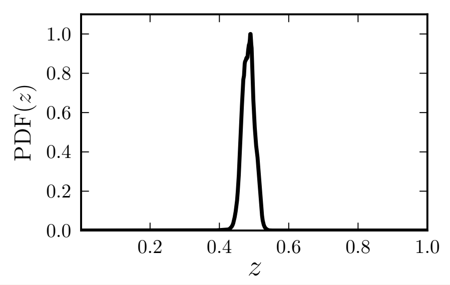

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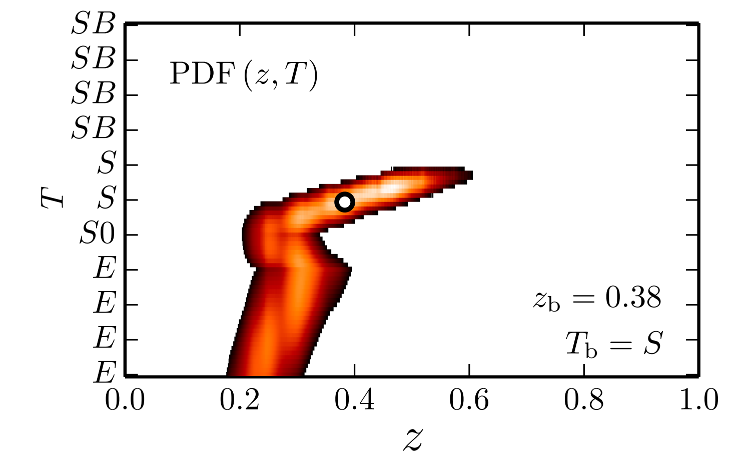
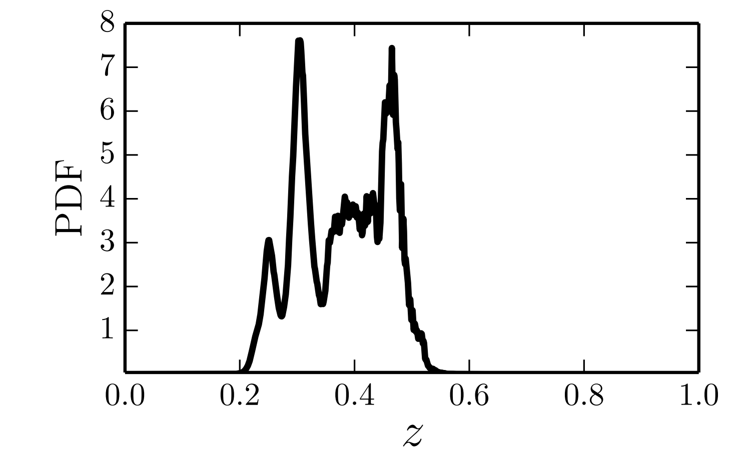
Probability Distribution Functions



The Bayesian Photometric Redshift (BPZ2, Benítez00) provides the redshift – template probability PDF (z, T).

Probability Distribution Functions

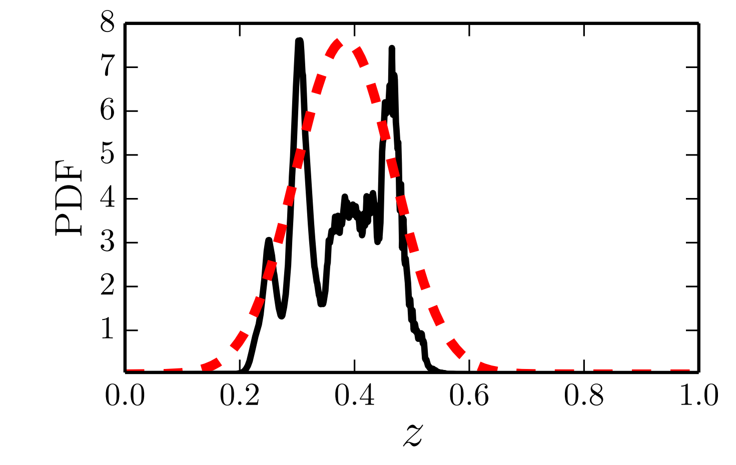
ALHAMBRA SURVEY



The redshift PDF is computed as

$$\mathrm{PDF}\,(z) = \int \mathrm{PDF}\,(z, T)\,\mathrm{d}T$$

Probability Distribution Functions



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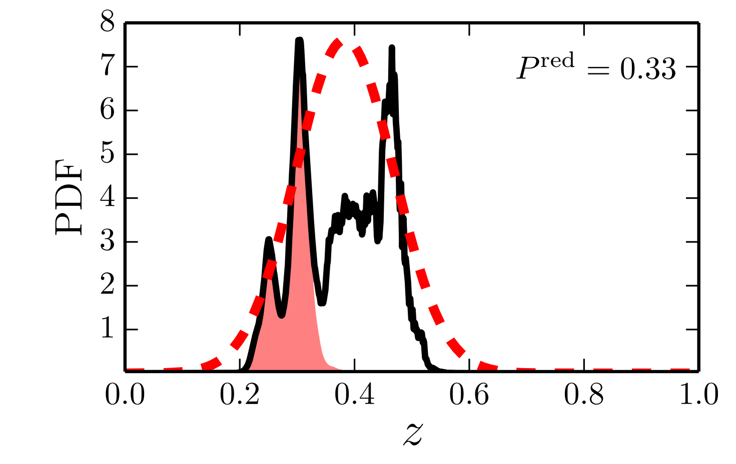
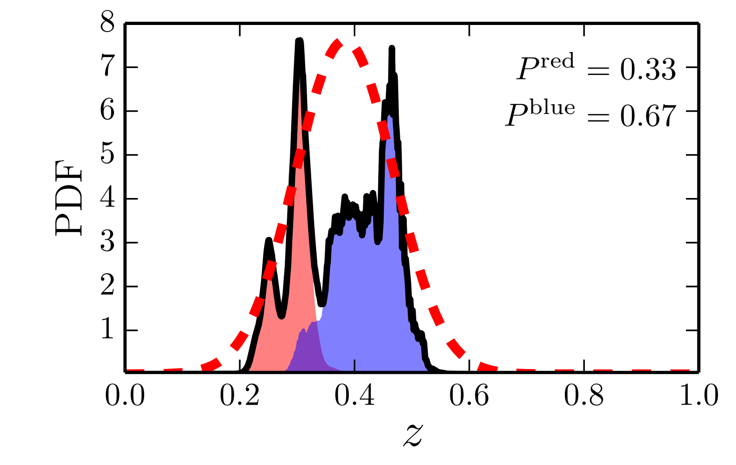


The redshift PDF is computed as

$$\mathrm{PDF}(z) = \int \mathrm{PDF}(z, \mathrm{E/S0})\, \mathrm{d}T + \int \mathrm{PDF}(z, \mathrm{S/SB})\, \mathrm{d}T$$

Probability Distribution Functions



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The join $z - M_B$ posterior: $\mathrm{PDF}(z, M_B)$

ALHAMBRA SURVEY

The luminosity function is $\Phi(z, M_B) = \sum_i \mathrm{PDF}_i(z, M_B)$.

$\mathrm{PDF}(z, T)$
$M_B(z, T \mid I)$

$\Downarrow$

$P(z, M_B \mid I)$
$\mathrm{PDF}(I_0 \mid I, \sigma_I)$

$\Downarrow$

$\mathrm{PDF}(z, M_B)$

The starting point is the BPZ posterior $\mathrm{PDF}(z, T \mid C)$.

The join $z - M_B$ posterior: $\mathrm{PDF}\,(z, M_B)$

The luminosity function is $\Phi\,(z, M_B) = \sum_i \mathrm{PDF}_i\,(z, M_B)$.

$\mathrm{PDF}\,(z, T)$
$M_B\,(z, T \mid I)$

⇓

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⇓

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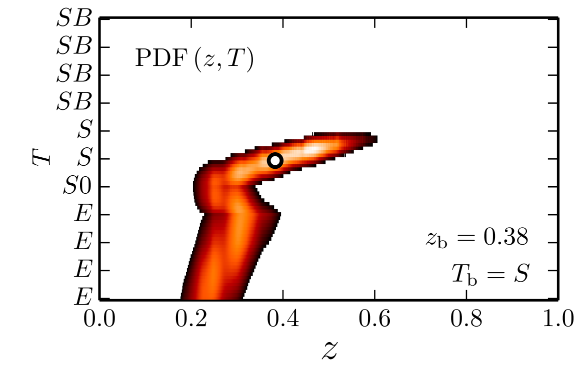

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The join $z - M_B$ posterior: PDF (z, M_B)

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PDF (z, T)
$M_B(z, T \mid I)$

⇓

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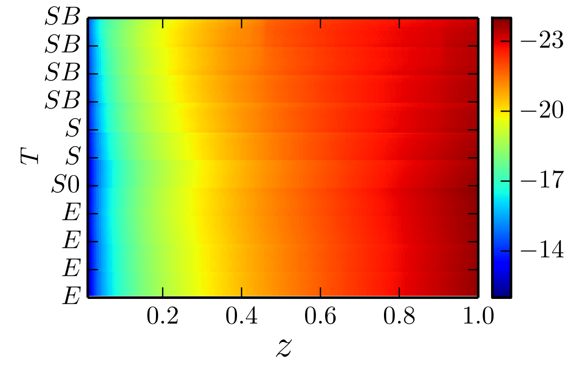
PDF $(I_0 \mid I, \sigma_I)$

⇓

PDF (z, M_B)



The function $M_B(z, T \mid I)$
maps the absolute magnitude with z and T.

The join $z - M_B$ posterior: PDF (z, M_B)

The luminosity function is $\Phi(z, M_B) = \sum_i \mathrm{PDF}_i(z, M_B)$.

PDF (z, T)
$M_B(z, T \mid I)$

⇓

$P(z, M_B \mid I)$
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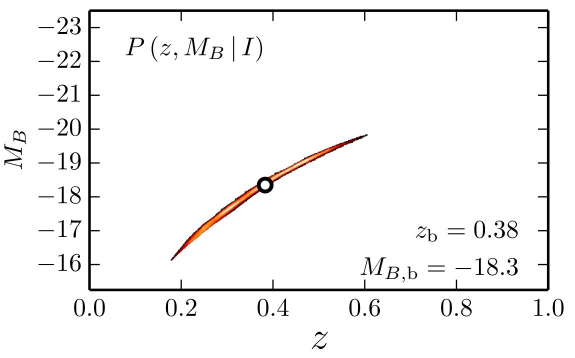
⇓

PDF (z, M_B)



We construct $P(z, M_B | I)$ weighting $M_B(z, T \mid I)$ by PDF (z, T).

The join $z - M_B$ posterior: $\mathrm{PDF}\,(z, M_B)$

The luminosity function is $\Phi\,(z, M_B) = \sum_i \mathrm{PDF}_i\,(z, M_B)$.

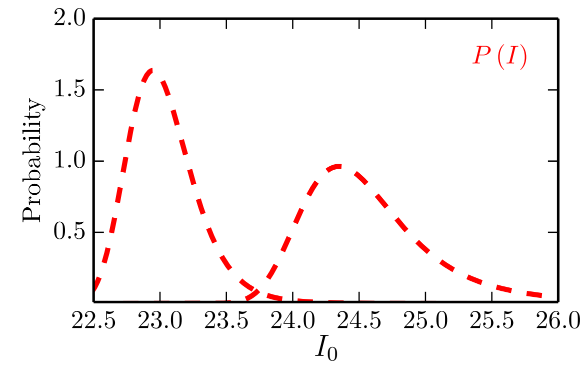
$\mathrm{PDF}\,(z, T)$
$M_B\,(z, T \,|\, I)$

$\Downarrow$

$P\,(z, M_B \,|\, I)$
$\mathrm{PDF}\,(I_0 \,|\, I, \sigma_I)$

$\Downarrow$

PDF (z, M$_B$)



The PDF of the $I-$band magnitude (e.g. Coppin06)

$$\mathrm{PDF}\,(I_0) = P(I \,|\, I_0, \sigma_I) \times C(I_0)$$

The join $z - M_B$ posterior: $\mathrm{PDF}\,(z, M_B)$

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$\mathrm{PDF}\,(z, T)$
$M_B\,(z, T \,|\, I)$

$\Downarrow$

$P\,(z, M_B \,|\, I)$
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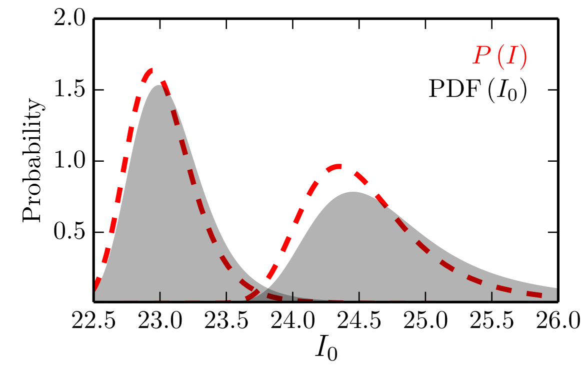
$\Downarrow$

PDF (z, M$_B$)



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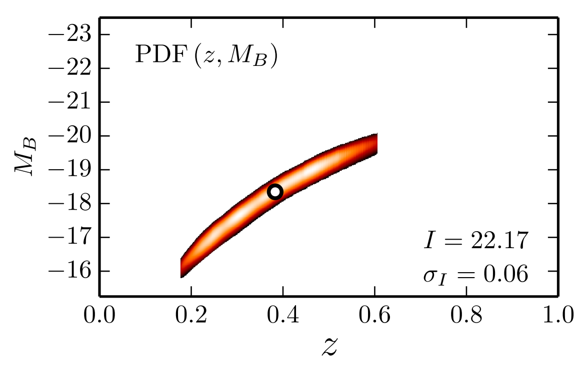
PDF (z, M_B)



The final posterior $\mathrm{PDF}(z, M_B)$ is
$P(z, M_B | I) * \mathrm{PDF}(I_0 - I \mid 0, \sigma_I)$

The join $z - M_B$ posterior: PDF (z, M_B)

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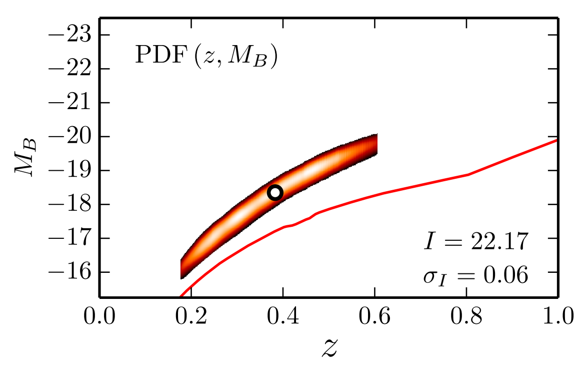
PDF (z, T)
$M_B\,(z, T \mid I)$

$\Downarrow$

$P\,(z, M_B \mid I)$
PDF $(I_0 \mid I, \sigma_I)$

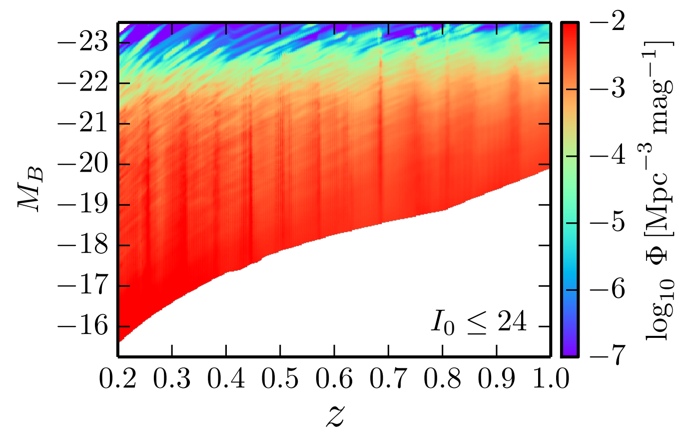
$\Downarrow$

PDF (z, M_B)



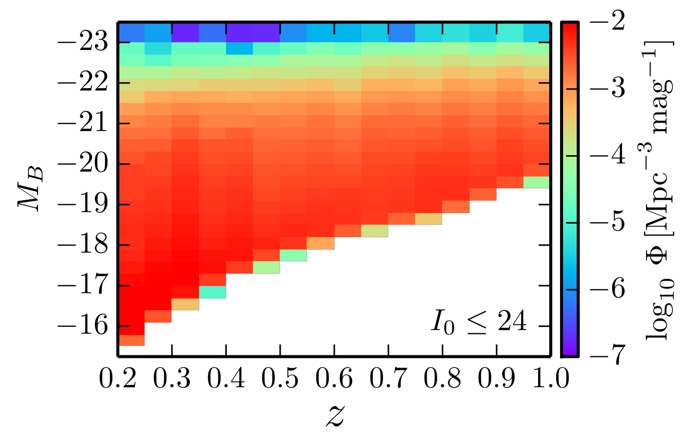
We can select 100% complete samples.
In the following, $I_0 \leq 24$.

The ALHAMBRA $\Phi\,(z, M_B)$



$$\Phi_{\rm HD}\,(z, M_B) = \frac{1}{A} \sum_i {\rm PDF}_i\,(z, M_B) \left(\frac{{\rm d}V}{{\rm d}z}\right)^{-1} \quad [{\rm mag}^{-1}\ {\rm Mpc}^{-3}]$$

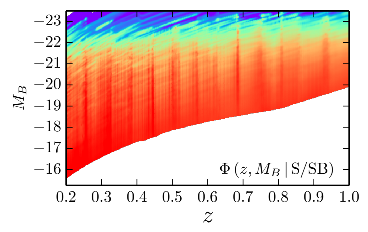
The ALHAMBRA $\Phi(z, M_B)$



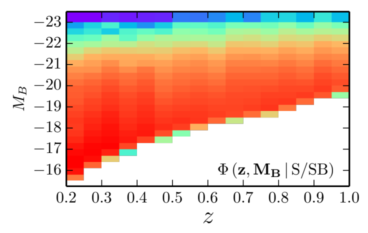
$$\Phi_{\mathrm{LD}}(z_k, M_{B,q}) = \frac{1}{\Delta V_k \Delta M_{B,q}} \int\int \Phi_{\mathrm{HD}}(z, M_B) \frac{\mathrm{d}V}{\mathrm{d}z}\, \mathrm{d}z\, \mathrm{d}M_B$$

$\Phi\,(z, M_B)$ as a function of spectral type

$\Phi\,(z, M_B\,|\,\mathrm{S/SB})$



HD→LD ⟶

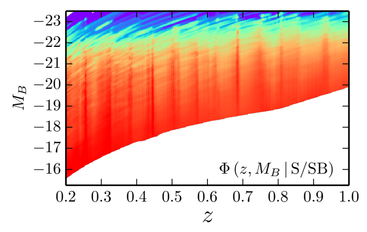


$\Phi\,(z, M_B\,|\mathrm{E/S0})$

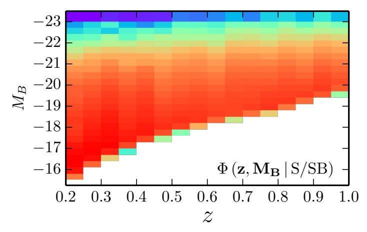
HD→LD ⟶

$\Phi\,(z, M_B)$ as a function of spectral type

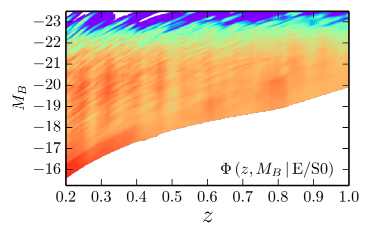
$\Phi\,(z, M_B\,|\,\mathrm{S/SB})$



HD→LD



$\Phi\,(z, M_B\,|\mathrm{E/S0})$



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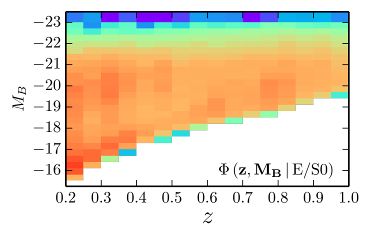
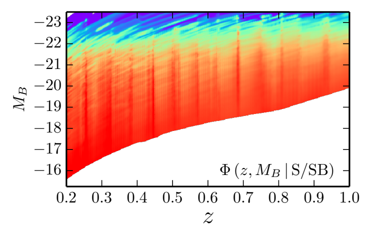


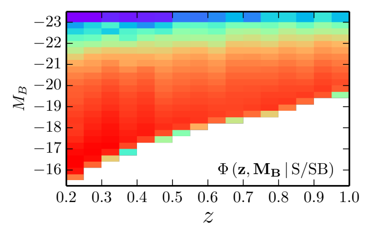
The modelling of $\Phi\,(z, M_B)$

ALHAMBRA SURVEY

Observations



$\overrightarrow{HD \to LD}$



Model + selection effects

$\Updownarrow \chi^2$ with emcee

$M_B^*\,(z)$
$\phi^*\,(z)$
$\alpha\,(z)$

$\overrightarrow{HD \to LD}$

The modelling of $\Phi\,(z, M_B)$

ALHAMBRA SURVEY

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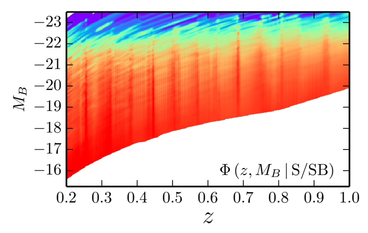

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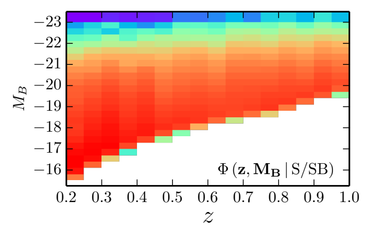

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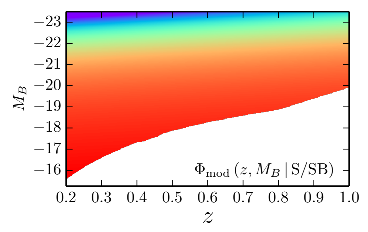

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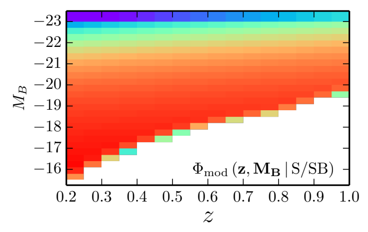

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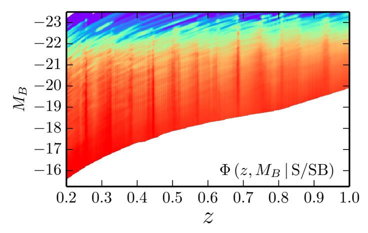

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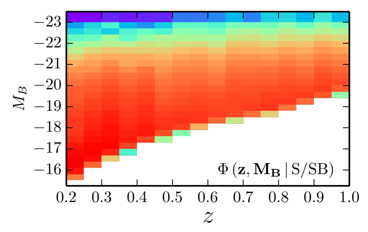

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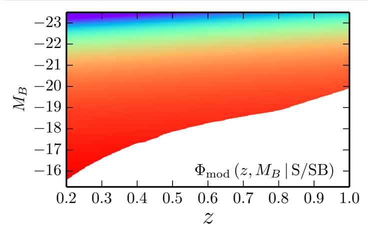

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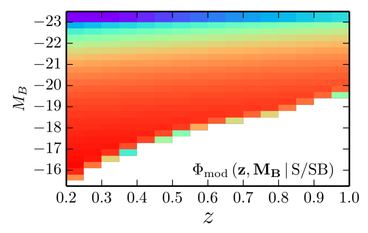


The modelling of $\Phi\,(z, M_B)$

ALHAMBRA SURVEY

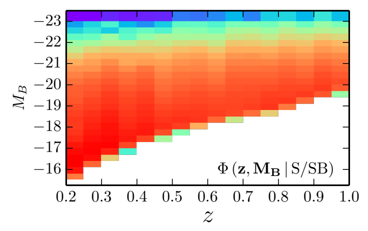
(1) We have an unbiased estimator ($\delta_{\rm sys} \rightarrow 0$) of $\Phi(z, M_B)$ thanks to the ALHAMBRA PDFs

(2) To perfom a robust modelling of $\Phi\,(z, M_B)$, we have to compute the the covariance matrix Σ_Φ,

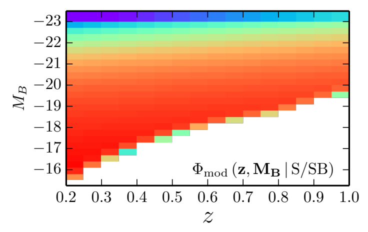
$$\chi^2 = \frac{1}{2}[\Phi - \Phi_{\rm mod}]^{\rm T}\Sigma_\Phi^{-1}[\Phi - \Phi_{\rm mod}]$$

The covariance matrix must include $\Sigma_{\rm stat}$ and $\Sigma_{\rm CV}$.

Observations vs Model



$\Updownarrow$ χ^2 with emcee



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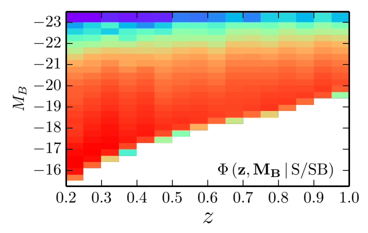

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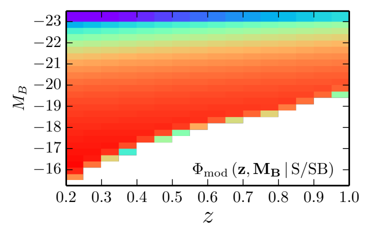
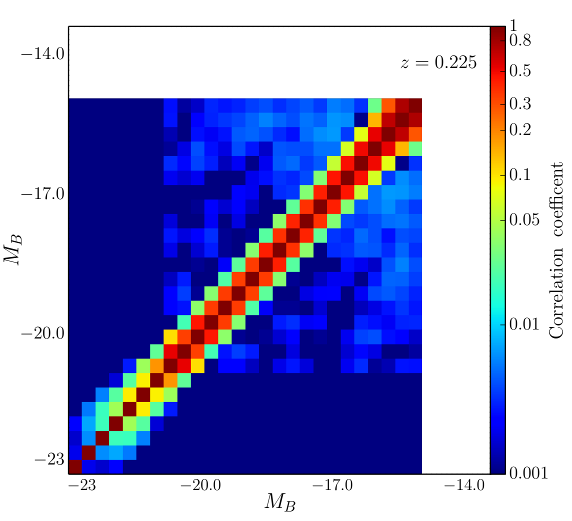


The LF covariance matrix



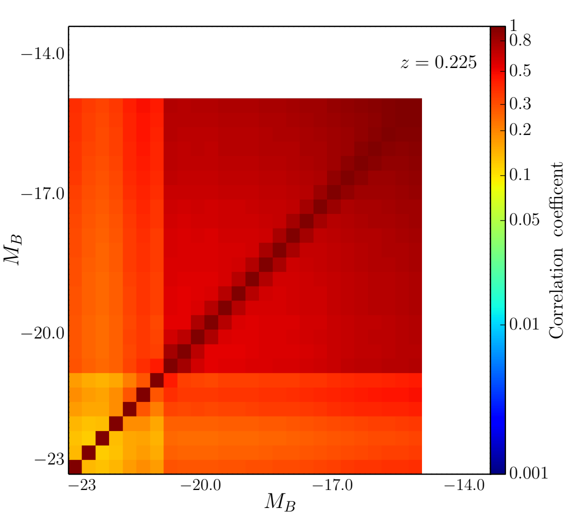
The LF covariance Σ_Φ is a

2 x 2 (type) ×
16 x 16 (z) ×
30 x 30 (M_B) matrix

composed by the shot noise $\Sigma_{\rm stat}$ term

and the cosmic variance $\Sigma_{\rm CV}$ term. (Smith12)

The LF covariance matrix



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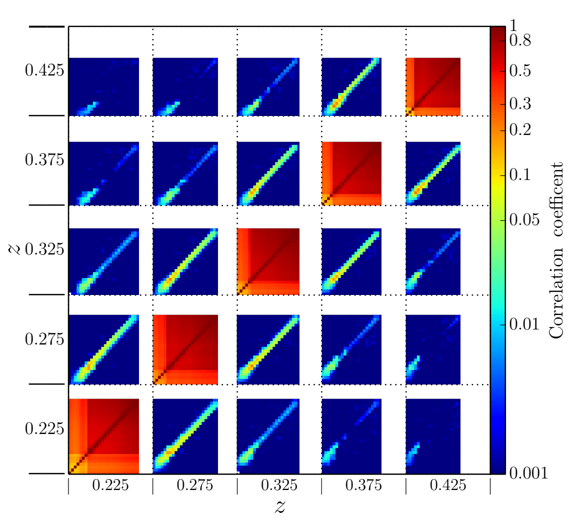
ALHAMBRA SURVEY



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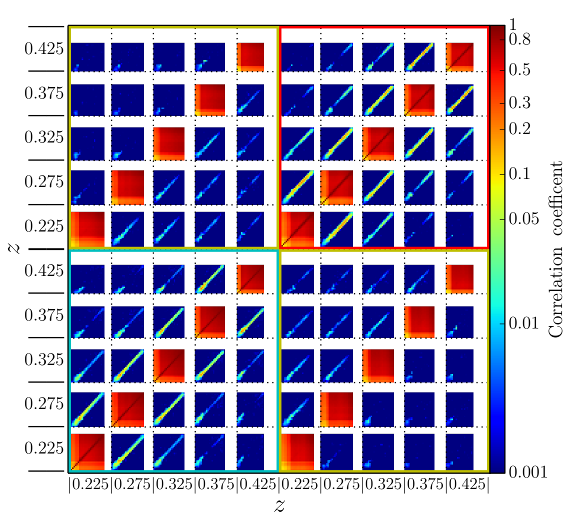

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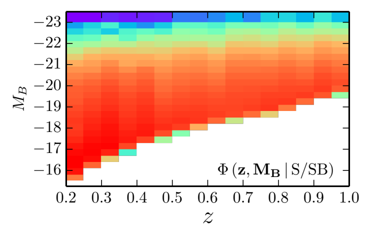
(2) We have estimated the covariance matrix Σ_Φ to ensure a robust modelling of Φ.

$$\chi^2 = \frac{1}{2}[\Phi - \Phi_{\rm mod}]^{\rm T}\Sigma_\Phi^{-1}[\Phi - \Phi_{\rm mod}]$$

Now we can enjoy the results!!

Observations vs Model



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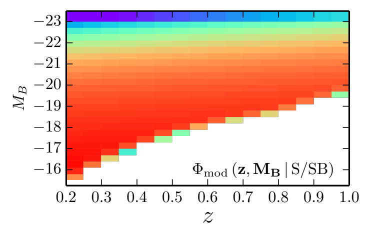
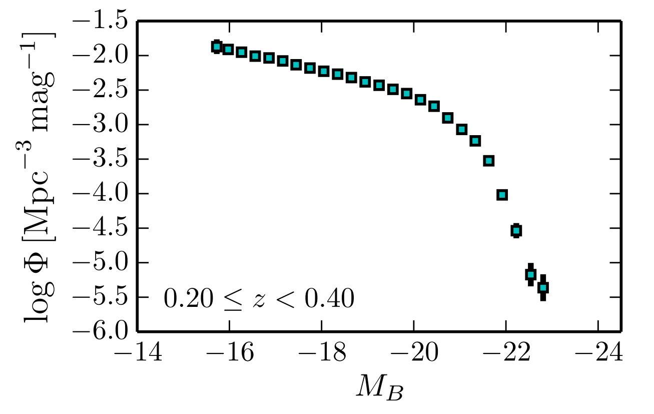


The ALHAMBRA $\Phi(z, M_B \,|\, \mathrm{S/SB})$



ALHAMBRA

DEEP2 + COMBO-17 (Faber+07)

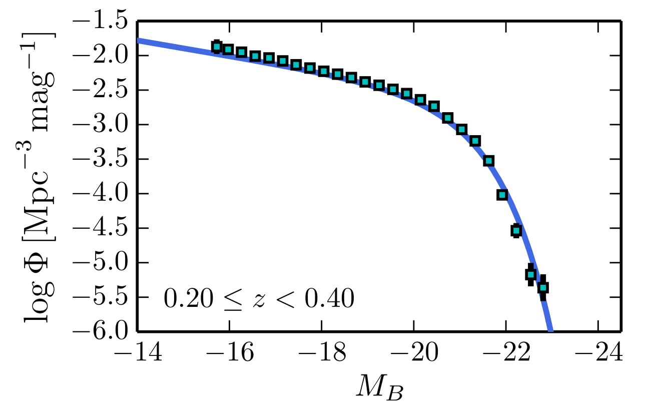
Salimbeni+08

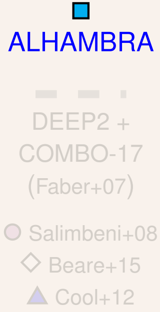
Beare+15

Cool+12

$$M_B^* = -21.00 - 0.99(z - 0.5)$$
$$\log \phi^* = -2.51 - 0.02(z - 0.5)$$
$$\alpha = -1.28$$

The ALHAMBRA $\Phi(z, M_B \mid \mathrm{S/SB})$





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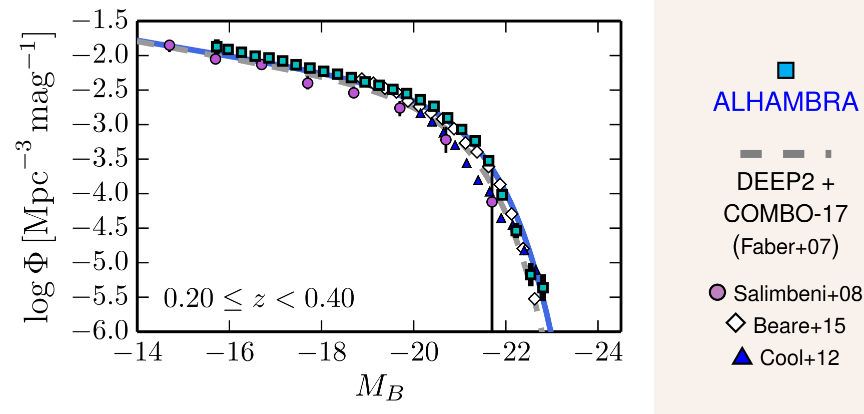

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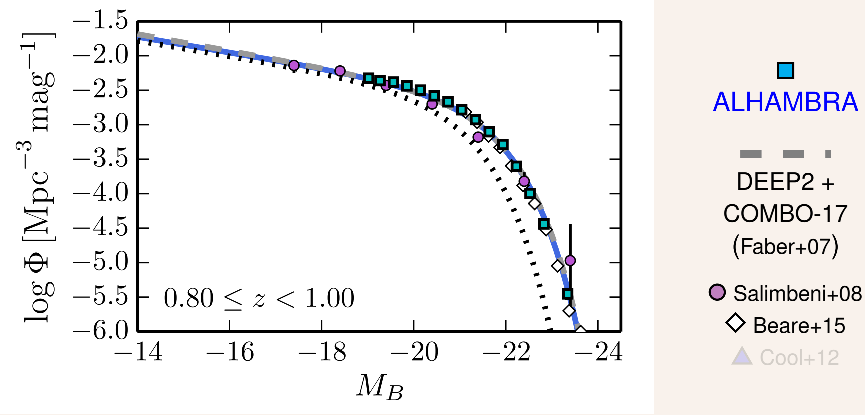

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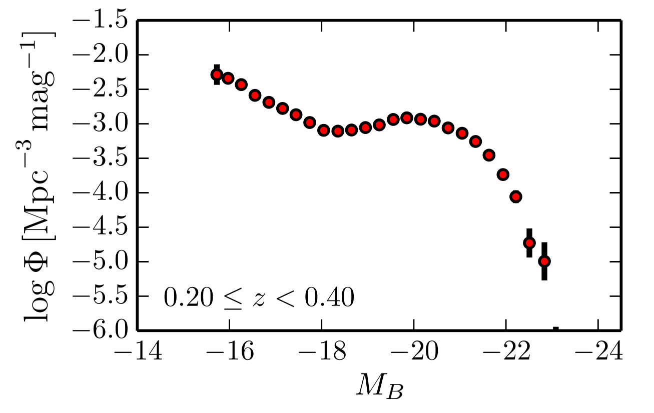
ALHAMBRA SURVEY



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DEEP2 + COMBO-17 (Faber+07)

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Cool+12

Drory+09

Salimbeni+08

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Bright galaxies

$M_B^* = -20.83 - 0.77(z - 0.5)$

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Faint galaxies

$M_{B,\mathrm{f}} = -17.3;\ \phi_{\mathrm{f}} = \phi^*$

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Madgwick+02,Salimbeni+08,Drory+09,etc.

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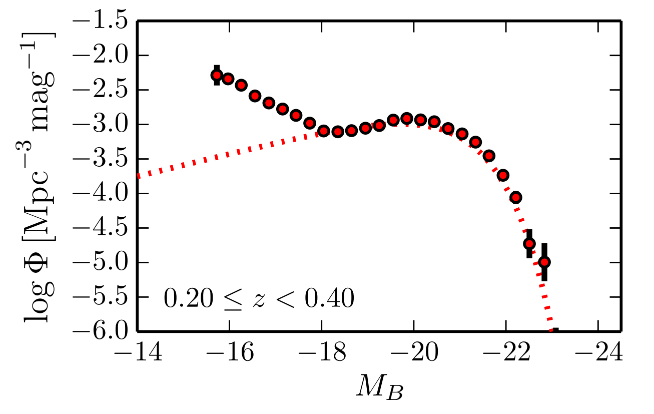

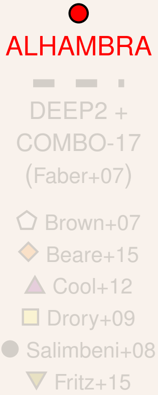

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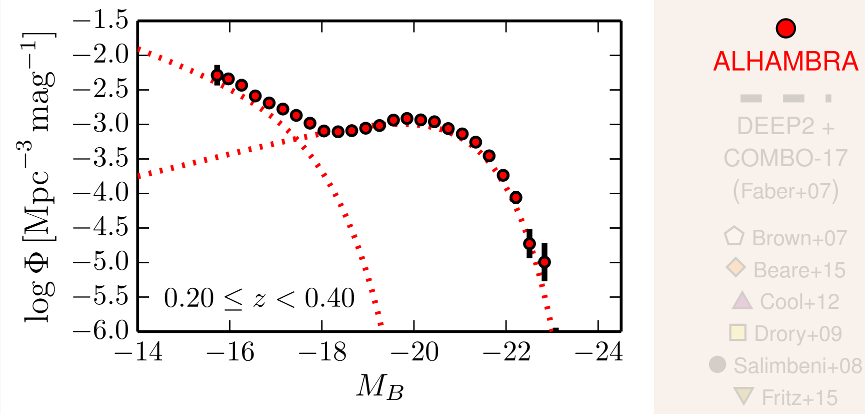

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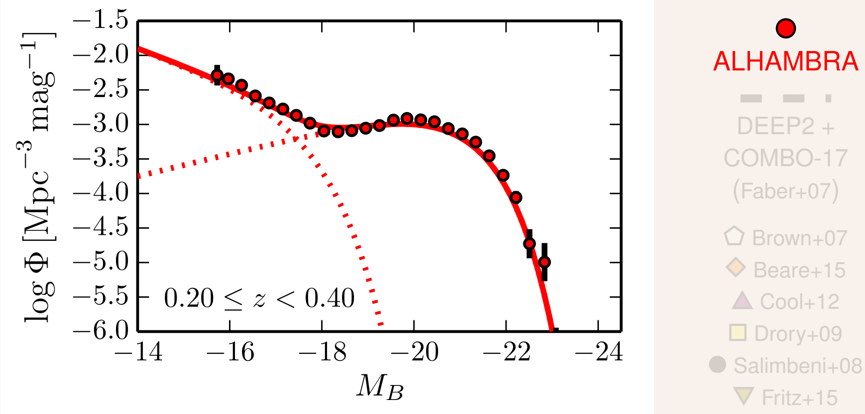

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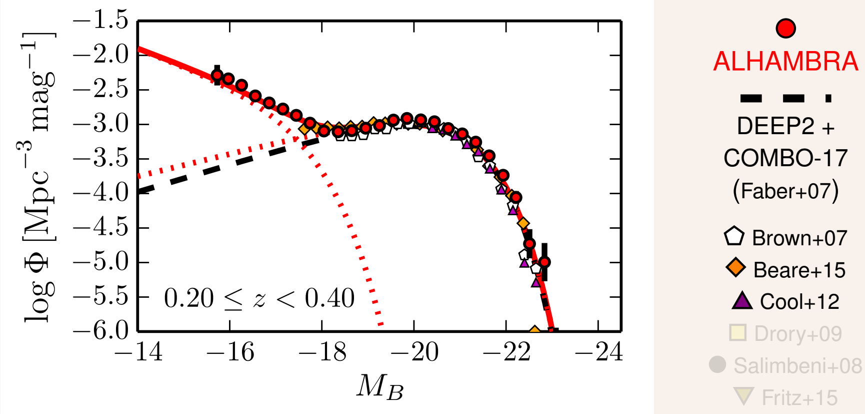

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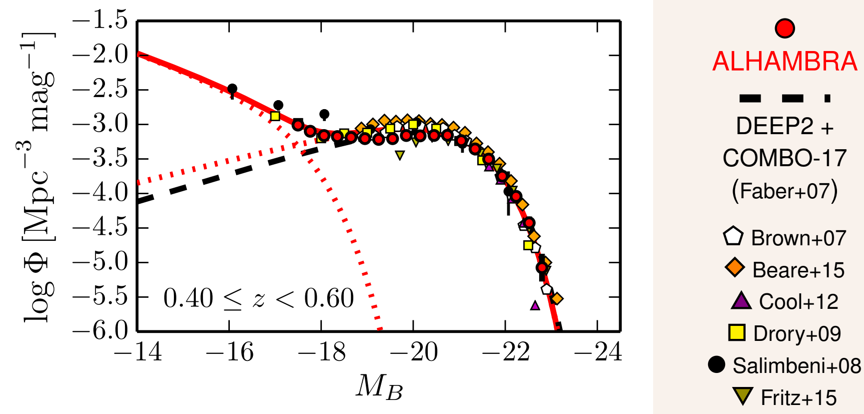

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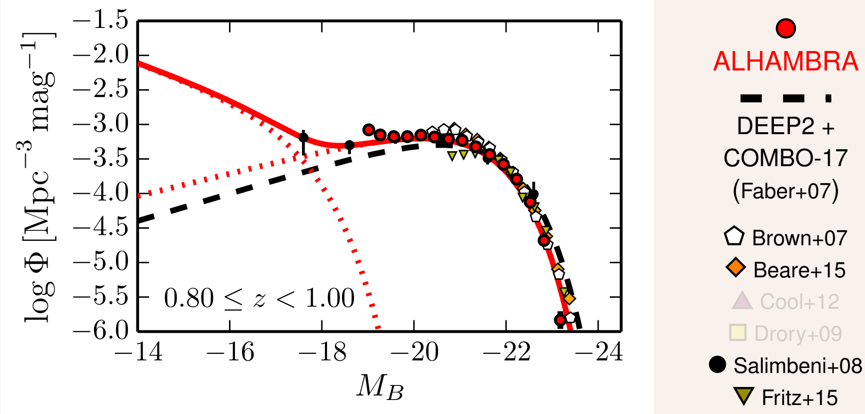

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Sumary and conclusions

ALHAMBRA SURVEY

ALHAMBRA Luminosity Function (profuse.cefca.es)

Using the ALHAMBRA PDFs,
we have developed an **unbiased LF estimator**.

We have estimated $\Phi(z, M_B)$ for red and blue galaxies,
and **accurately modelled** the observed LF **thanks to** Σ_Φ.

Our results agree with the literature:

- M_B^* fades by 1.0 mag since $z = 1$ and ϕ^* is nearly constant, reflecting the descent in the star formation rate.
- The red sequence is accreting new members: a significant population (10%-15%) of faint, red galaxies is present at $z < 1$.

We will have suited tools for the next generation
large-area surveys **J-PAS, Euclid, and LSST**.

Thanks for your attention!!

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