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Department of Astronomy, Tsinghua University

The Measurements of Galaxy Abundance and Clustering at $0 < z < 2$

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Collaboration workshop on cosmology and galaxy formation, Shanghai/Suzhou, 2023.6.21

Outline

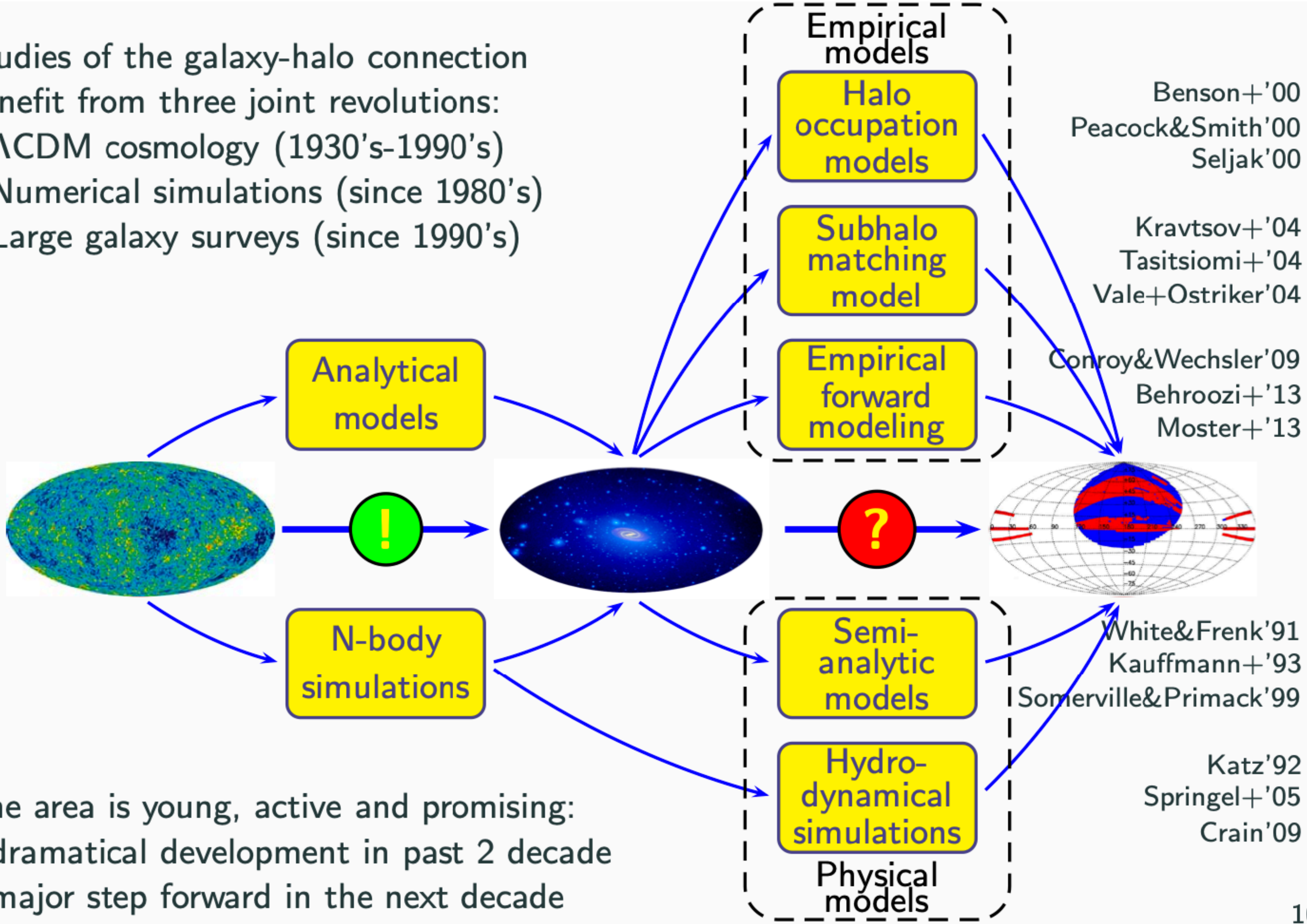
1. Introduction
2. Conditional luminosity function with the galaxy imaging survey at low-z.

   (Meng, J., Li, C., Mo, H. J., et al. 2023, ApJ, 944, 75)
3. Measuring galaxy abundance and clustering at high redshift from incomplete spectroscopic data: test on mocks. (Meng, J., Li, C., Mo, H. J., et al. submitted to ApJ, arXiv: 2008.13733)
4. Summary

1. Woking pipeline for galaxy formation in ΛCDM universe

Studies of the galaxy-halo connection benefit from three joint revolutions:

- ΛCDM cosmology (1930's-1990's)
- Numerical simulations (since 1980's)
- Large galaxy surveys (since 1990's)



The area is young, active and promising:

- dramatical development in past 2 decade
- major step forward in the next decade

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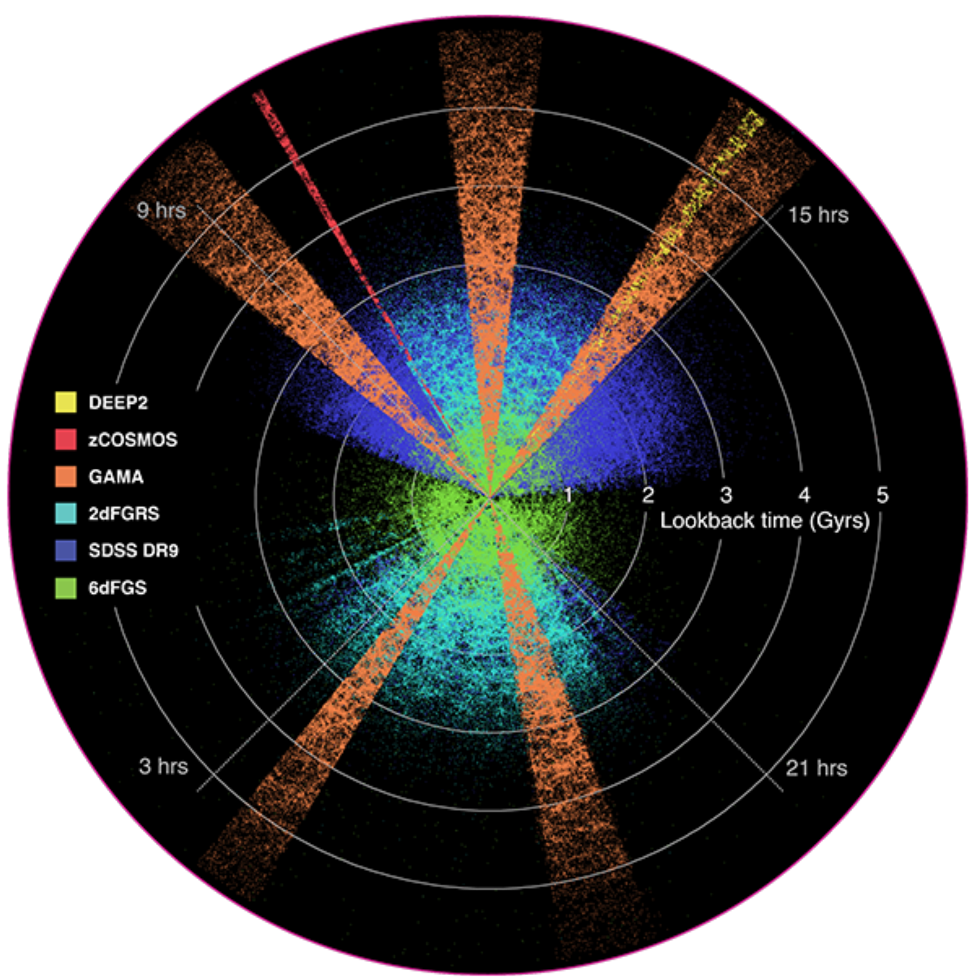
Slide from Prof. Li

1. Galaxy spectroscopic survey and image survey

Spectroscopic survey:

Low-z: 2dFGRS, SDSS (r < 17.77, 1%$M_{*,MW}$), GAMA…

High-z: DEEP2, VVDS, zCOSMOS, VIPERS, PFS (future), MOONS (future)…

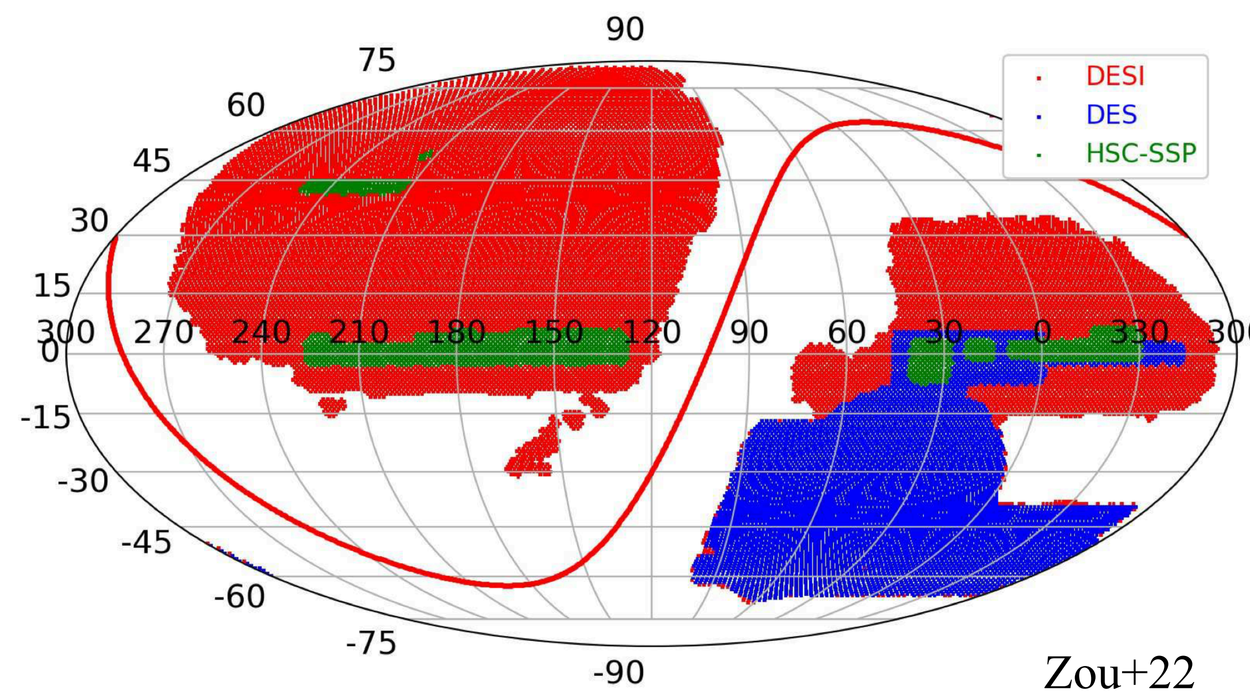


Credit: Simon Driver and the GAMA team.
https://www.icrar.org/our-research/science-program/

Image survey:

DESI legacy survey (r < 23.5, 0.01%$M_{*,MW}$),

DES, HSC SSP, KiDS, CSST (future), Euclid (future), LSST (future)…



Shortcoming:

- Low-z redshift surveys are still shallow. —Combine deep image data
- High-z data are lacking and incomplete. —Large scale survey in the future.

1. How to study the halo-galaxy connection

Statistical Analysis of the survey (SPACE)

- **S**caling relations of galaxy **P**roperties: $M_* - \sigma$, Tully-Fisher relation, Faber-Jackson relation…
- **A**bundance: (Conditional) Galaxy stellar mass/luminosity function…
- **C**lustering: 2-point correlation function, 3-point correlation function…
- **E**volution of the above relations and functions.

Models for Halo-galaxy Connection

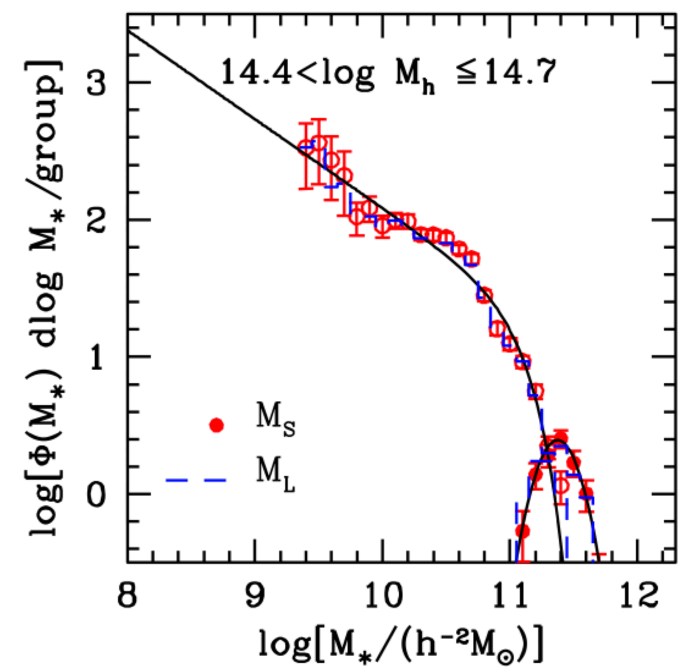
- Statistical model: Abundance Matching, Halo Occupation Distribution (HOD).
- Semi-analytical model.
- Empirical model.
- Hydrodynamical simulation.

We need mock surveys!

- Test the method for the statistical analysis and quantify the systematic errors.
- Compare the models and observations, different models fairly.
- Make the predictions for the survey in the future.

2. The conditional luminosity function at low redshift

Conditional luminosity function $\Phi\left(L \mid M_{\mathrm{h}}\right)$

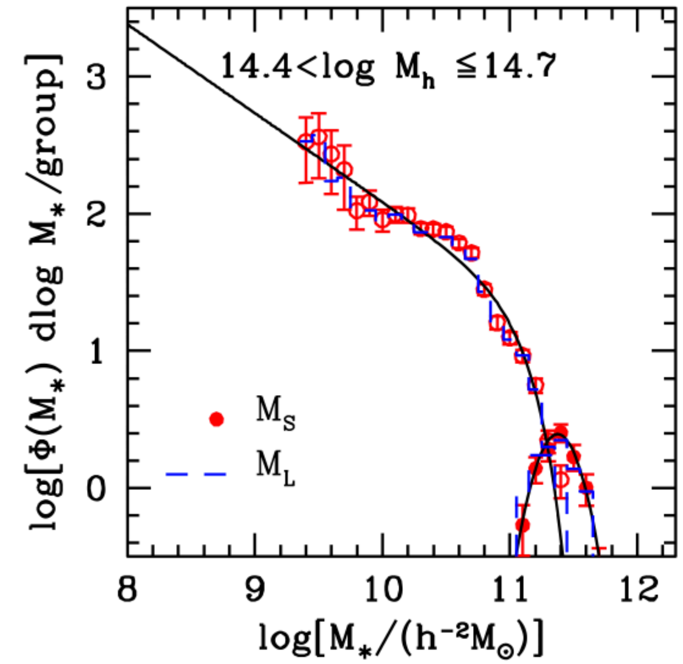


r<17.77

Yang+09

2. The conditional luminosity function at low redshift

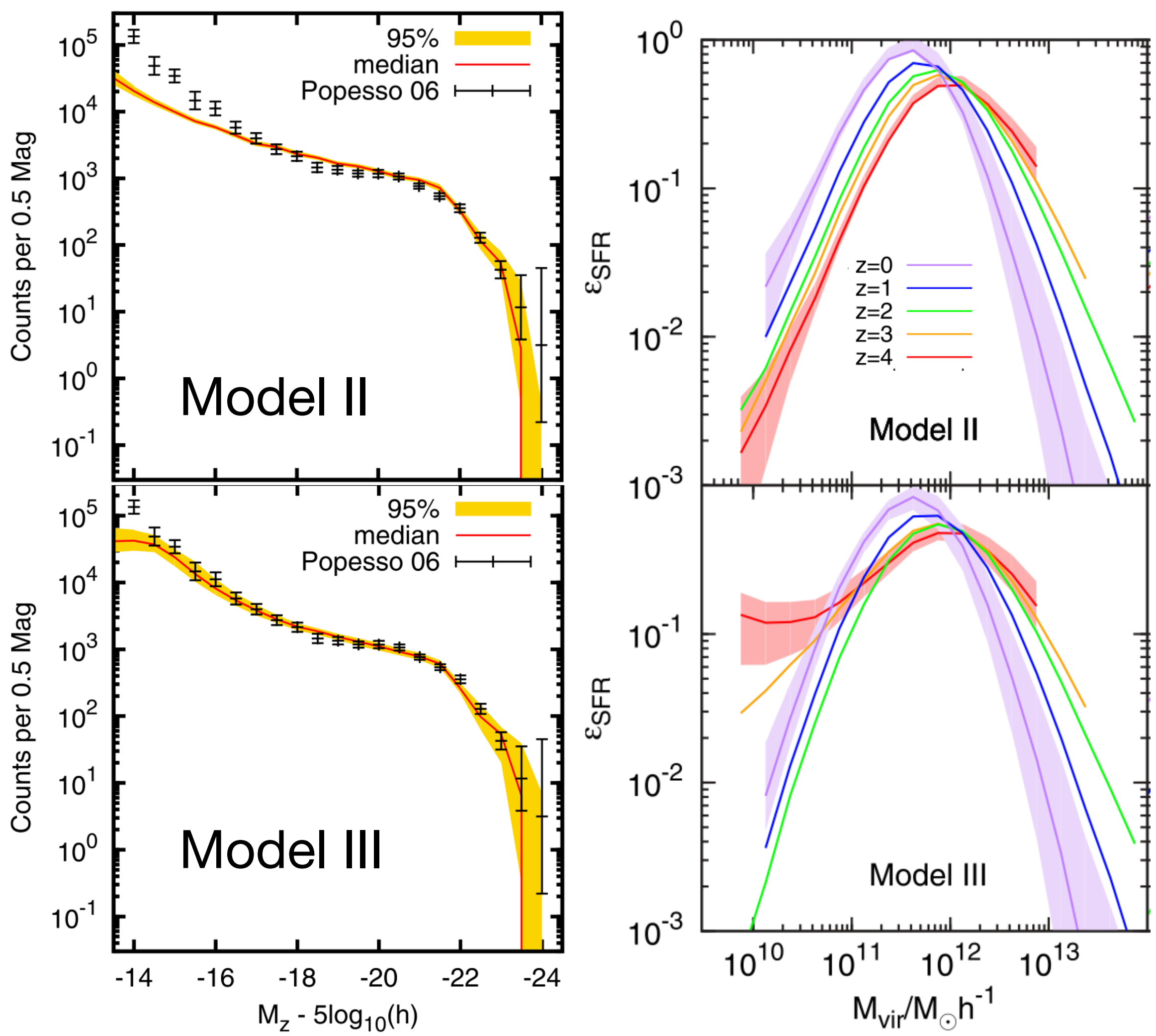
Conditional luminosity function $\Phi\left(L \mid M_{\rm h}\right)$



r<17.77

Yang+09

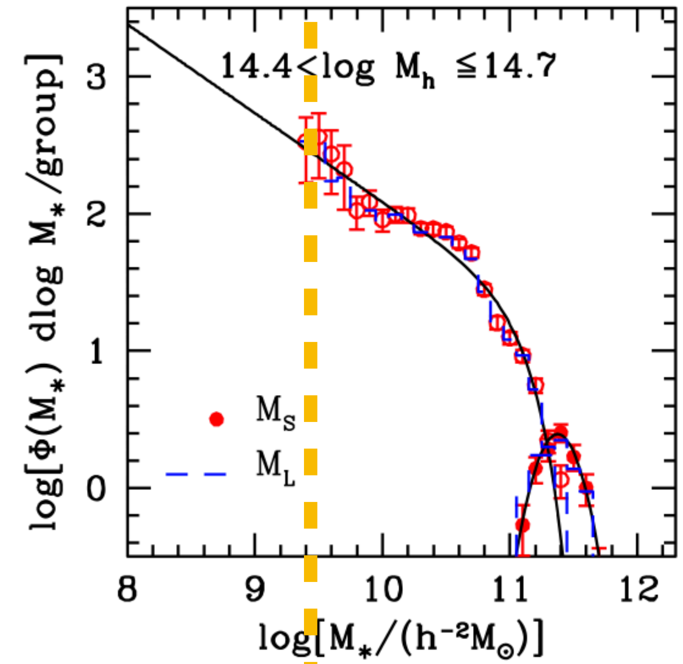
Faint-end slope α ?



Lu+14

2. The conditional luminosity function at low redshift

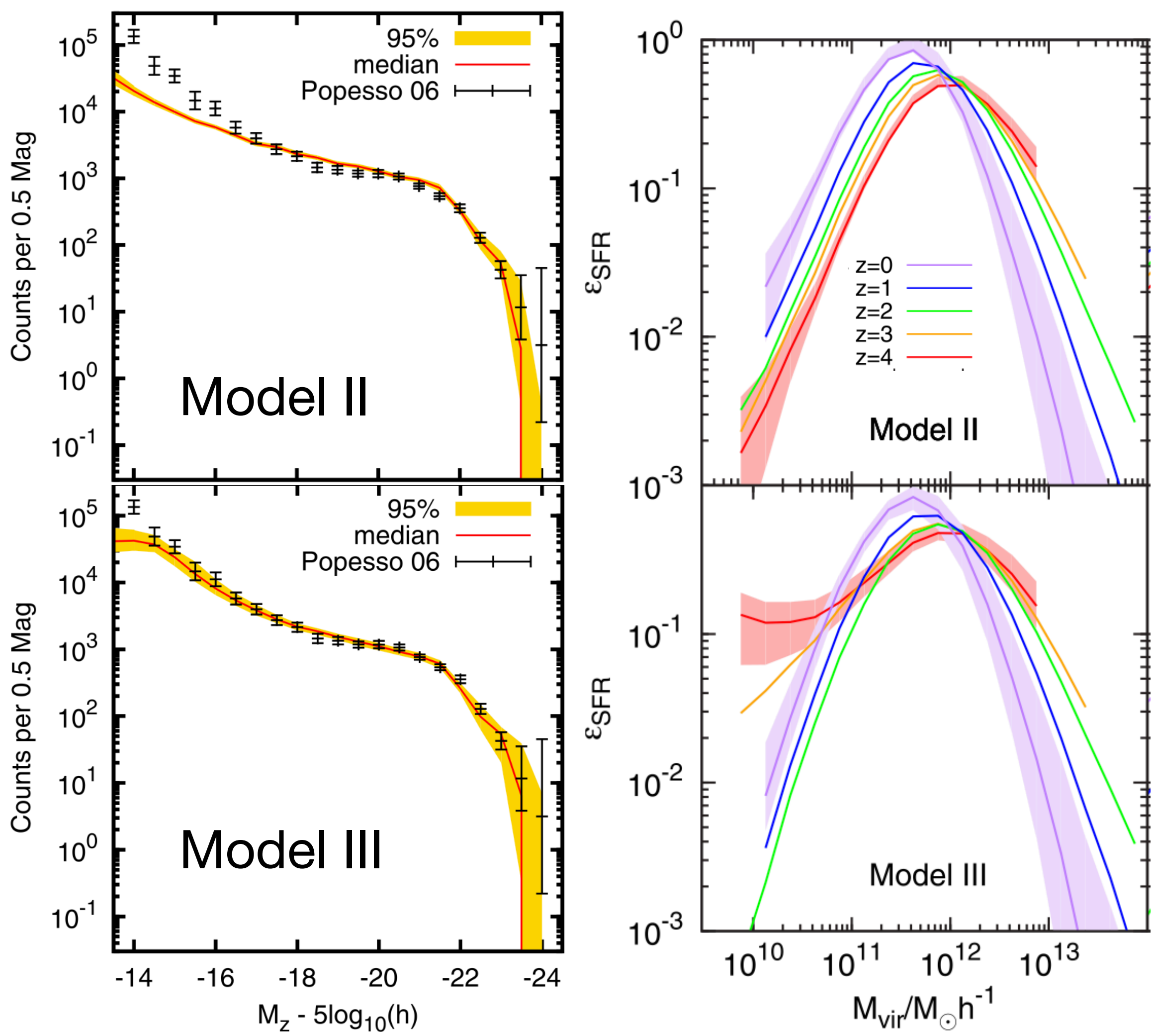
Conditional luminosity function $\Phi\left(L \mid M_{\mathrm{h}}\right)$



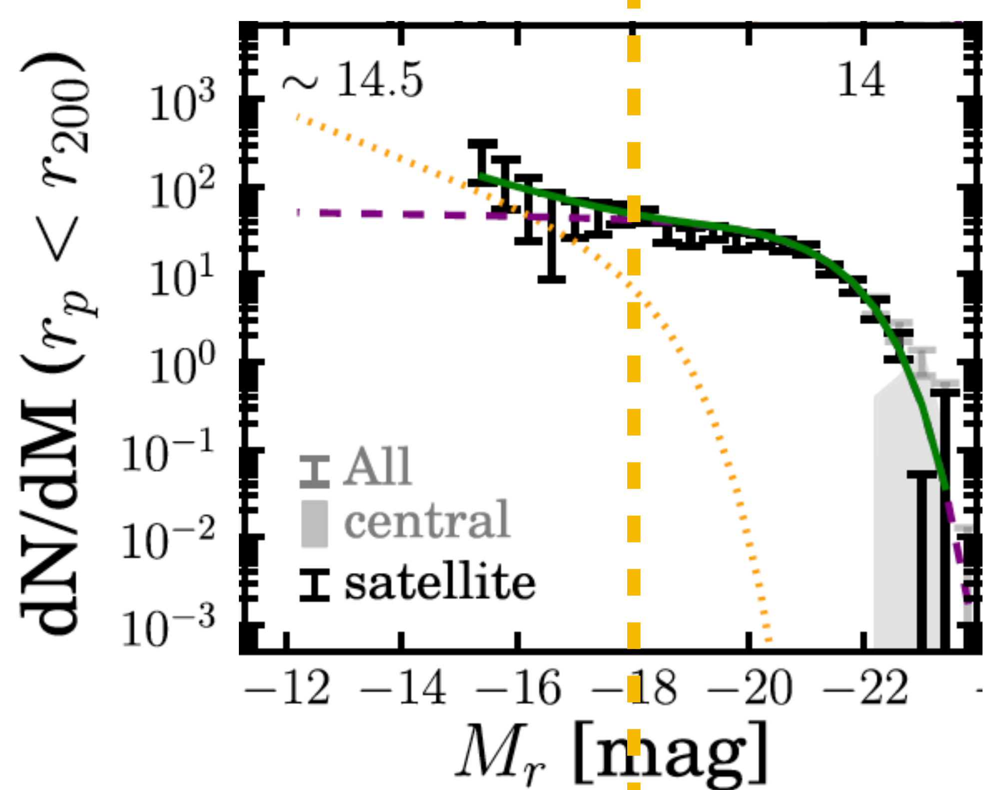
r<17.77

Yang+09

Faint-end slope α ?



Lu+14



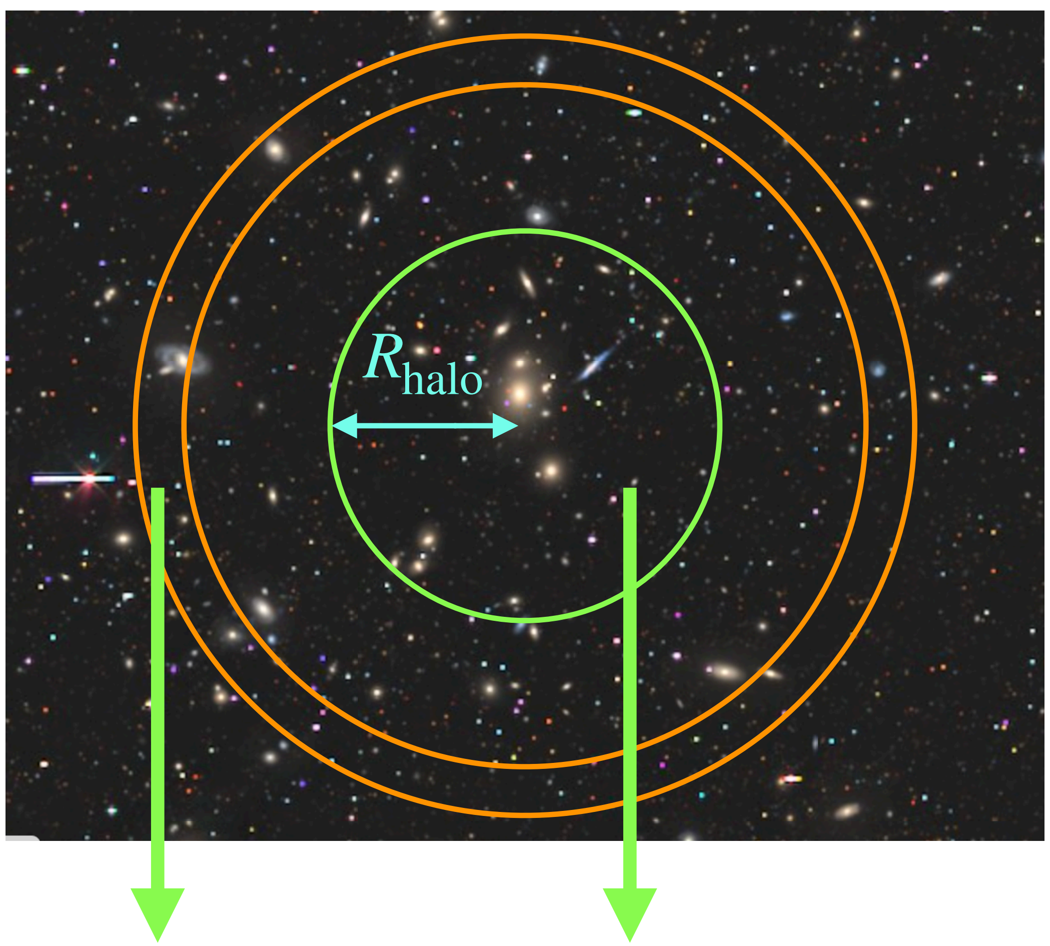
r<21

Lan+16

2. The method to identify member galaxies from imaging data

In our work: SDSS group catalog (Yang+07) + DESI Legacy Imaging Survey DR9 (r < 23).

Projection effect



$\Phi_{\rm bkg,i}(\vec{\mathbf{q}} \mid M_{\rm h})$ $\Phi_{\rm grp,i}(\vec{\mathbf{q}} \mid M_{\rm h})$

$\vec{\mathbf{q}}$: galaxy property vector; estimated at group redshift z_i

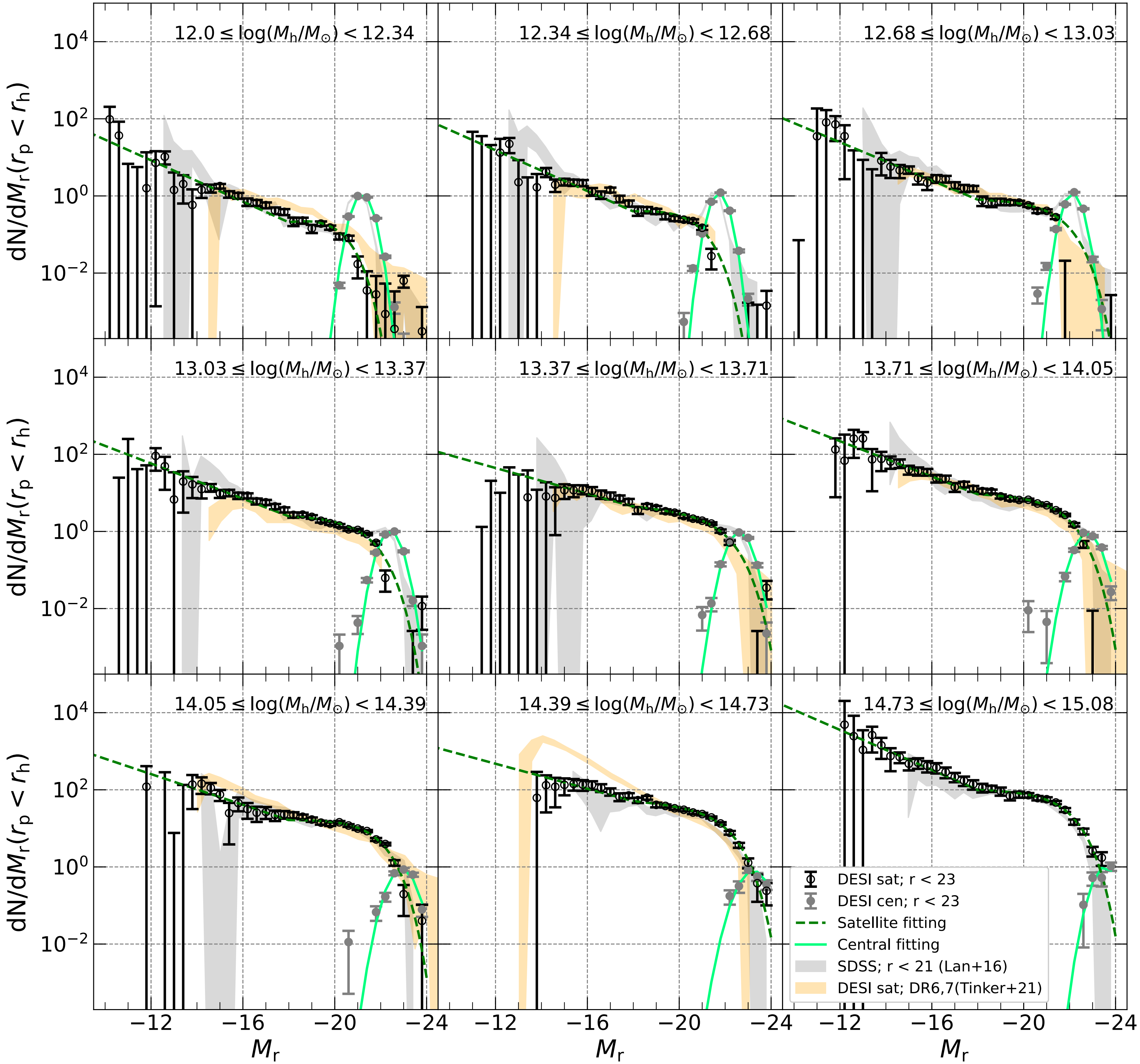
- **Conditional distribution function:**

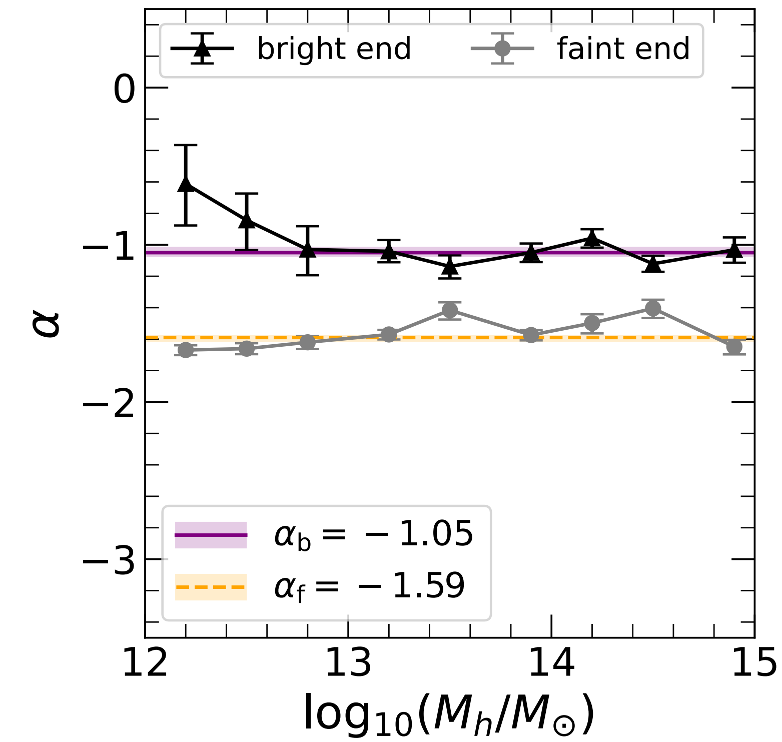
$$\Phi(\vec{\mathbf{q}} \mid M_{\rm h}) = \left\langle \Phi_{\rm grp,i}(\vec{\mathbf{q}} \mid M_{\rm h}) - f_{\rm A,i} \times \Phi_{\rm bkg,i}(\vec{\mathbf{q}} \mid M_{\rm h}) \right\rangle_{\rm i}$$

- **K-correction for photometric galaxies:**

Use the nearest neighbor in the observed (g-r)-(r-z)-redshift space from NYU-VAGC.

2. CLFs measured down to $M_{\rm r} \sim -10$, 2 mag deeper than previous work



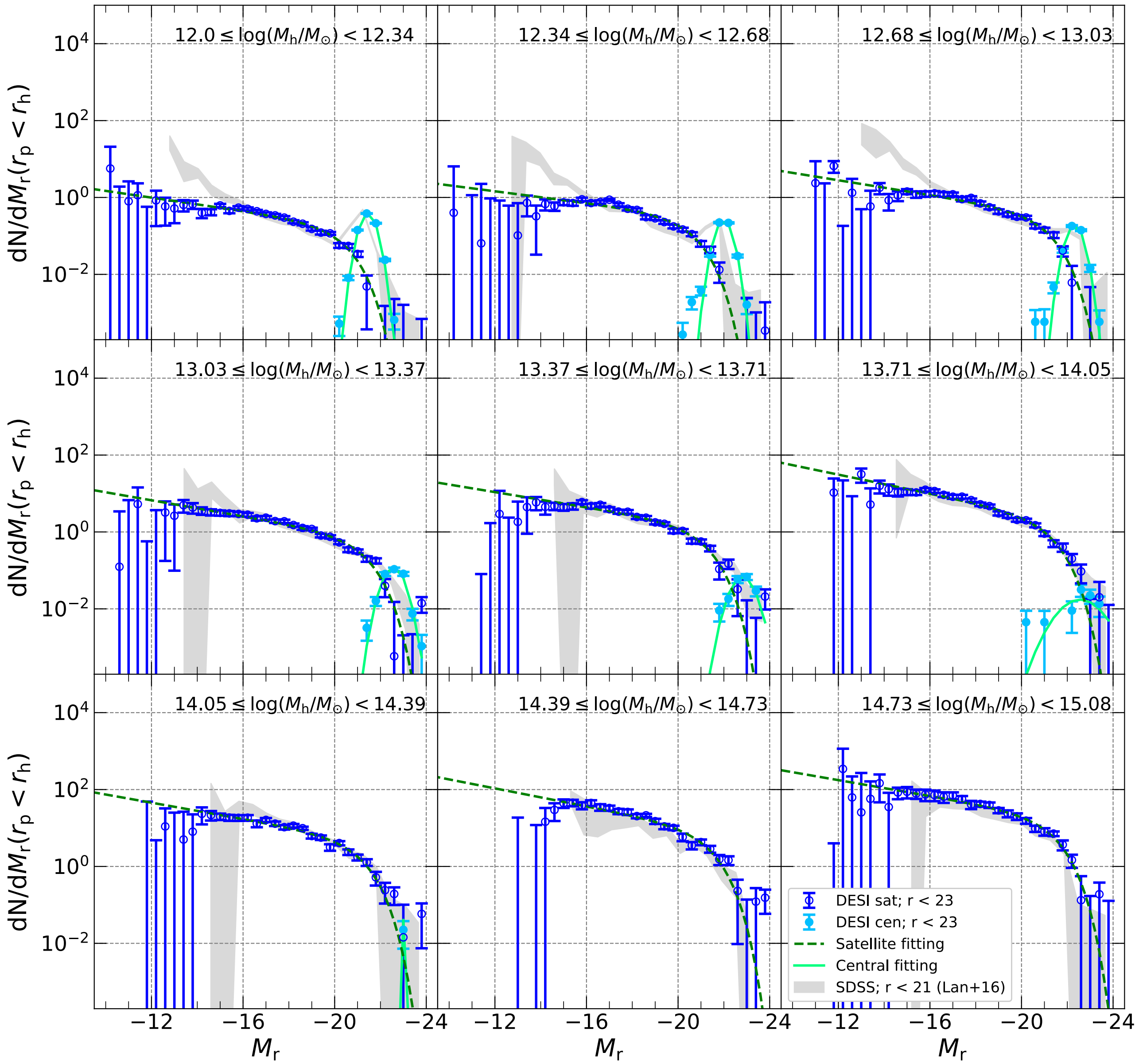


Faint-end slope $\alpha \sim -1.6$

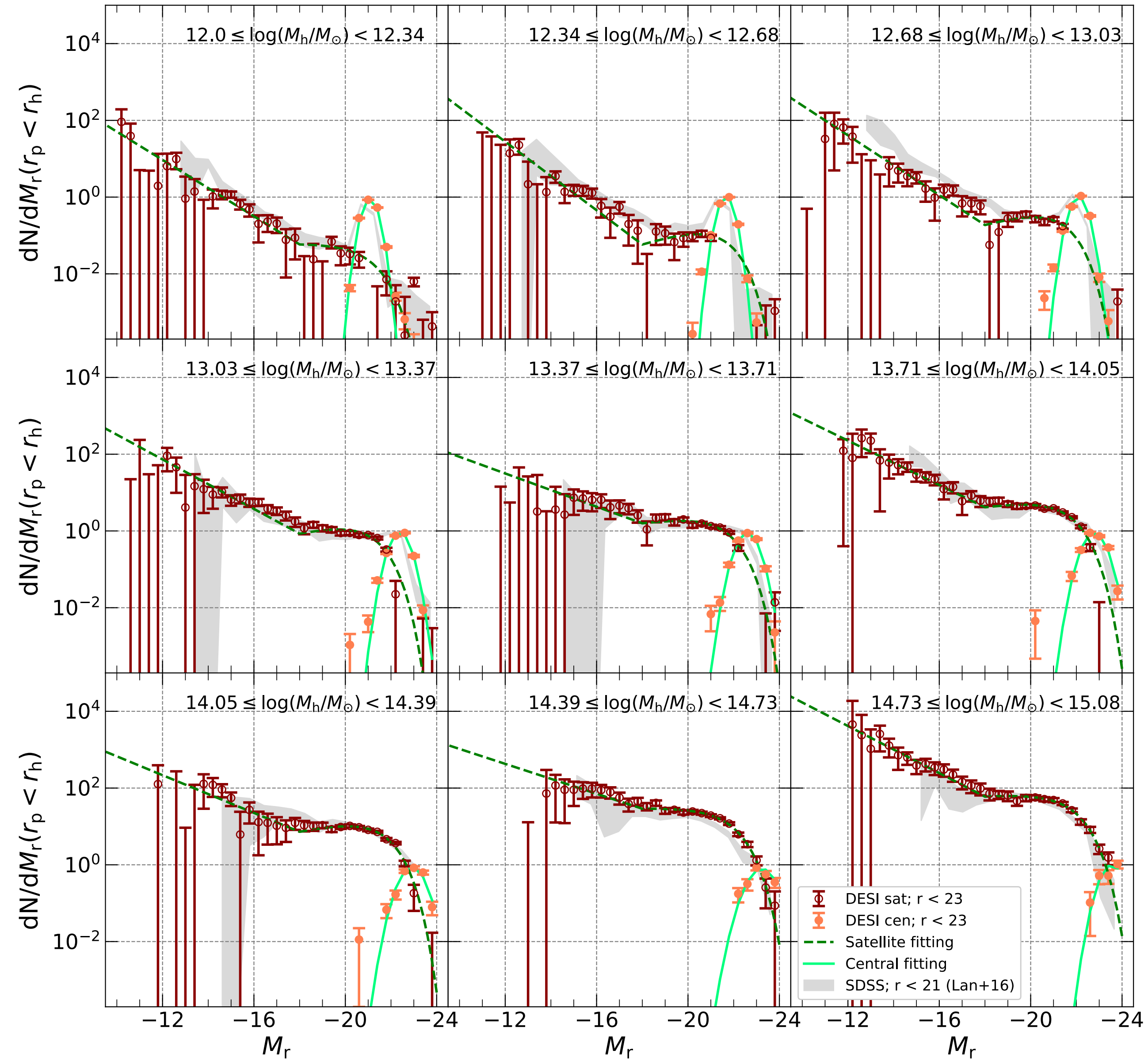
- Independent on halo mass;
- Comparable to general galaxy sample, e.g. SDSS LF (Blanton+05a; Li+22), SDSS GSMF (Chen+19) and GAMA GSMF (Driver+22).

2. Old satellites present steep upturn at faint end

Blue (young) galaxies, $\alpha \approx -1.25$

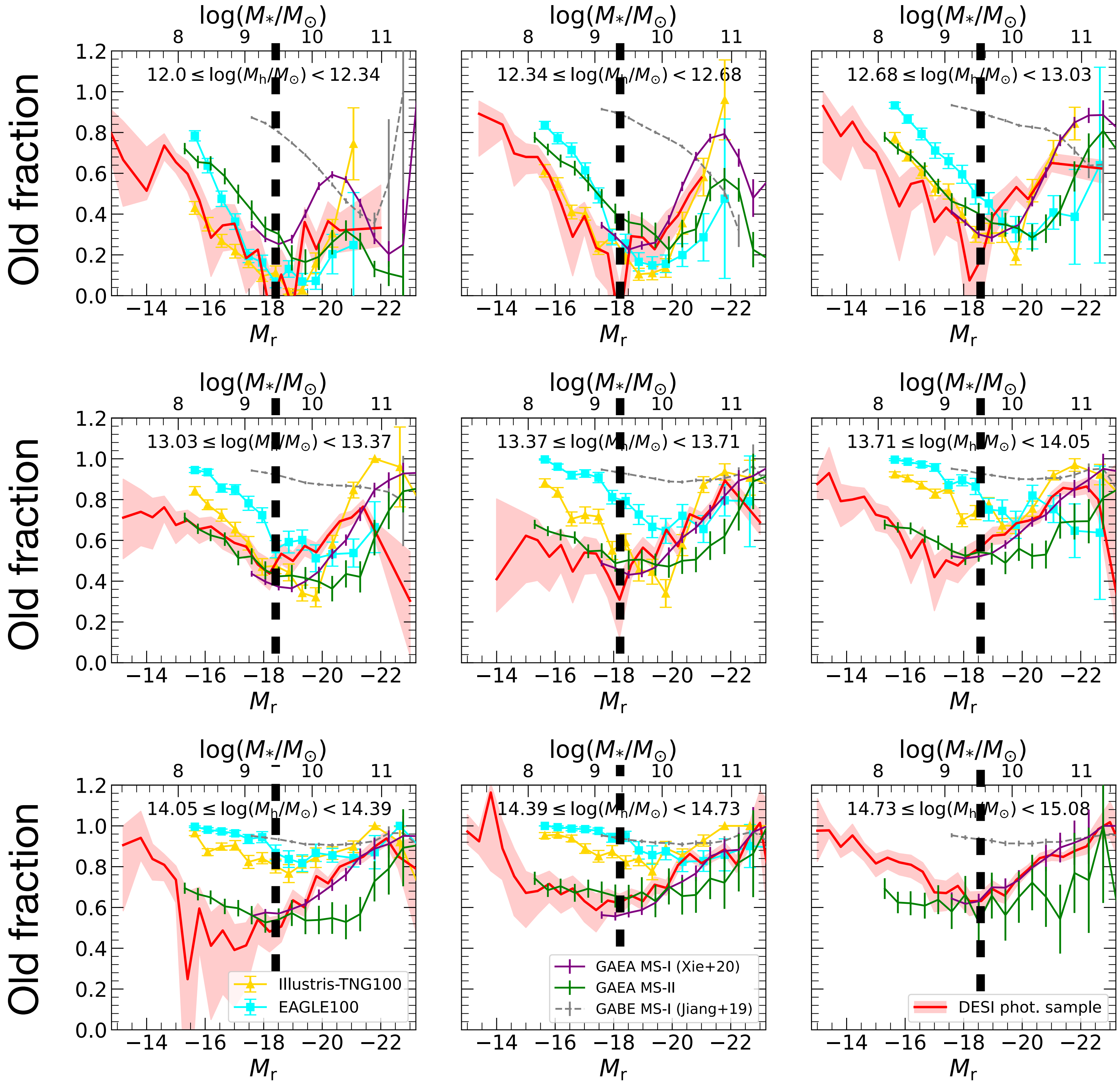


Red (old) galaxies, $\alpha \approx -1.8$



- The faint end slopes are independent on halo mass for both red and blue galaxies.

2. Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$



- Characteristic stellar mass is independent on halo mass.

- **Failure:**

TNG, EAGLE and GABE over-predict the quenched fraction.

- **Success:**

GAEA: large cold gas fraction at infall+improved satellite quenching;

L-Galaxies (Henriques+17): comprehensive treatment of satellite quenching.

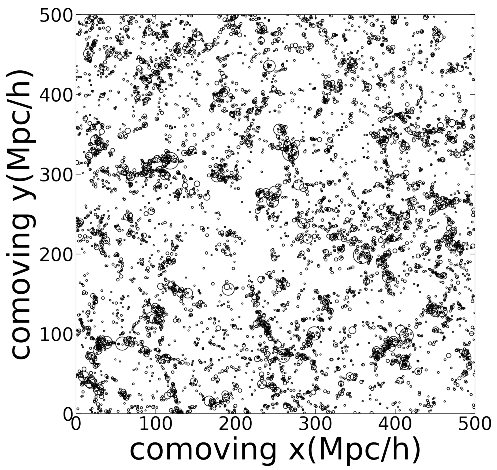
3. Mock catalog for high redshift spectroscopic survey

	SDSS (main sample)	zCOSMOS	VIPERS	PFS (future)
Selection criteria	$r < 17.77$	$I < 22.5$	$I < 22.5$	$y < 22.5$ or $J < 22.8$
Redshift range	z < 0.3	0.1 < z < 1.2	0.5 < z < 1.2	0.7 < z < 1.7
Area	8000 deg^2	1.6 deg^2	16 deg^2	14.5 deg^2
Number	~1 million	~20k	~90k	~250k
Sampling rate	Nearly 100%	56% (central region) 48%(overall region)	30%	50% (z < 1) 70% (z > 1)

We need mock catalogs!

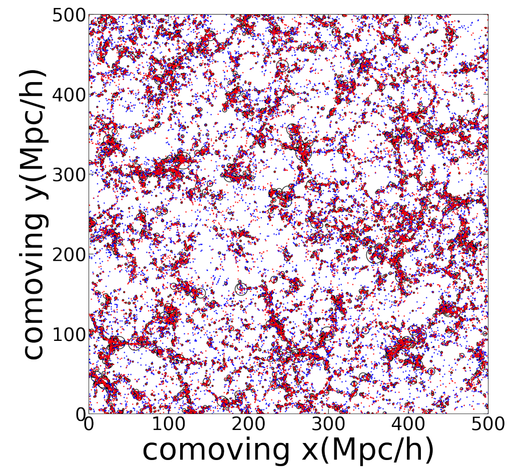
3. The pipeline of the construction of the high-z mock surveys

1. N-body simulation

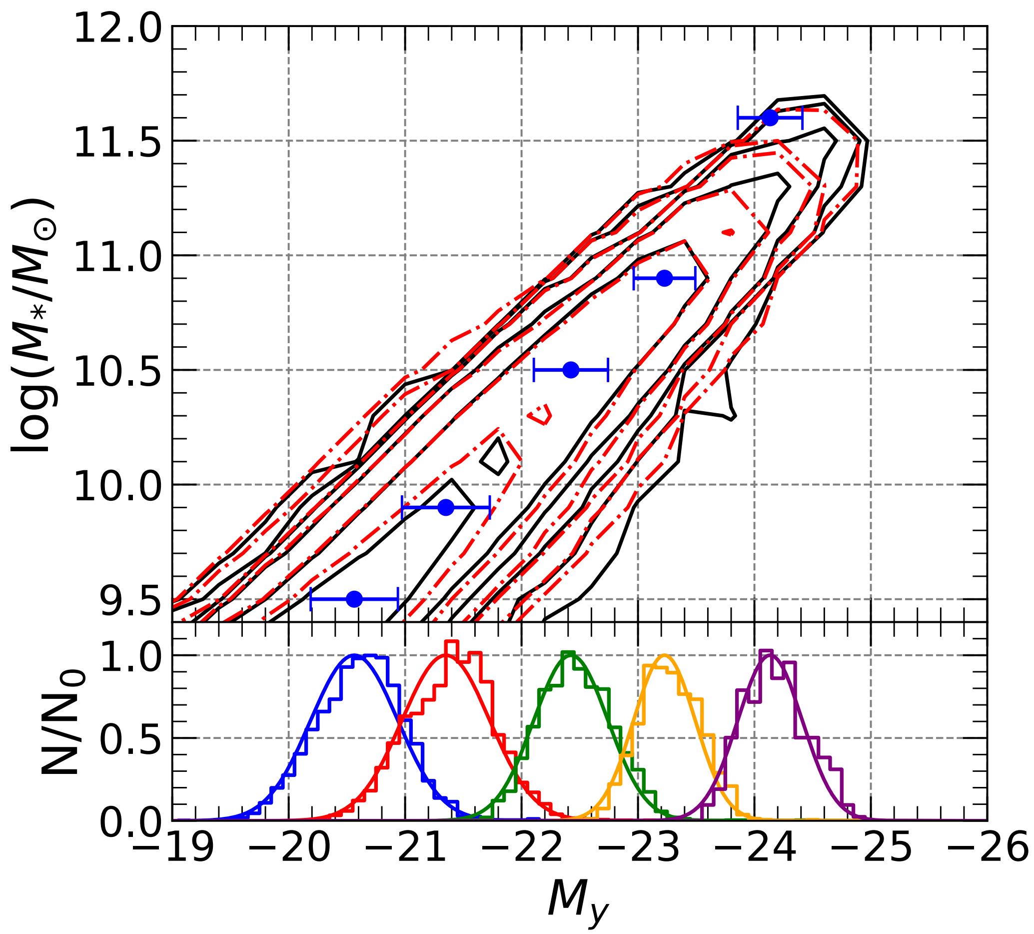


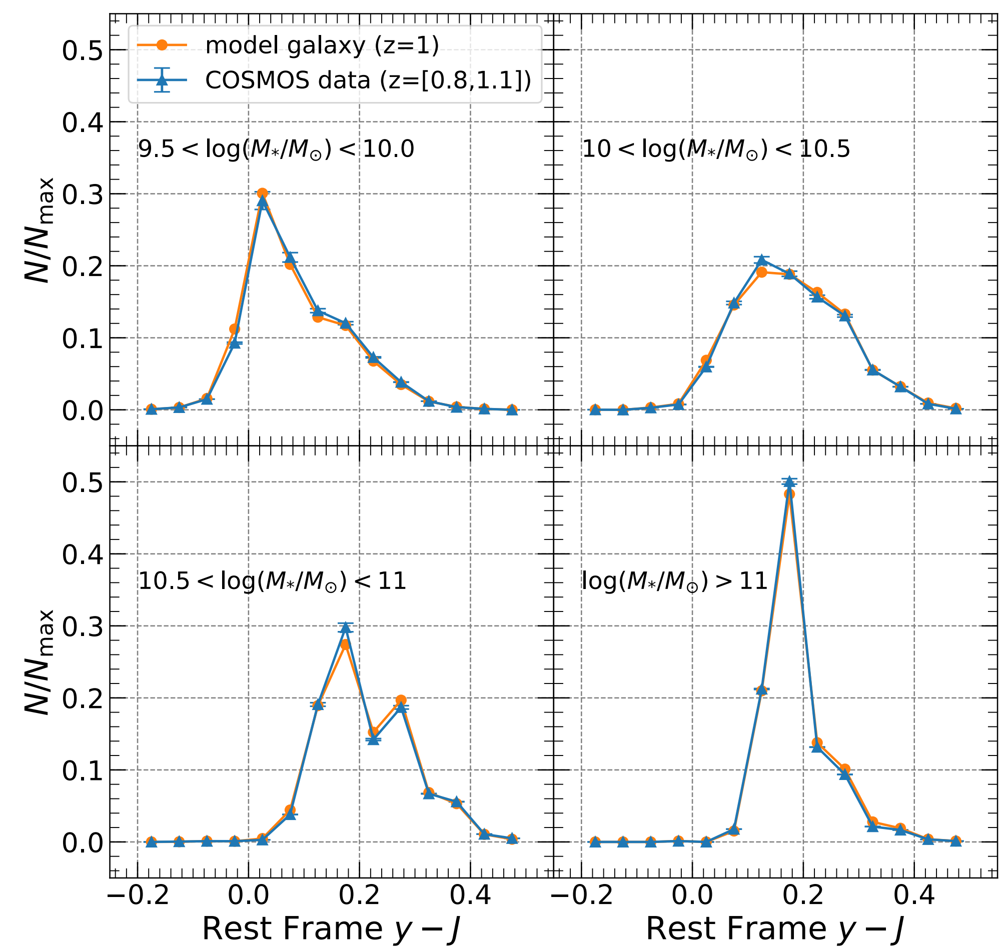
- ELUCID N-body simulation (Wang+16)

2. Model galaxy



- Empirical model (Lu+14, 15; Chen+19) + age distribution matching (Hearin+13)

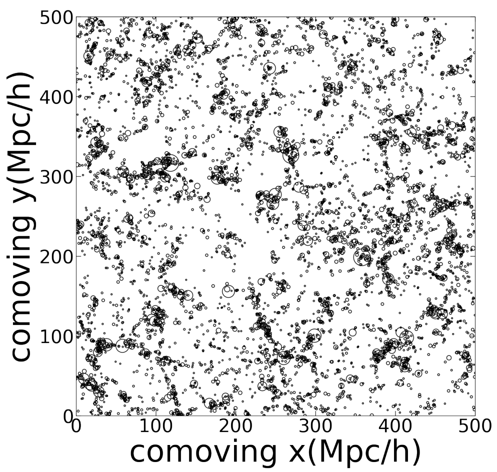




Calibration data: COSMOS2020 (Weaver+22)

3. The pipeline of the construction of the high-z mock surveys

1. N-body simulation



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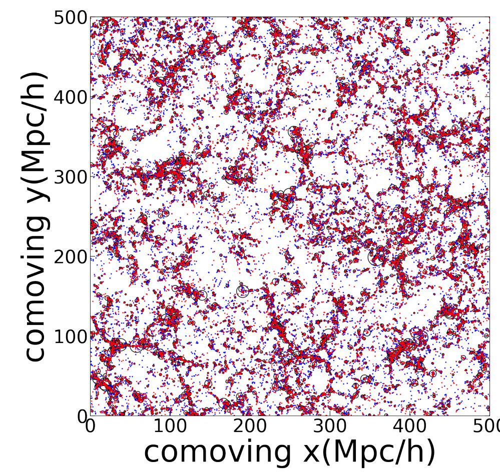
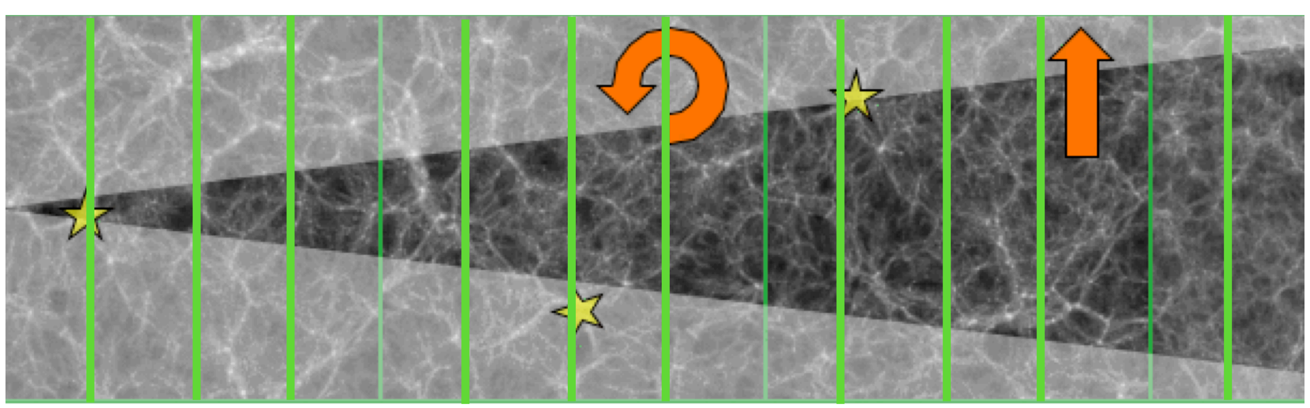


- Empirical model (Lu+14, 15; Chen+19) + age distribution matching (Hearin+13)

3. Construct lightcone

(Blaizot+05)

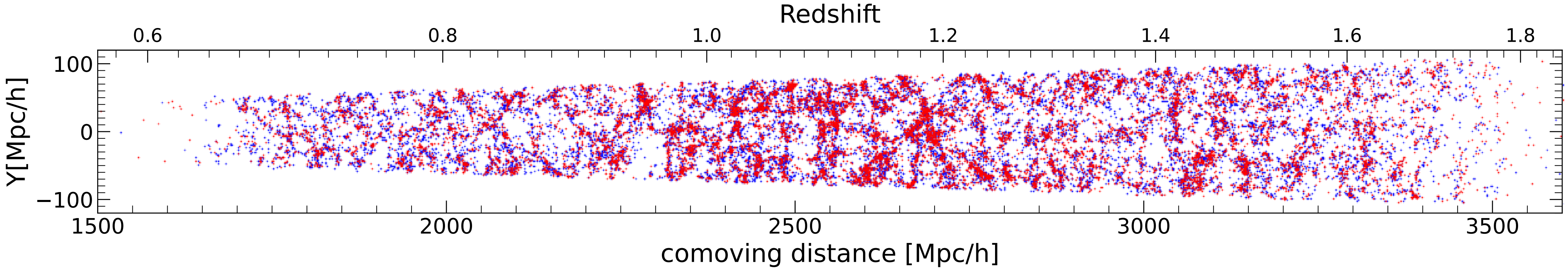


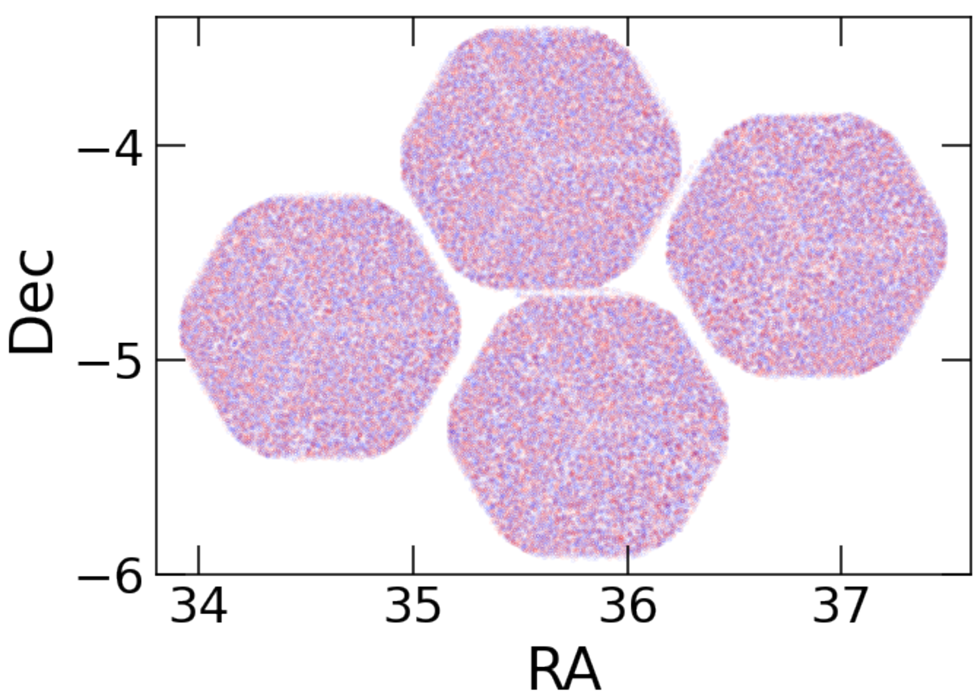
4. Observational effect

- Flux limit selection criteria.
- Sampling rate.
- Fiber/slit collision.
- …

We get the mock survey!

3. The pipeline of the construction of the high-z mock surveys





PFS-like survey XMM-LSS field

We have constructed 20 sets of mocks for **zCOSMOS, VIPERS and PFS galaxy-evolution** survey which are publicly available at https://lig.astro.tsinghua.edu.cn/astrodata/

3. The observation effects in high-z survey

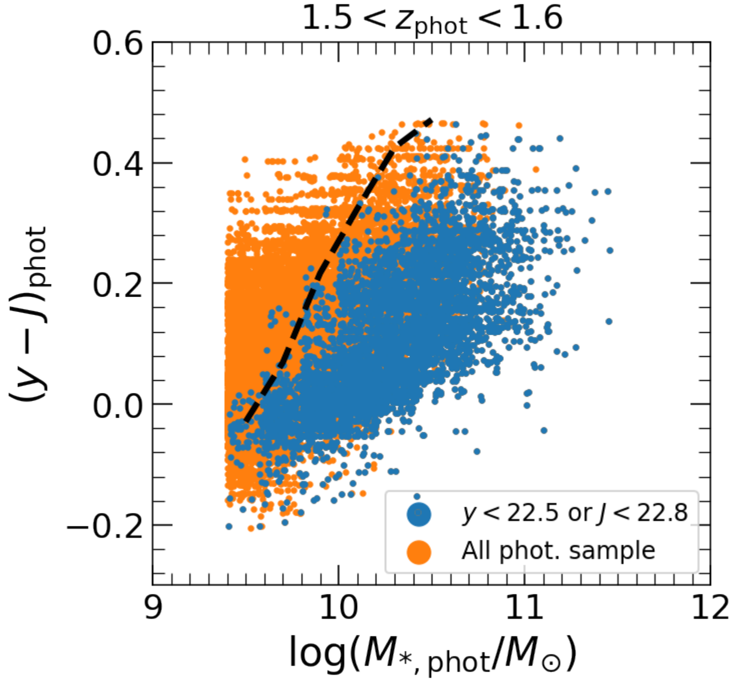
	Sampling rate effect		Fiber/Slit collision effect	Flux limit effect
	Target sampling rate	Redshift success rate		
Abundance	Weights based on local density.	Weights based on galaxy properties.	No correction is needed.	$\frac{V_{\rm survey}}{V_{\rm max}}$ + phot. sam Schmidt 1968
Clustering			$F(\theta) = \frac{1 + w_{\rm p}(\theta)}{1 + w_{\rm s}(\theta)}$ Hawkins+03, Li+06	Weighting method **Our new method!**

$w_{\rm sky}$ $w_{\rm coll}$

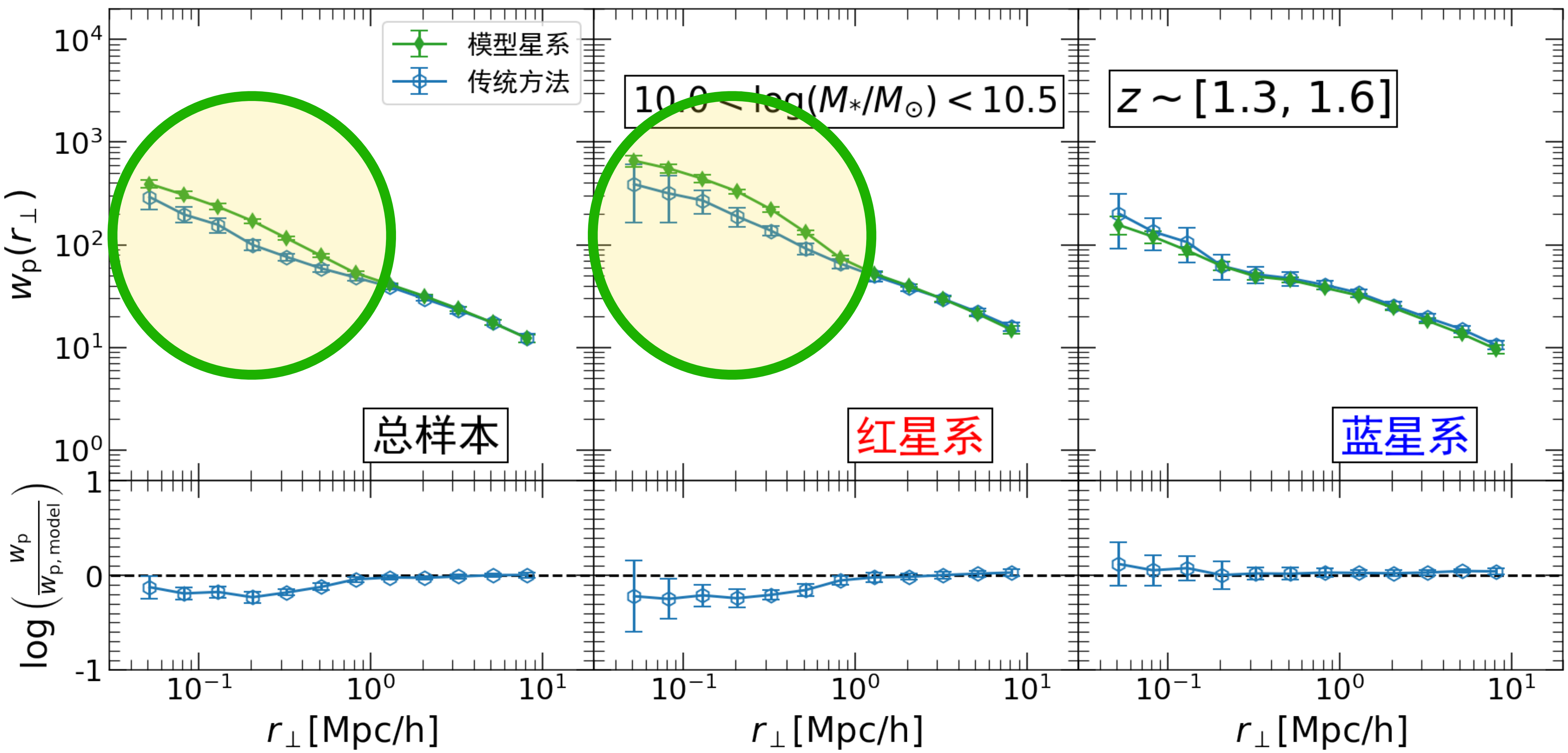
We take PFS-like mock survey as an example to study those observation effects and make the prediction for the PFS survey.

3. Flux limit effect on the projected 2PCF measurement

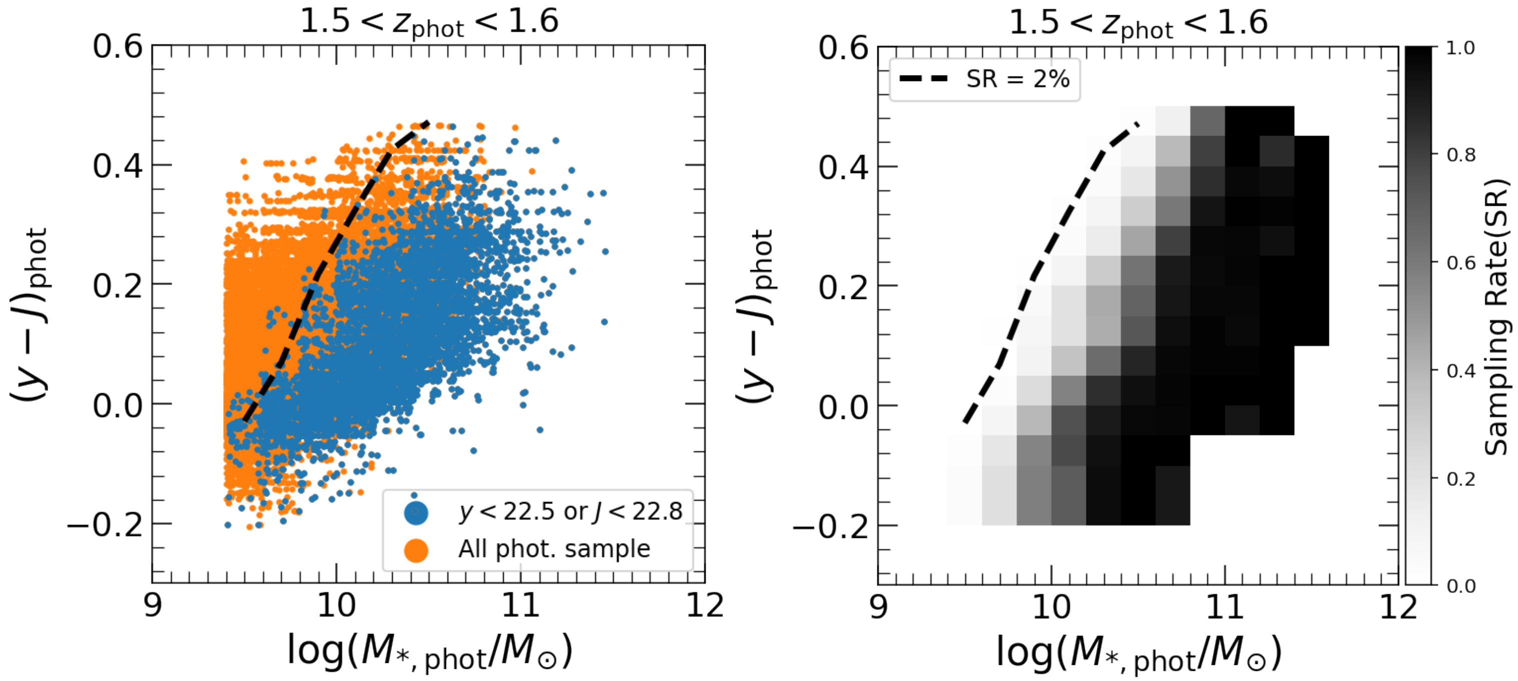
- Underestimate the projected 2PCF (Meneux+08, 09; Marulli+13).
- Miss **low-mass red galaxies** which are satellite galaxies in massive halos and have large M_*/L.



Conventional method: $w_{sky} \times w_{coll}$

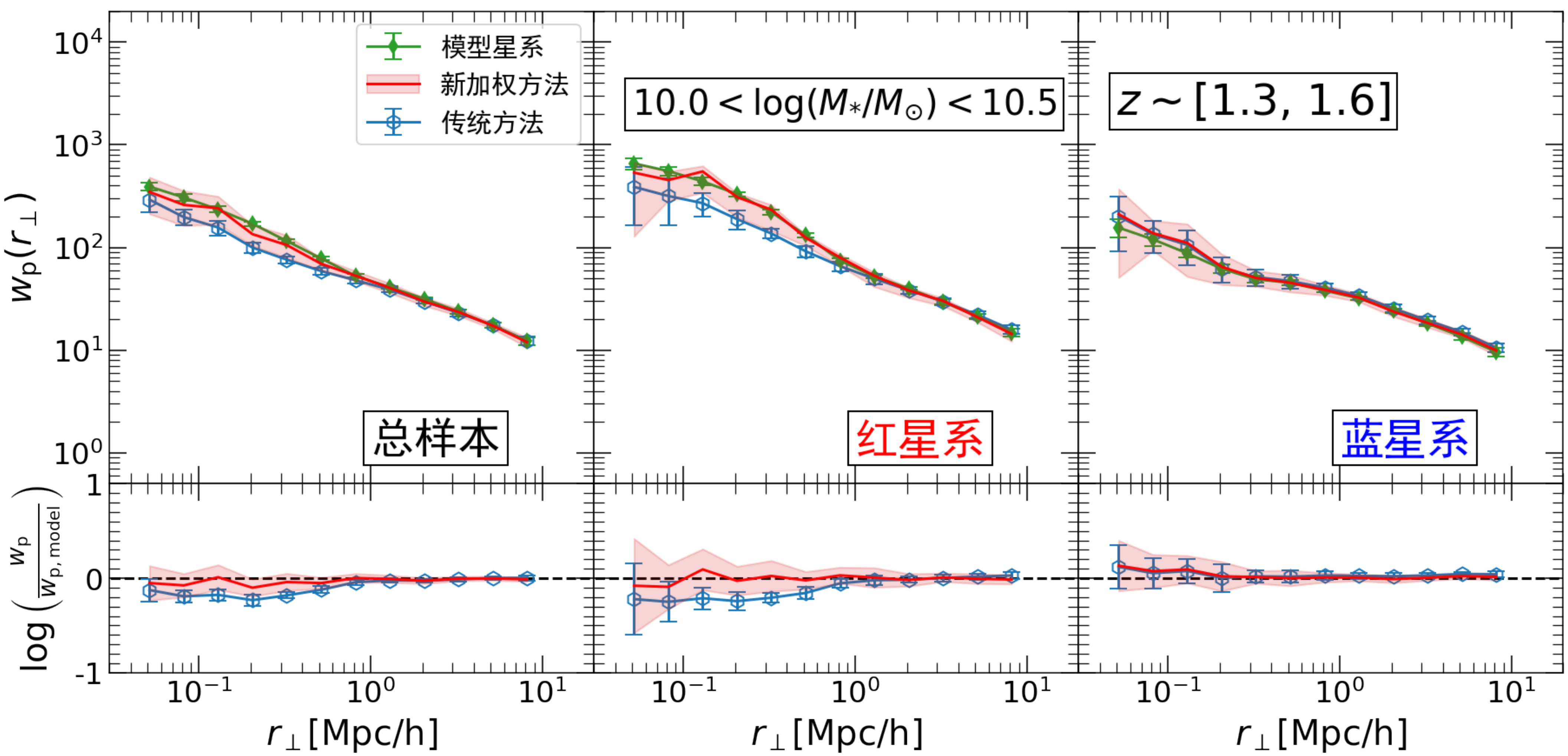


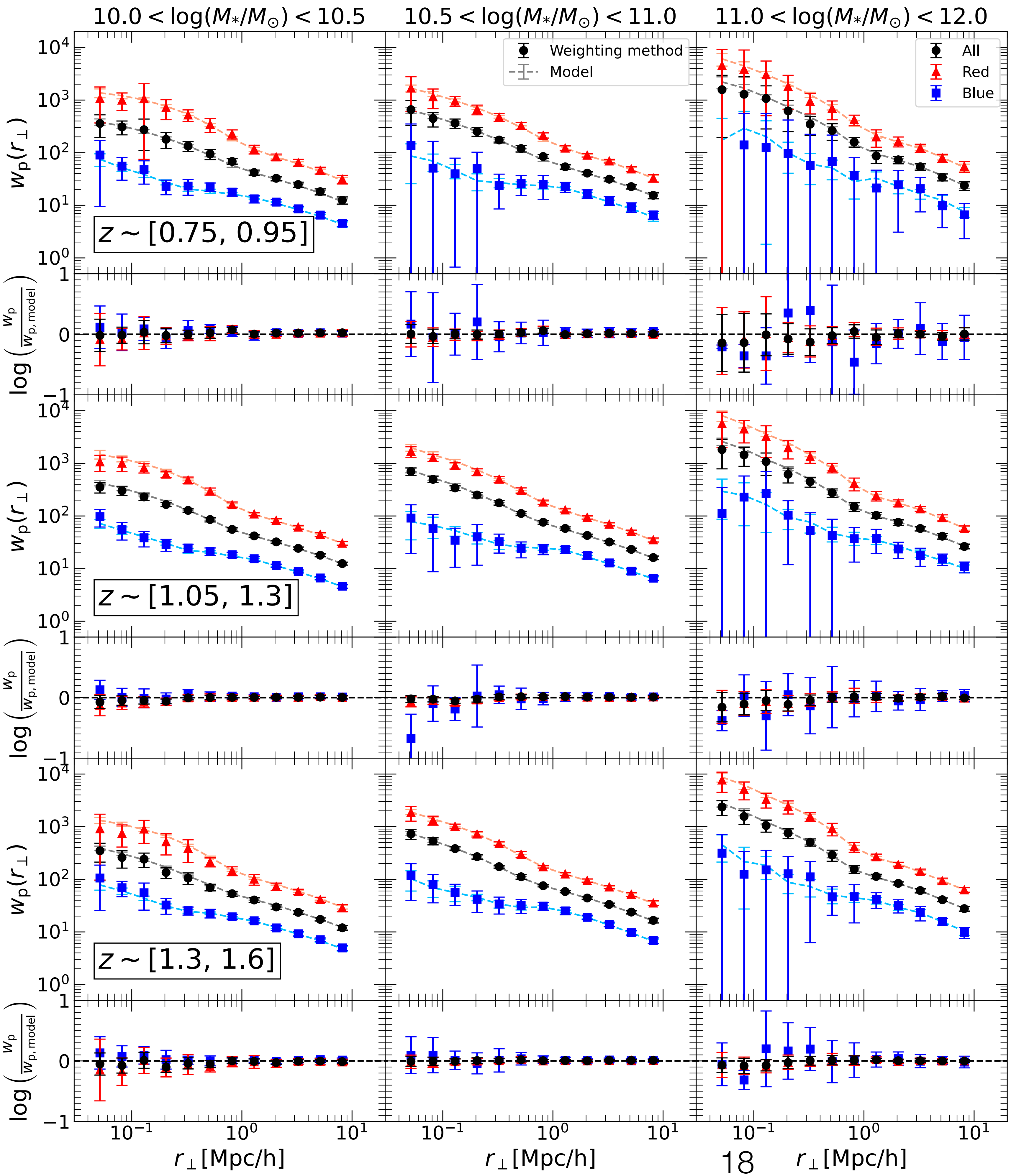
3. Weighting scheme to correct flux limit effect



$$w_{\mathrm{flux}} = \frac{1}{\mathrm{SR}} = \frac{N_{\mathrm{all\ phot.}}}{N_{y<22.5,J<22.8}}$$

New method: $w_{\mathrm{sky}} \times w_{\mathrm{coll}} \times w_{\mathrm{flux}}$

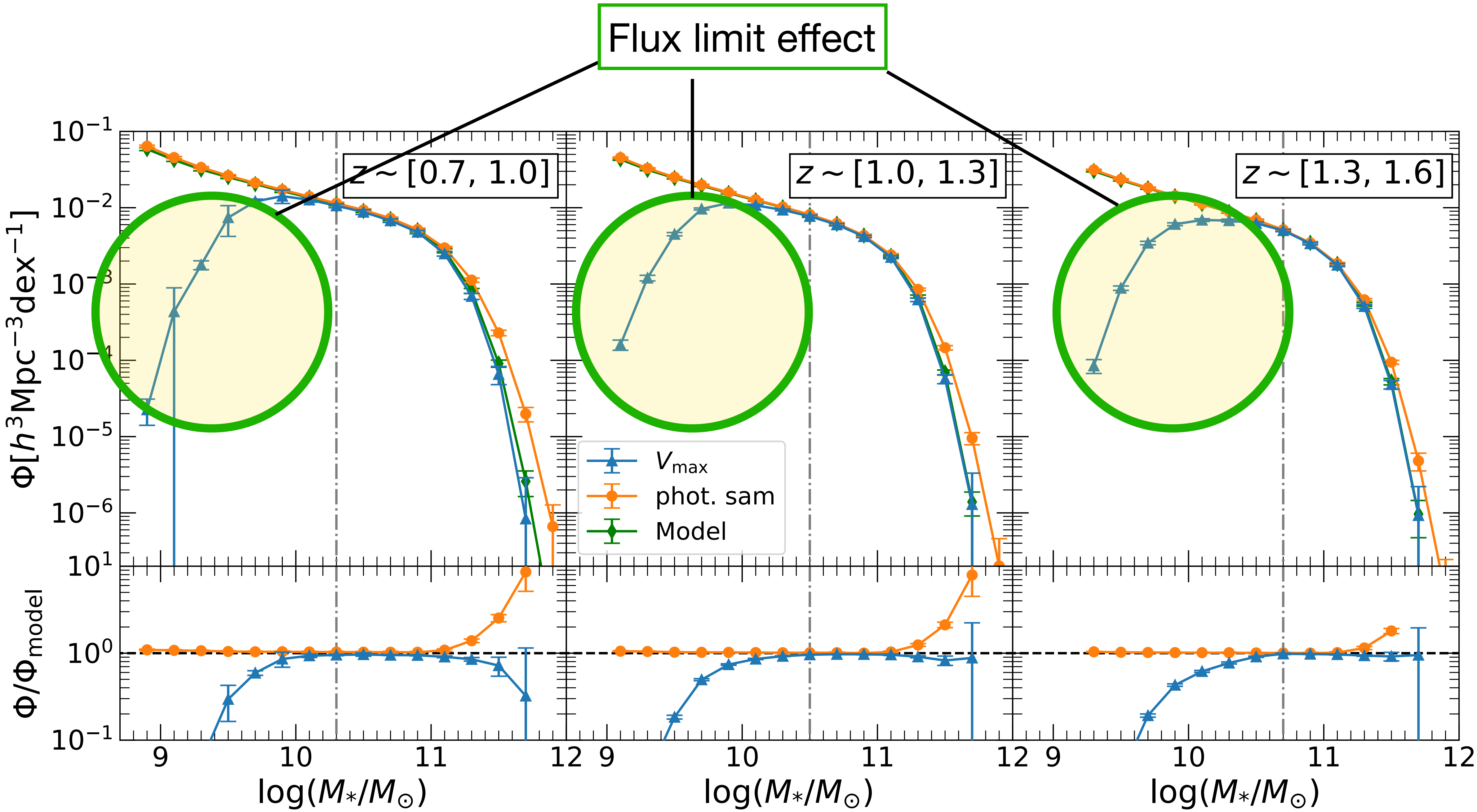




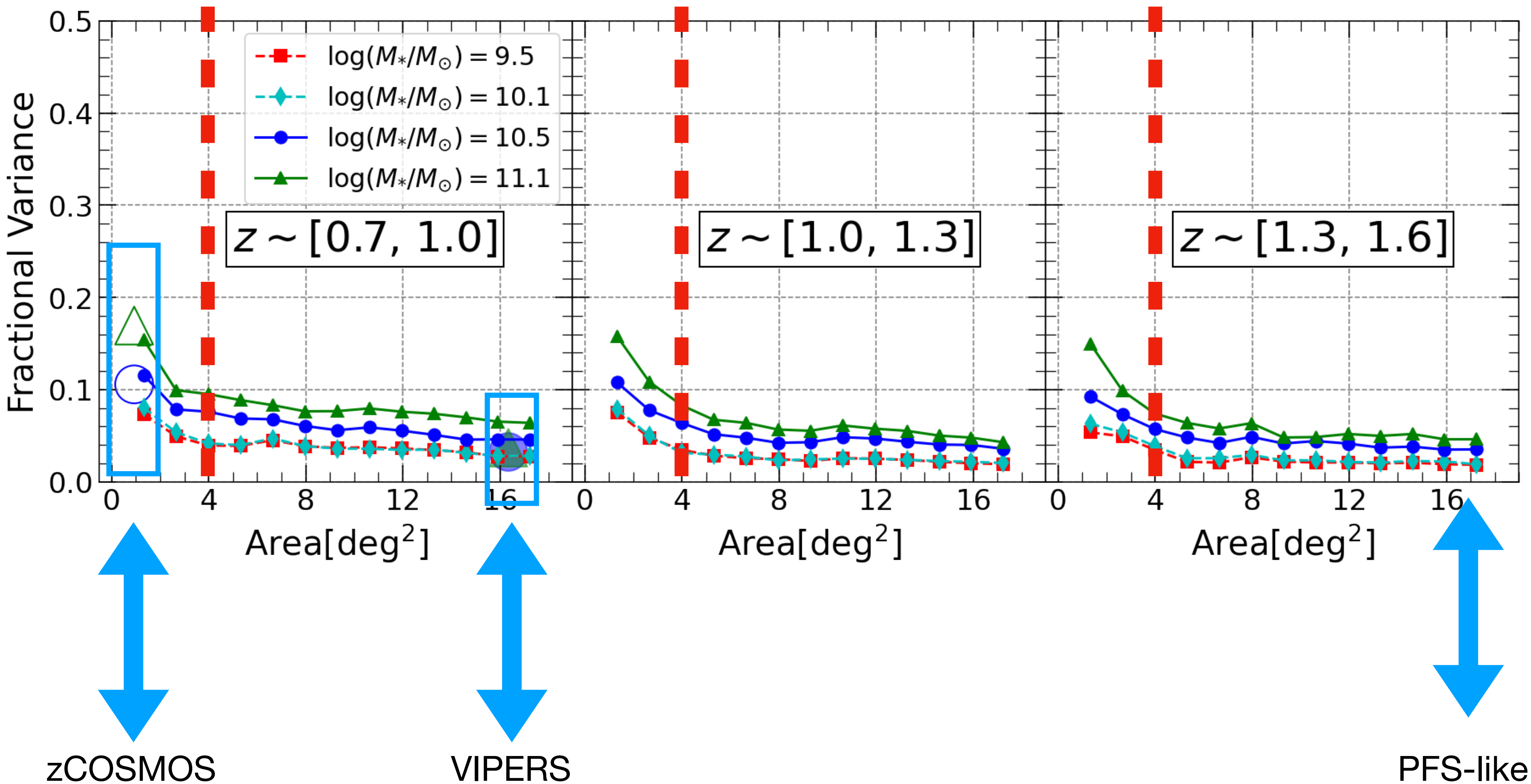
Our method is valid for all stellar mass and redshift and also for red and blue galaxy samples.

3. Test the method for measurement of abundance with our high-z mock surveys

- High-mass end: $w_{\rm sky} \times \frac{V_{\rm survey}}{V_{\rm max}}$ using spec. sample.
- Low-mass end: measurements from phot. sample.

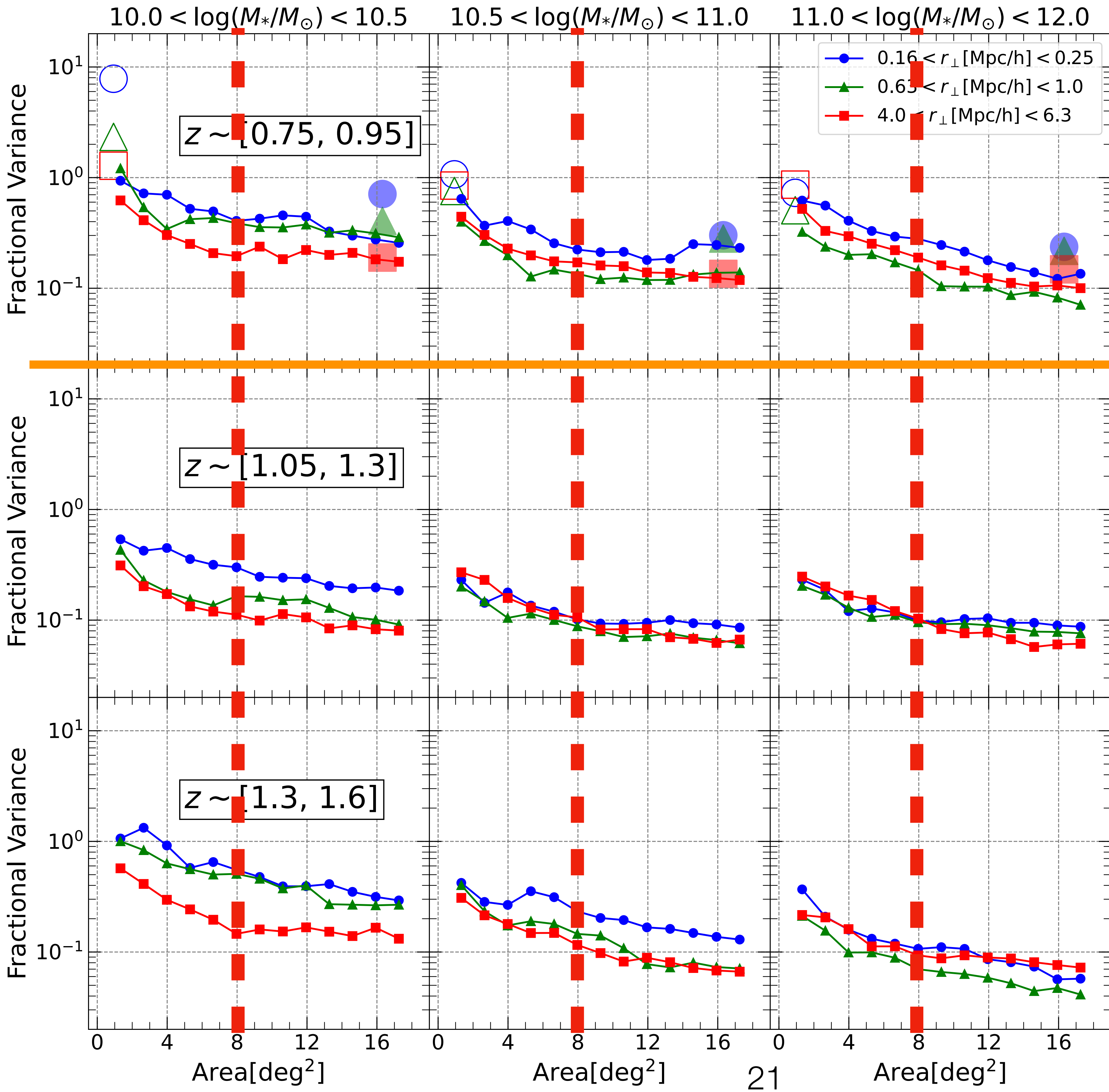


3. Quantify the total errors of GSMF with our mock surveys



The error of GSMF for PFS is about 2 times smaller compared with zCOSMOS.

3. Quantify the total errors of 2PCF with our mock surveys



4-10 times smaller errors

50% sampling rate

70% sampling rate

When area larger than about 8 deg², we need to increase sampling rate to reduce the shot noise.

Summary

- **Low redshift conditional luminosity function with the galaxy image survey.** (Meng, J., Li, C., Mo, H. J., et al. 2023, ApJ, 944, 75)

  ① We measure the CLF down to $M_{\rm r} = -10 \sim -12$ mag (2 mag fainter than previous) and find clear faint-end upturn for red galaxies with $\alpha \approx -1.8$.

  ② The fraction of old/red satellite galaxies has a minimum at a characteristic luminosity at $M_{\rm r} \sim -18$ ($M_* \sim 10^{9.5} M_\odot$) independent on halo mass.

- **Measuring galaxy abundance and clustering at high redshift from incomplete spectroscopic data: test on mocks.** (Meng, J., Li, C., Mo, H. J., et al. submitted to ApJ, arXiv:2008.13733)

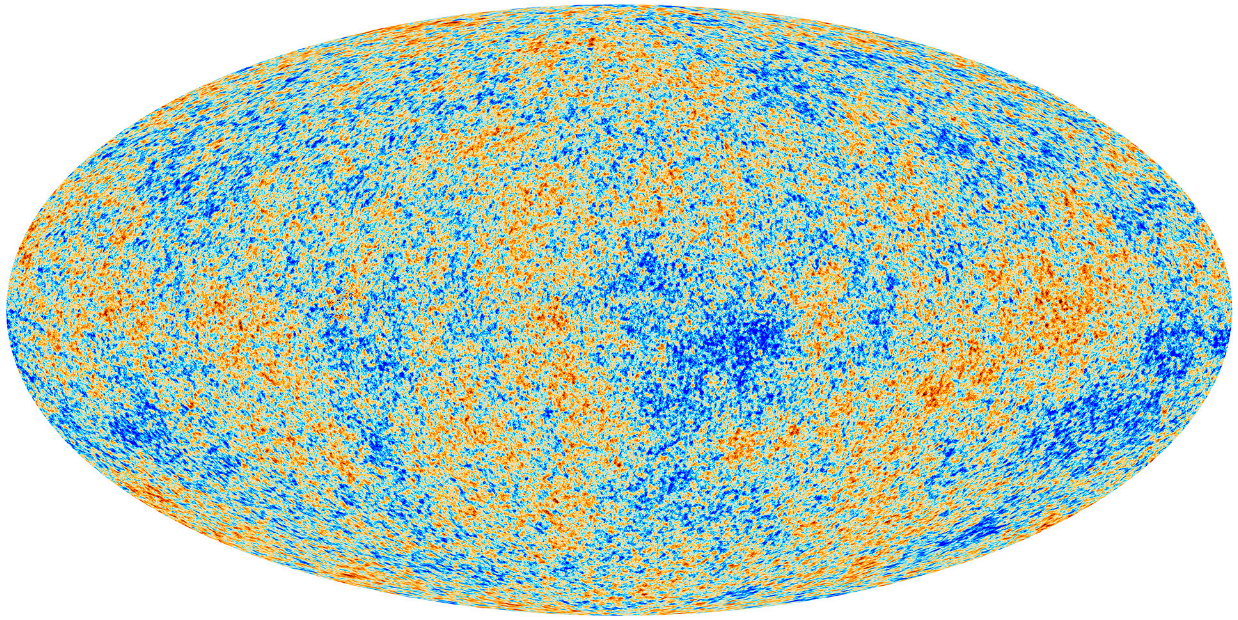
  ① Construct the 20 mock catalogs for zCOSMOS, VIPERS and PFS-like (future) surveys.

  ② The flux-limit selection criteria underestimate the projected 2PCF of low mass galaxies at high redshift. Our weighting scheme can correct it.

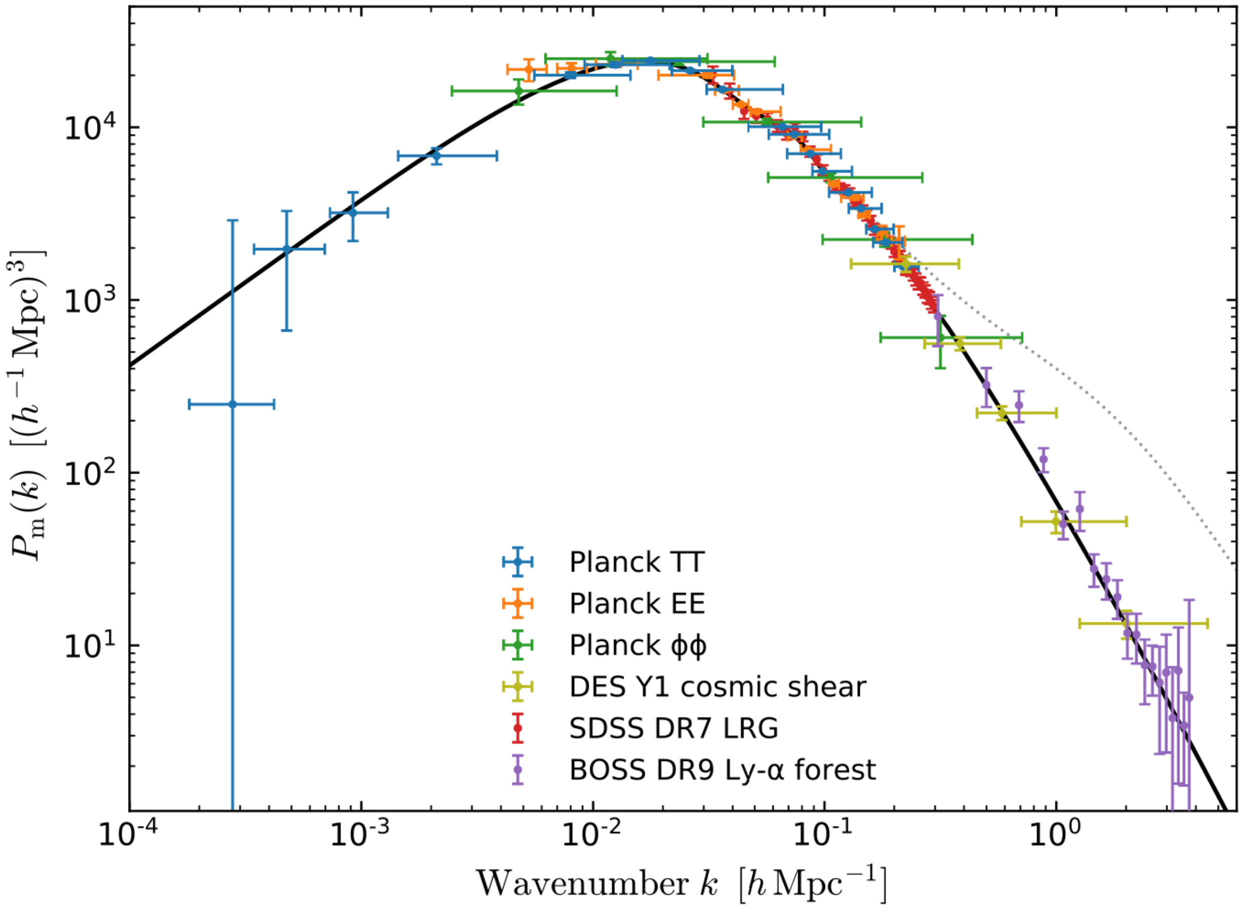
  ③ We make the prediction on the errors of GSMF and projected 2PCF for PFS-like survey, and they would be 2-10 times smaller than zCOSMOS survey.

Backup

Standard cosmology: ΛCDM cosmology model



CMB map seen by Planck
(https://www.esa.int/Science_Exploration/Space_Science/Planck/Planck_and_the_cosmic_microwave_background)

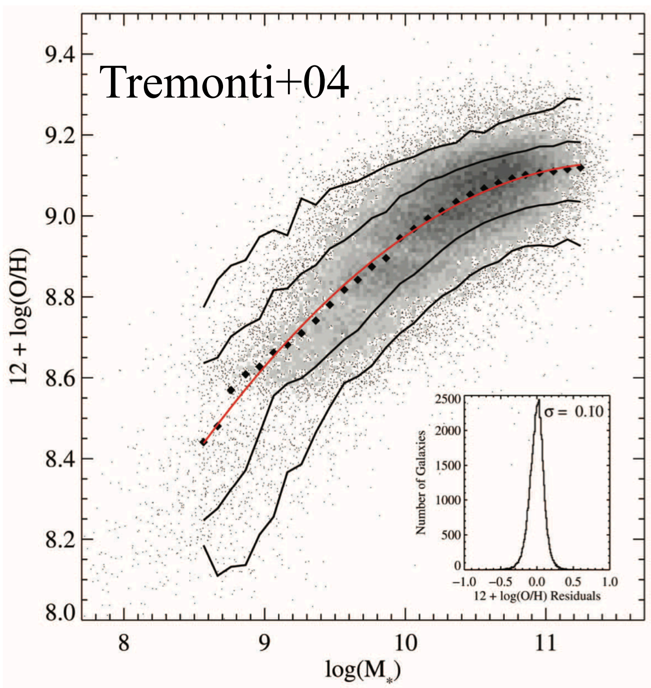


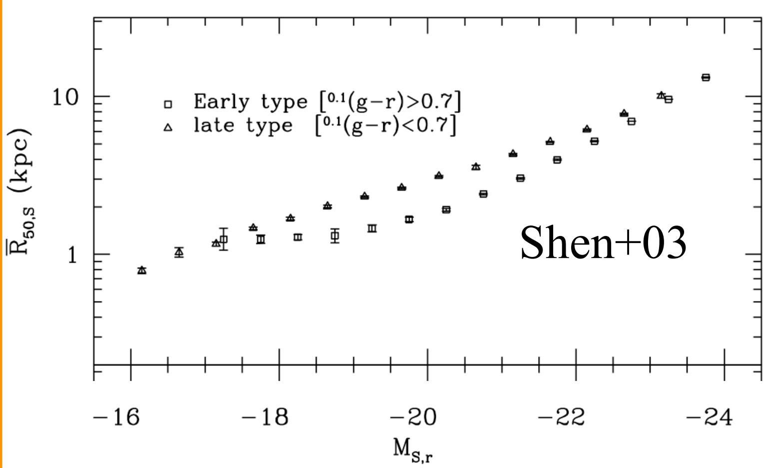
Planck 2018 results

- We get into the era of the precise cosmology.
- Solid foundation for studying the galaxy formation and evolution.

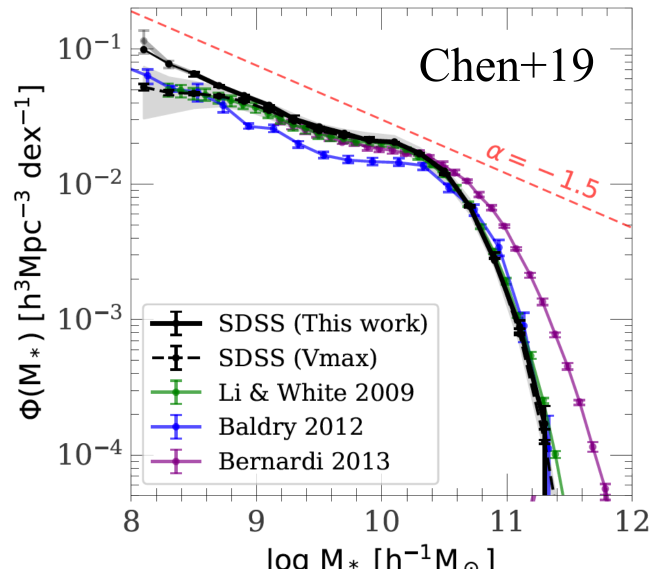
Statistical Analysis of the survey (SPACE)

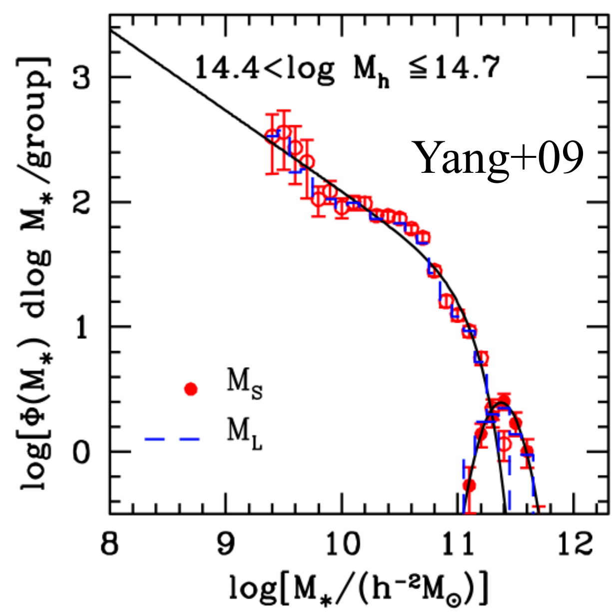
Scaling relations of galaxy Properties



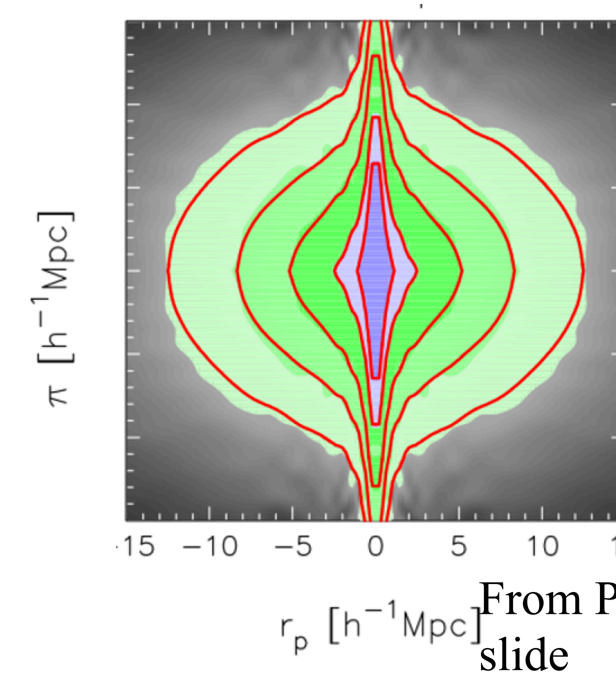


Abundance

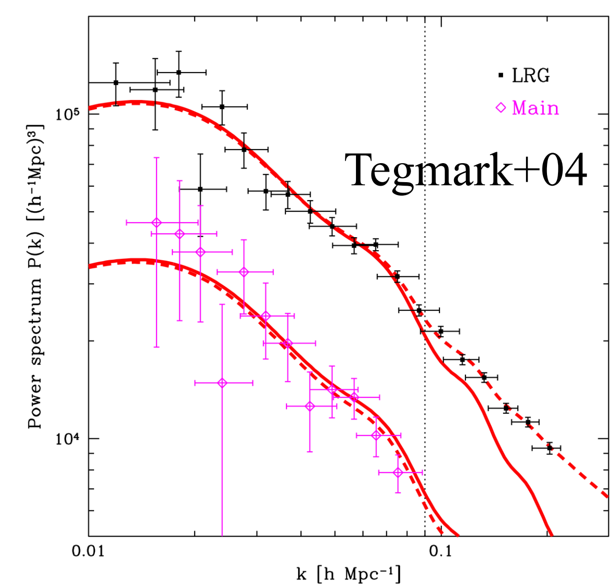




Clustering

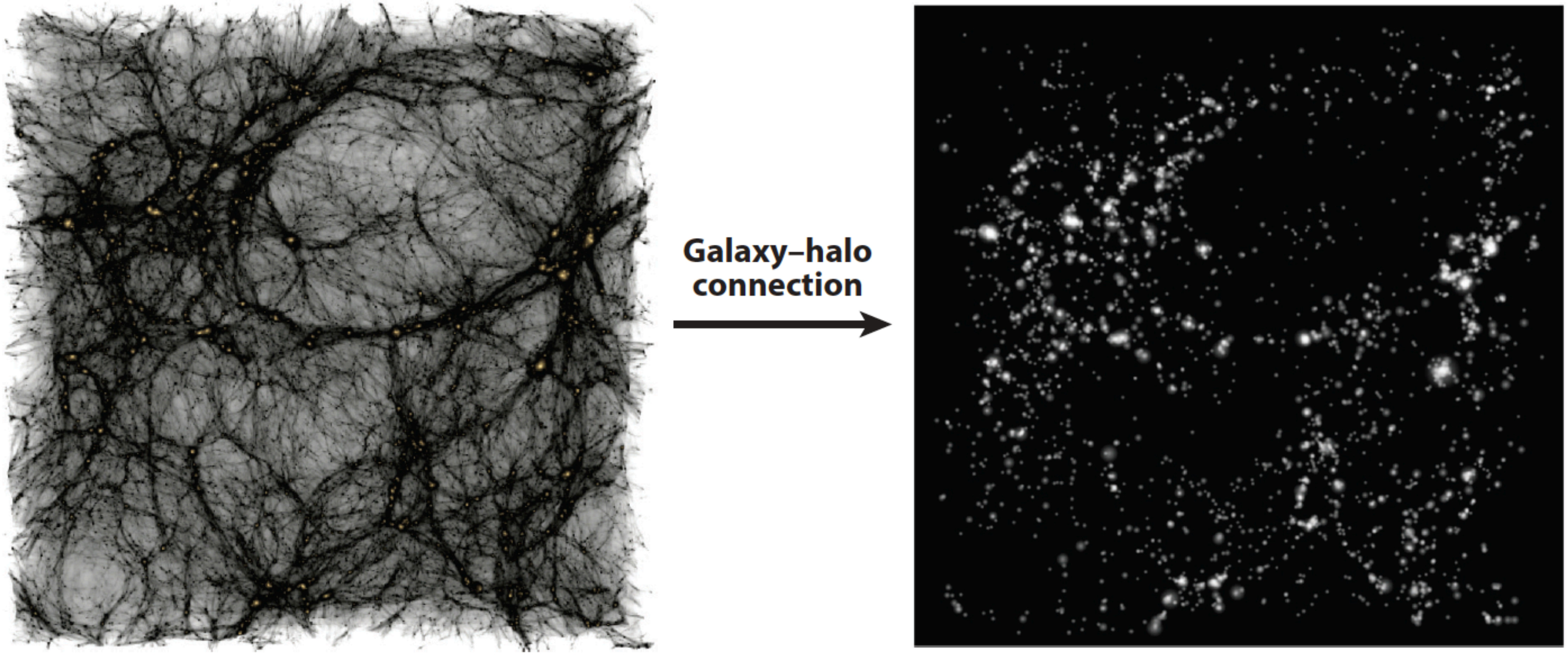


From Prof. Li's slide



Evolution of the above relations and functions.

Models of the halo-galaxy connection



Approaches to modeling the galaxy–halo connection

← Physical models ... Empirical models →

Hydrodynamical simulations	Semianalytic models	Empirical forward modeling	Subhalo abundance modeling	Halo occupation models
Simulate halos and gas; star formation and feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos and subhalos) plus assumptions about galaxy–(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

Wechsler&Tinker 18

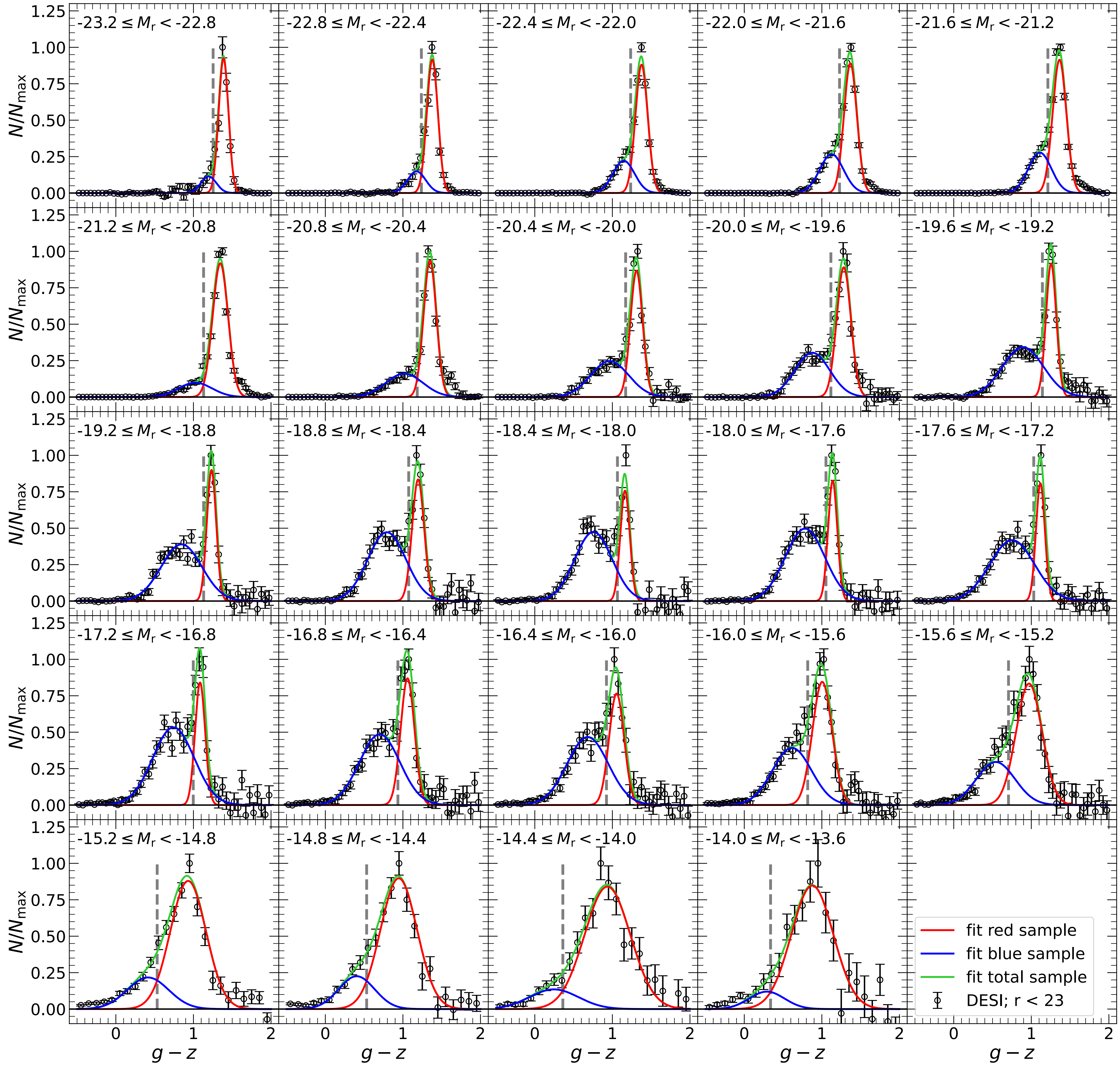
How to study the halo-galaxy connection

Models for Halo-galaxy Connection

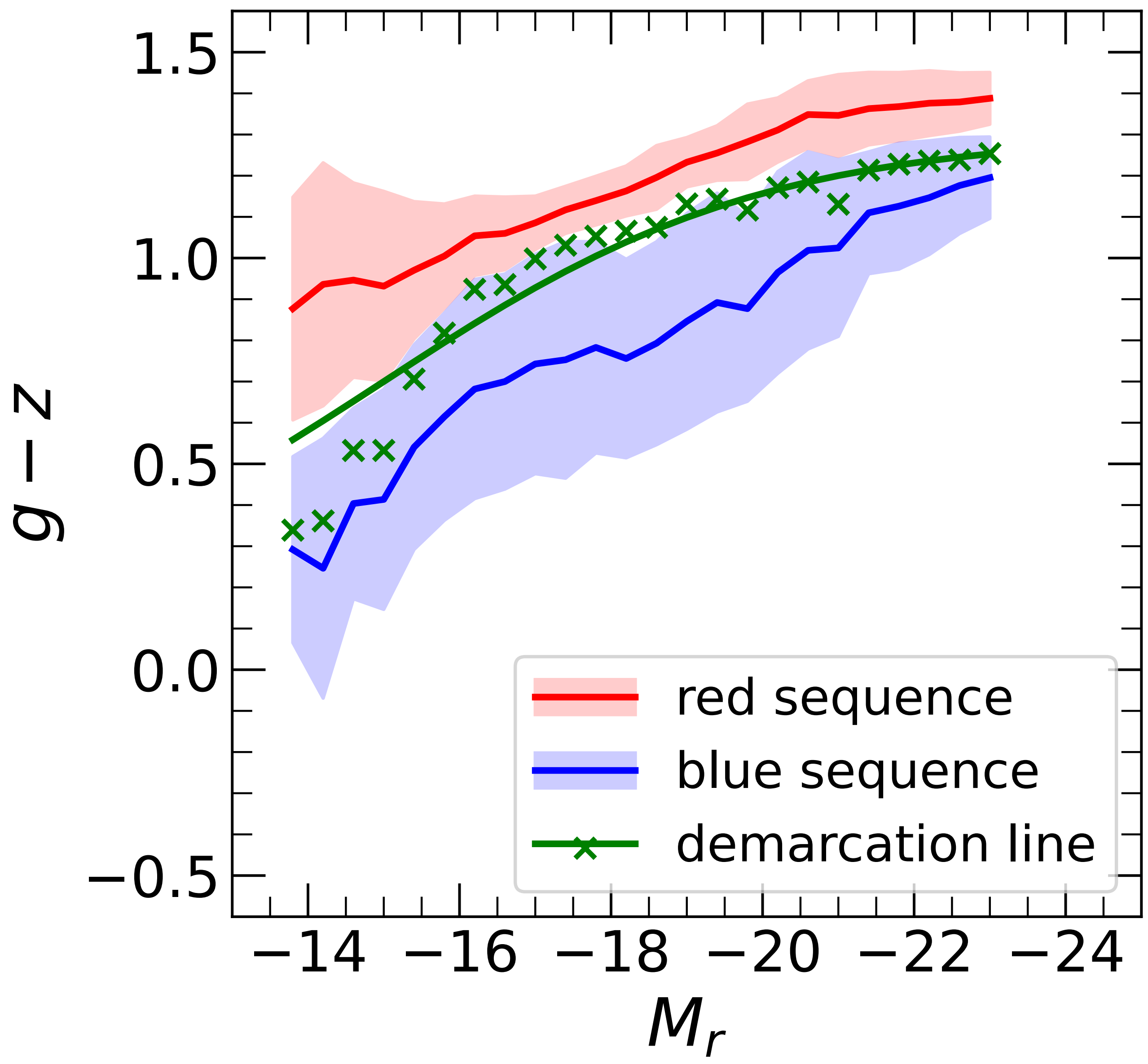
Statistical Analysis of the survey (SPACE)

We need mock surveys!

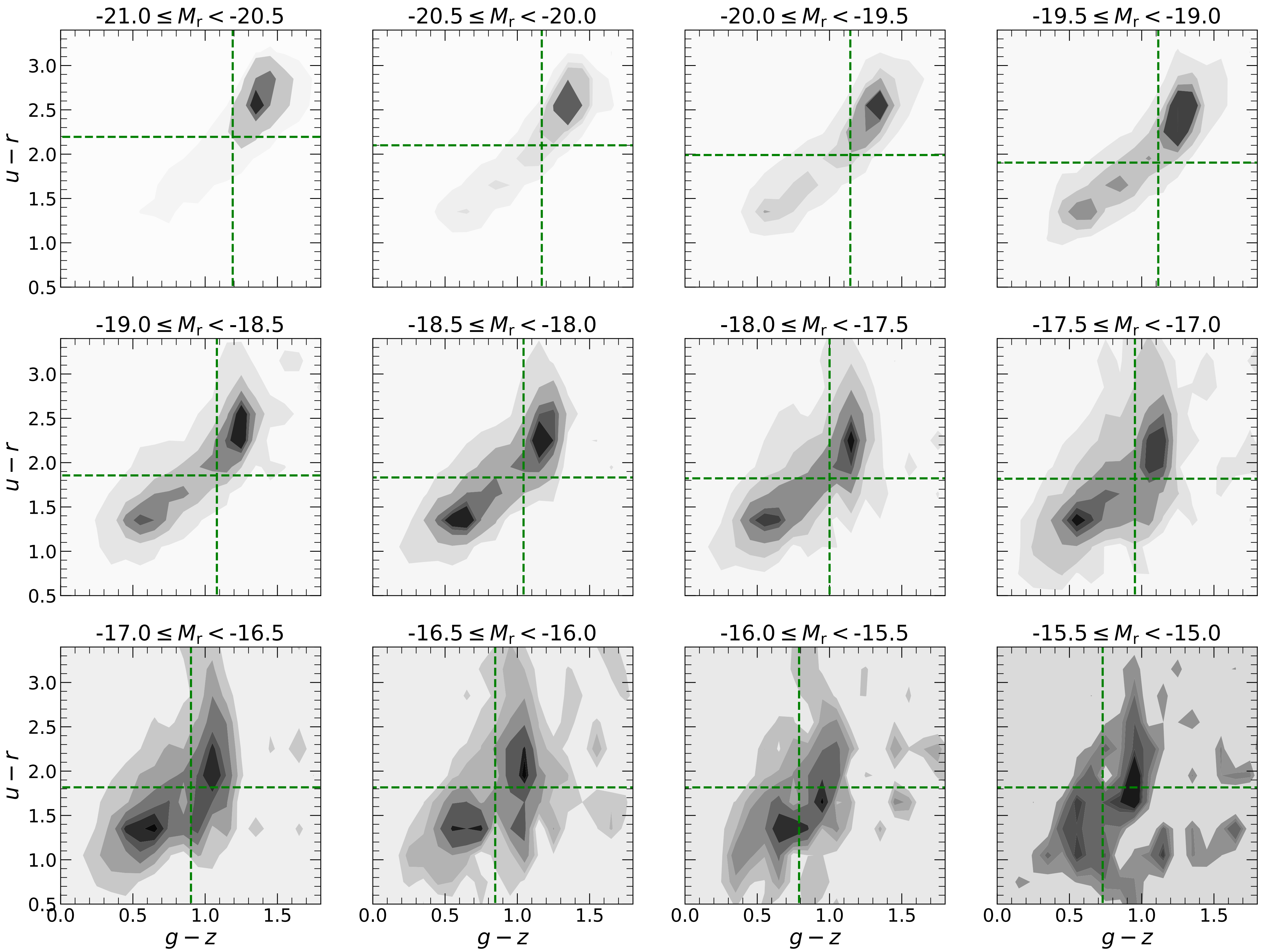
- Test the method for the statistical analysis and quantify the systematic errors.
- Compare the models and observations, different models fairly.
- Make the predictions for the survey in the future.



-23.2 ≤ M_r < -22.8
-22.8 ≤ M_r < -22.4
-22.4 ≤ M_r < -22.0
-22.0 ≤ M_r < -21.6
-21.6 ≤ M_r < -21.2
-21.2 ≤ M_r < -20.8
-20.8 ≤ M_r < -20.4
-20.4 ≤ M_r < -20.0
-20.0 ≤ M_r < -19.6
-19.6 ≤ M_r < -19.2
-19.2 ≤ M_r < -18.8
-18.8 ≤ M_r < -18.4
-18.4 ≤ M_r < -18.0
-18.0 ≤ M_r < -17.6
-17.6 ≤ M_r < -17.2
-17.2 ≤ M_r < -16.8
-16.8 ≤ M_r < -16.4
-16.4 ≤ M_r < -16.0
-16.0 ≤ M_r < -15.6
-15.6 ≤ M_r < -15.2
-15.2 ≤ M_r < -14.8
-14.8 ≤ M_r < -14.4
-14.4 ≤ M_r < -14.0
-14.0 ≤ M_r < -13.6
N/N_max
g − z
fit red sample
fit blue sample
fit total sample
DESI; r < 23



$$T(M_{\mathrm{r}}) = 0.7 - 0.6\tanh\left(\frac{M_{\mathrm{r}}+15}{5}\right)$$

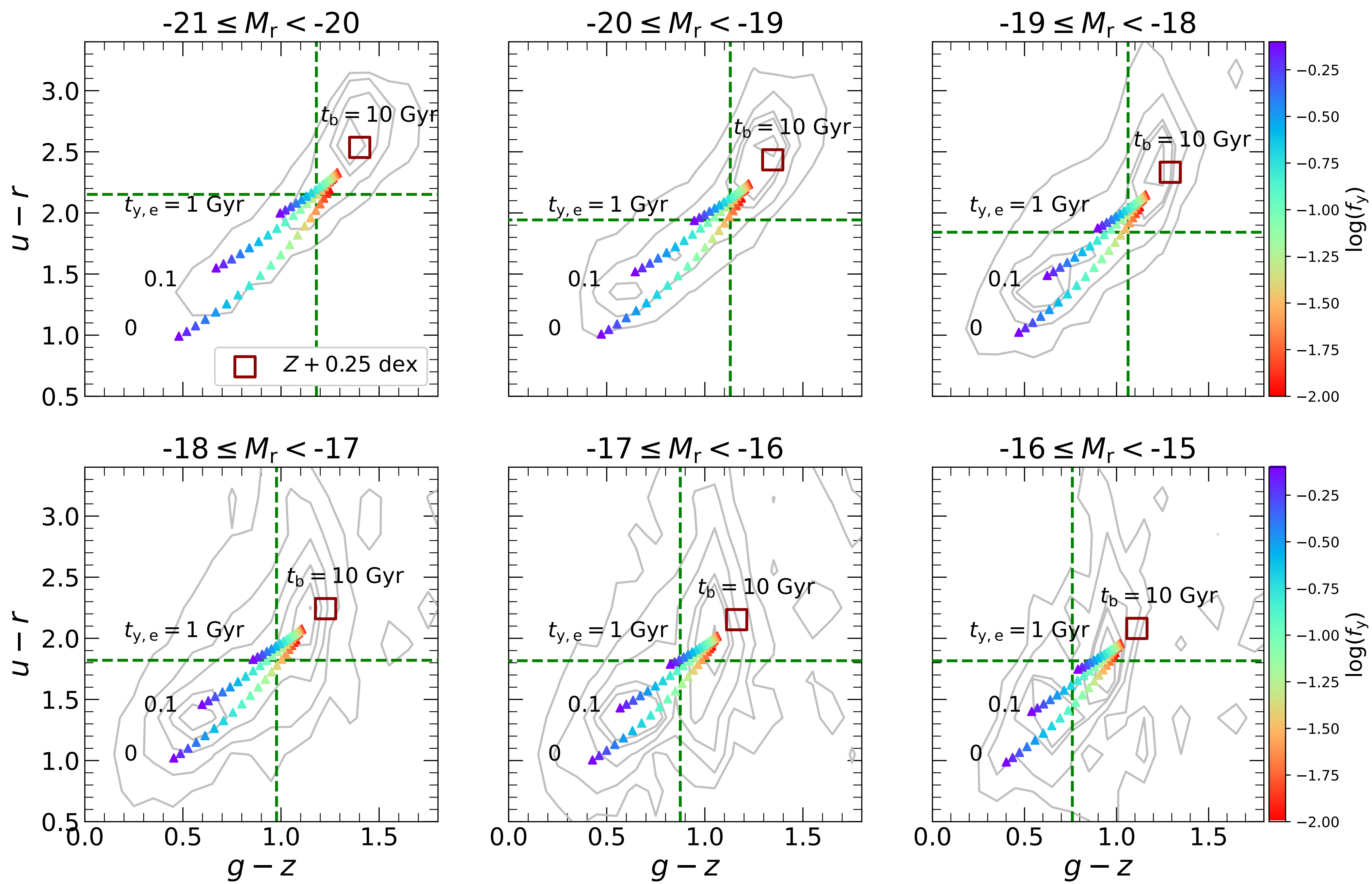


-21.0 ≤ M_r < -20.5
-20.5 ≤ M_r < -20.0
-20.0 ≤ M_r < -19.5
-19.5 ≤ M_r < -19.0
-19.0 ≤ M_r < -18.5
-18.5 ≤ M_r < -18.0
-18.0 ≤ M_r < -17.5
-17.5 ≤ M_r < -17.0
-17.0 ≤ M_r < -16.5
-16.5 ≤ M_r < -16.0
-16.0 ≤ M_r < -15.5
-15.5 ≤ M_r < -15.0
$u-r$
$g-z$
0.5
1.0
1.5
2.0
2.5
3.0
0.0

$$\log\left(\frac{Z}{Z_\odot}\right) = (-1.69 \pm 0.04) + (0.30 \pm 0.02)\log\left(\frac{M_*}{10^6 M_\odot}\right)$$ Kirby+13

$$\log\left(\frac{M_*}{M_\odot}\right) = -0.22 + 0.51\times(g-z) - 0.40\times(M_\mathrm{r} - 4.64) - 0.15$$ Bell+03

$$\Psi(t) \propto (1-f_\mathrm{y})\,\delta(t-t_\mathrm{b}) + \left(\frac{f_\mathrm{y}}{t_\mathrm{y,o} - t_\mathrm{y,e}}\right)\mathcal{H}(t_\mathrm{y,o} - t)\,\mathcal{H}(t - t_\mathrm{y,e}),$$

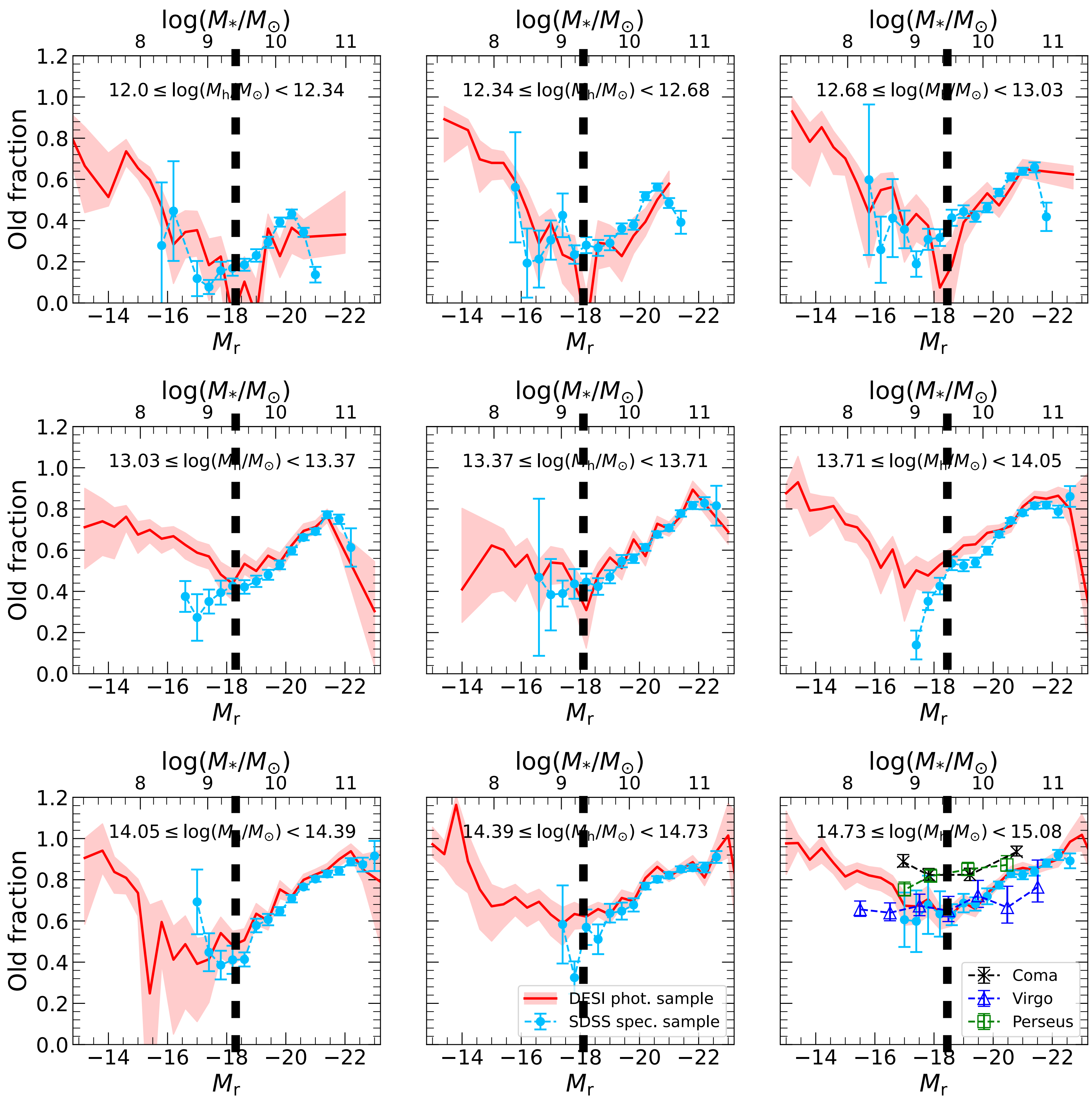


1. Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$

Red galaxies are dominated by old populations.

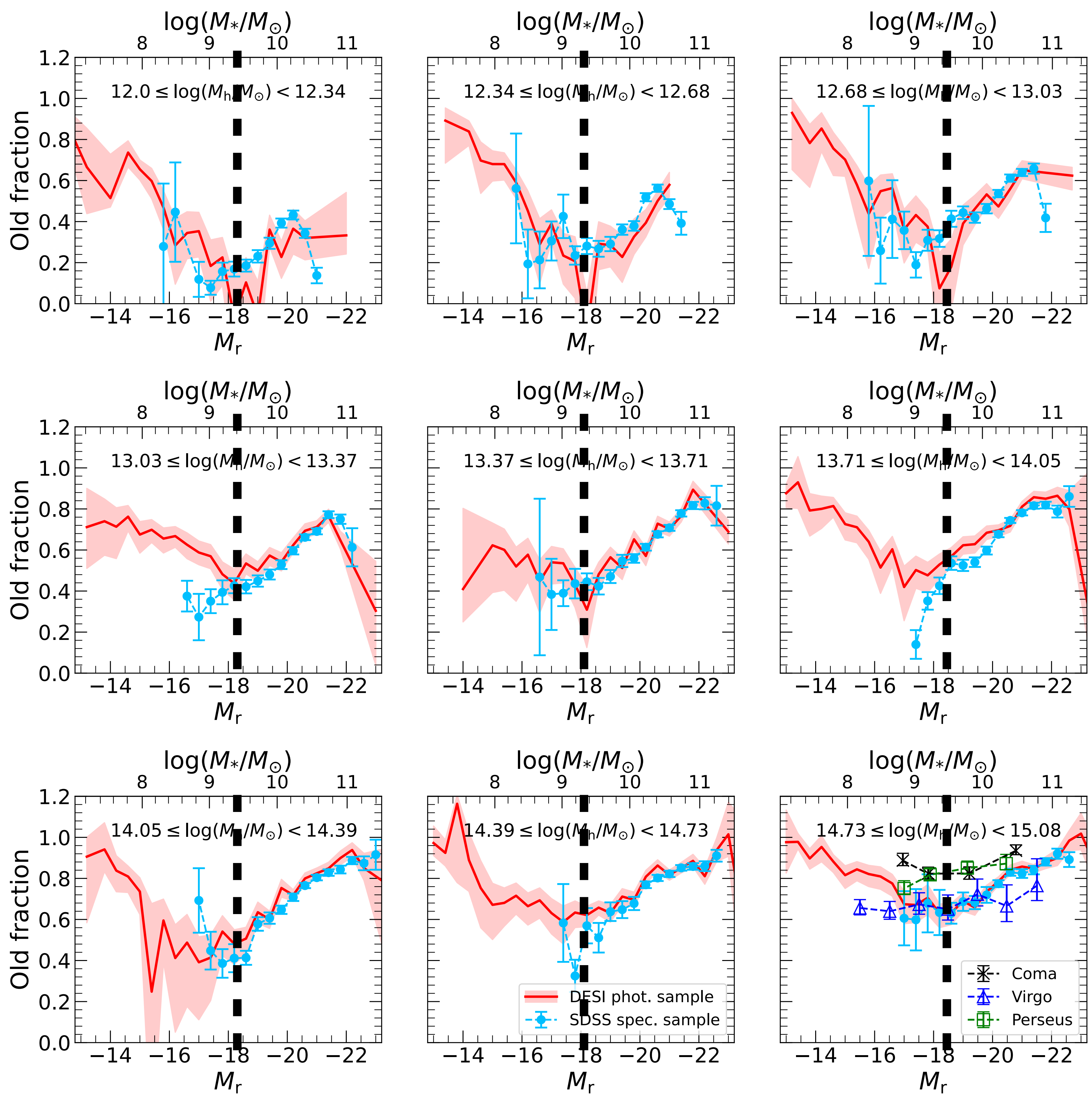
$$\text{Old fraction} = \frac{\mathrm{CLF_{red}}}{\mathrm{CLF_{total}}}$$

- Characteristic stellar mass is independent on halo mass.
- Old fraction increases with decreasing luminosity for all halo mass below characteristic stellar mass.

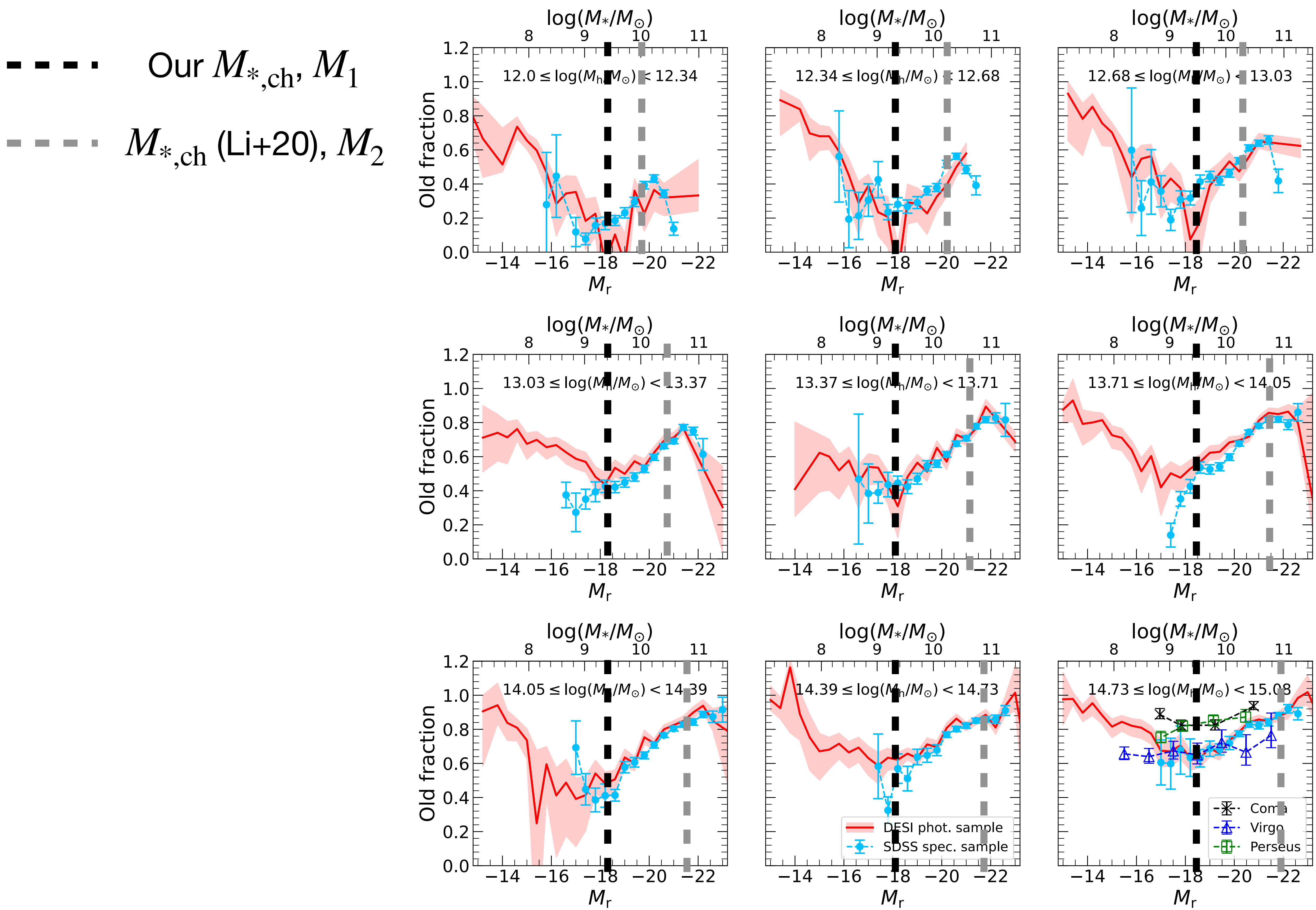


1. **Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$**

Our $M_{*,\mathrm{ch}}$, M_1



1. Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$



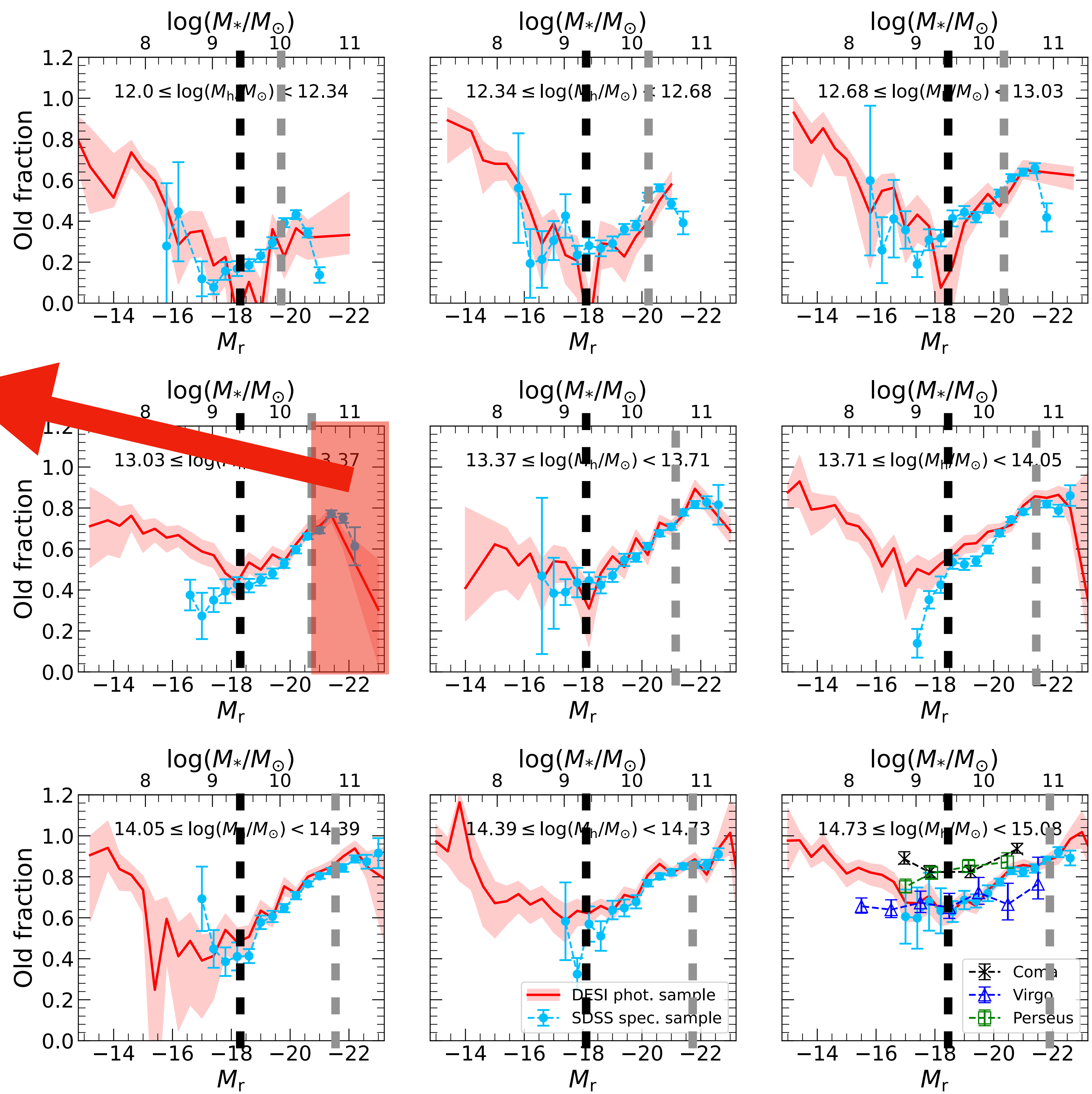
1. Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$

Our $M_{*,\mathrm{ch}}$, M_1

$M_{*,\mathrm{ch}}$ (Li+20), M_2

$M_* > M_2$:

- Internal process, e.g. AGN feedback.



1. Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$

- - - - Our $M_{*,\mathrm{ch}}$, M_1

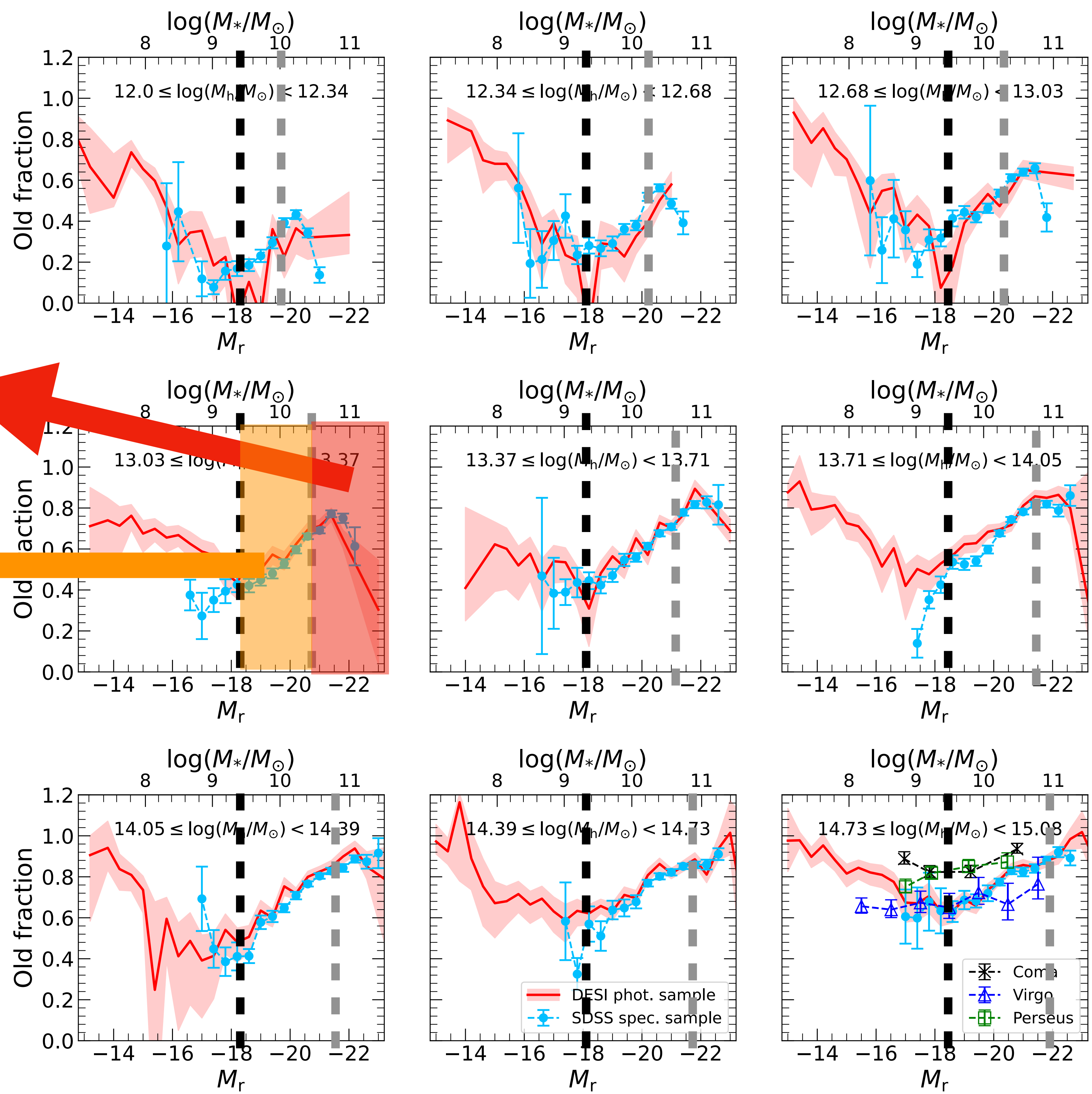
- - - - $M_{*,\mathrm{ch}}$ (Li+20), M_2

$M_* > M_2$:

- Internal process, e.g. AGN feedback.

$M_1 < M_* < M_2$:

- Strangulation.



1. Old fraction of satellite galaxies and characteristic stellar mass scale $M_* \sim 10^{9.5} M_\odot$

Our $M_{*,\mathrm{ch}}$, M_1

$M_{*,\mathrm{ch}}$ (Li+20), M_2

$M_* > M_2$:

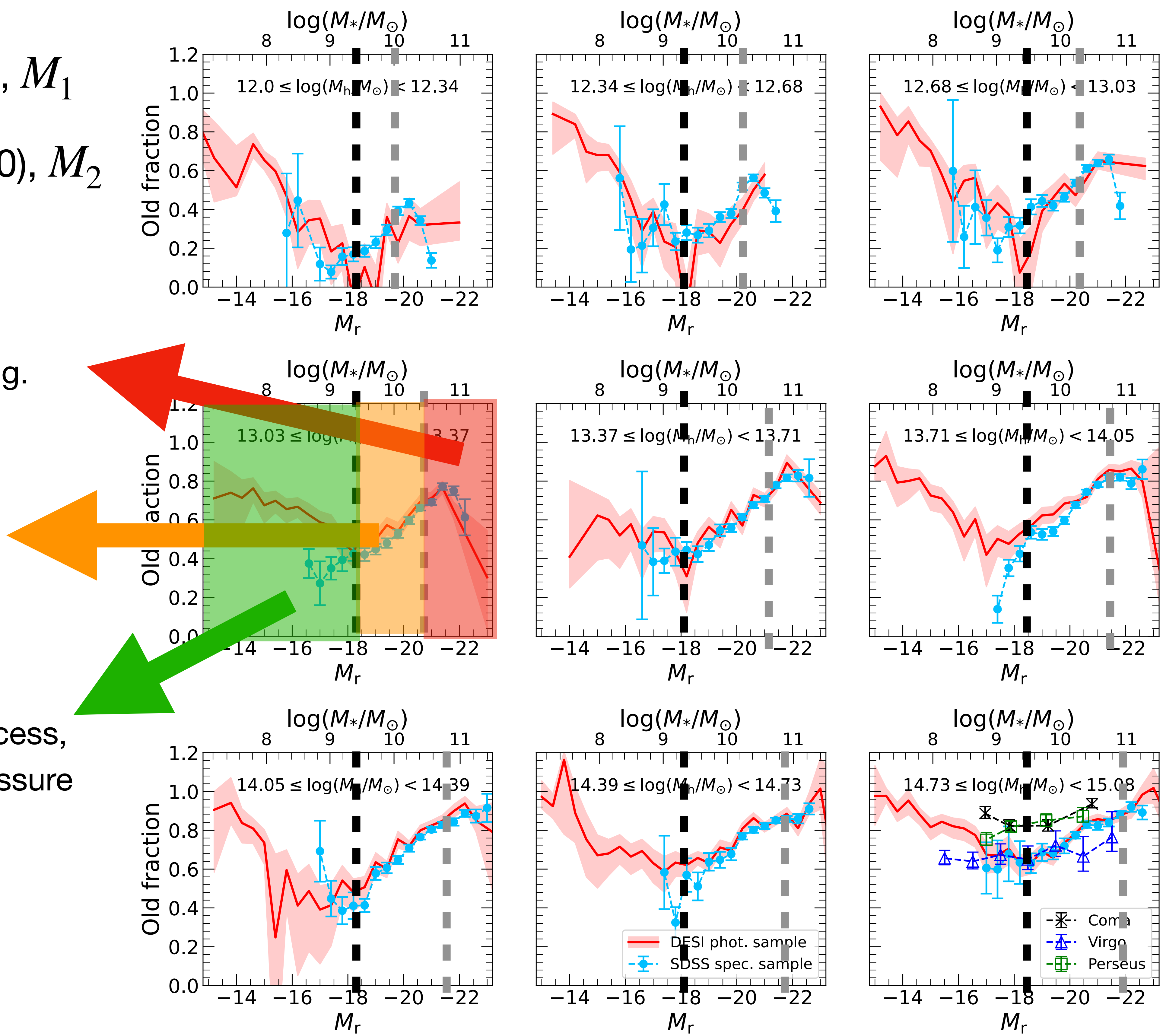
- Internal process, e.g. AGN feedback.

$M_1 < M_* < M_2$:

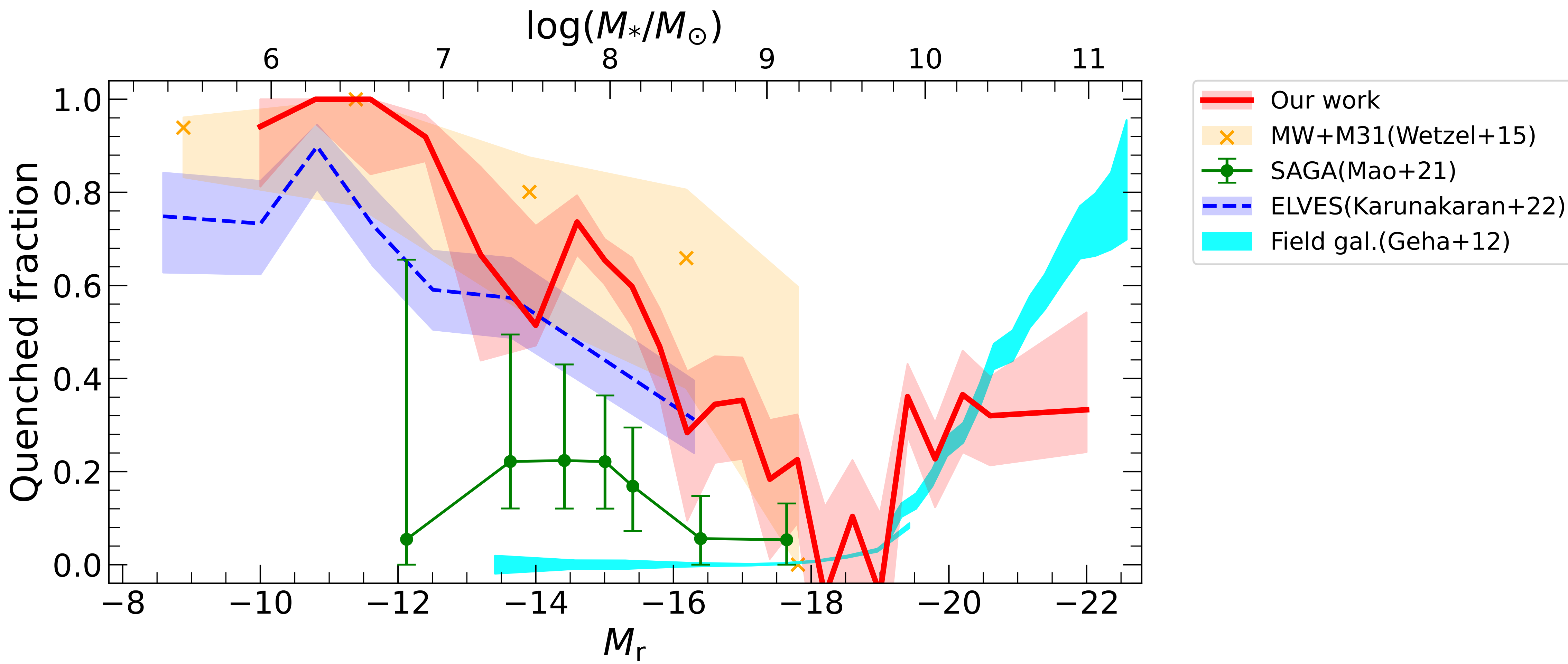
- Strangulation.

$M_* < M_1$:

- Violent external process, e.g. tidal or ram pressure stripping.



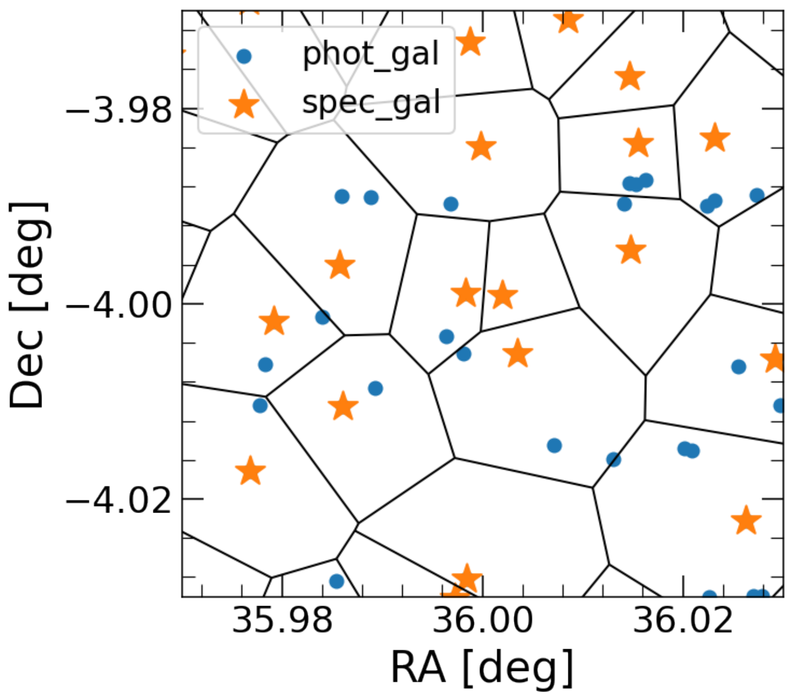
2. Quenched fraction of satellite galaxies in MW-mass halos



- MW is a typical system for the quenched fraction.
- SAGA sample is incomplete at low-mass end (Karunakaran+22).

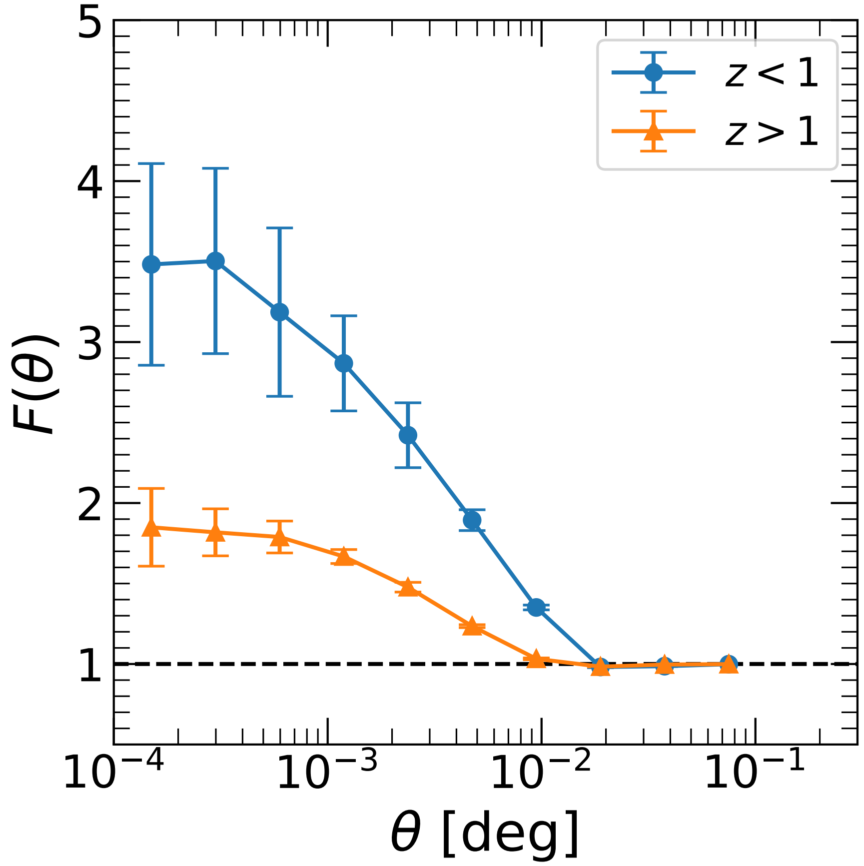
3. Sampling rate effect and fiber collision effect

- **Target sampling rate:** Voronoi tessellation $f_{s,i} = \dfrac{1}{N_{p,i}}$



- **Redshift success rate:**

$f_{z,i} = \dfrac{N_{\rm succ}}{N_{\rm obs}}$ as function of galaxy properties.



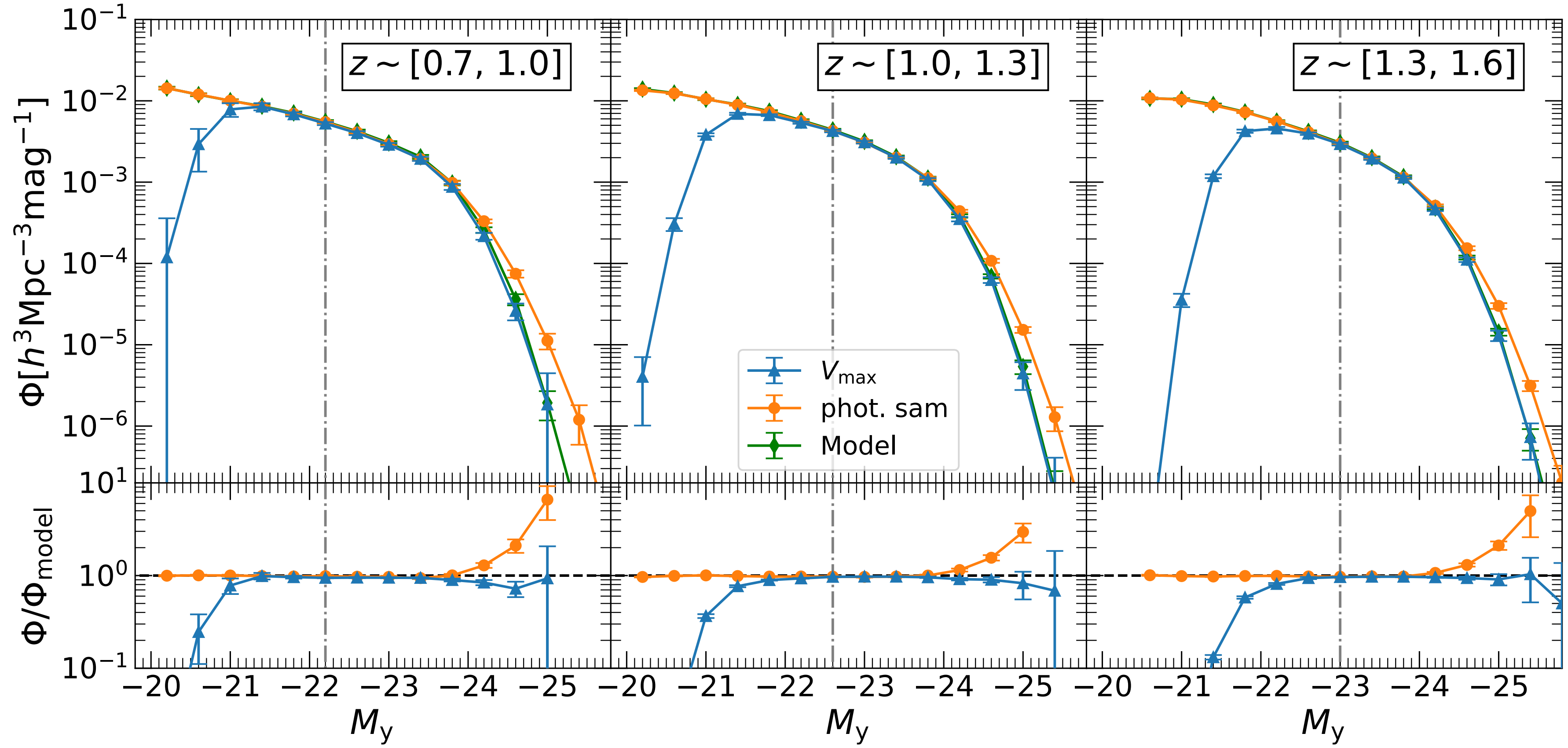
Weight for sampling rate effect:

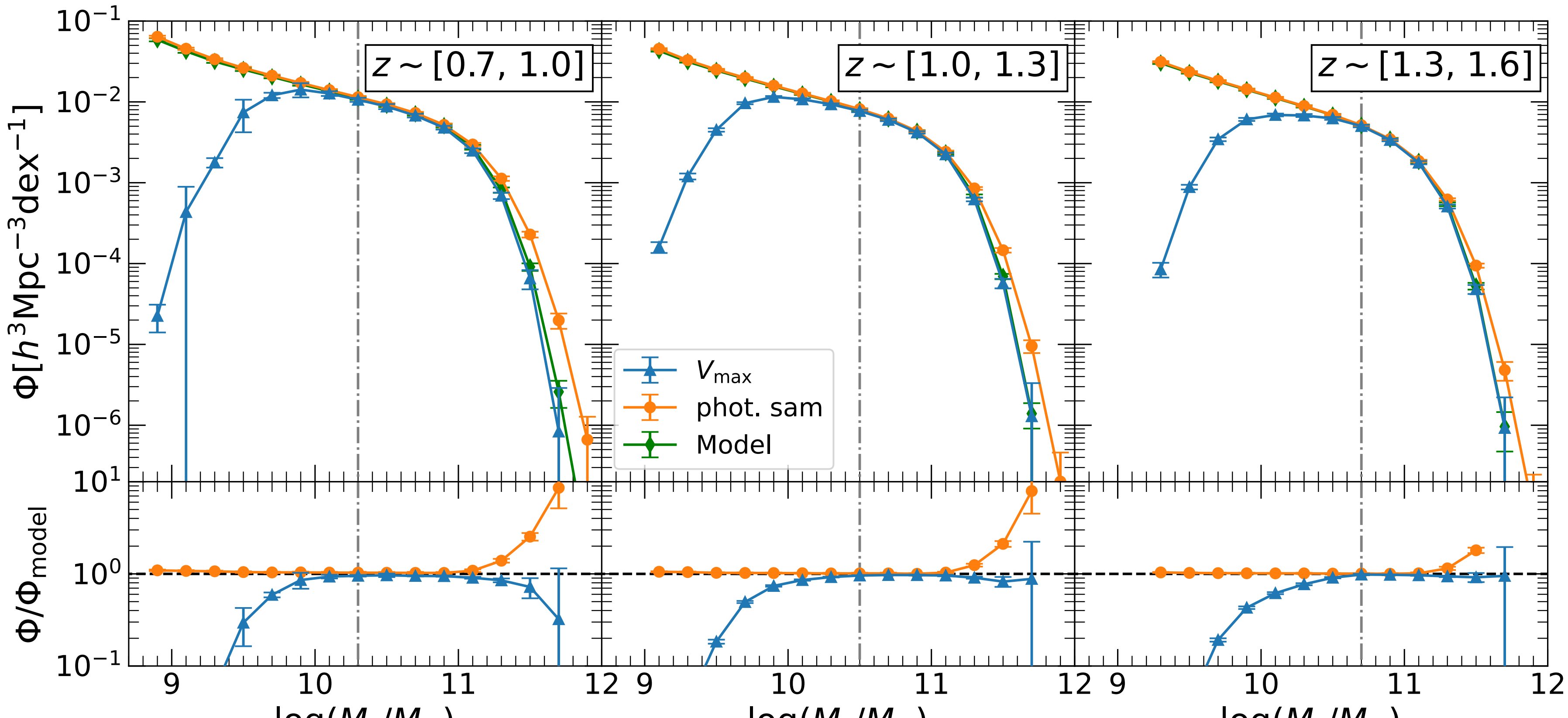
$$w_{\rm sky,i} = \frac{1}{f_{s,i} \times f_{z,i}}$$

Weight for fiber collision effect:

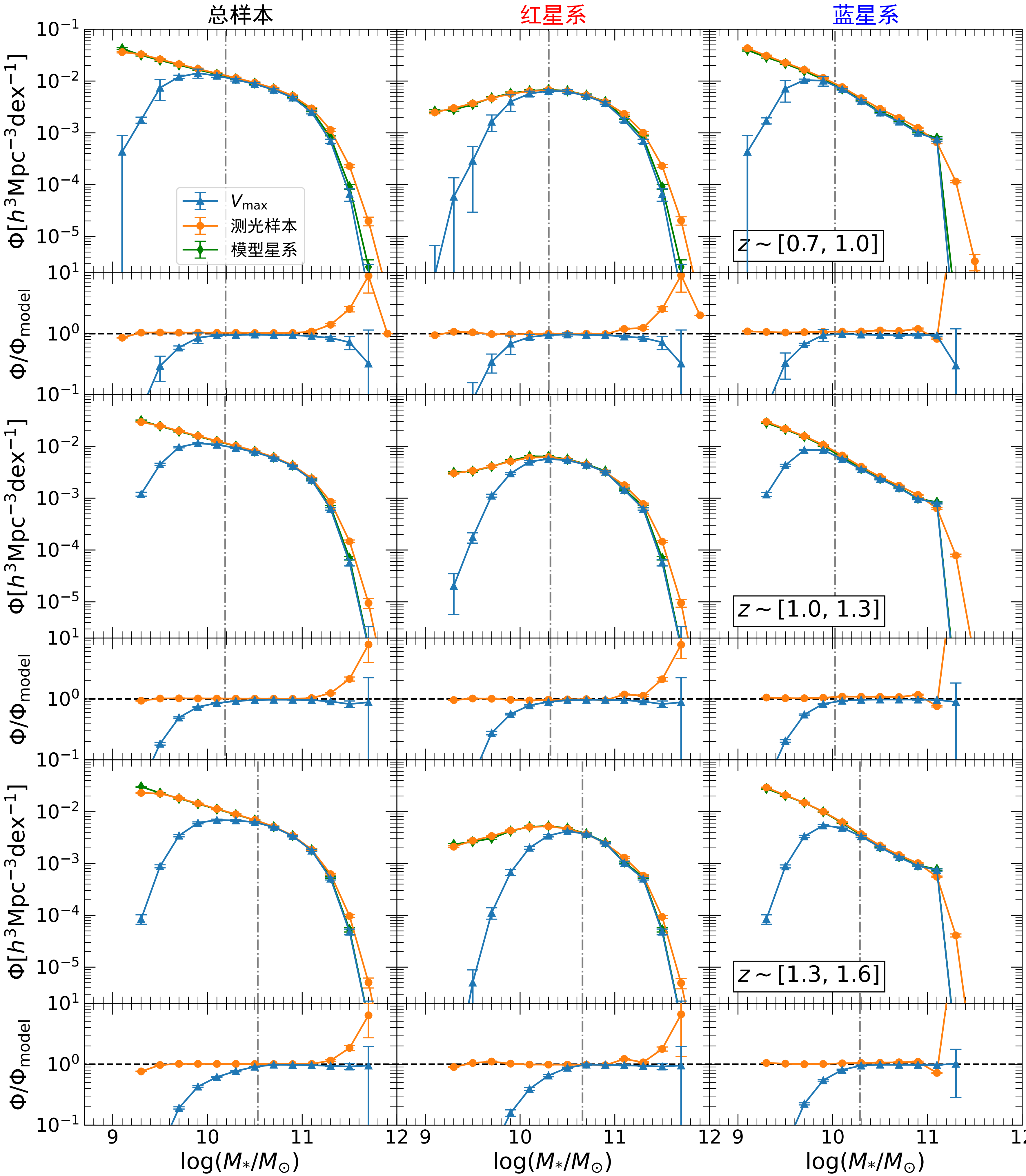
$$w_{\rm coll,ij} = F(\theta) = \frac{1 + w_{\rm p}(\theta)}{1 + w_{\rm s}(\theta)}$$

3. Test the method for measurement of GSMF and LF with our high-z mock surveys

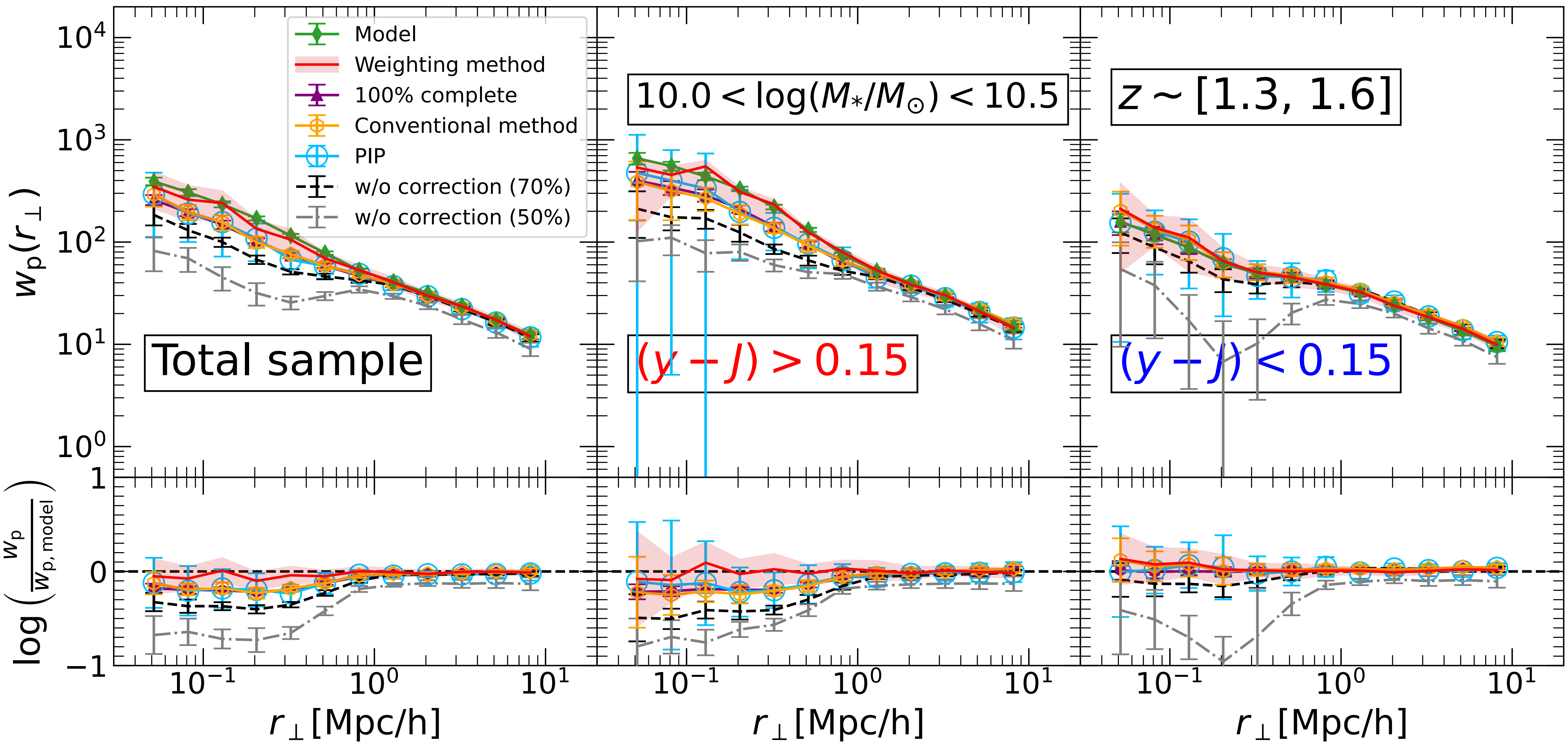




- Spectroscopic sample for high-mass (bright) end and photometric sample for low-mass (faint) end.



总样本
红星系
蓝星系
V_{max}
测光样本
模型星系
$z\sim[0.7, 1.0]$
$z\sim[1.0, 1.3]$
$z\sim[1.3, 1.6]$
$\Phi[h^3\mathrm{Mpc}^{-3}\mathrm{dex}^{-1}]$
Φ/Φ_{model}
$\log(M_*/M_\odot)$


Model
Weighting method
100% complete
Conventional method
PIP
w/o correction (70%)
w/o correction (50%)
Total sample
10.0 < log(M*/M⊙) < 10.5
(y − J) > 0.15
z ∼ [1.3, 1.6]
(y − J) < 0.15
wp(r⊥)
log(wp/wp, model)
r⊥ [Mpc/h]