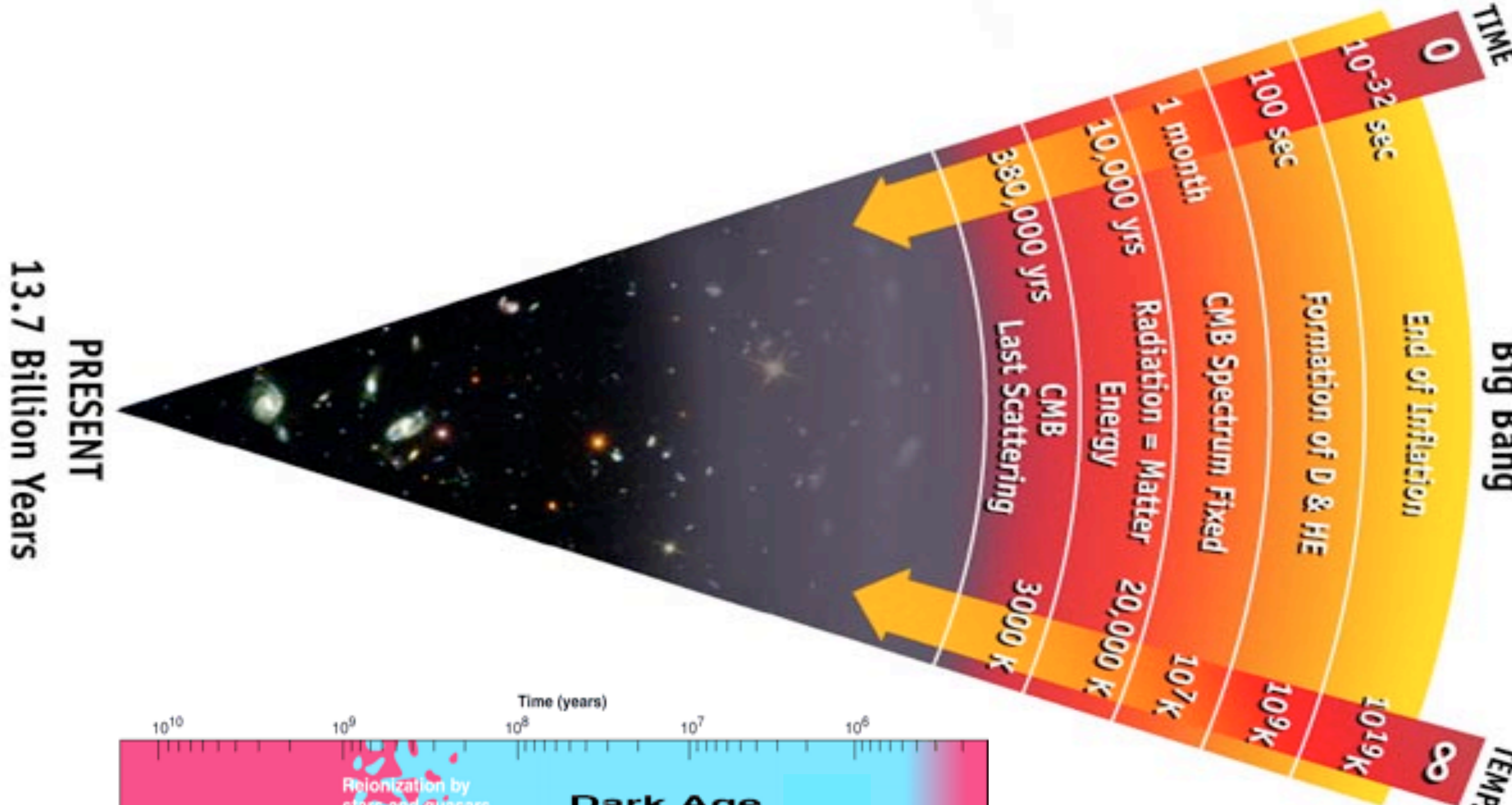
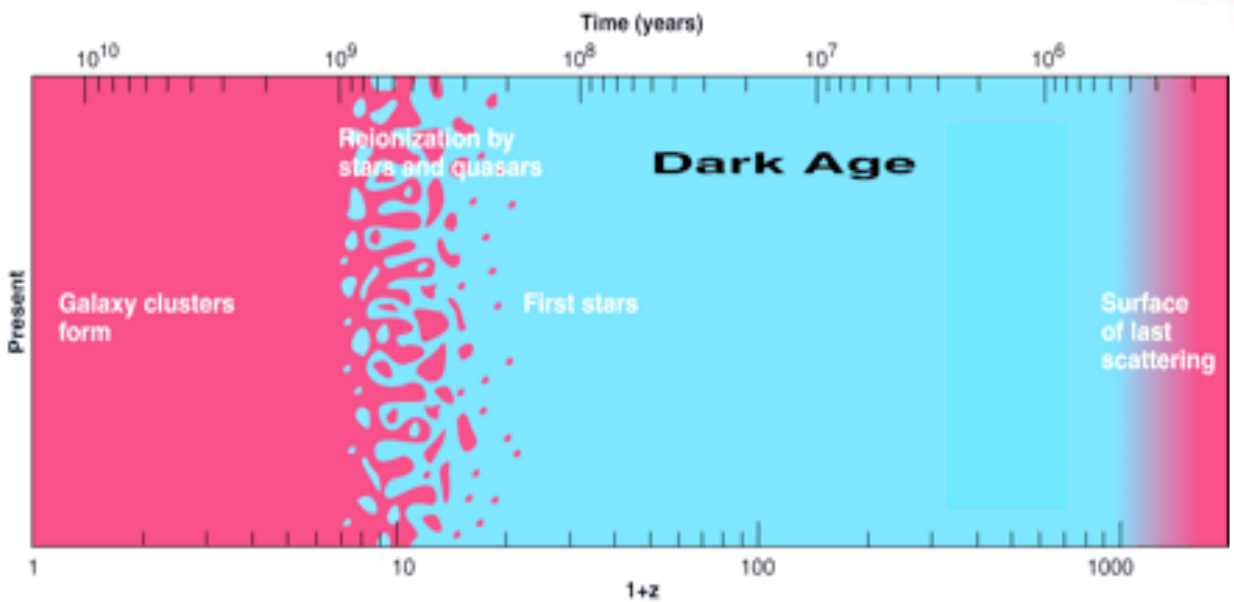
“The luminosity function and stellar mass function of galaxies out to z=4: new insights into galaxy formation and evolution”

Danilo Marchesini (Yale University)

Osservatorio Astronomico di Bologna - Seminar - 07 May 2009

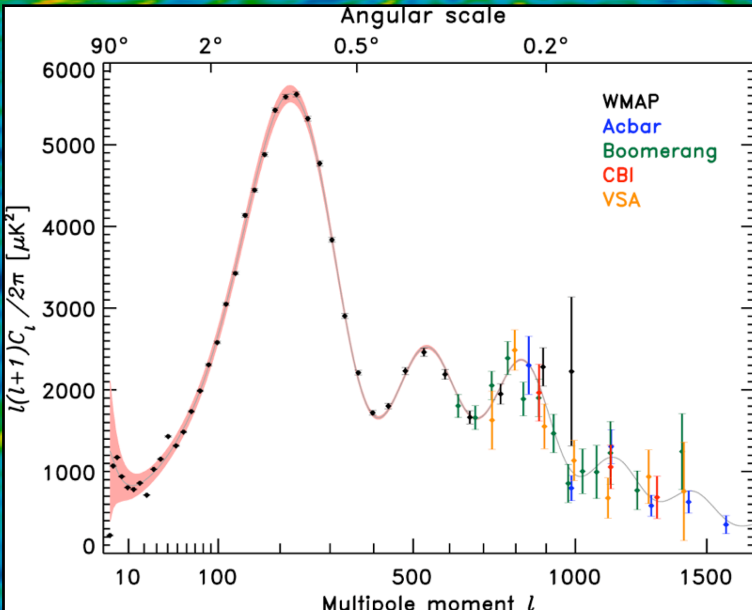




(Jordi Miralda-Escude, 2003)

The concordance ΛCDM Cosmology

(Spergel et al. 2003, 2006; Komatsu et al. 2009)

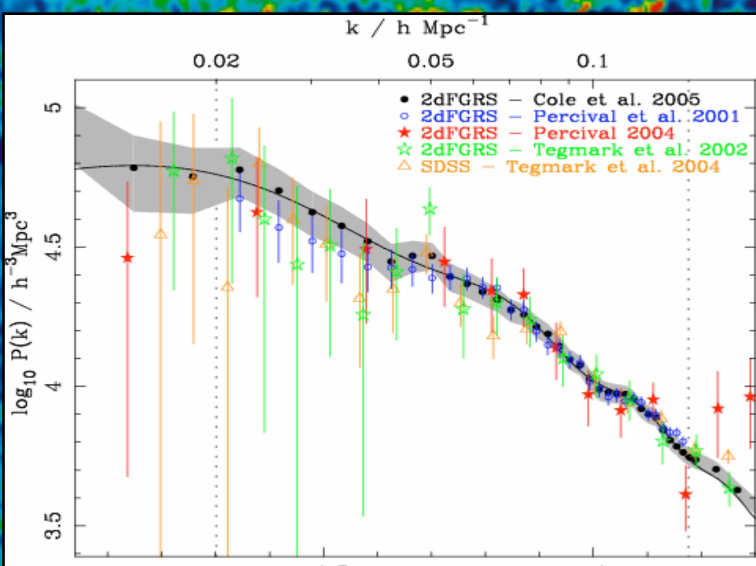


$$\Omega_{\rm m} = \Omega_{\rm dm} + \Omega_{\rm b} = 0.24$$

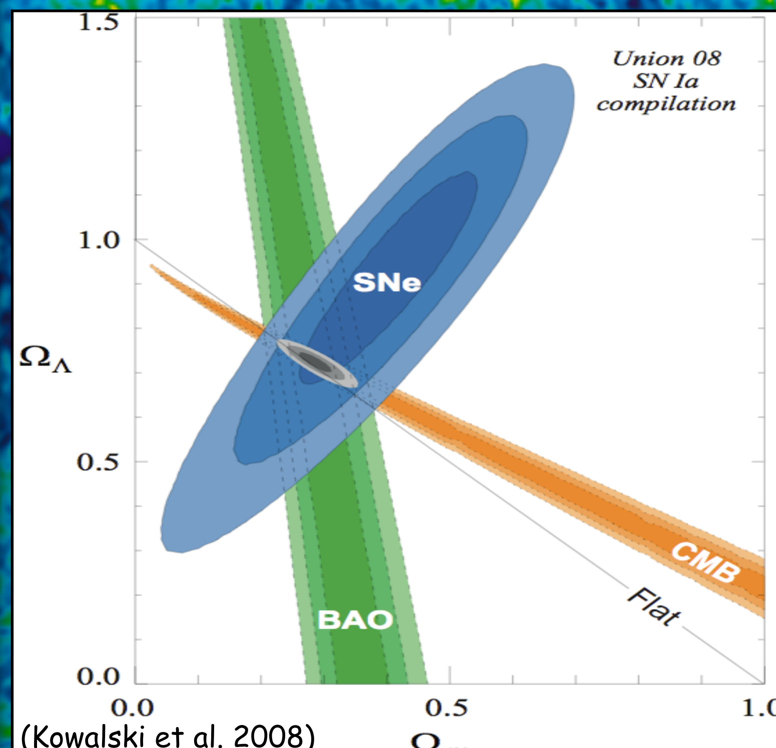
$$\Omega_\Lambda = 0.76 \qquad \Omega_{\rm b} = 0.041$$

$$h = 0.73 \qquad n_{\rm s} = 0.95$$

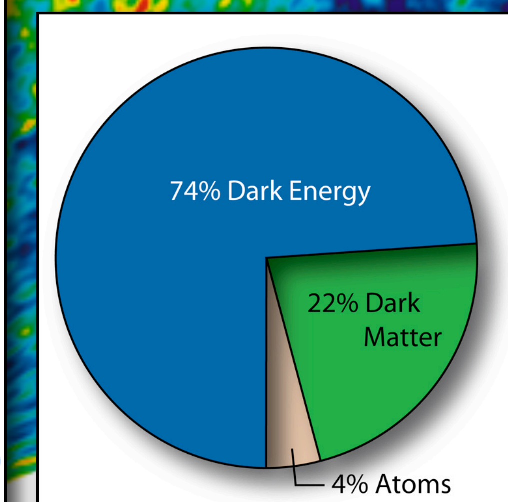
$$\tau = 0.088 \qquad \sigma_8 = 0.74$$

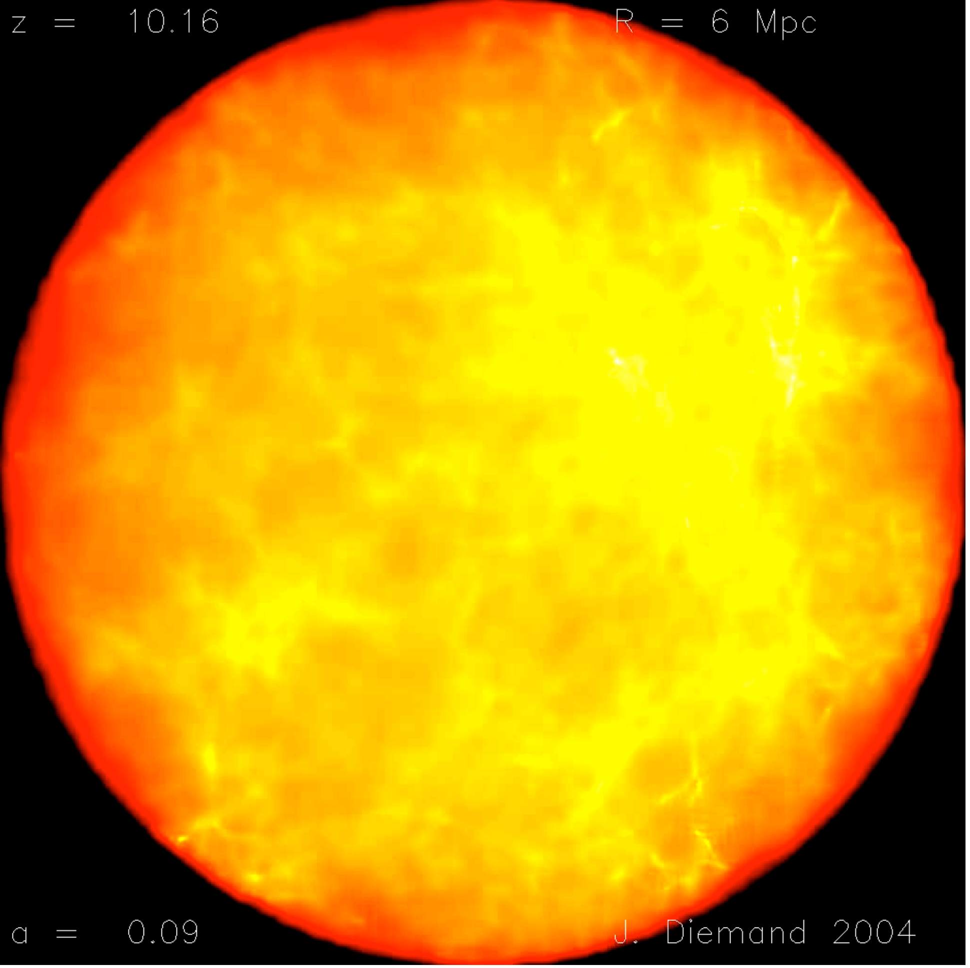


(Percival et al. 2006)



(Kowalski et al. 2008)





Formation of a CDM cluster by J. Diemand, J. Stadel, & B. Moore (zBox supercomputer at University of Zurich)

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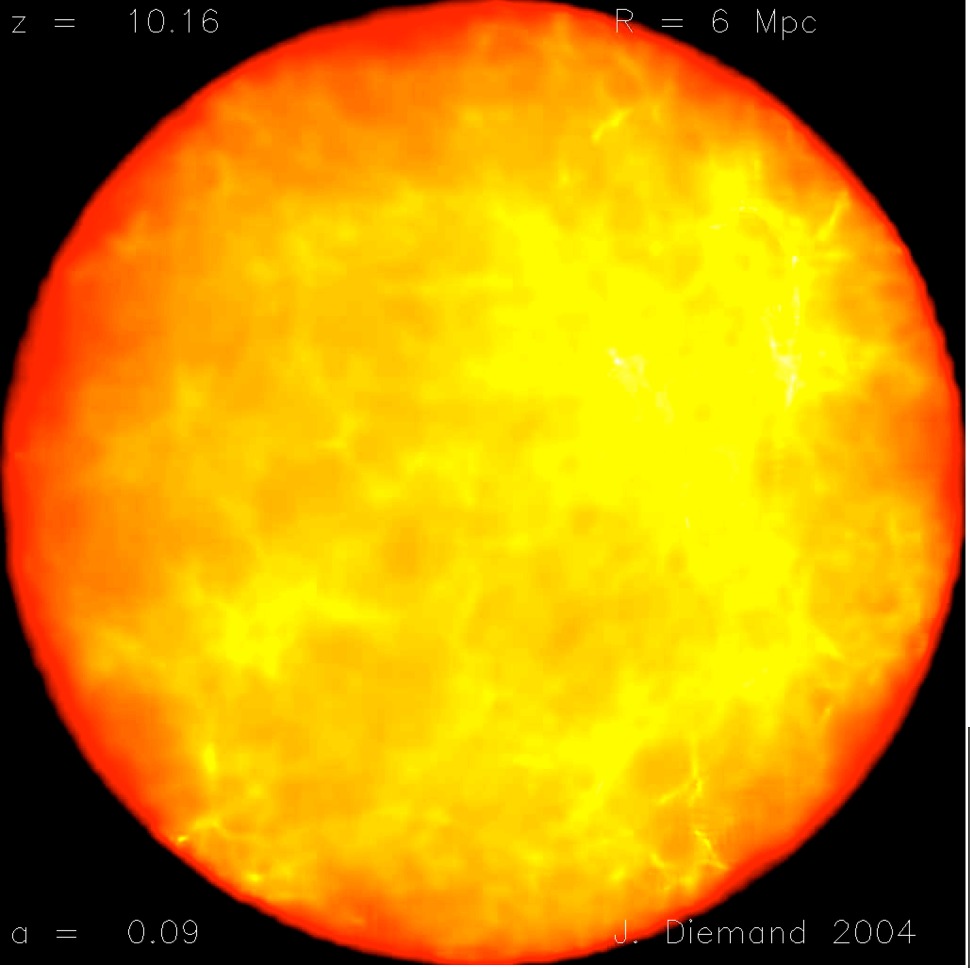
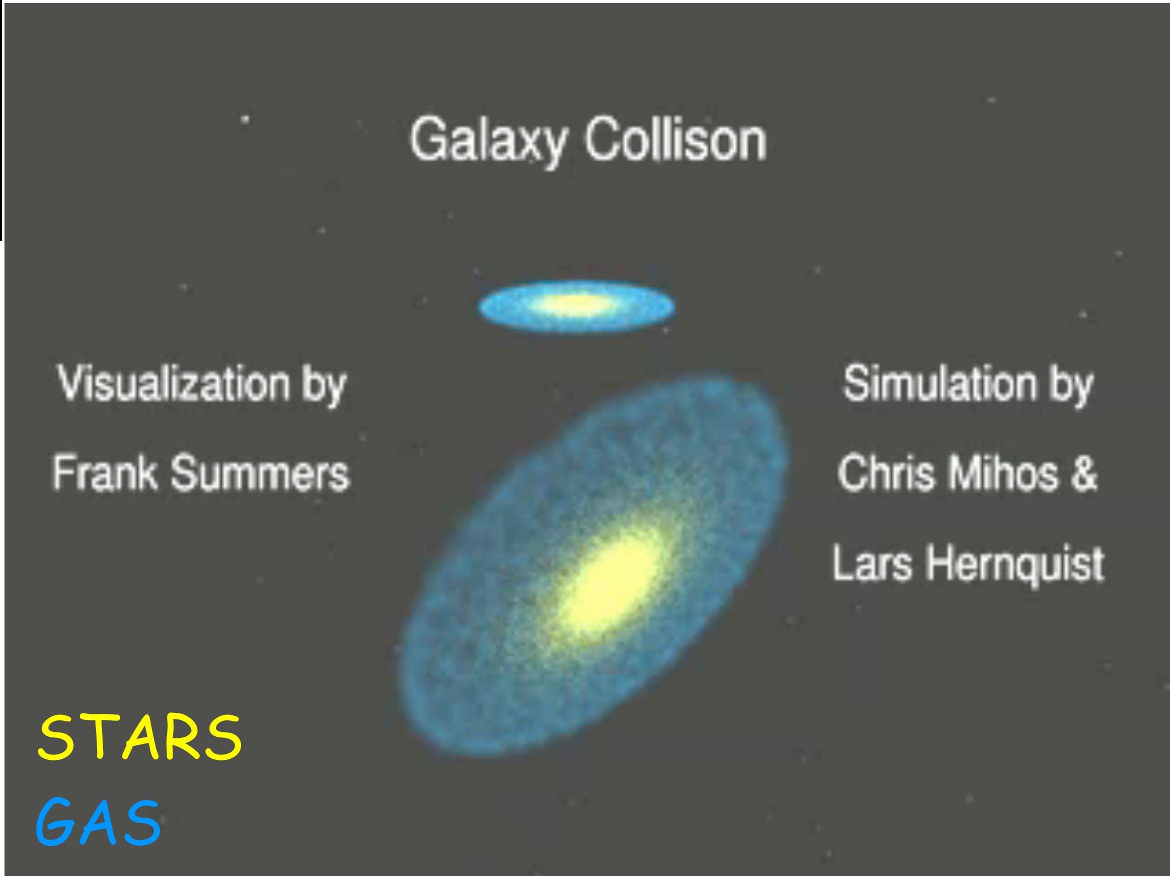


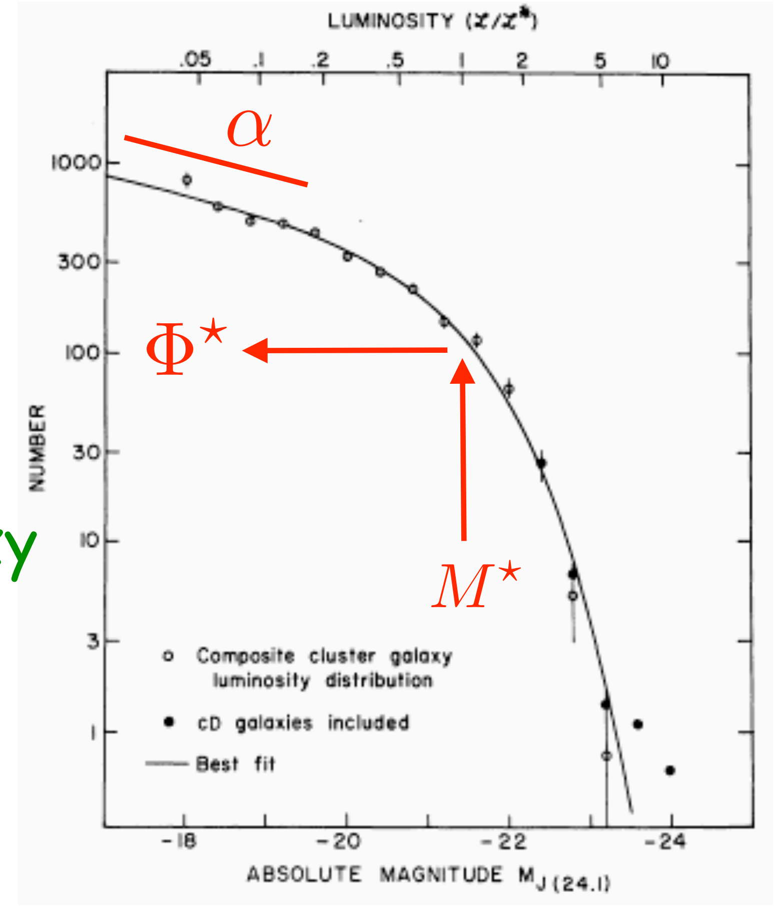


The Luminosity and Stellar Mass Functions

★ most fundamental of all cosmological observables

★ most basic descriptors of a galaxy population

★ their shapes retain the imprint of galaxy formation and evolution processes



(Schechter 1976)

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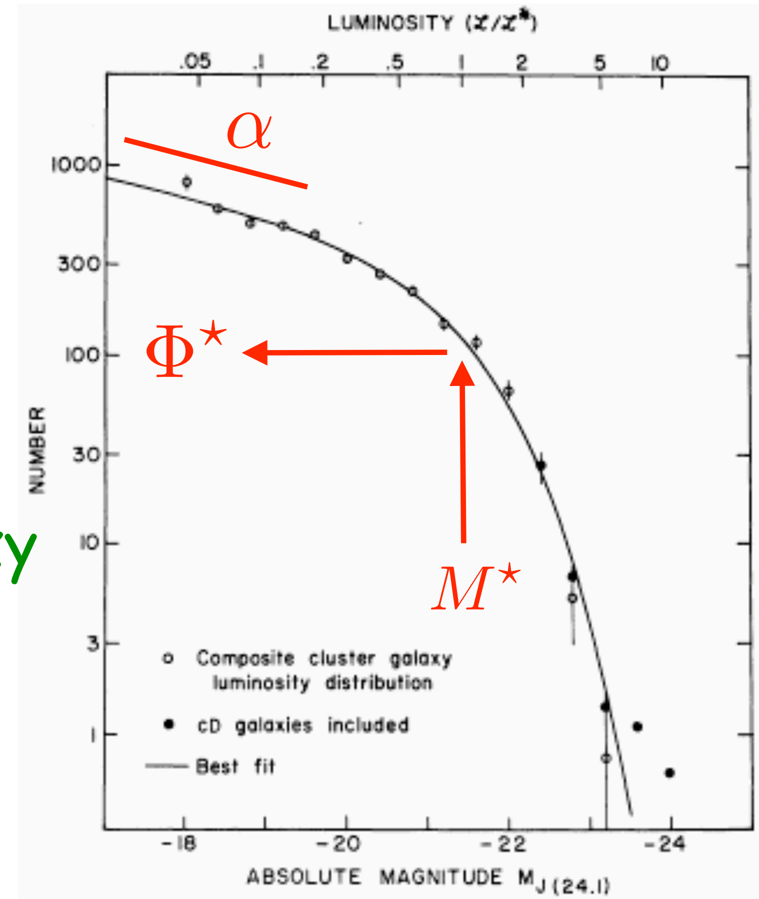


(Schechter 1976)

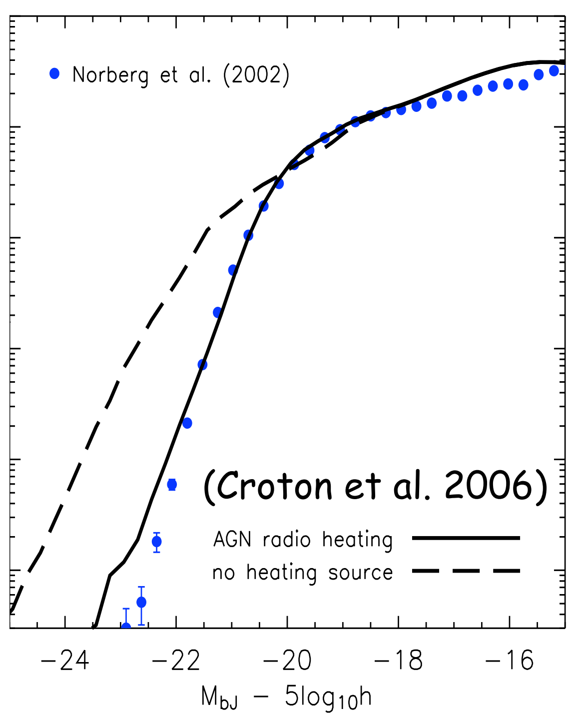
the LF/SMF are among the most powerful tools to constrain the physical processes encoded in the theoretical models

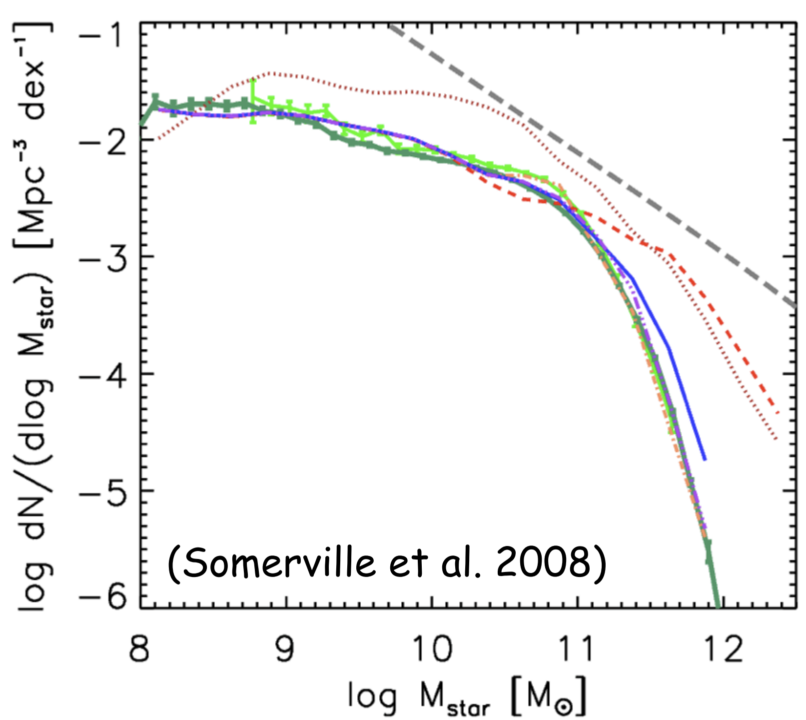
The shaping of faint end is associated to:

- ☑ suppression of gas cooling due to a background of photo-ionizing radiation (Benson et al. 2002)
- ☑ feedback from SNs --> gas heating and winds (Dekel & Silk 1986)

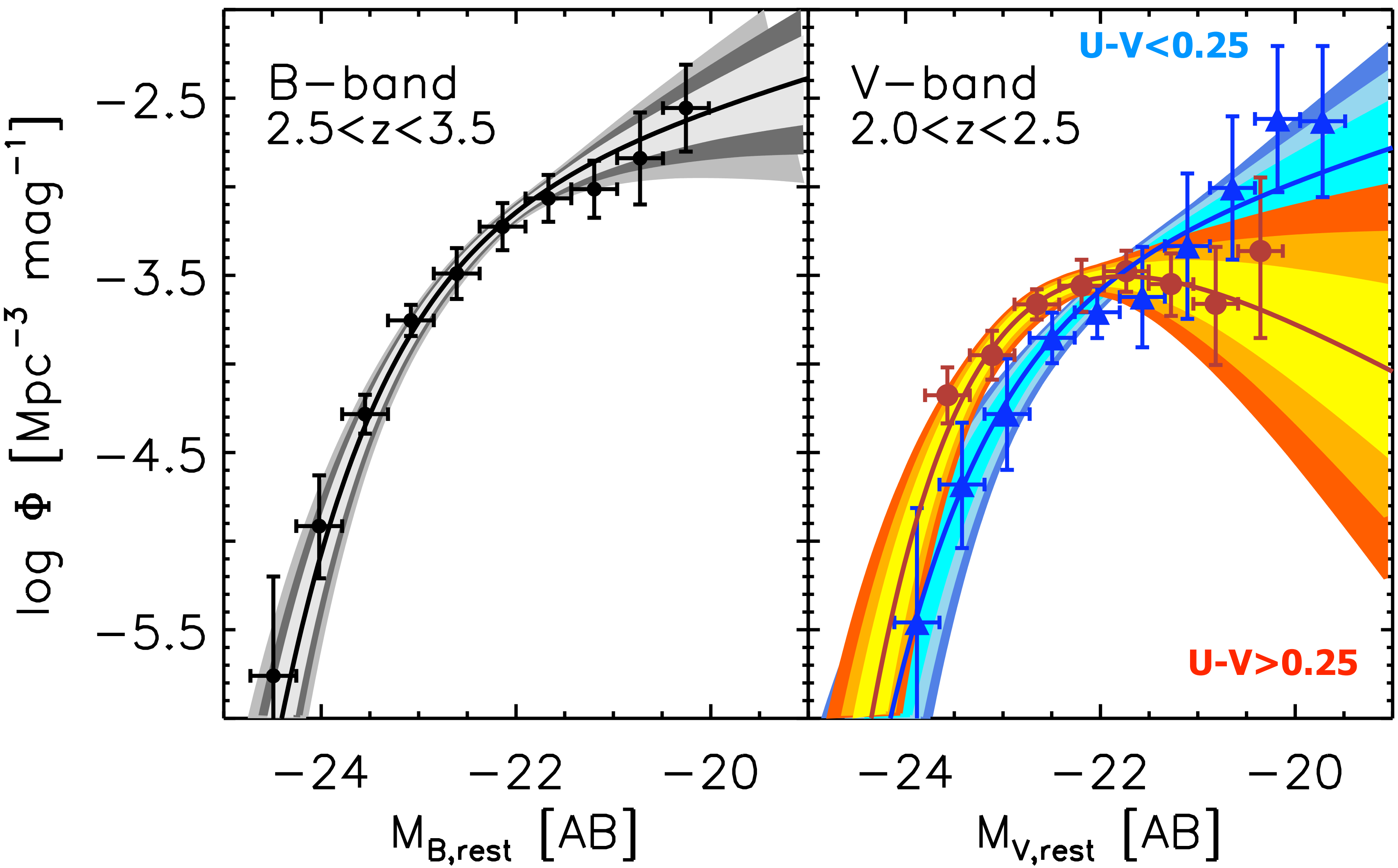
The bright/high-mass end is influenced by:

- ☑ potential AGN feedback (Bower et al. 2006; Croton et al. 2006)
- ☑ environmental effects (e.g., gravitational heating; Khochfar & Ostriker 2008)



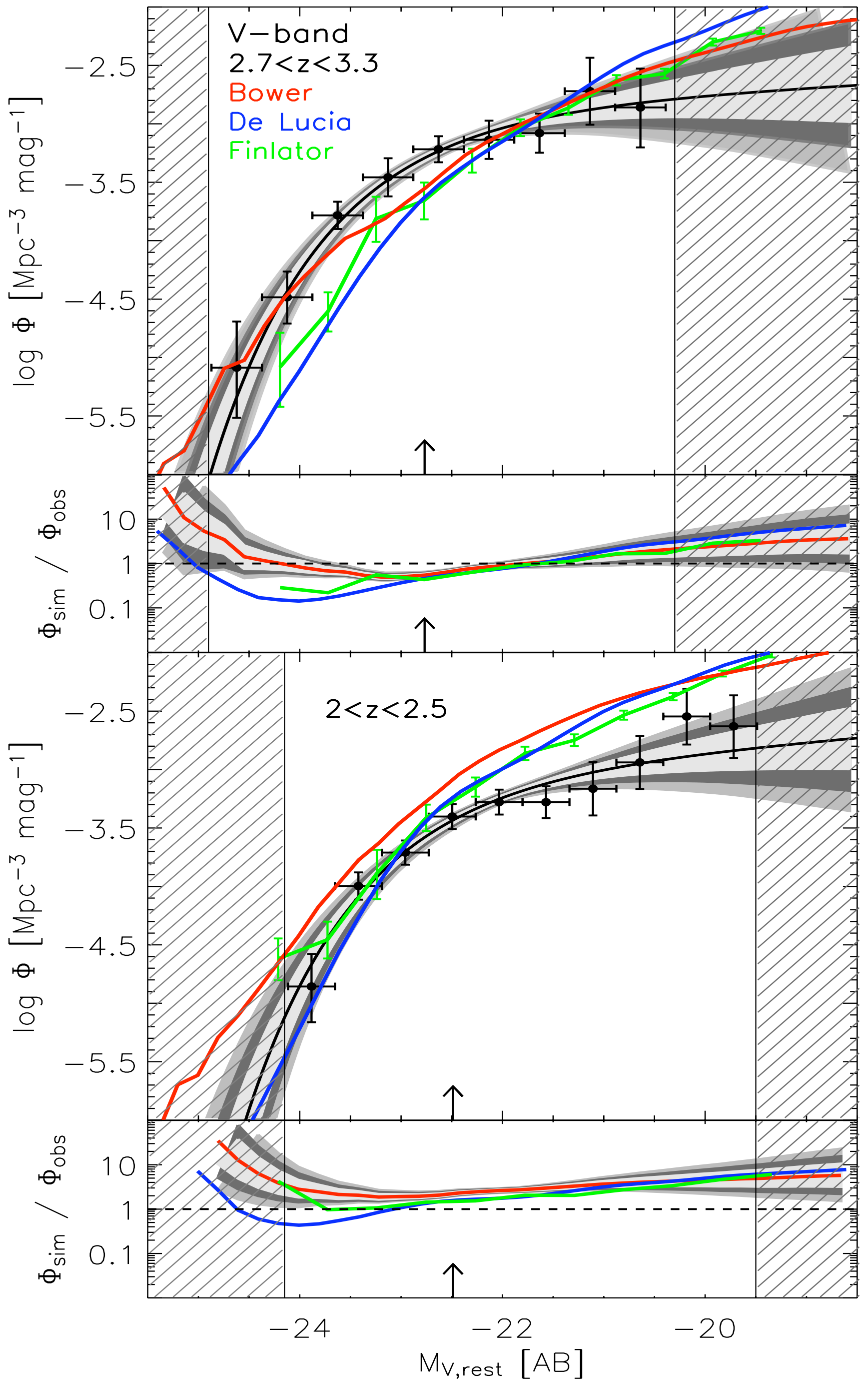


Rest-frame Optical LFs from MUSYC/GOODS/FIRES



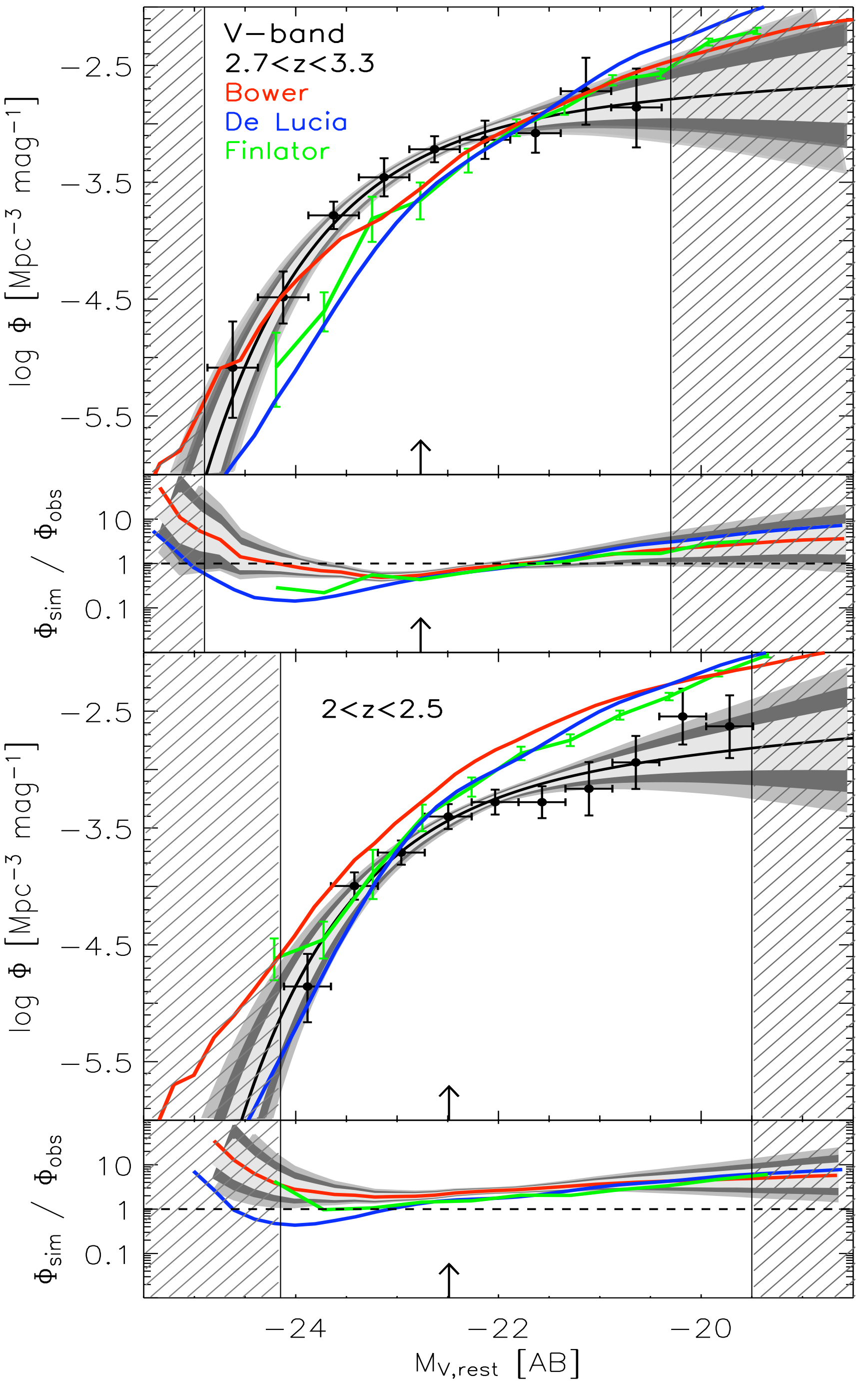
(Marchesini et al., 2007)

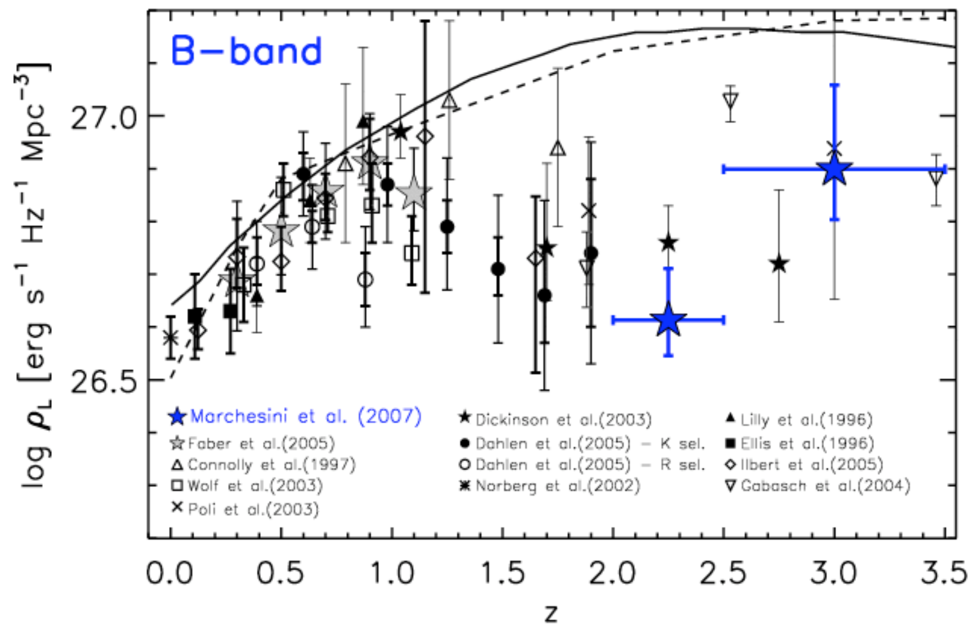
Comparison with models of the LF out to z=3.5



(Marchesini et al. 2007;
Marchesini & van Dokkum 2007)

Comparison with models of the LF out to z=3.5





(Marchesini et al. 2007;
Marchesini & van Dokkum 2007)

Splitting the sample into RED and BLUE galaxies

1. Split the sample based on rest-frame U-V color:

$$U - V \geq 0.25 \quad \text{red galaxies}$$
$$U - V < 0.25 \quad \text{blue galaxies}$$

2. Split the sample based on rest-frame B-V color:

$$B - V \geq 0.5 \quad \text{red galaxies}$$
$$B - V < 0.5 \quad \text{blue galaxies}$$

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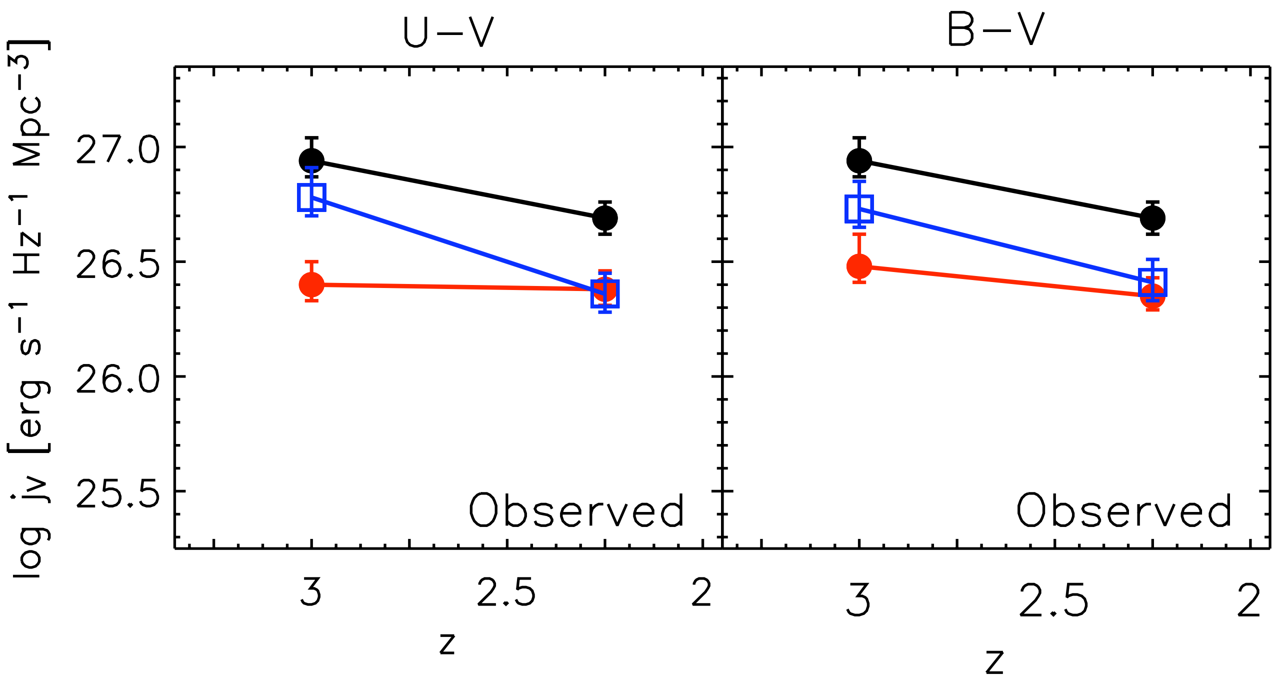

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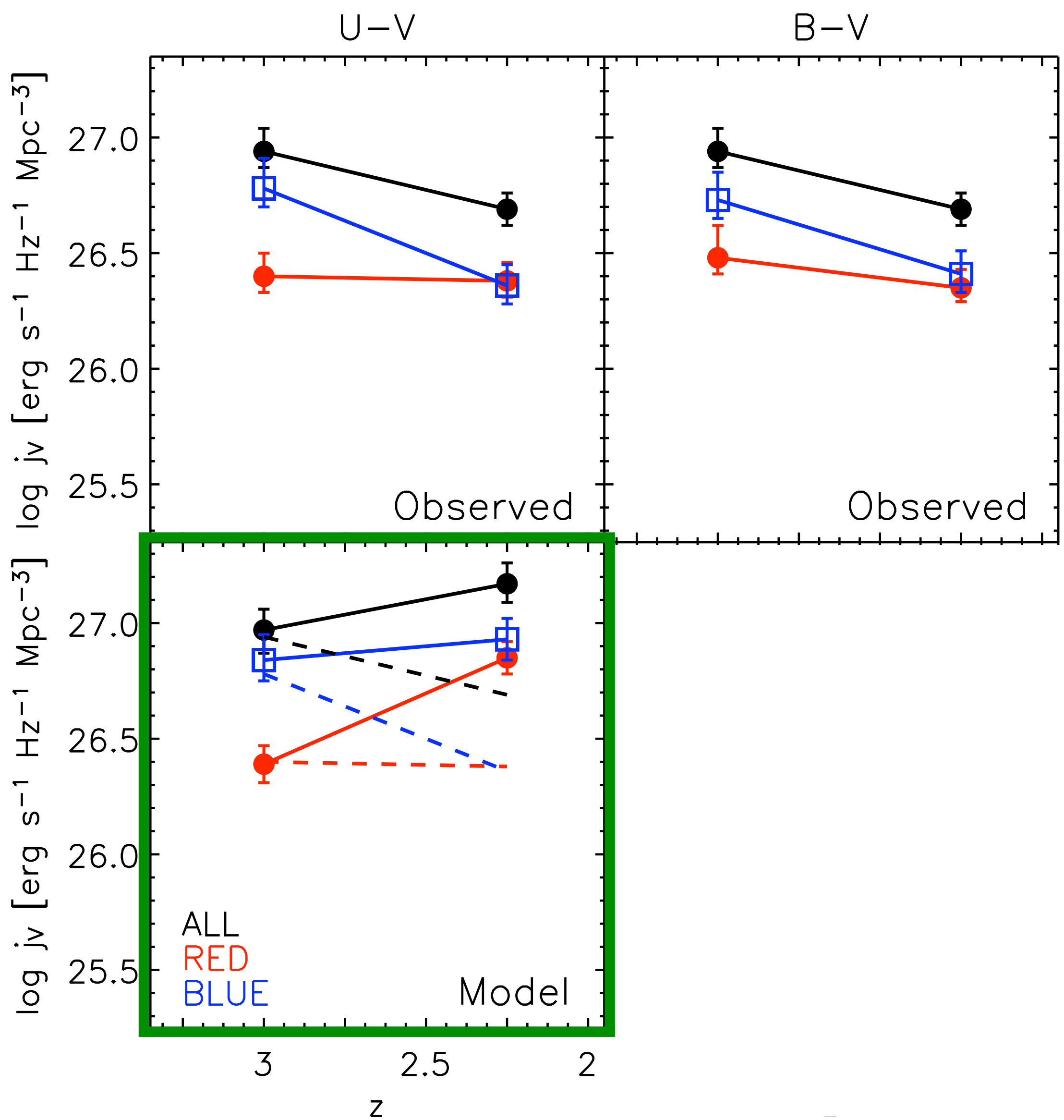

(Marchesini & van Dokkum 2007)

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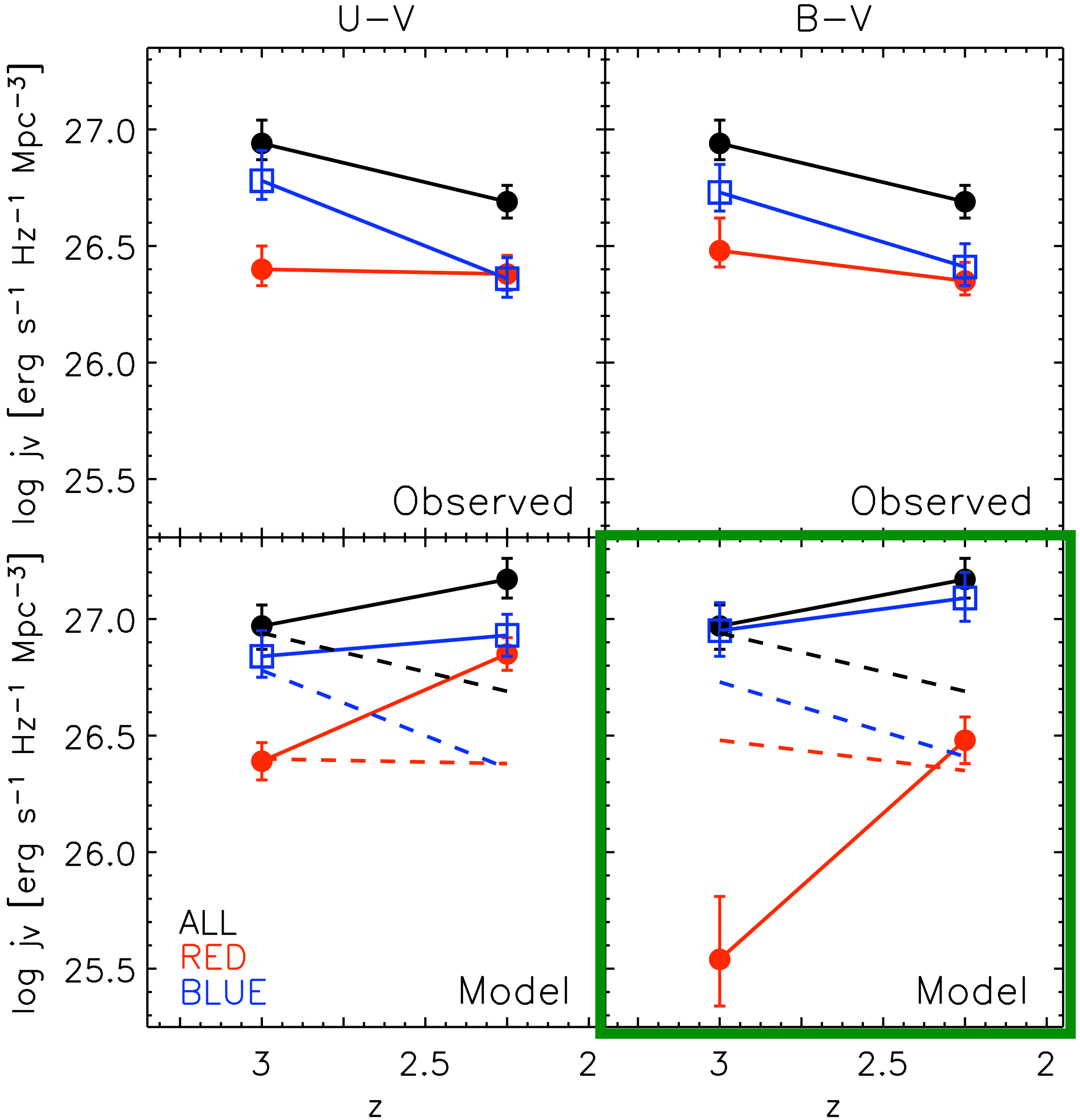

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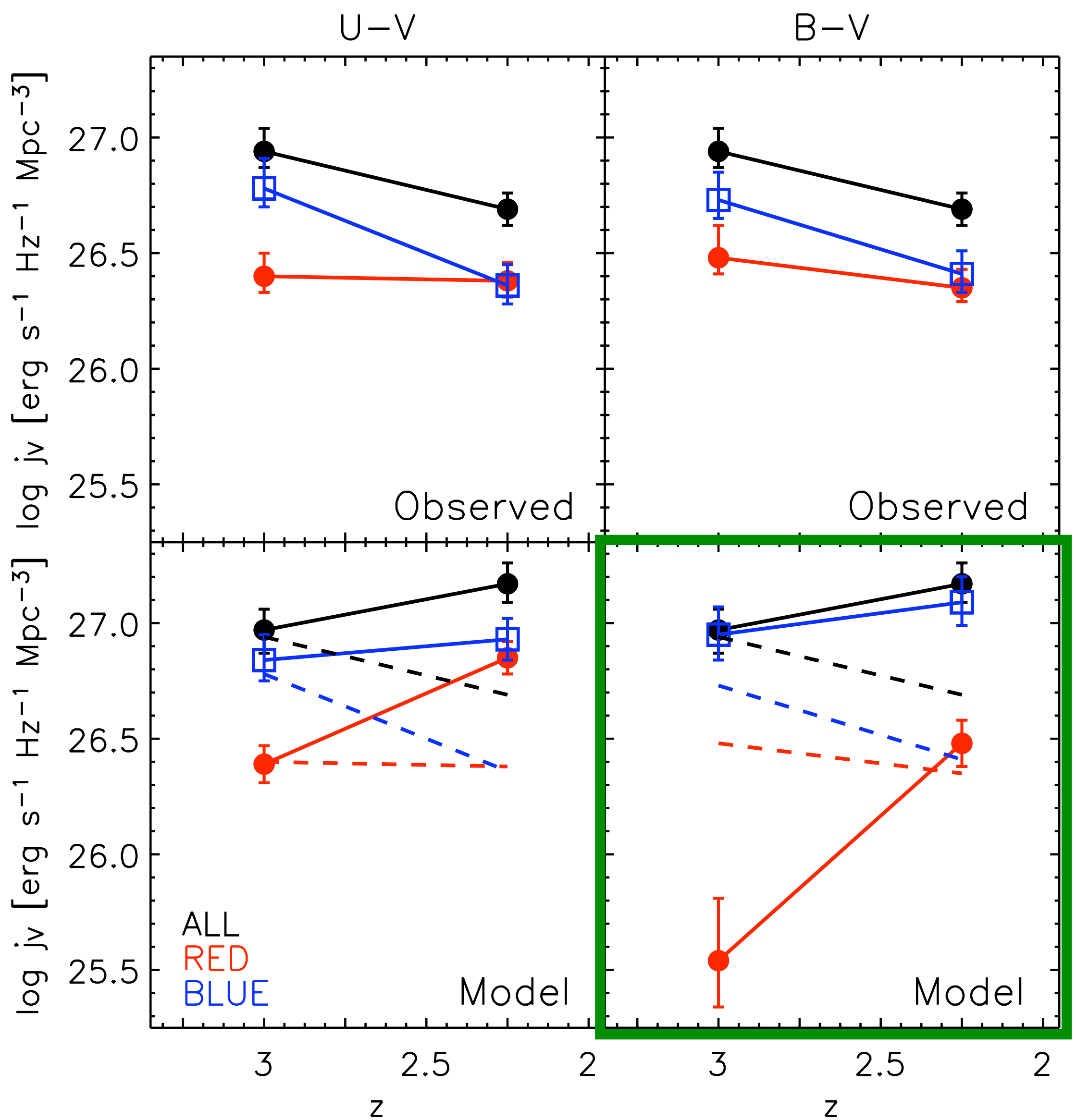
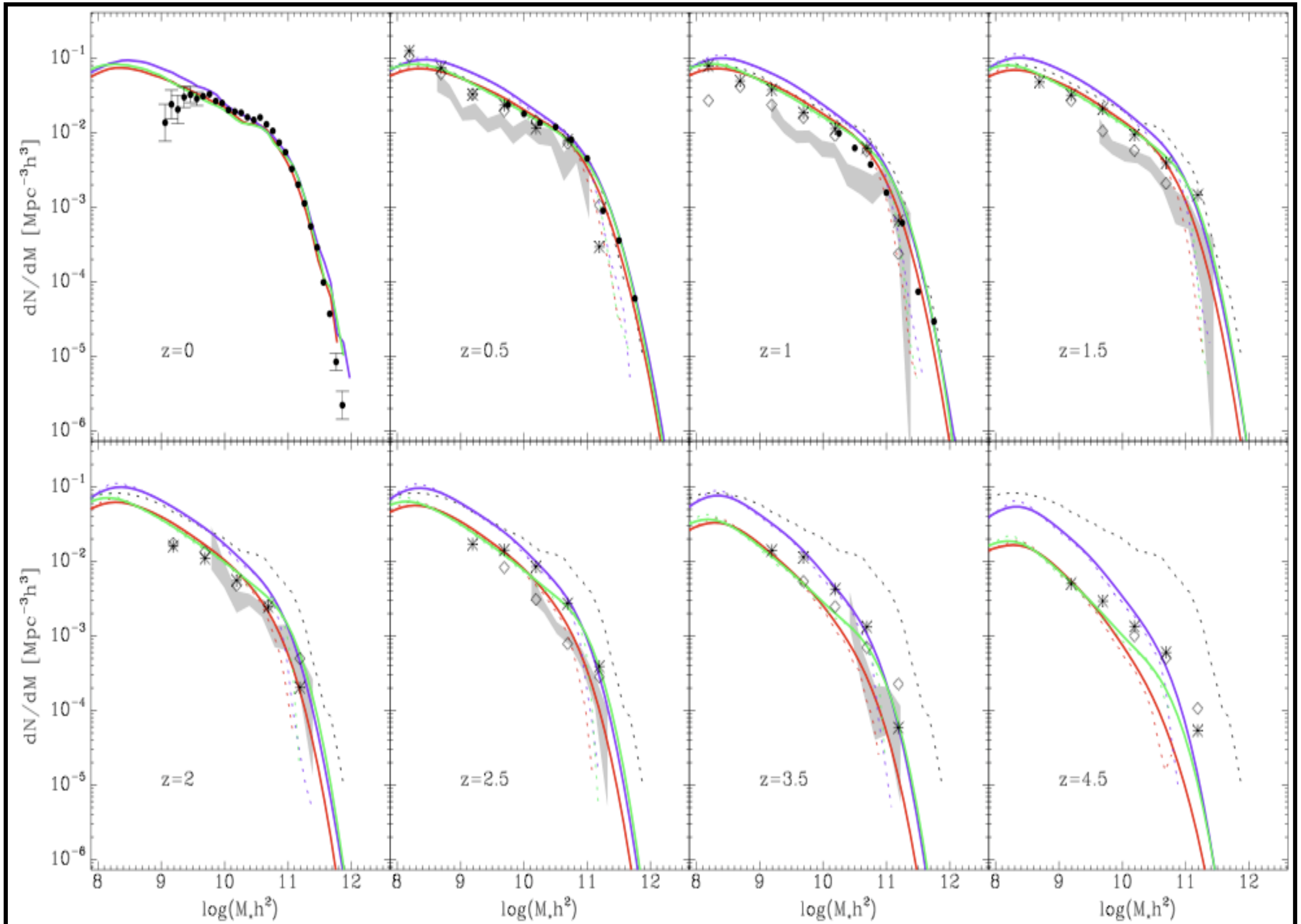
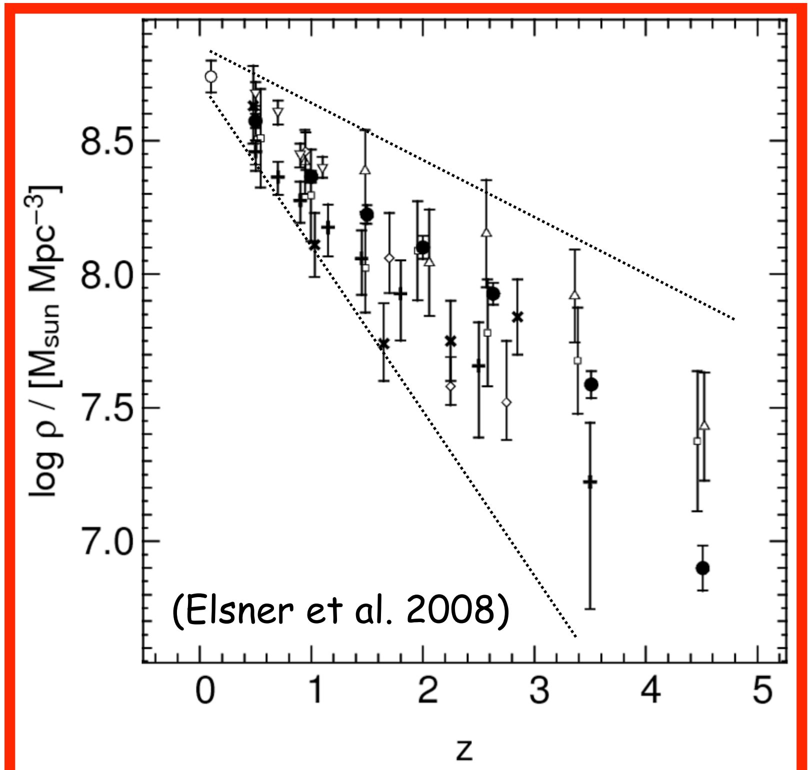


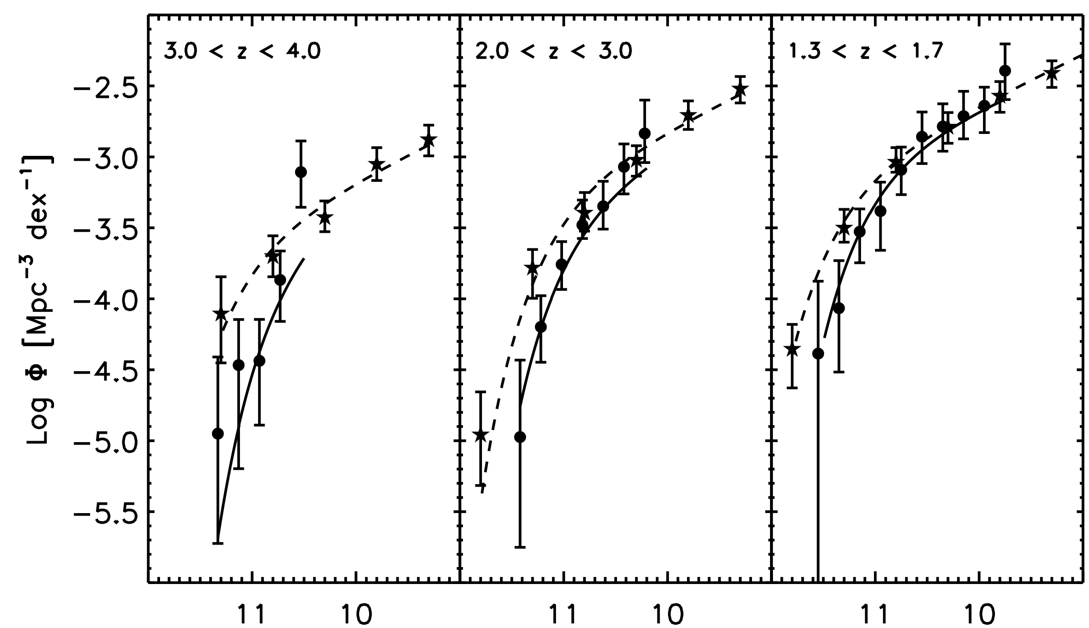
THE PREDICTED EVOLUTION OF THE RED AND BLUE LUMINOSITY DENSITIES IS IN QUALITATIVE DISAGREEMENT WITH THE OBSERVED EVOLUTION

The stellar mass function (SMF)

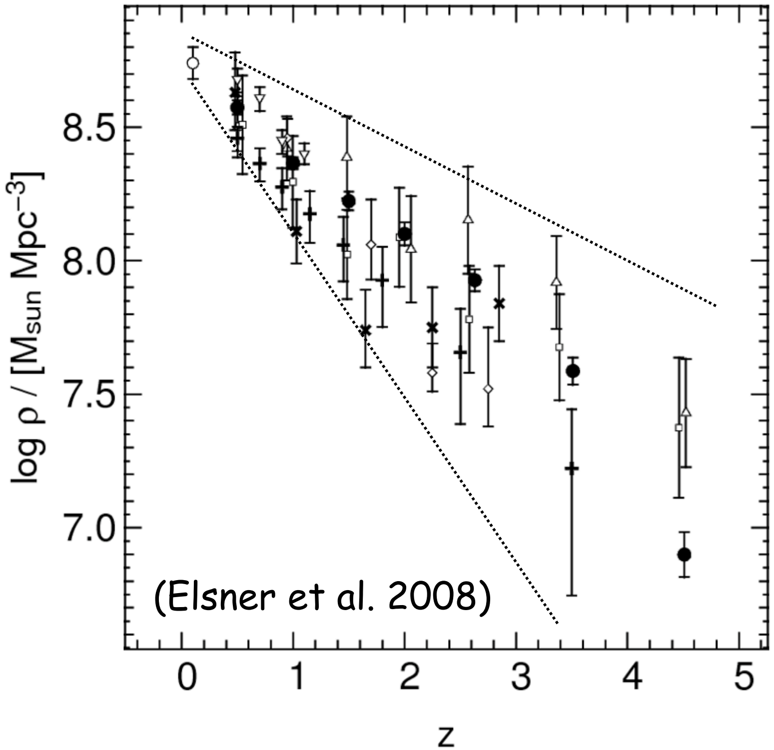


(Cole et al. 2001; Drory et al. 2005; Fontana et al. 2006)
(Wang et al. 2007)

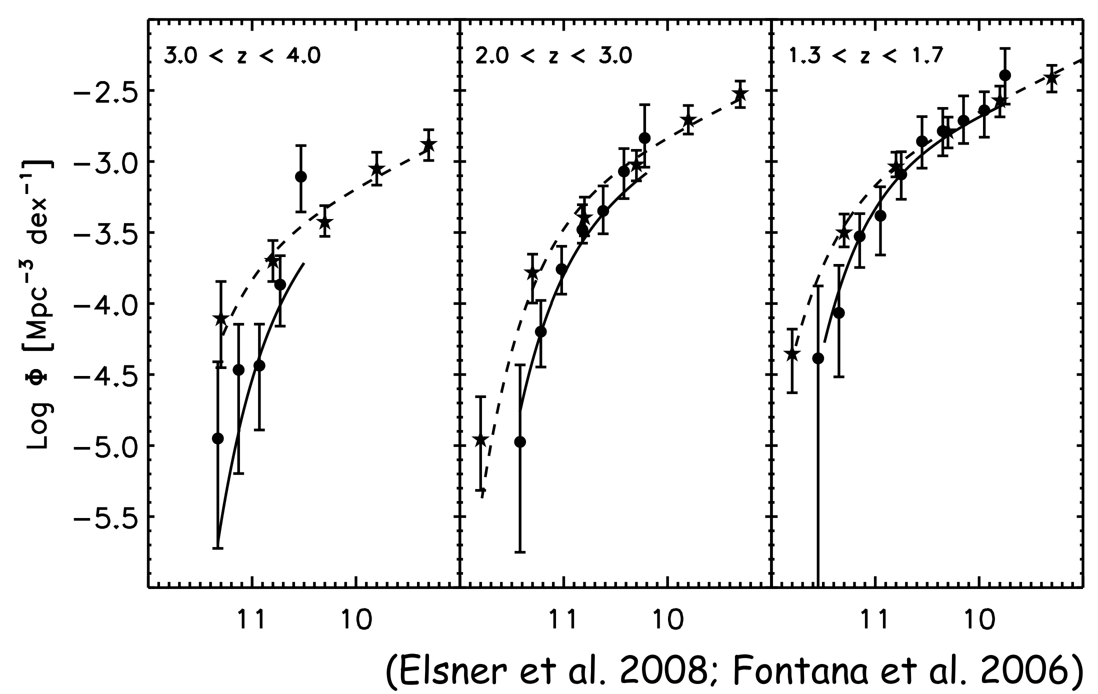




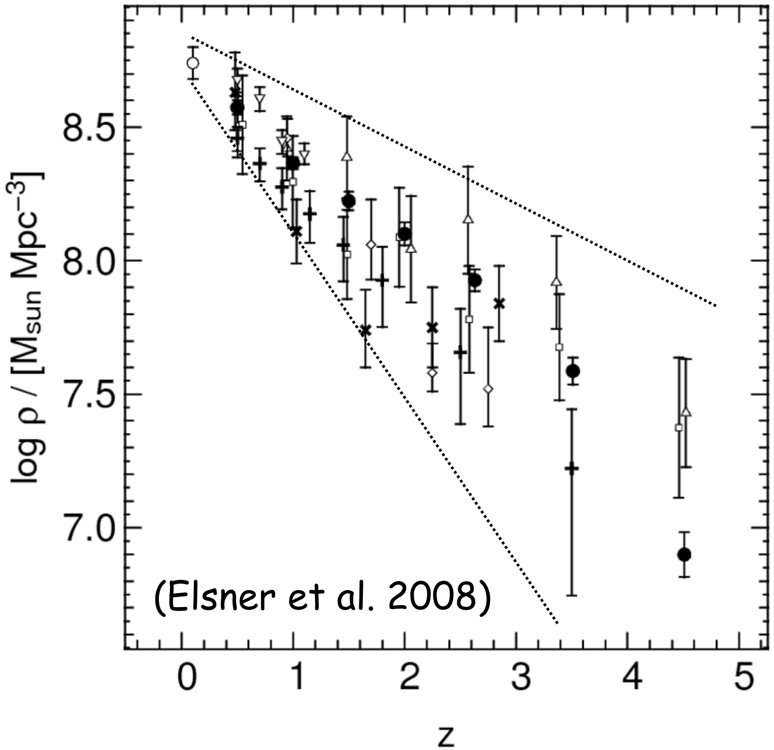
(Elsner et al. 2008; Fontana et al. 2006)



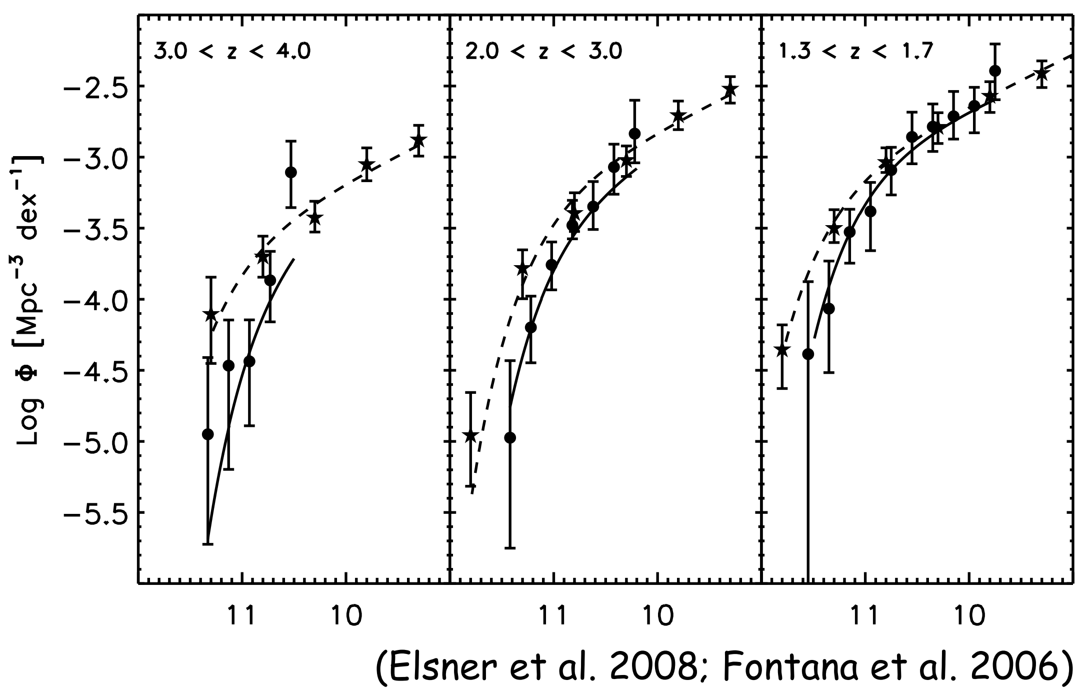
log ρ / [Msun Mpc−3]
8.5
8.0
7.5
7.0
0
1
2
3
4
5
z
(Elsner et al. 2008)



3.0 < z < 4.0
2.0 < z < 3.0
1.3 < z < 1.7
Log Φ [Mpc−3 dex−1]
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
11
10
(Elsner et al. 2008; Fontana et al. 2006)



SAME CATALOG!!



Errors affecting the SMF of galaxies

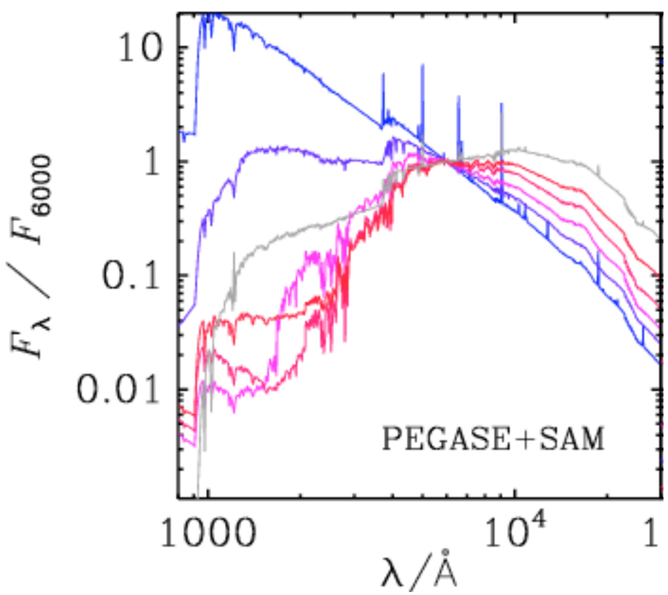
- Poisson errors
- Errors due to photometric redshift uncertainties
    - random errors, caused by uncertainties in the photometry
    - systematic uncertainties, due to specific choice of, e.g., template set.
- Sample variance (aka cosmic variance)
- Systematic effects due to SED modeling assumptions (stellar population synthesis model, IMF, metallicity, extinction curve)

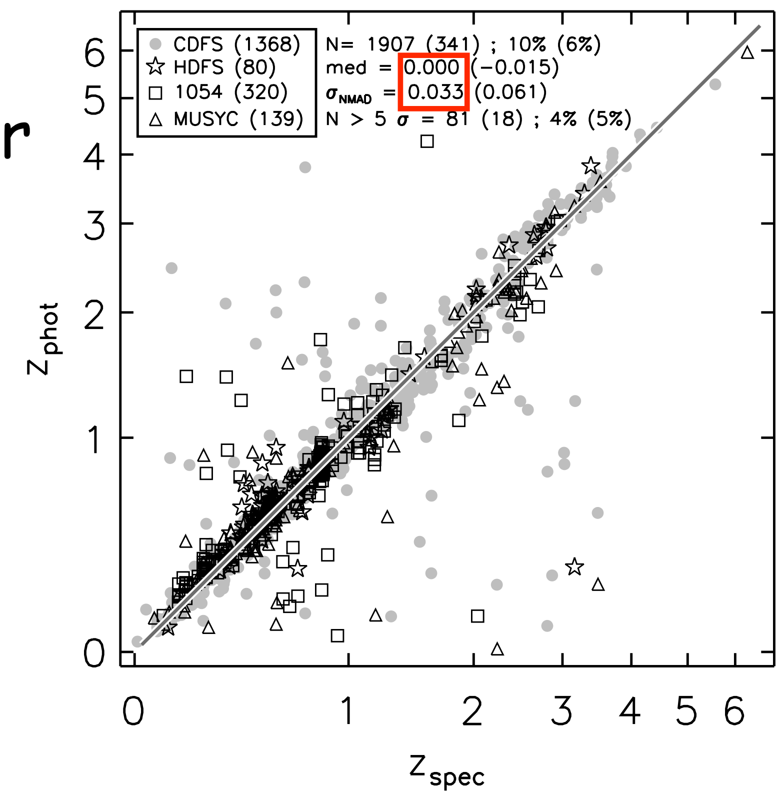
The K-selected sample

- K-selected sample constructed from:
  I. the deep NIR MUSYC (Quadri, DM et al. 2007): four 10'x10' fields with homogeneous coverage in 13 broad-bands (www.astro.yale.edu/musyc)
  II. the ultra-deep FIRES (Franx et al. 2003): 2 fields (HDFS Proper and MS1054)
  III. the very deep GOODS-CDFS (Giavalisco et al. 2004): FIREWORKS catalog by Wuyts et al. (2008) with 16 bands
- High-quality optical to mid-IR photometry
- the composite sample (~3060 galaxies with $K_{\mathrm{S}}^{\mathrm{tot}}(AB) < 25.5$ at $1.3 \leq z < 4.0$) is unique for its combination of surveyed area (~ $510\ arcmin^2$) and depth

Photometric redshifts

- Photometric redshifts estimated with EAZY (Brammer et al. 2008):
  - I. optimized template set, based on semi-analytical models
  - II. template mismatch addressed by a rest-frame template error function
  - III. apparent magnitude prior





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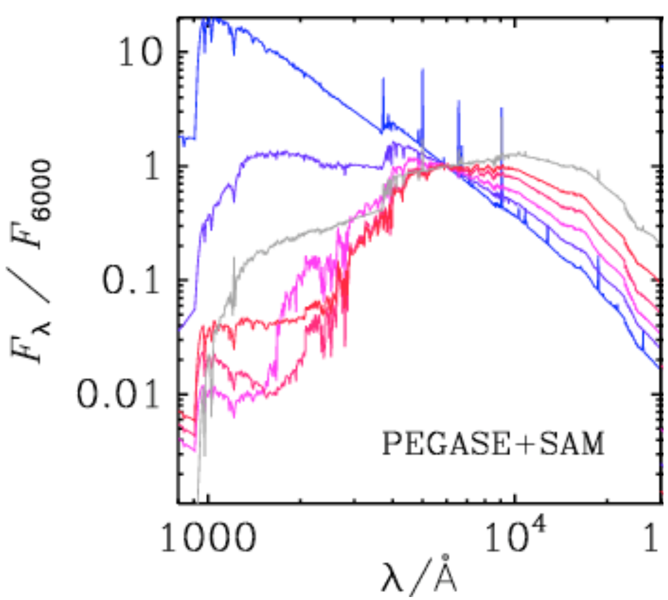
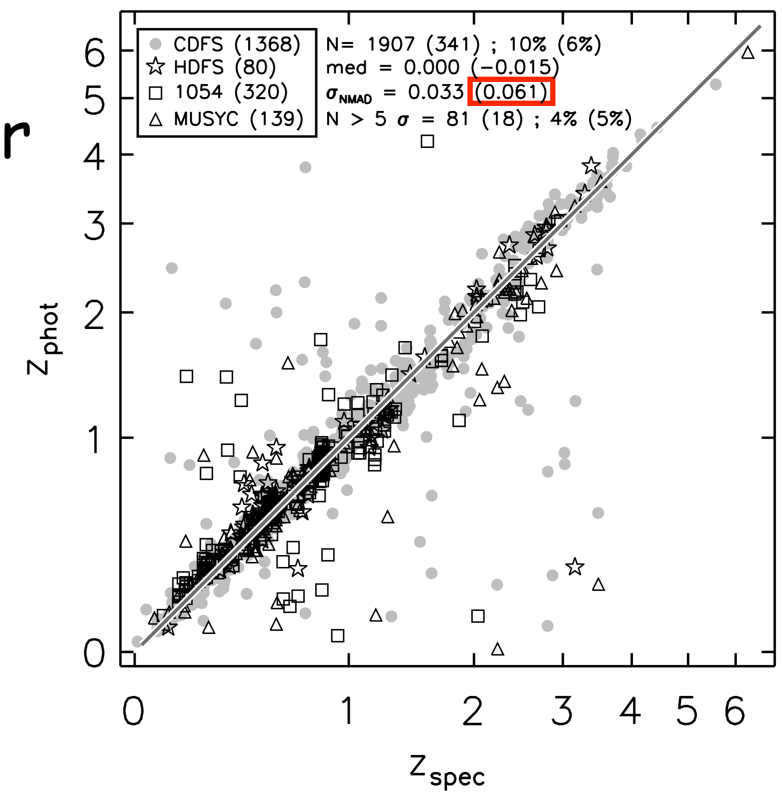
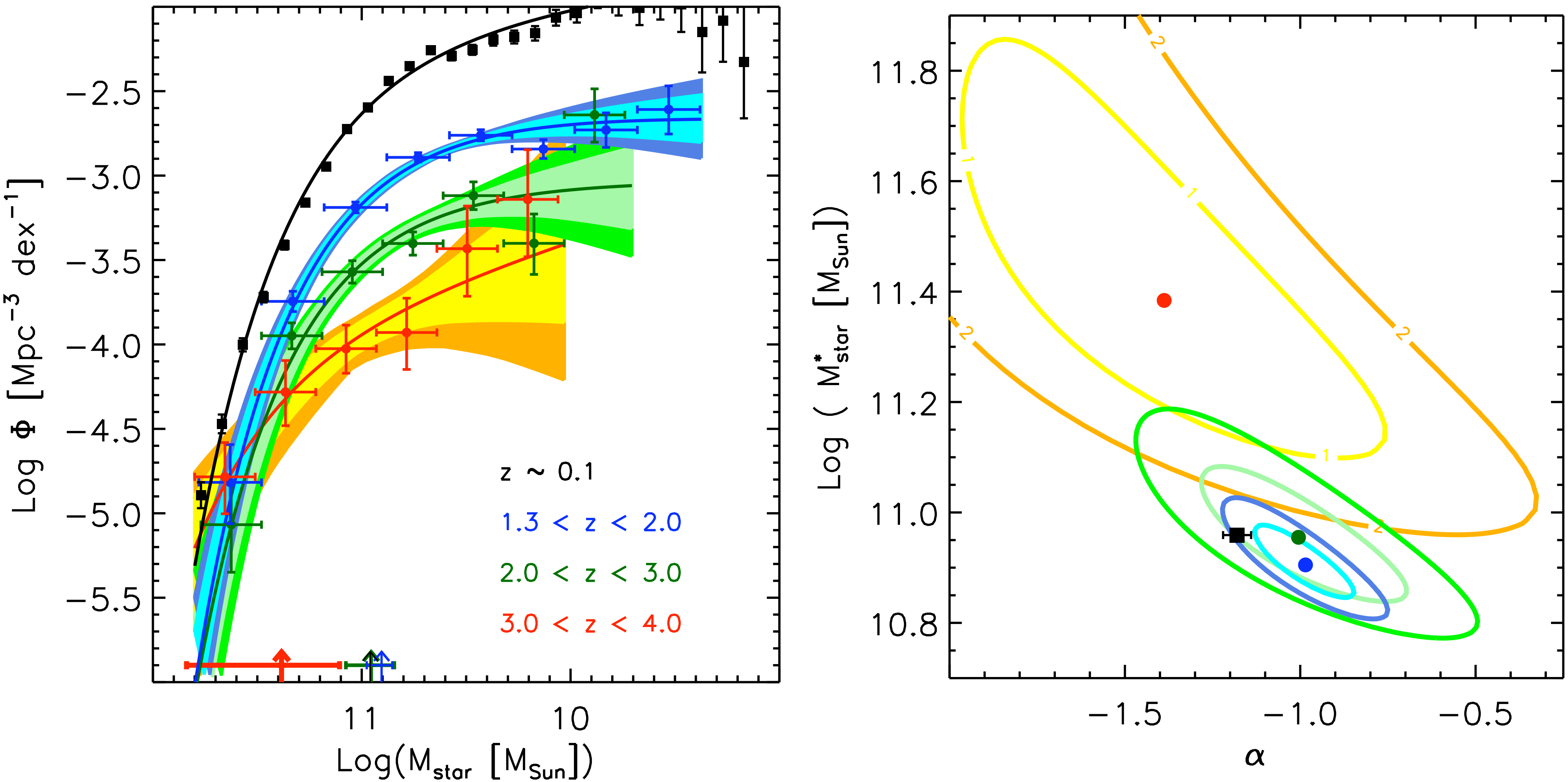




Default SED modeling assumptions

- ☑ Stellar population synthesis model: Bruzual & Charlot (2003) - BC03
- ☑ Metallicity: $Z_\odot$
- ☑ IMF: pseudo-Kroupa (2001)
- ☑ Extinction curve: Calzetti et al. (2000), $A_{\rm V} \in [0, 4]$

The SMF of galaxies at 1.3<z<4.0



(DM et al., 2009)

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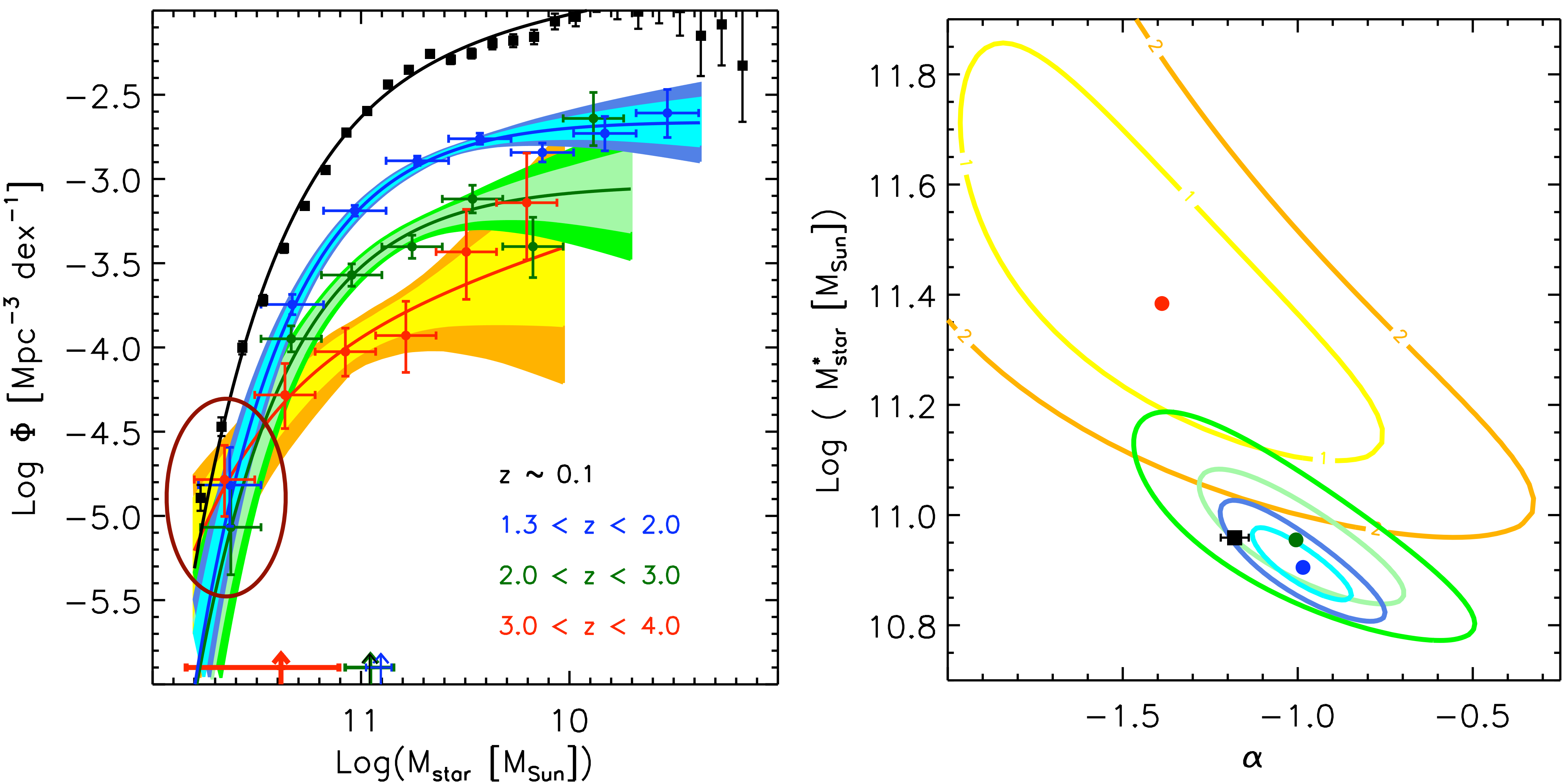

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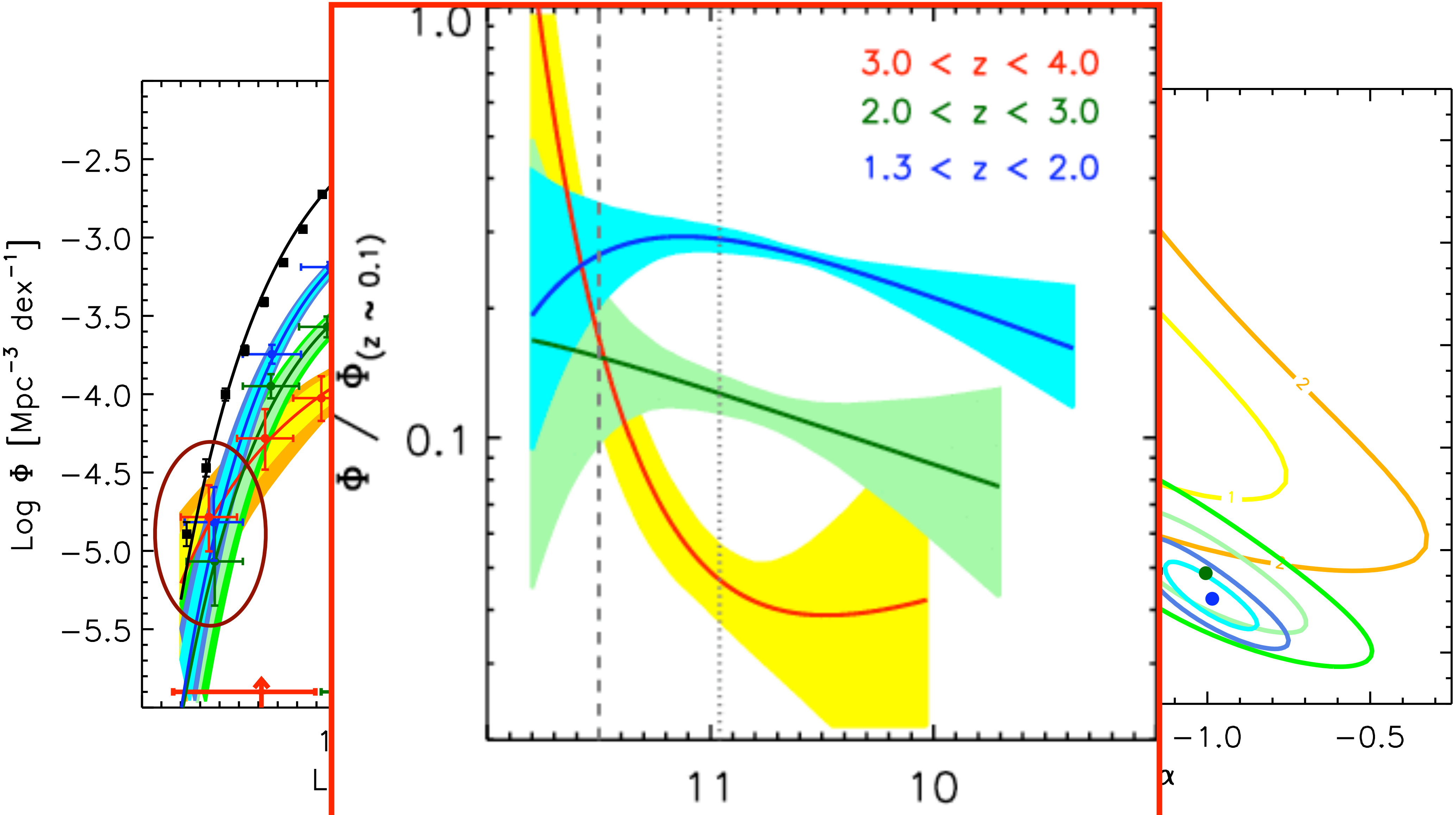

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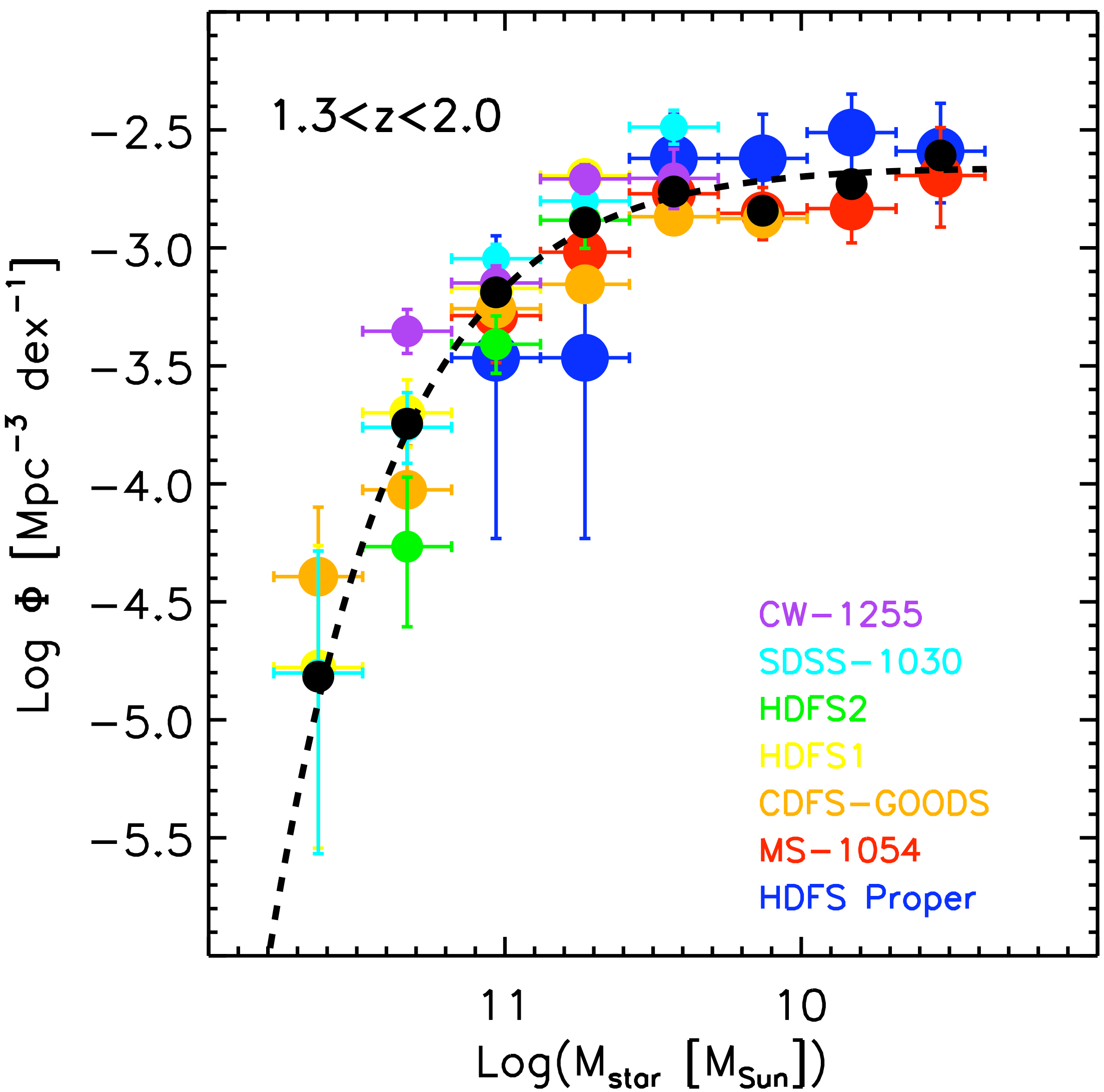

Errors affecting the SMF of galaxies

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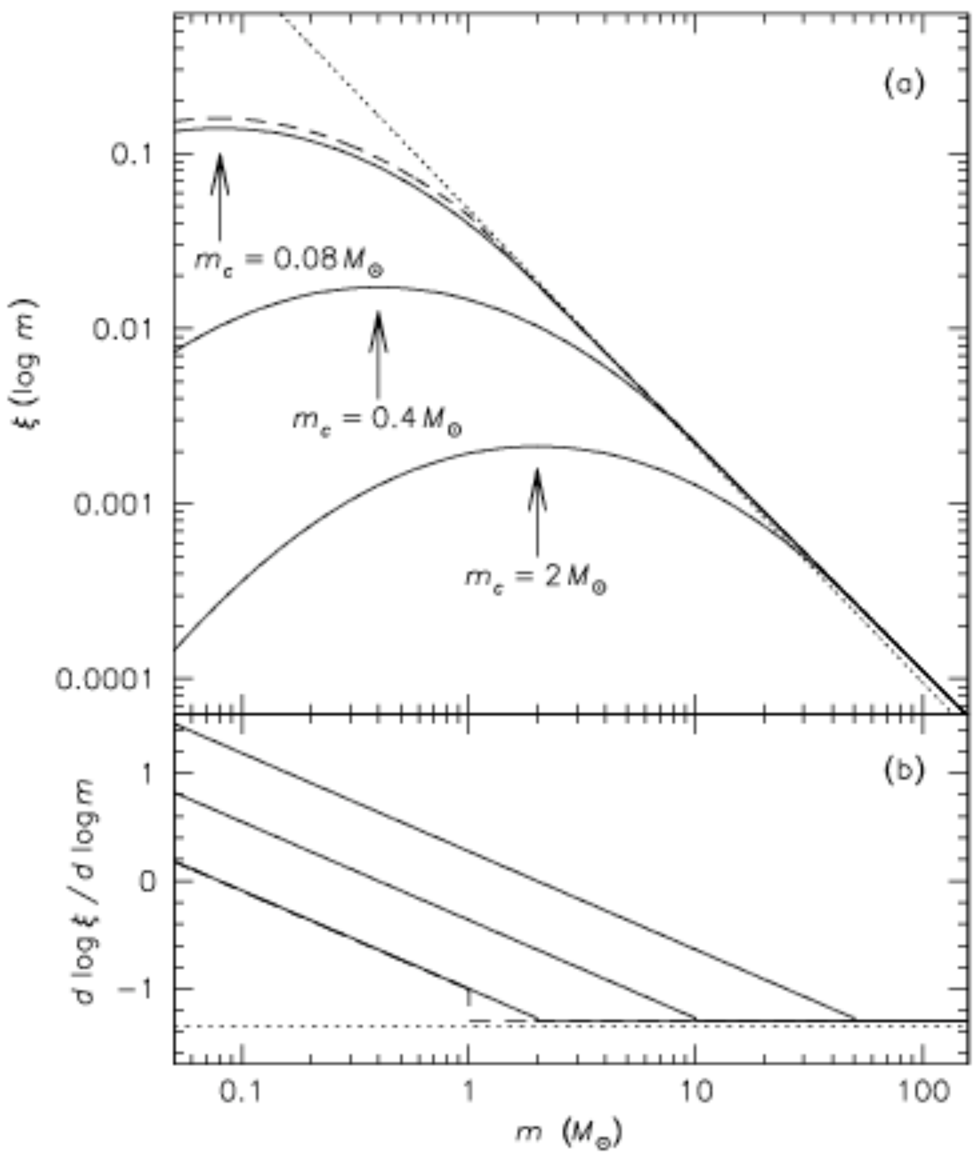
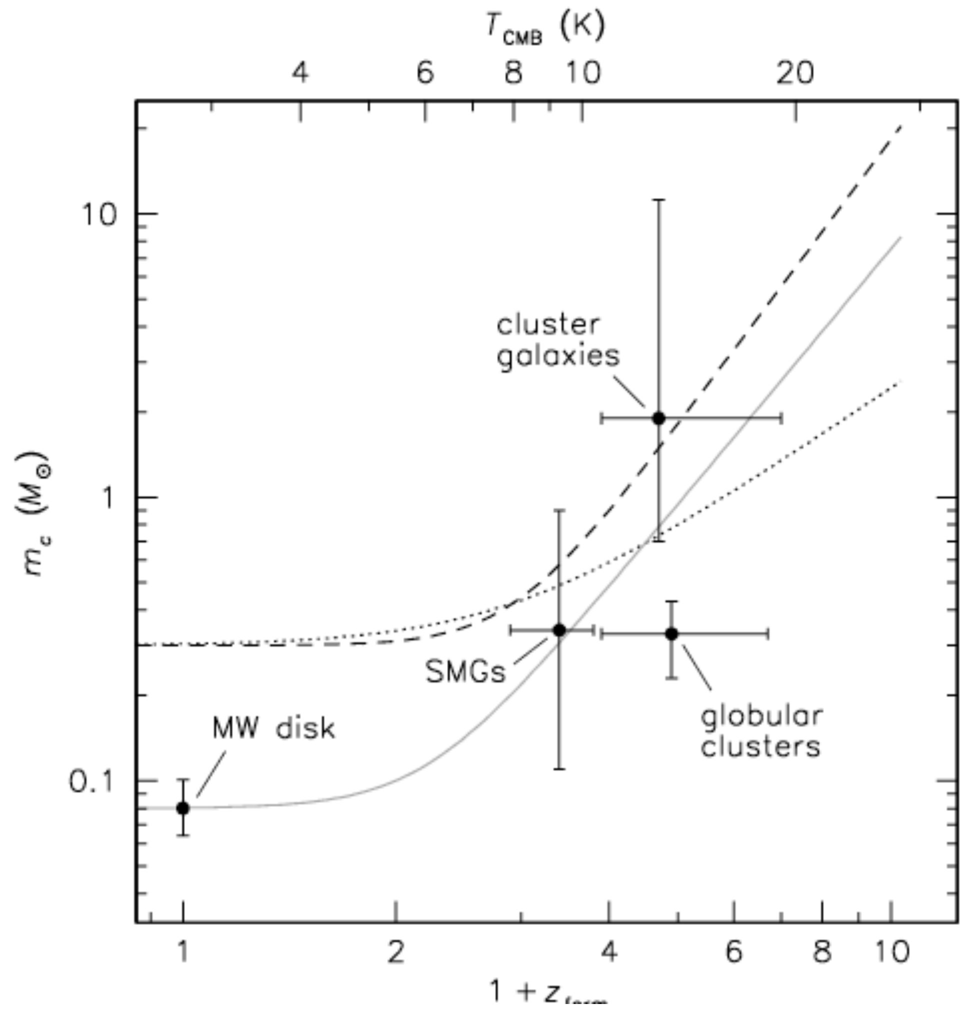
- [x] Errors due to photometric redshift uncertainties
    - [x] random errors, caused by uncertainties in the photometry
    - [x] systematic uncertainties, due to specific choice of, e.g., template set.
- [ ] Systematic effects due to SED modeling assumptions

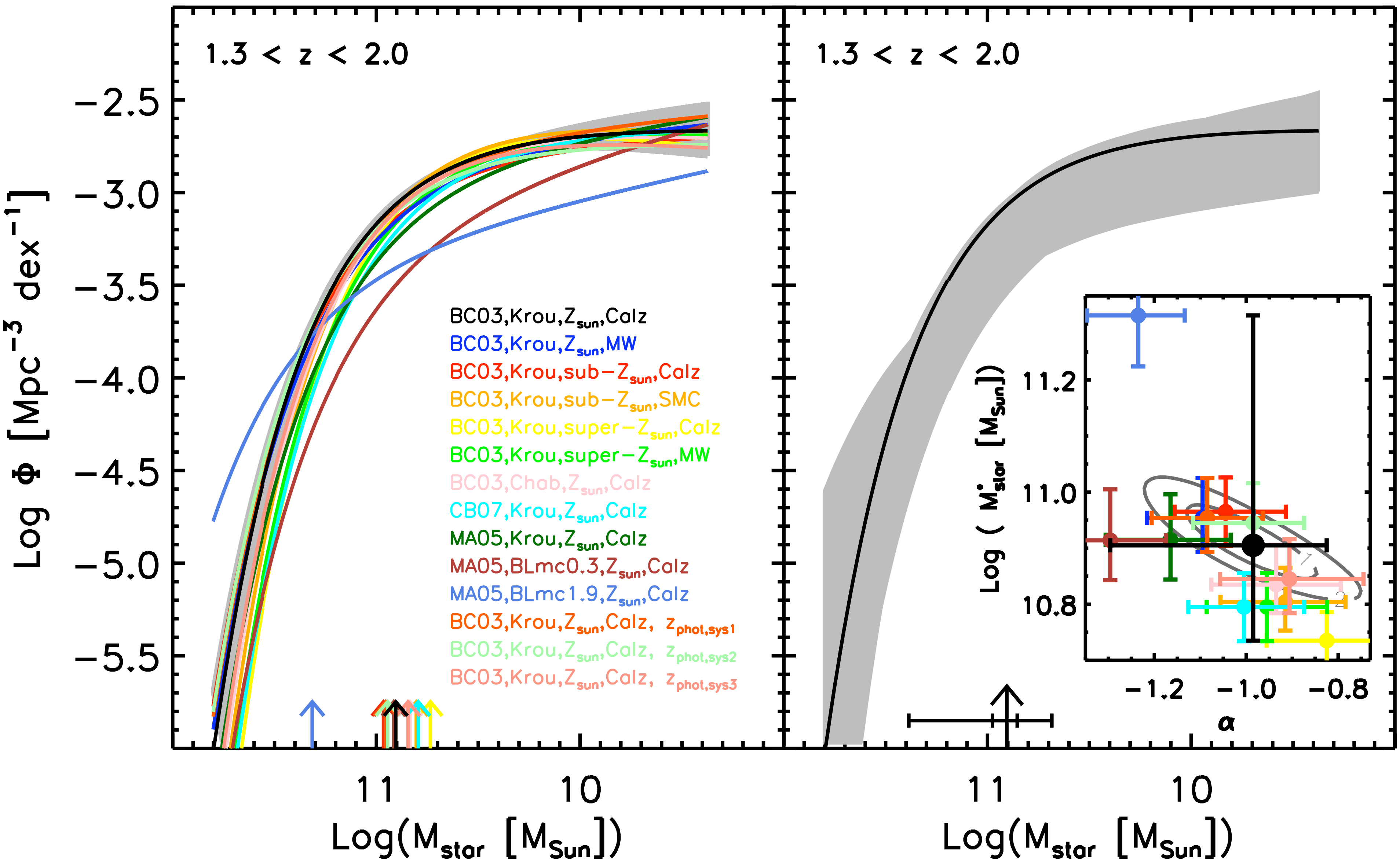
1. BC03 --> MA05 (Maraston 2005); CB08 (Charlot & Bruzual 2008)
2. $Z_\odot$ --> sub-solar ($0.2 \cdot Z_\odot$) and super-solar ($2.5 \cdot Z_\odot$) metallicities
3. Calzetti law --> MW and SMC extinction curves
4. Kroupa IMF --> Chabrier and two bottom-light IMFs (e.g., Dave' 2008; van Dokkum 2008)

Bottom-light IMFs

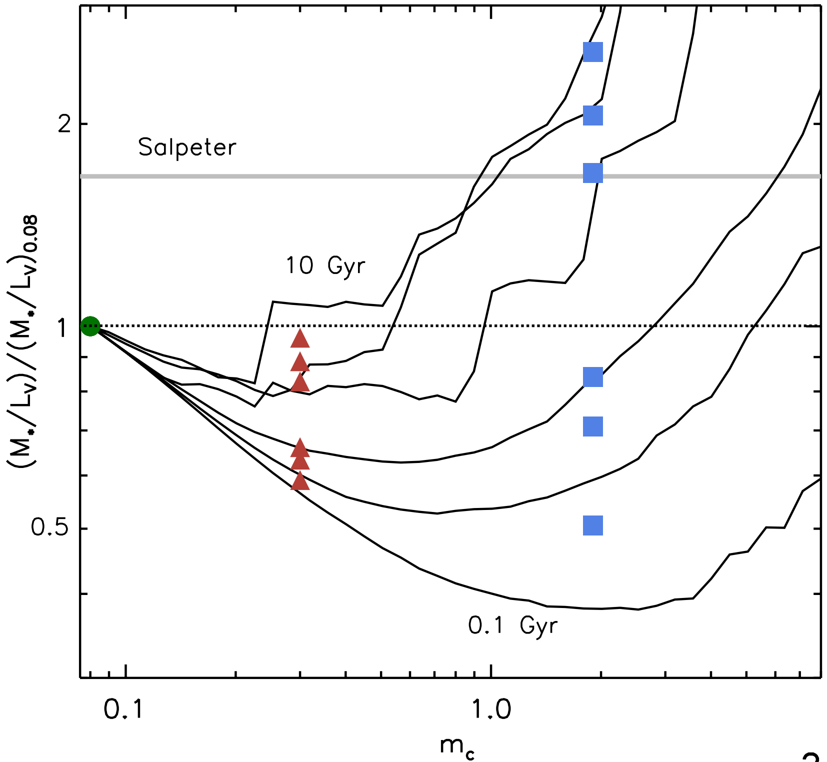




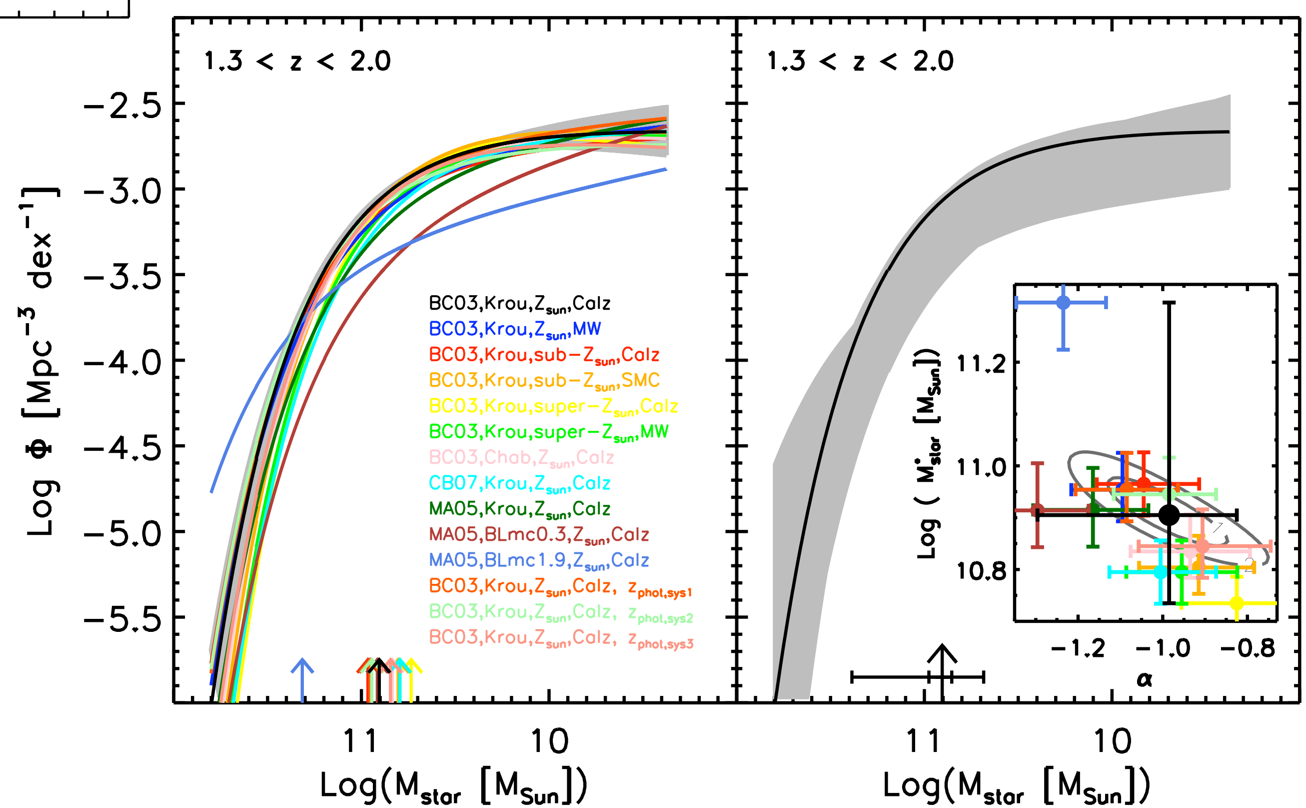
(e.g., van Dokkum 2008)



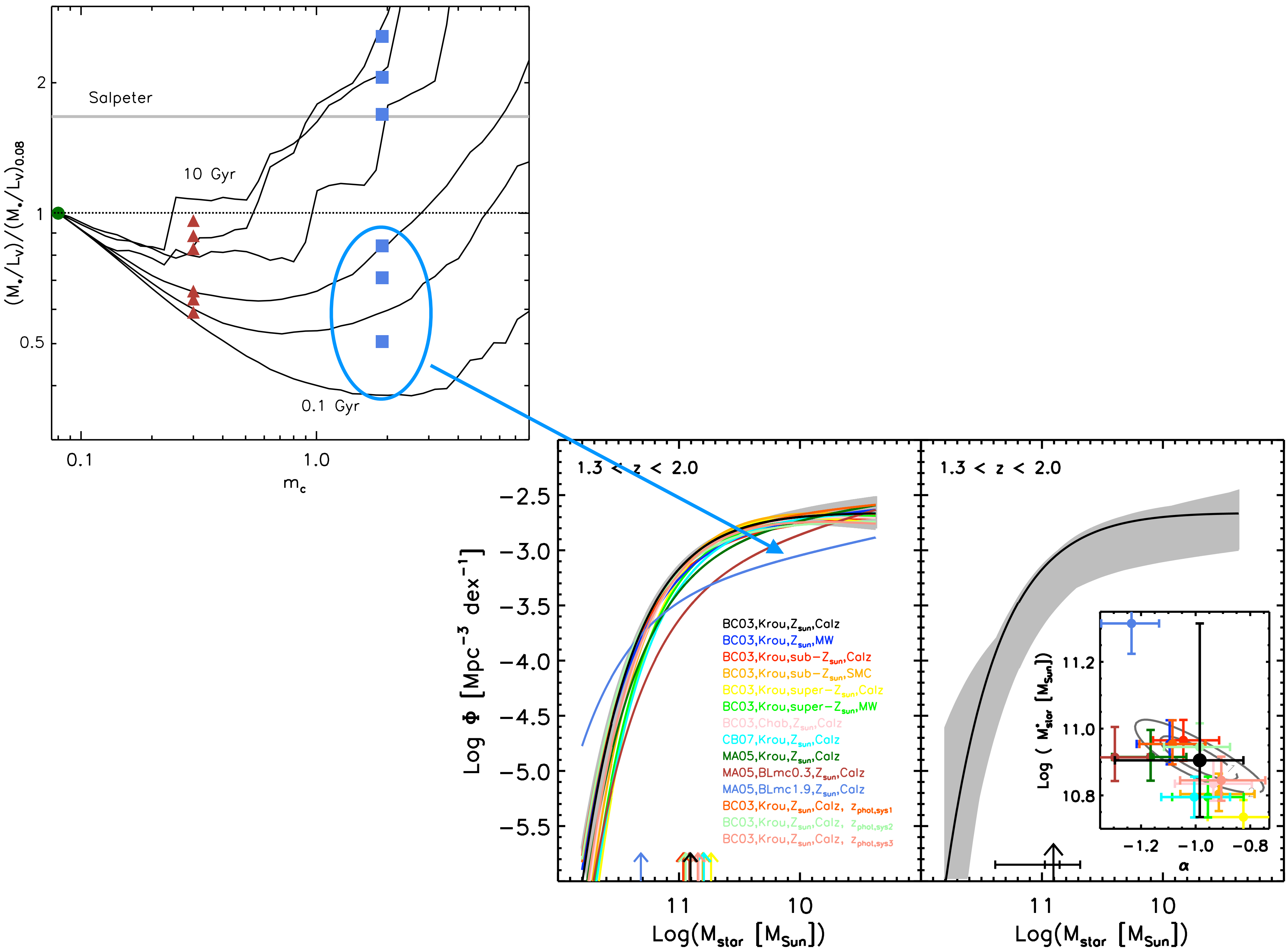
(Marchesini et al. 2009)



Salpeter
10 Gyr
0.1 Gyr
$(M_*/L_V)/(M_*/L_V)_{0.08}$
m_c
0.1
1.0
0.5
1
2



1.3 < z < 2.0
1.3 < z < 2.0
Log Φ [Mpc^{-3} dex^{-1}]
Log(M_{star} [M_{Sun}])
Log(M_{star} [M_{Sun}])
BC03,Krou,Z_{sun},Calz
BC03,Krou,Z_{sun},MW
BC03,Krou,sub−Z_{sun},Calz
BC03,Krou,sub−Z_{sun},SMC
BC03,Krou,super−Z_{sun},Calz
BC03,Krou,super−Z_{sun},MW
BC03,Chab,Z_{sun},Calz
CB07,Krou,Z_{sun},Calz
MA05,Krou,Z_{sun},Calz
MA05,BLmc0.3,Z_{sun},Calz
MA05,BLmc1.9,Z_{sun},Calz
BC03,Krou,Z_{sun},Calz, $z_{phot,sys1}$
BC03,Krou,Z_{sun},Calz, $z_{phot,sys2}$
BC03,Krou,Z_{sun},Calz, $z_{phot,sys3}$
Log (M^*_{star} [M_{Sun}])
α



Salpeter
10 Gyr
0.1 Gyr
$(M_*/L_V)/(M_*/L_V)_{0.08}$
m_c
1.3 < z < 2.0
1.3 < z < 2.0
Log Φ [Mpc^{-3} dex^{-1}]
Log(M_{star} [M_{Sun}])
Log(M_{star} [M_{Sun}])
BC03,Krou,Z_{sun},Calz
BC03,Krou,Z_{sun},MW
BC03,Krou,sub-Z_{sun},Calz
BC03,Krou,sub-Z_{sun},SMC
BC03,Krou,super-Z_{sun},Calz
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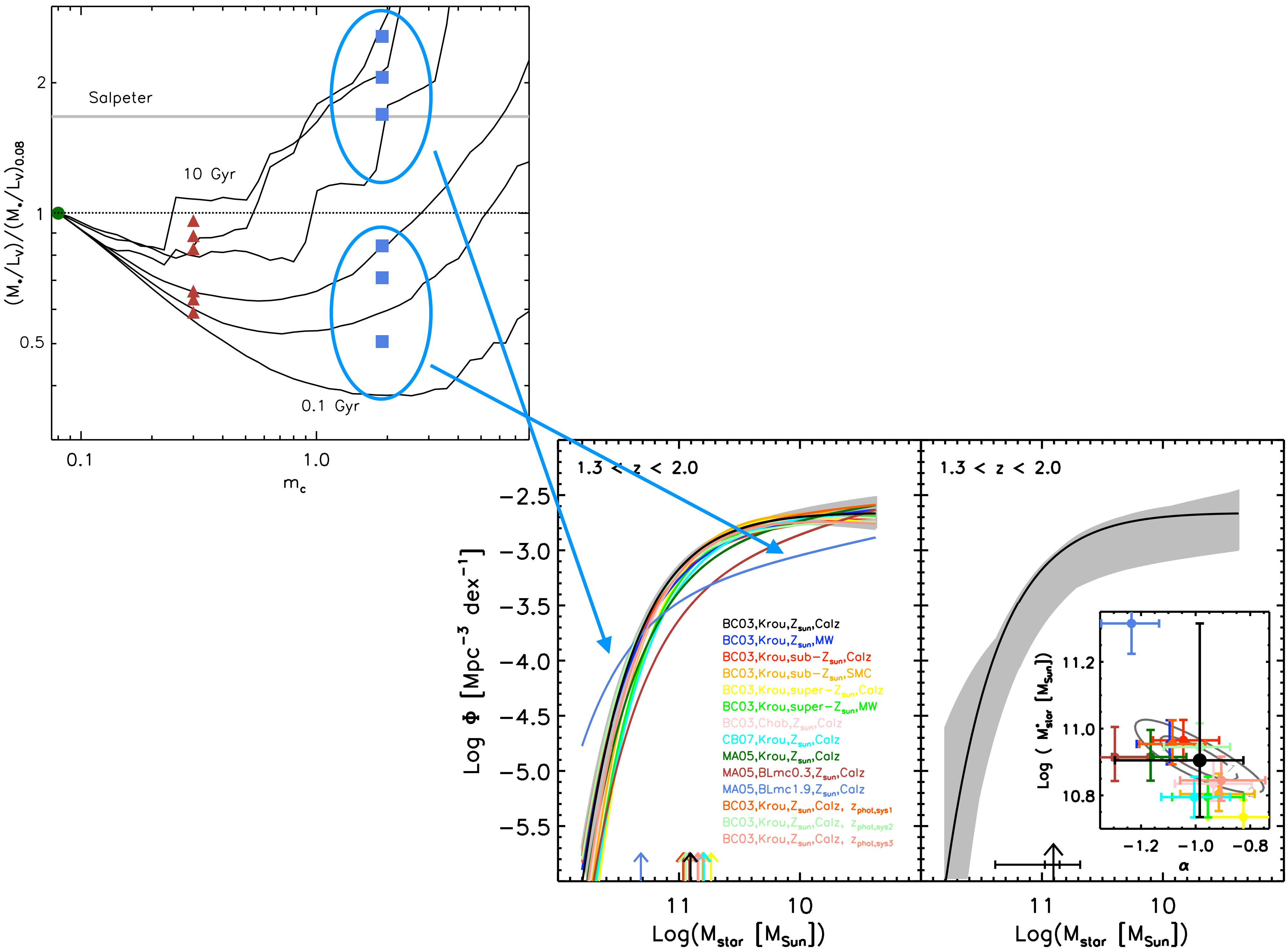
BC03,Chab,Z_{sun},Calz
CB07,Krou,Z_{sun},Calz
MA05,Krou,Z_{sun},Calz
MA05,BLmc0.3,Z_{sun},Calz
MA05,BLmc1.9,Z_{sun},Calz
BC03,Krou,Z_{sun},Calz, $z_{phot,sys1}$
BC03,Krou,Z_{sun},Calz, $z_{phot,sys2}$
BC03,Krou,Z_{sun},Calz, $z_{phot,sys3}$
Log (M^*_{star} [M_{Sun}])
α



Salpeter
10 Gyr
0.1 Gyr
$(M_*/L_V)/(M_*/L_V)_{0.08}$
m_c
1.3 < z < 2.0
1.3 < z < 2.0
Log Φ [Mpc^{-3} dex^{-1}]
Log(M_{star} [M_{Sun}])
Log(M_{star} [M_{Sun}])
BC03,Krou,Z_{sun},Calz
BC03,Krou,Z_{sun},MW
BC03,Krou,sub-Z_{sun},Calz
BC03,Krou,sub-Z_{sun},SMC
BC03,Krou,super-Z_{sun},Calz
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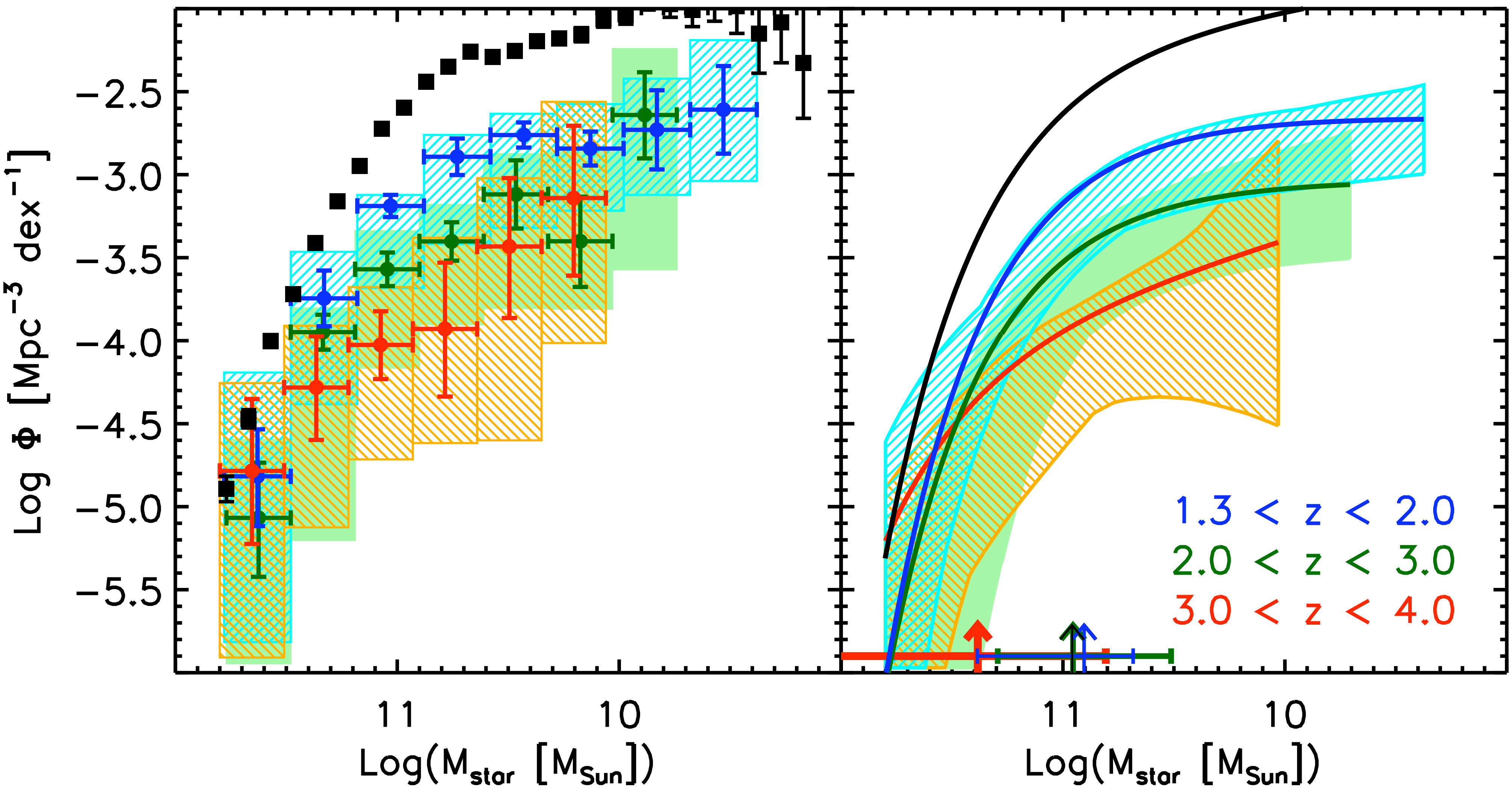
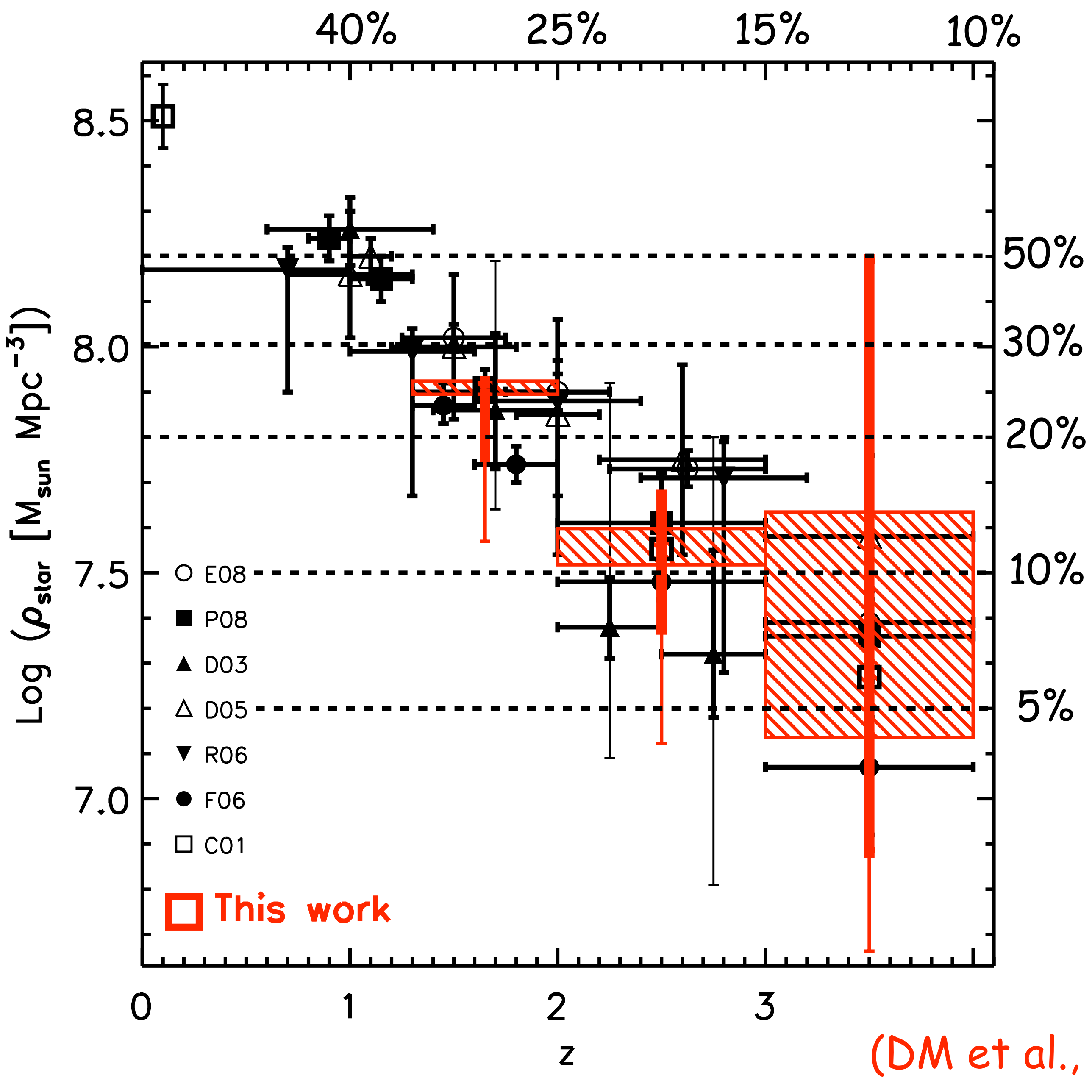
CB07,Krou,Z_{sun},Calz
MA05,Krou,Z_{sun},Calz
MA05,BLmc0.3,Z_{sun},Calz
MA05,BLmc1.9,Z_{sun},Calz
BC03,Krou,Z_{sun},Calz, $z_{phot,sys1}$
BC03,Krou,Z_{sun},Calz, $z_{phot,sys2}$
BC03,Krou,Z_{sun},Calz, $z_{phot,sys3}$
Log (M^*_{star} [M_{Sun}])
α



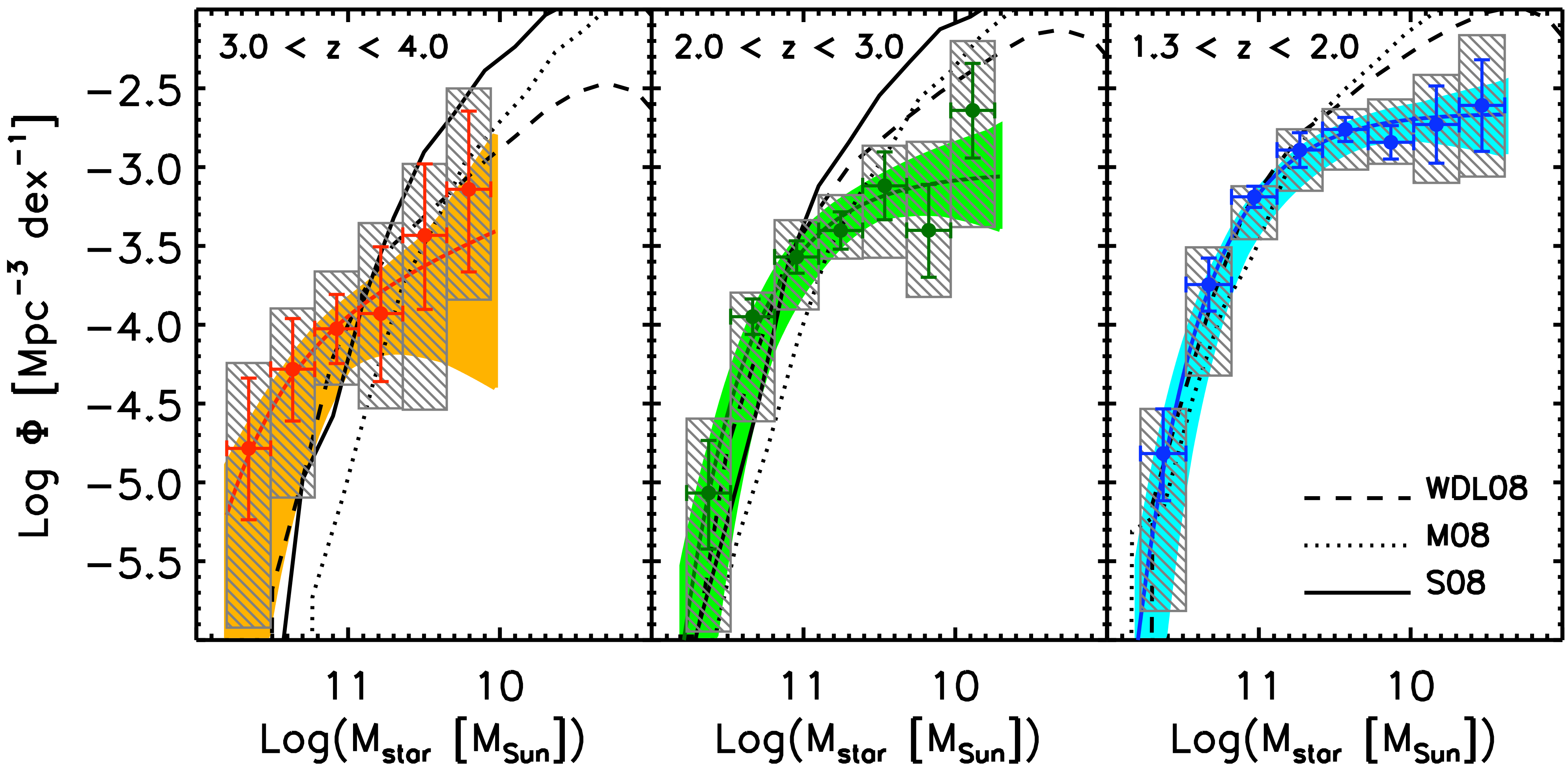
Log Φ [Mpc^-3 dex^-1]
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
11
10
Log(M_star [M_Sun])
1.3 < z < 2.0
2.0 < z < 3.0
3.0 < z < 4.0

Evolution of the stellar mass density



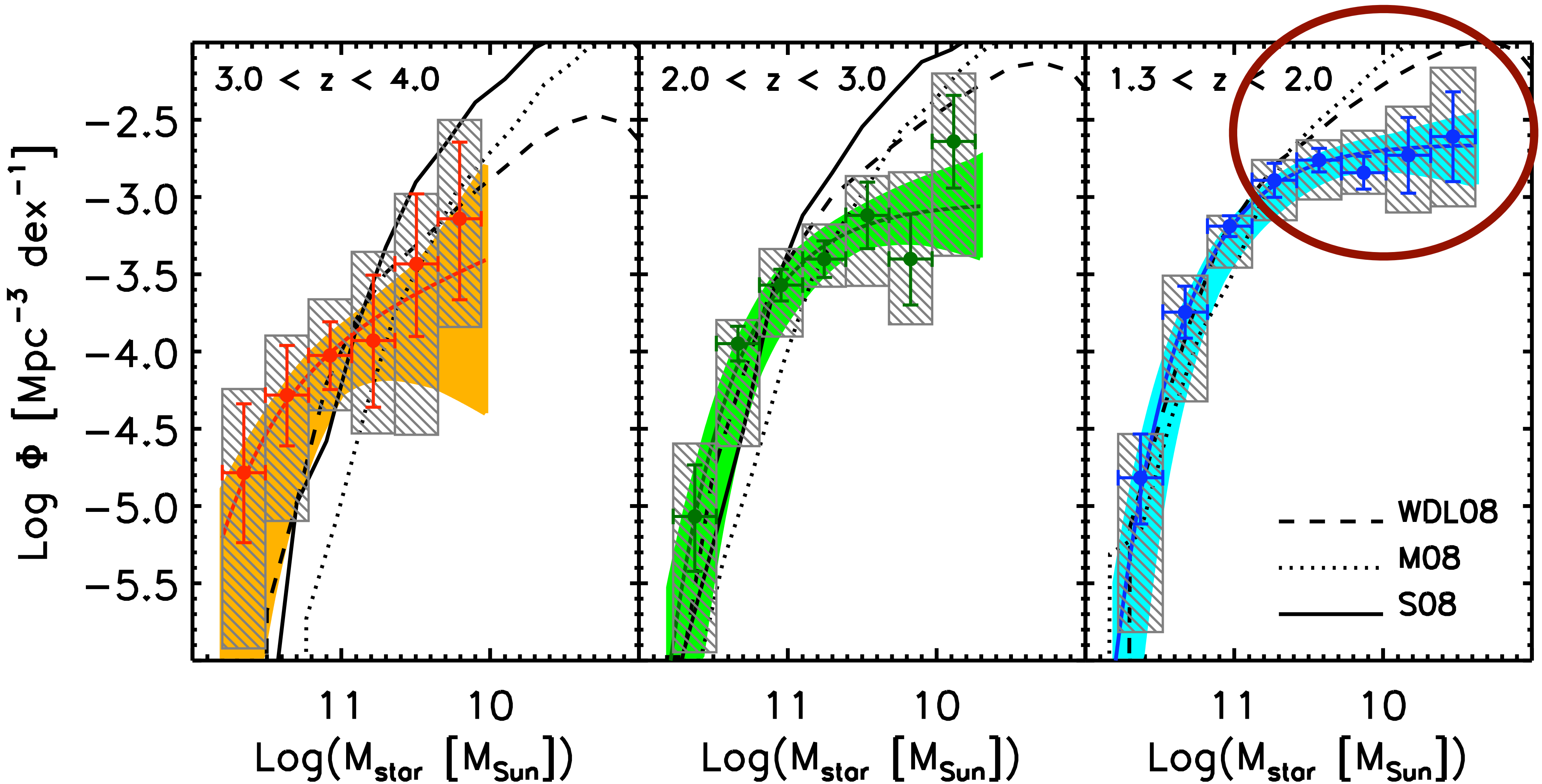
(DM et al., 2009)

Comparison with model predictions



(DM et al., 2009)

Comparison with model predictions



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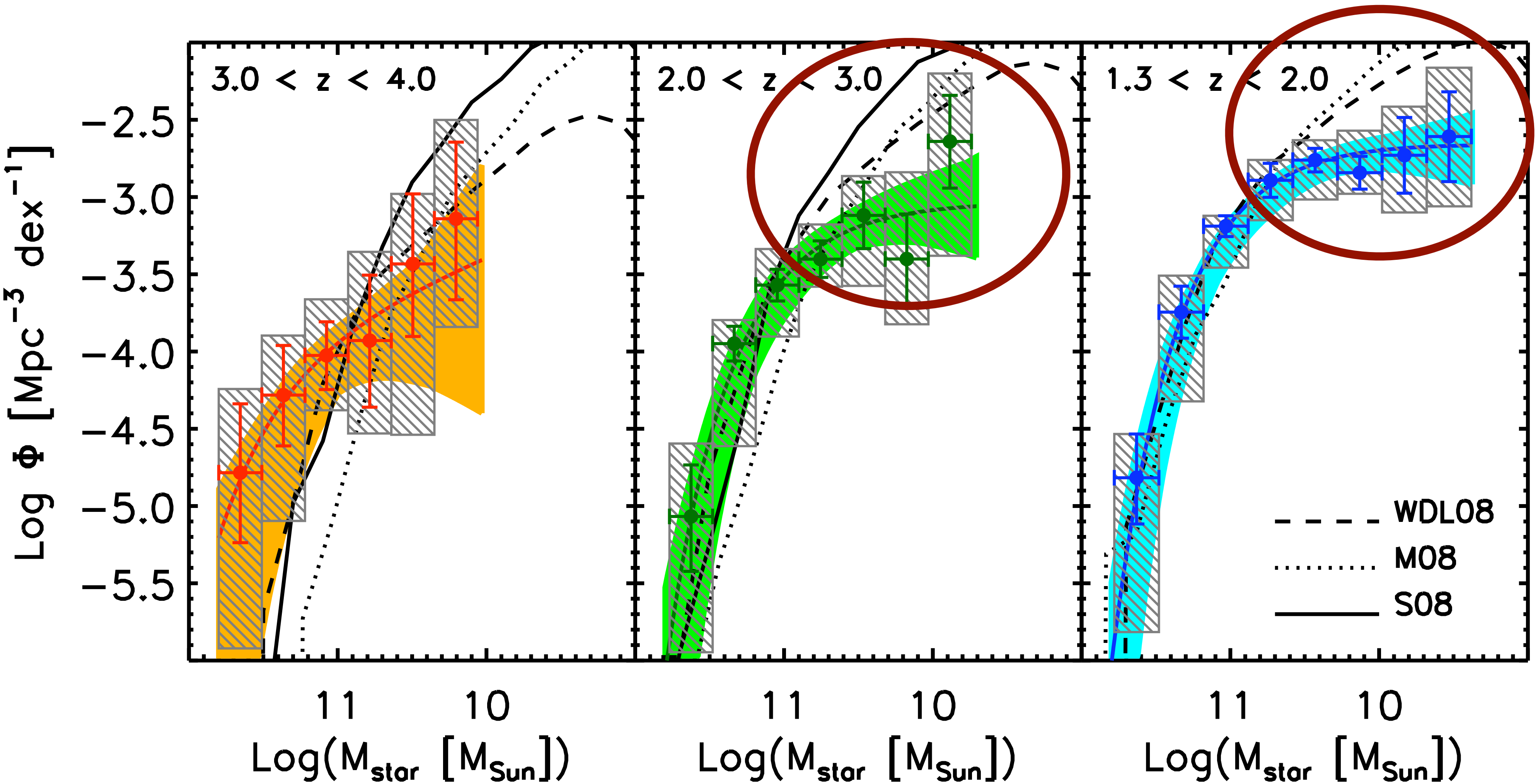

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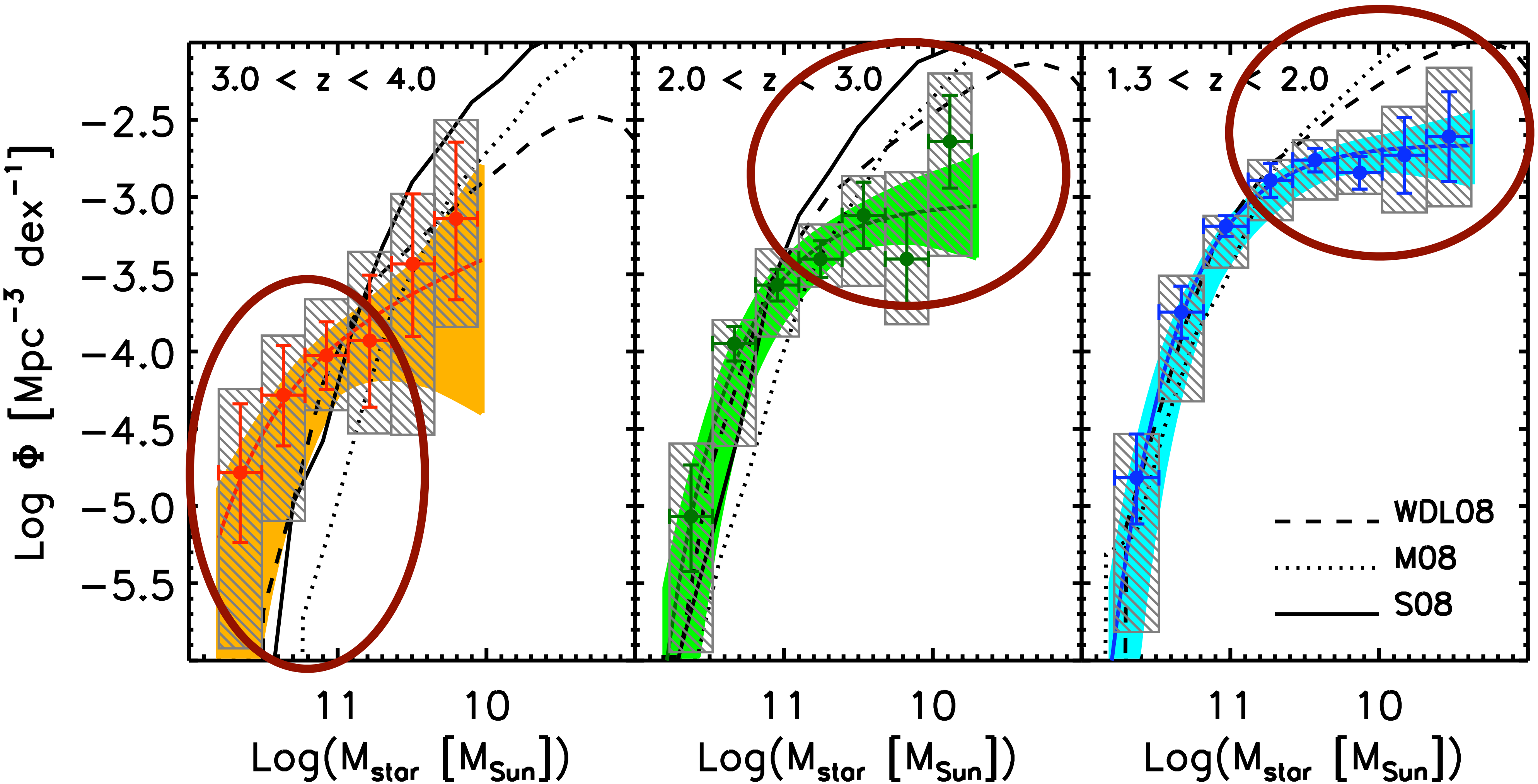

(DM et al., 2009)

Summary

- Presented the most accurate rest-frame optical luminosity functions and stellar mass functions of high-z galaxies from a K-selected sample constructed from the DEEP NIR MUSYC, FIRES and GOODS-CDFS surveys (DM et al., 2009)
- The mass density evolves by a factor of ~17 from z=4.0 and ~4 from z=1.3; the evolution is mostly driven by a change in normalization, rather than the slope or the characteristic stellar mass
- Evidence for mass-dependent evolution of the SMF are found: little evolution of the most massive galaxies, strong evolution in the number density of galaxies below M*
- Presented the first comprehensive analysis of the random and systematic errors affecting the SMF, including the effect of bottom-light IMFs on the derived SMF
- Comparison with predictions from theoretical models: the models fail in reproducing the observed evolution with cosmic time over the entire $0<z<4$ redshift range, especially for galaxies below M*; lack of massive galaxies at $z>3$ in the models

NEWFIRM Medium Band Survey

PI: van Dokkum; Marchesini, Labbe', Quadri, Brammer, Whitaker,
Kriek, Franx, Rudnick, Illingworth, Lee, Muzzin

- The current state of the art in photometric redshift estimate is the COSMOS field, with 30 optical+NIR+MIR filters

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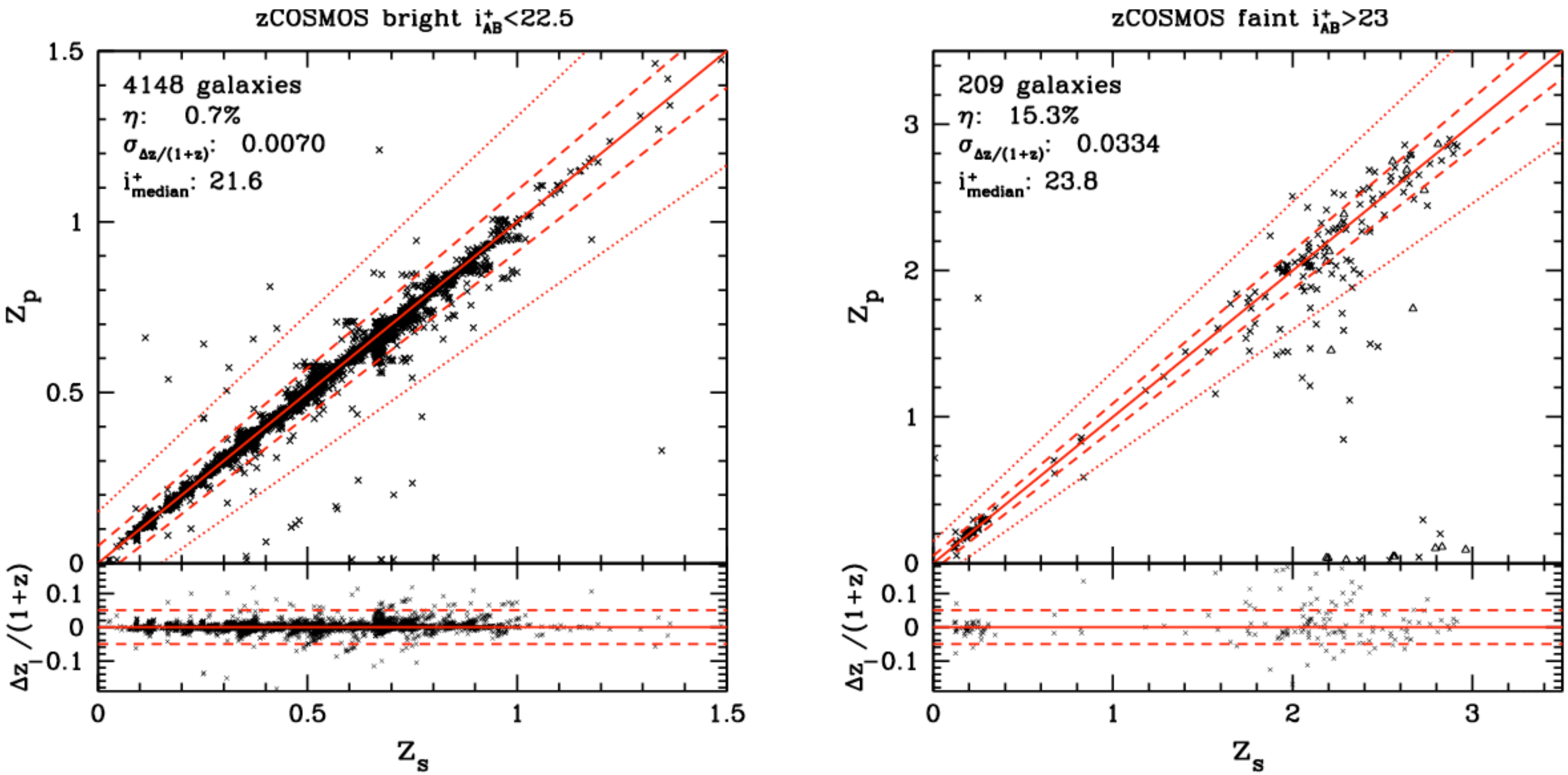

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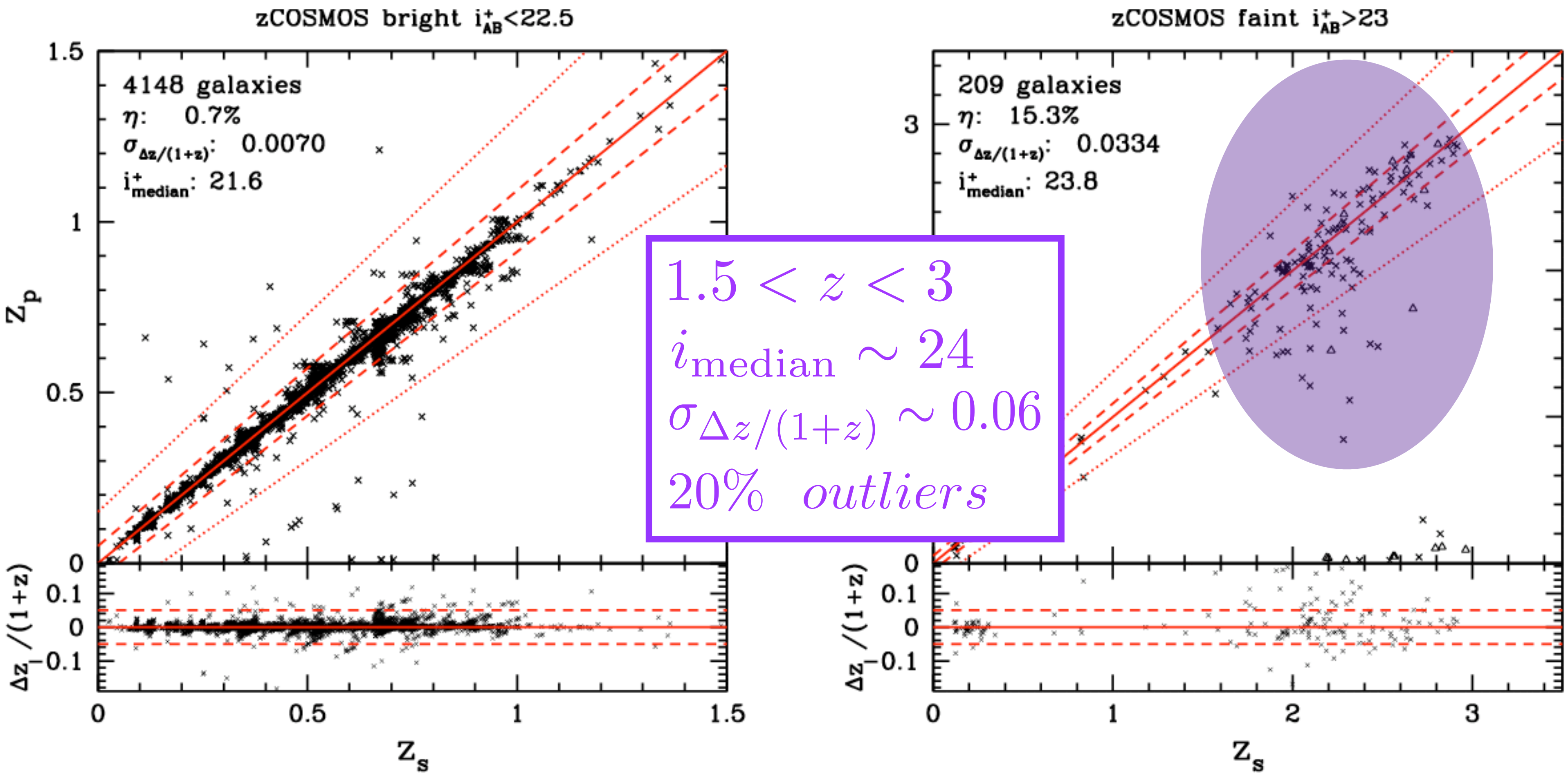

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- The current state of the art in photometric redshift estimate is the COSMOS field, with 30 optical+NIR+MIR filters
- This accuracy in photometric redshifts is not enough to study the colors, environment, and stellar populations of galaxies at $1.5<z<3.5$
- In order to extend these studies at $1.5<z<3.5$, accurate redshifts are required, to better than ~0.02 in $\Delta z/(1+z)$

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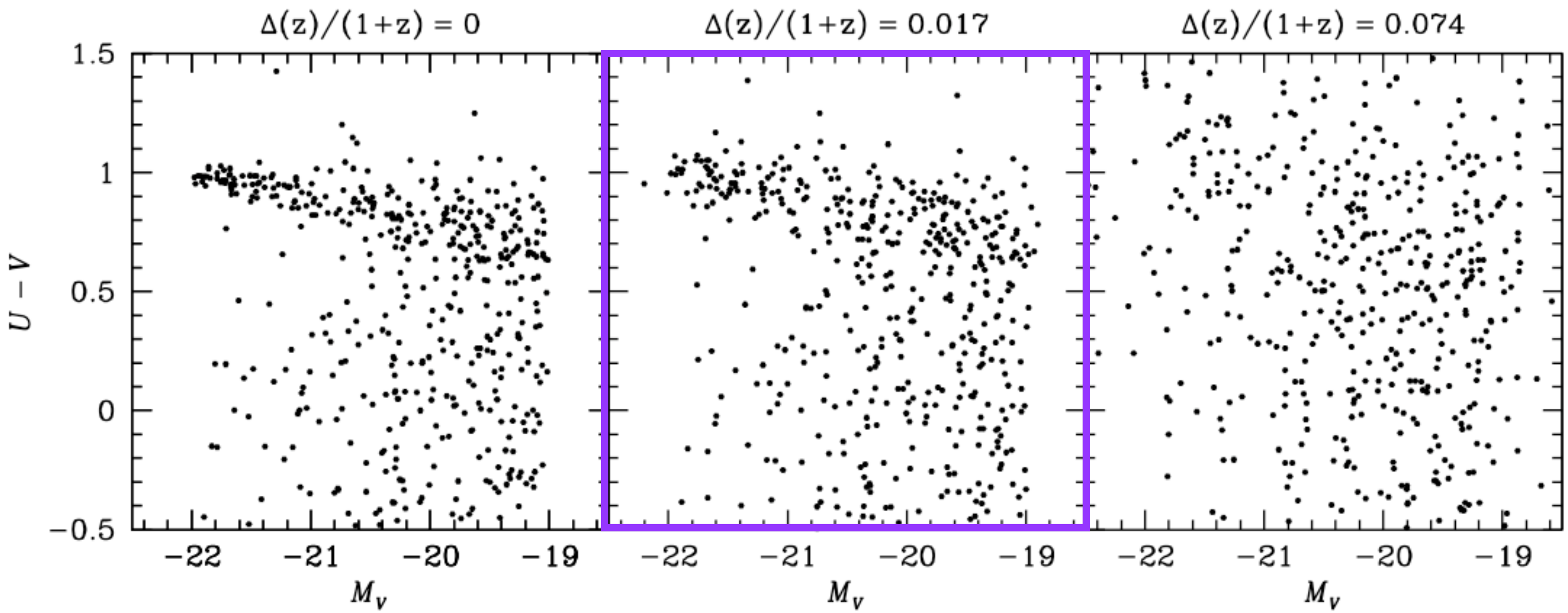

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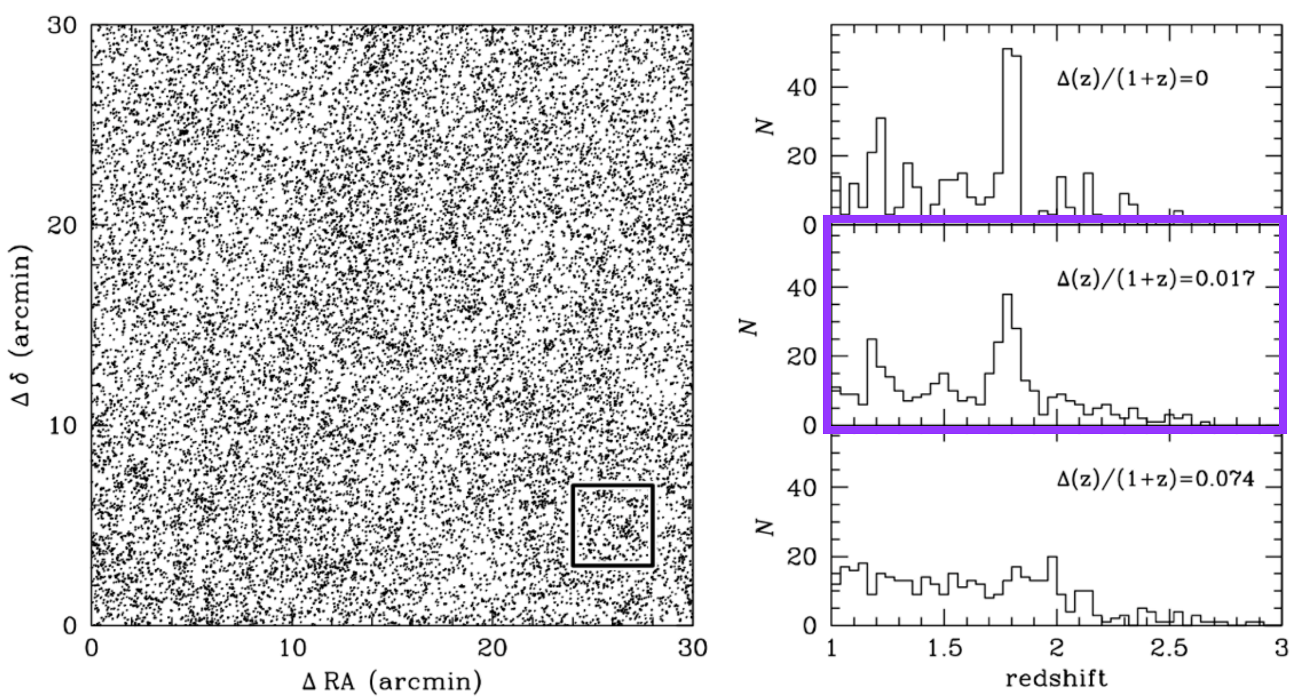

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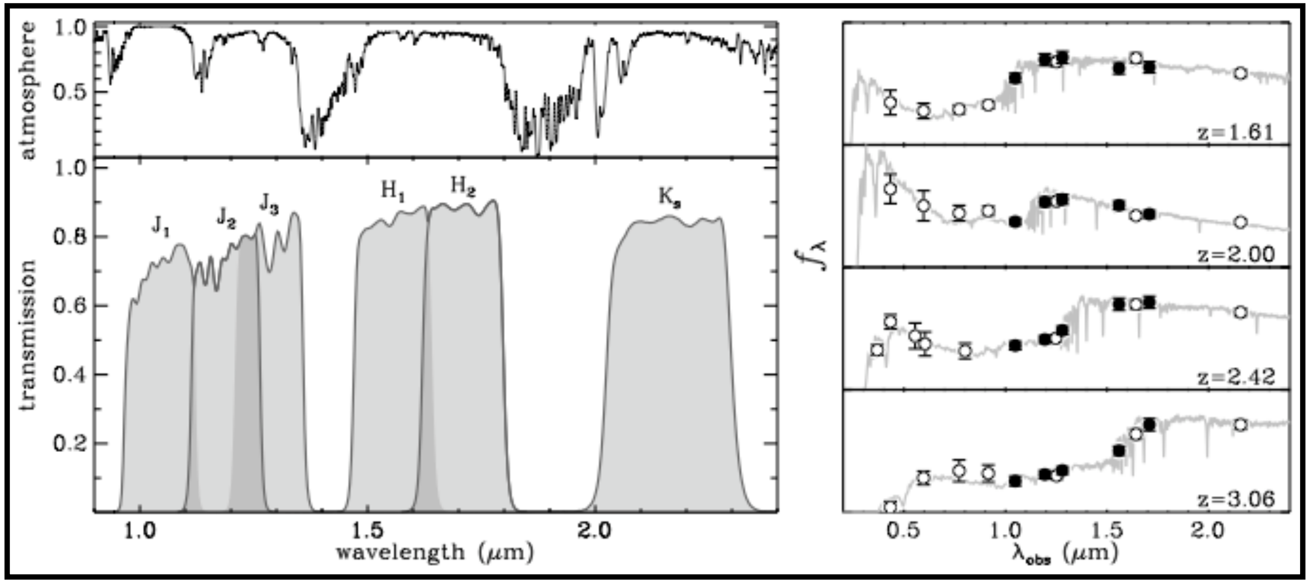
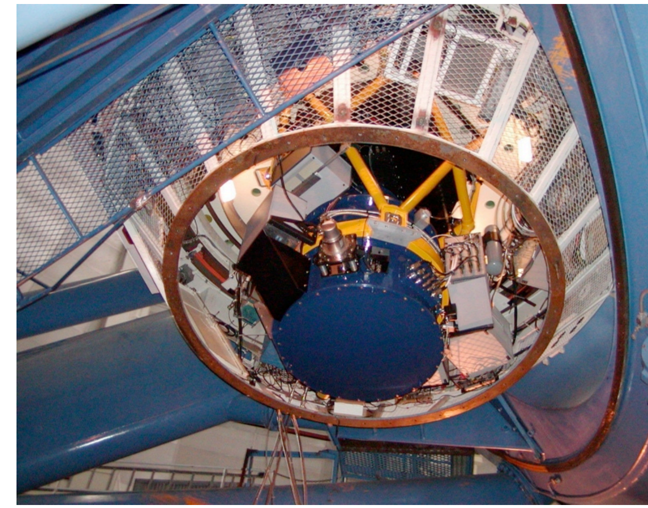




NEWFIRM on Mayall 4m

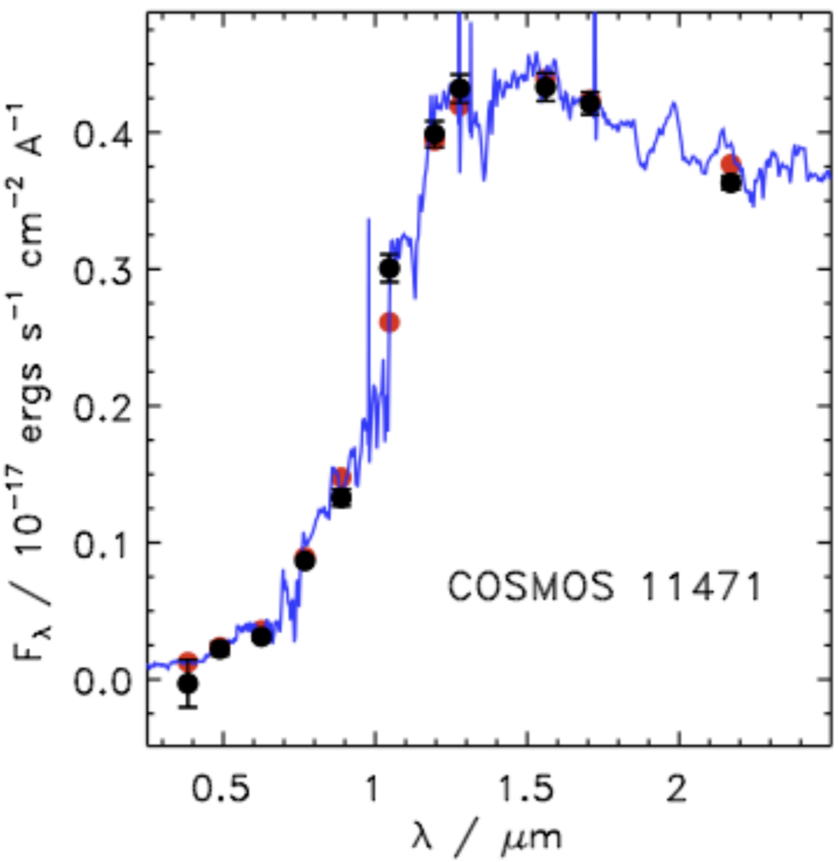
- designed and manufactured a custom set of 5 medium-bandwidth near-IR filters for NEWFIRM, providing "spectra" with a resolution of R~10 from 1-1.8 micron
- the filters pinpoint the location of the redshifted Balmer- or 4000A break from z=1.5 to z=3.5
- Goal: improve quality of photometric redshifts of K<21.5 galaxies at 1.5<z<3.5 to ~0.02

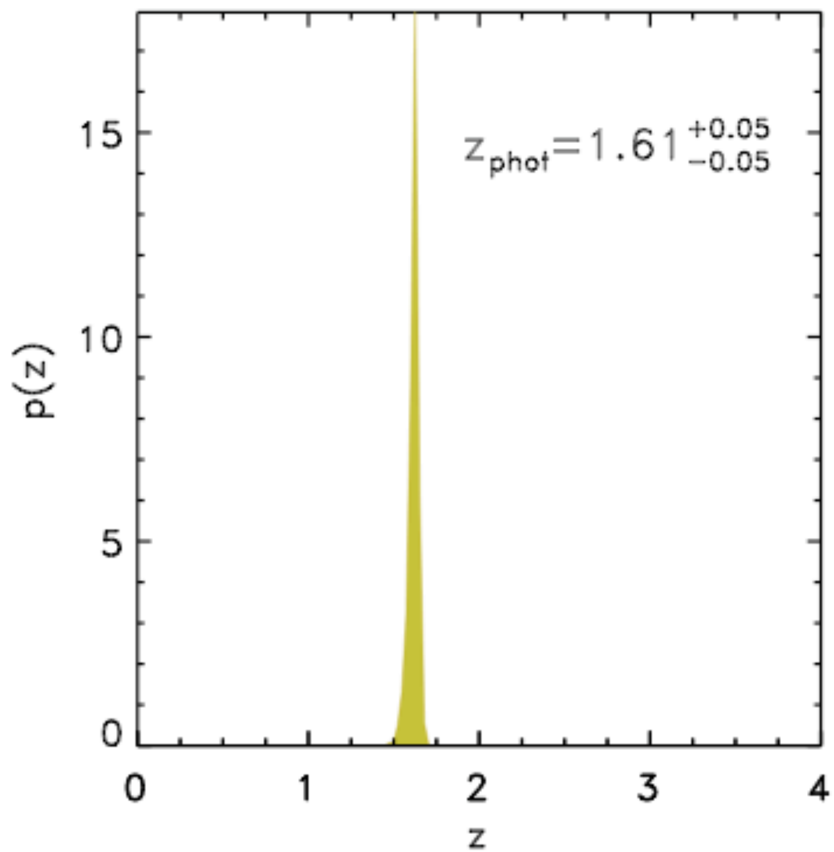
NEWFIRM Medium Band Survey

- 75 nights allocated through NOAO Survey Program in 08AB-09A
- Two 30′x30′, K<21.5 (Vega, 10σ), >8σ photometry in bands redward of Balmer break for most galaxies at 1.5<z<3.5
- Primary fields: COSMOS and AEGIS (wealth of ancillary data)
- Bad weather fields (e.g., SDSS 1030+05, CW1255, UKIDSS-UDS)
- ~2/3 already observed in 2008A/8B

Exiting science with the NMBS dataset

- Very accurate redshifts, rest-frame colors, luminosities, stellar masses; well-sampled SEDs, etc...

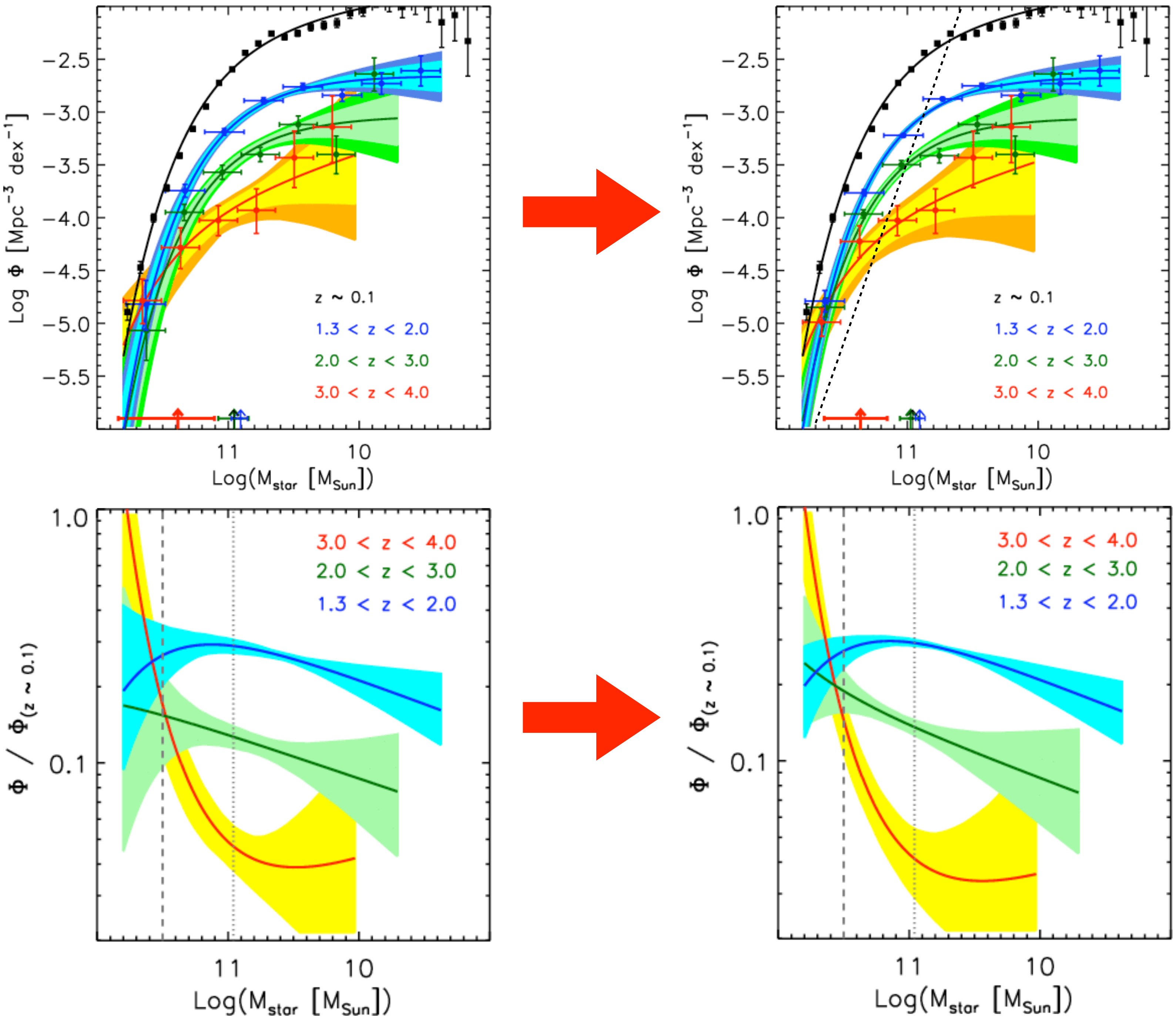




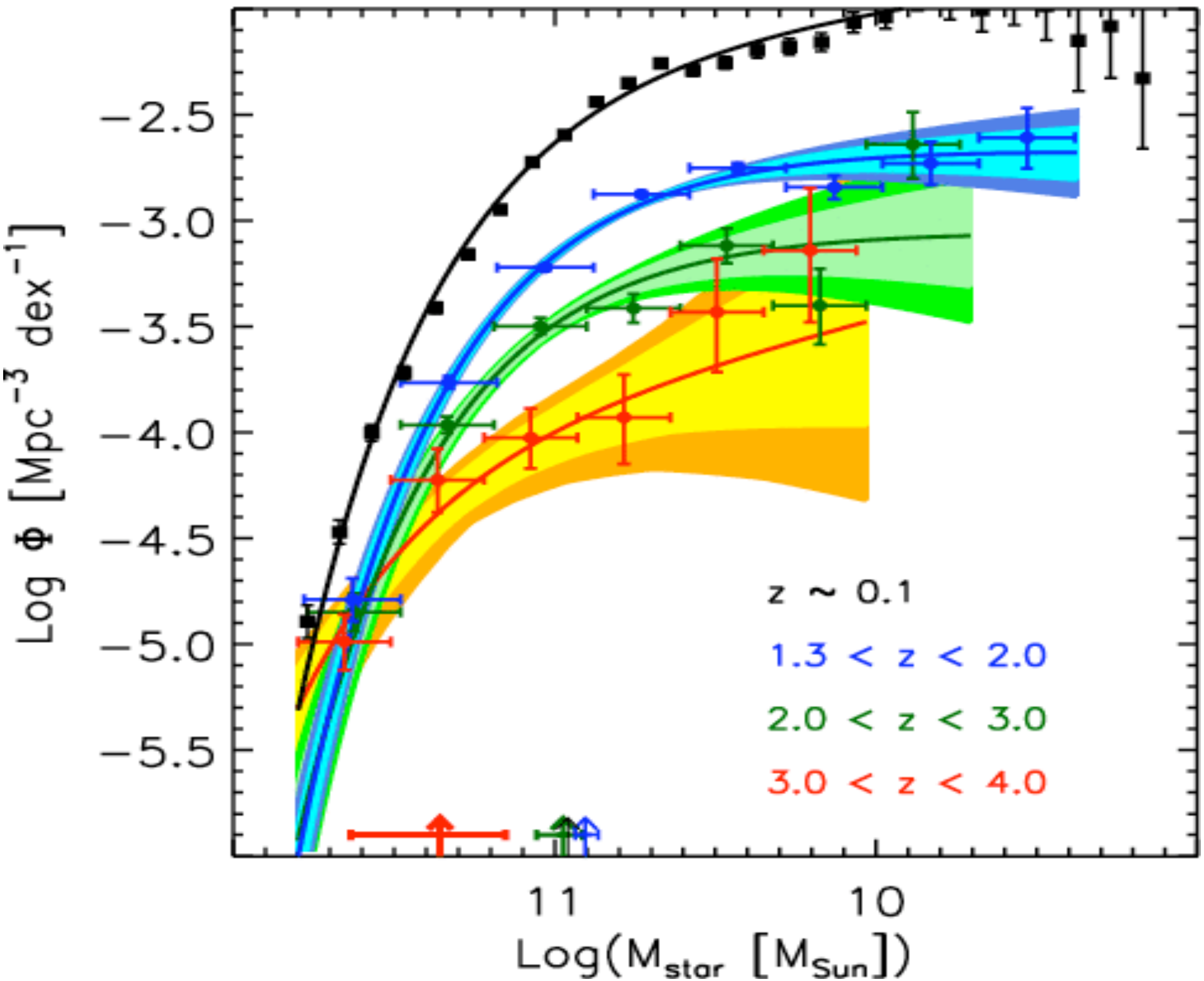
Exiting science with the NMBS dataset

- Very accurate redshifts, rest-frame colors, luminosities, stellar masses; well-sampled SEDs, etc...
- Study the evolution of the LF and SMF as function of redshift, galaxy type (spectral type, colors), and environment
  - ☑ significantly reduce cosmic variance
  - ☑ high-mass end probed much better, with x10 the current statistics
  - ☑ uncertainties due to photometric redshift errors significantly reduced, especially outliers
- Directly measure the build-up of the most massive galaxies from z~4

The SMF of galaxies at 1.3<z<4.0

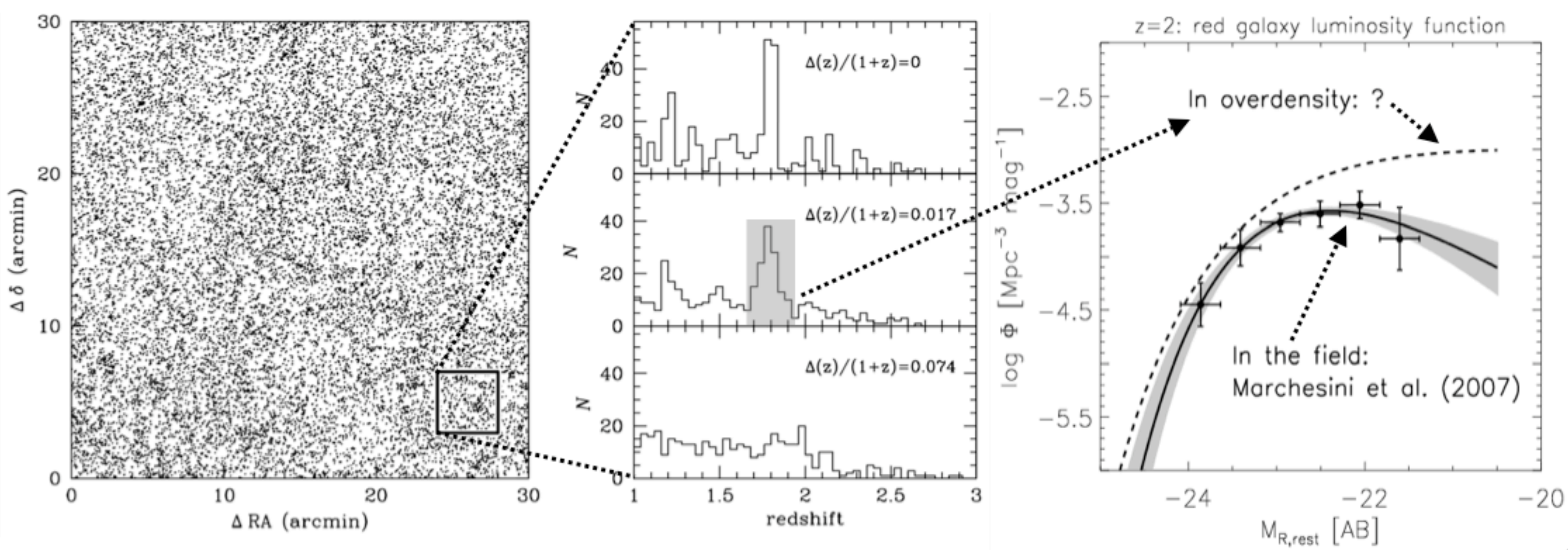


The SMF of galaxies at 1.3<z<4.0



Future science with the NMBS dataset

- Very accurate redshifts, rest-frame colors, luminosities, stellar masses; well-sampled SEDs, etc...
- Study the evolution of the LF and SMF as function of redshift, galaxy type (spectral type, colors), and environment
- Directly measure the build-up of the most massive galaxies from z~4
- Directly witness the growth of the red sequence from z=3
- Measure, for the first time, the effect of environment on the type-dependent LFs at z>1



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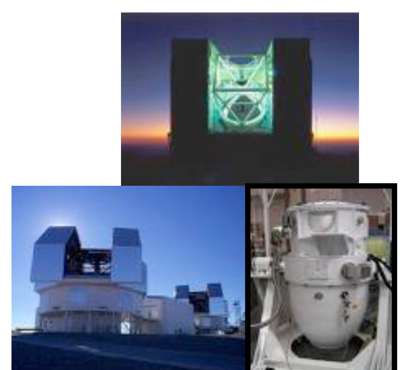
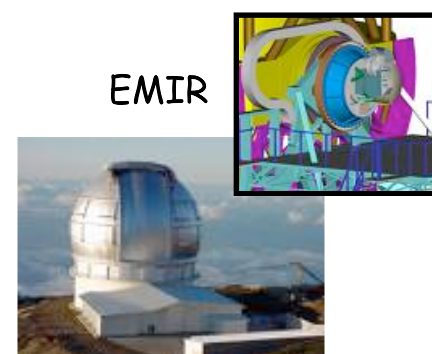
- NIR spectroscopic follow-up studies with multi-object spectrographs (e.g., MOSFIRE on Keck, FLAMINGOS-2 on Gemini, MMIRS on MMT/Magellan, EMIR on GTC)


MOSFIRE


Flamingos-2


MMIRS


EMIR

Future science with the NMBS dataset

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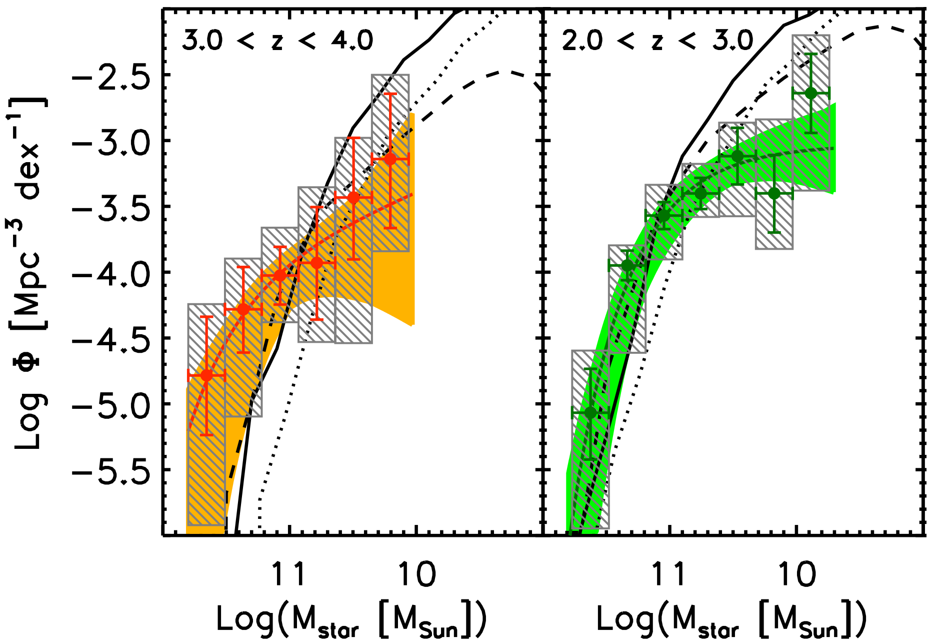
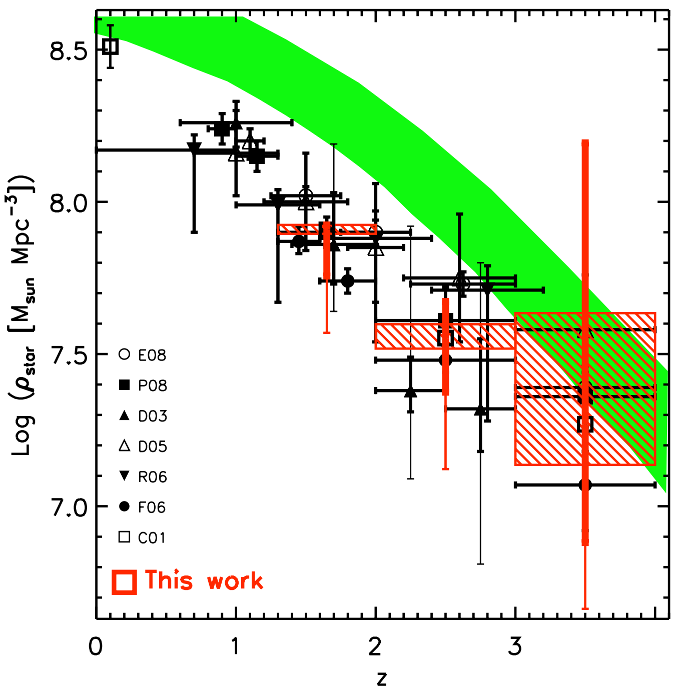
- NIR spectroscopic follow-up studies with multi-object spectrographs (e.g., MOSFIRE on Keck, FLAMINGOS-2 on Gemini, MMIRS on MMT/Magellan, EMIR on GTC)
- High-resolution near-IR imaging to study the evolution with cosmic time of the size of massive galaxies (e.g., WHIRC on WIYN)

Constrain the low-mass end of the high-z SMF





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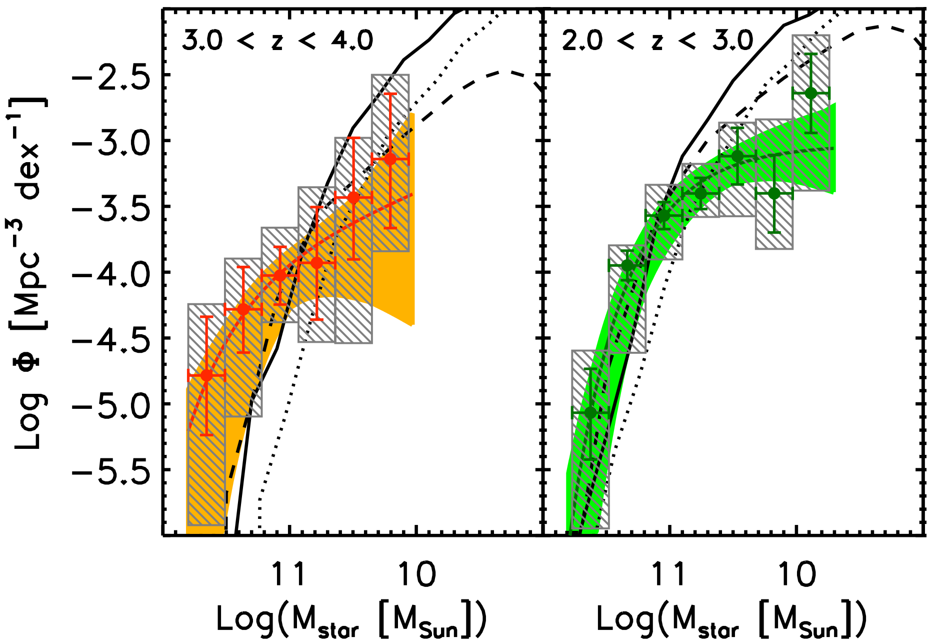
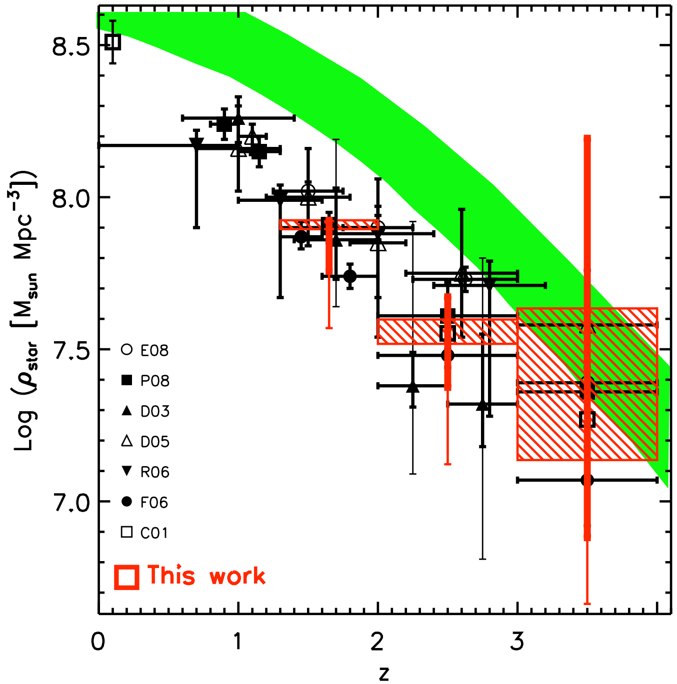
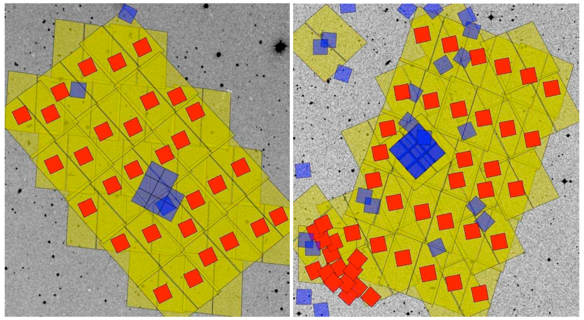
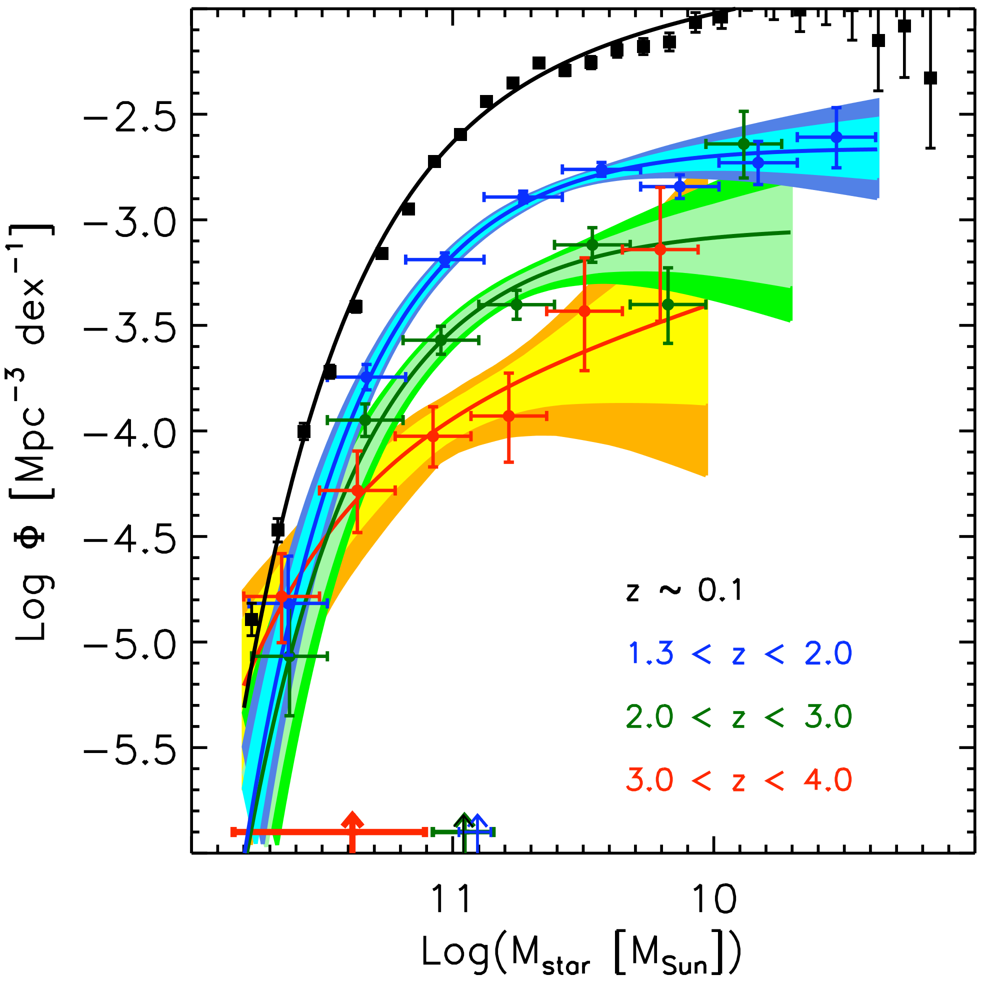




- Accepted HST proposal (HST-AR 11764; PI: Marchesini) to exploit ~73 arcmin^2 ultra-deep optical and NIR imaging in the GOODS fields



Self-consistent evolving IMF



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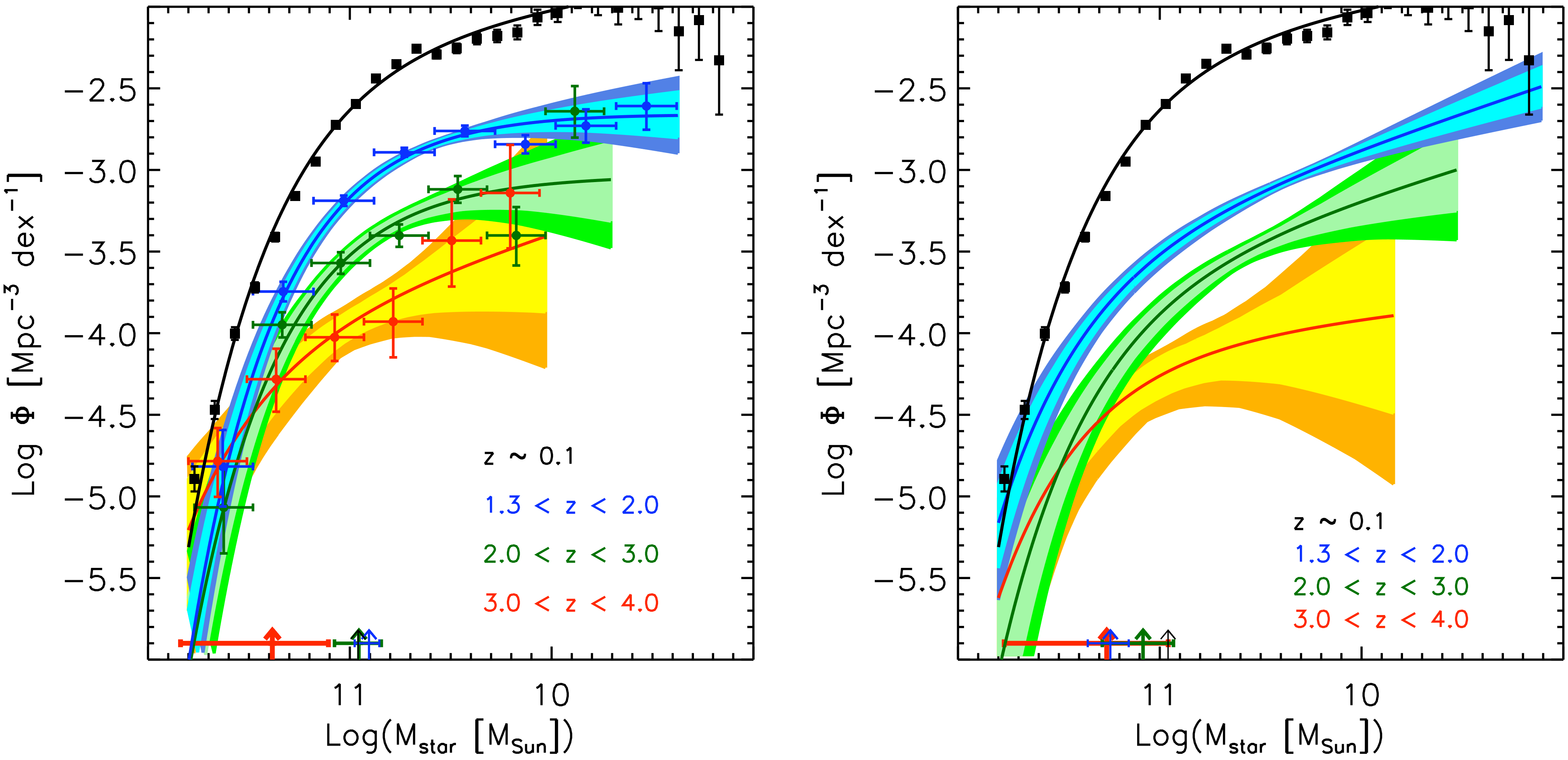

(Marchesini & Muzzin, in prep.)

COSMOLOGY MARCHES ON


COSMOLOGY MARCHES ON
Where the hell did it all come from?
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S. Harris

THANK YOU!