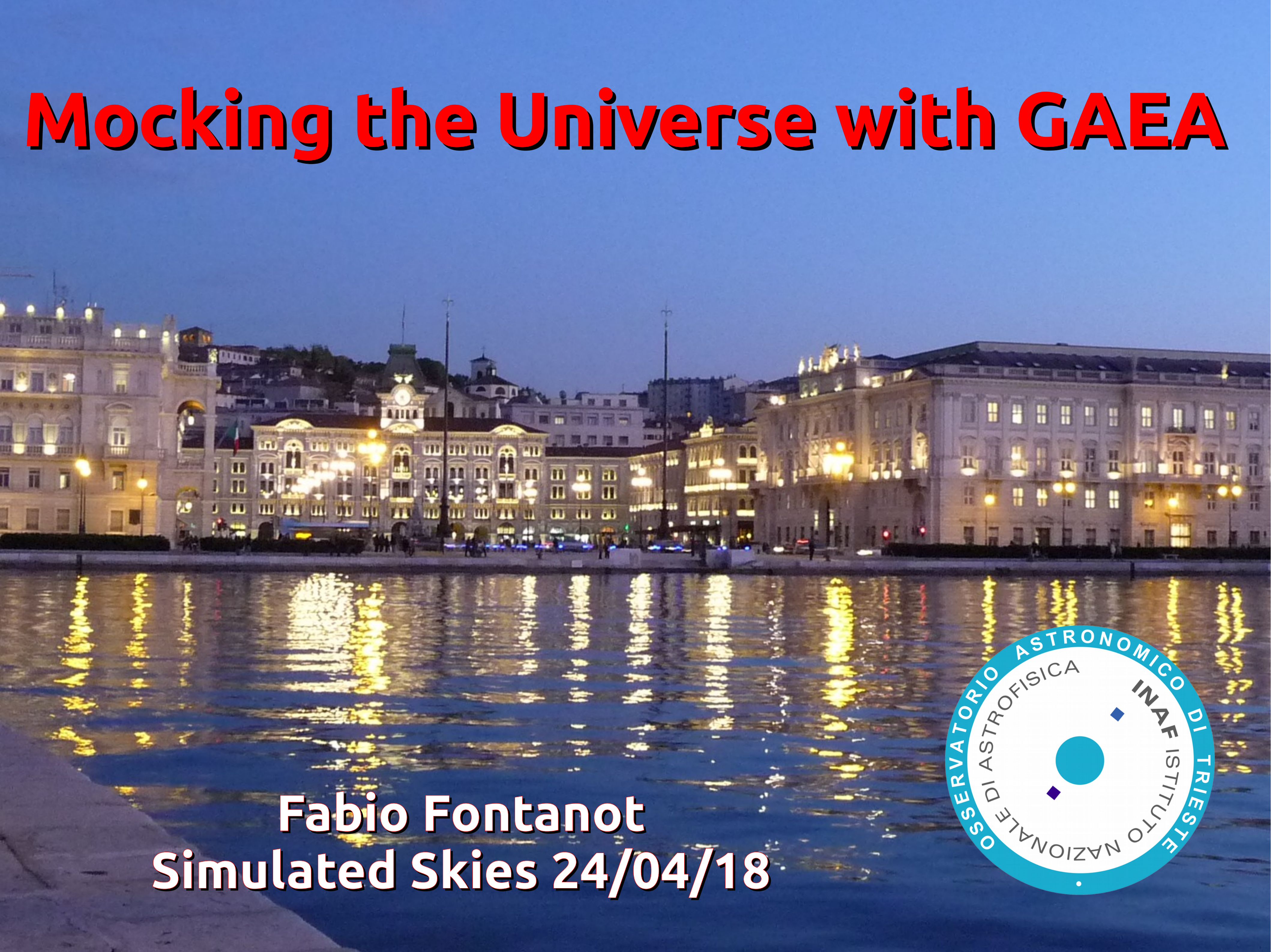
Mocking the Universe with GAEA



Fabio Fontanot

Simulated Skies 24/04/18

OSSERVATORIO ASTRONOMICO DI TRIESTE
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Mocking the Universe with GAEA

In collaboration with:
G. De Lucia, M. Hirschmann, L. Xie, A. Zoldan

Fabio Fontanot
Simulated Skies 24/04/18

Outline

- Part I: SAMs
  - Flexible and fast tools to study galaxy evolution
  - Needs statistical description of LSS (merger trees)
  - Modular components
  - New Semi-analytical Model of Galaxy Formation and Evolution (GAEA)

Outline

- Part I: SAMs
  - Flexible and fast tools to study galaxy evolution
  - Needs statistical description of LSS (merger trees)
  - Modular components
  - New Semi-analytical Model of Galaxy Formation and Evolution (GAEA)
- Part II: Dark Energy Cosmologies in SAMs


GAlaxy Evolution and Assembly

GAEA

- Evolution of the De Lucia & Blaizot 2007 SAM

GAEA

- Evolution of the De Lucia & Blaizot 2007 SAM
- Detailed Chemical Enrichment De Lucia+14

GAEA

- Evolution of the De Lucia & Blaizot 2007 SAM
- Detailed Chemical Enrichment De Lucia+14
  - No IRA
  - Explicit timescales for SNIa SNII and AGB stars

GAEA

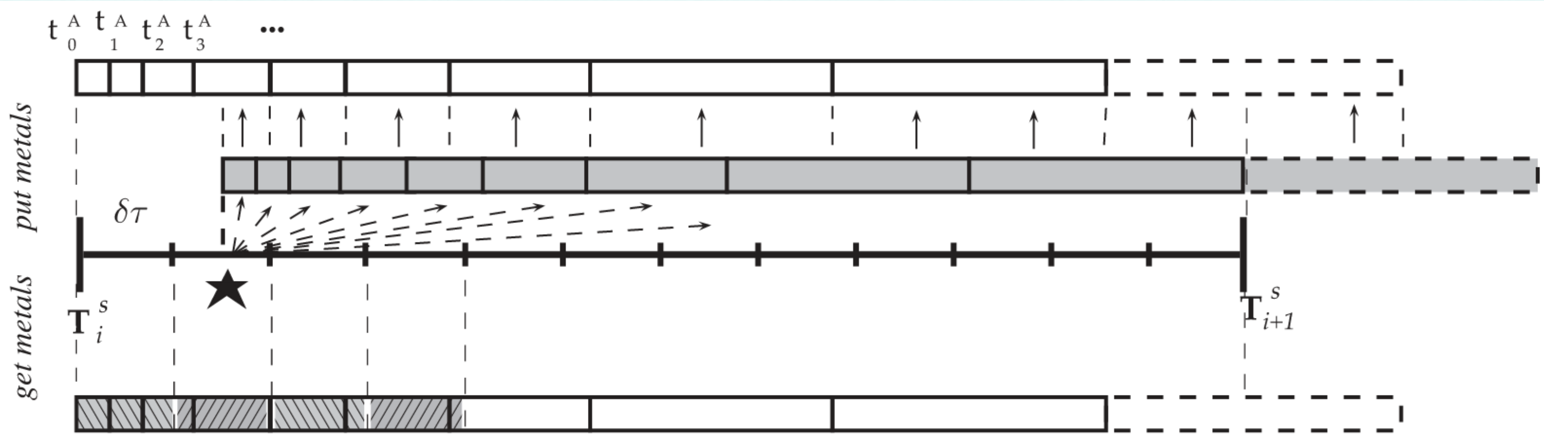
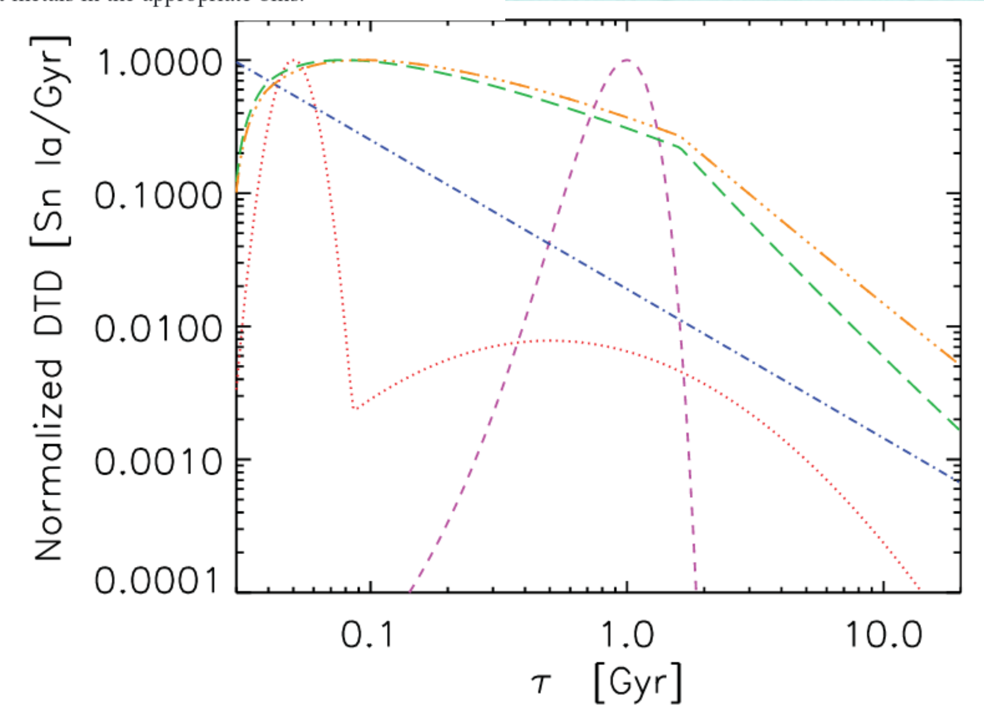


Figure 2. Schematic illustration of the method adopted to store the contributions from different types of stars in the future, and incorporate the metals in the baryonic gaseous phase of model galaxies during their evolution. The thick line shows the time interval between two subsequent snapshots. The two arrays at the top and at the bottom of the figure represent a 'metal restitution array' (RETURNEDMET) that is associated with each model galaxy and contains the mass of elements returned, at any time in the future, by the SSPs that constitute the model galaxy under consideration. At each time-step, the code computes the elements produced and adds them to the future bins (in case there is an episode of star formation), and then reads from the array RETURNEDMET the amount of metals that needs to be re-incorporated. The grey array shown in the figure is a 'virtual array' used to project metals in the appropriate bins.

DeLucia+14



GAEA

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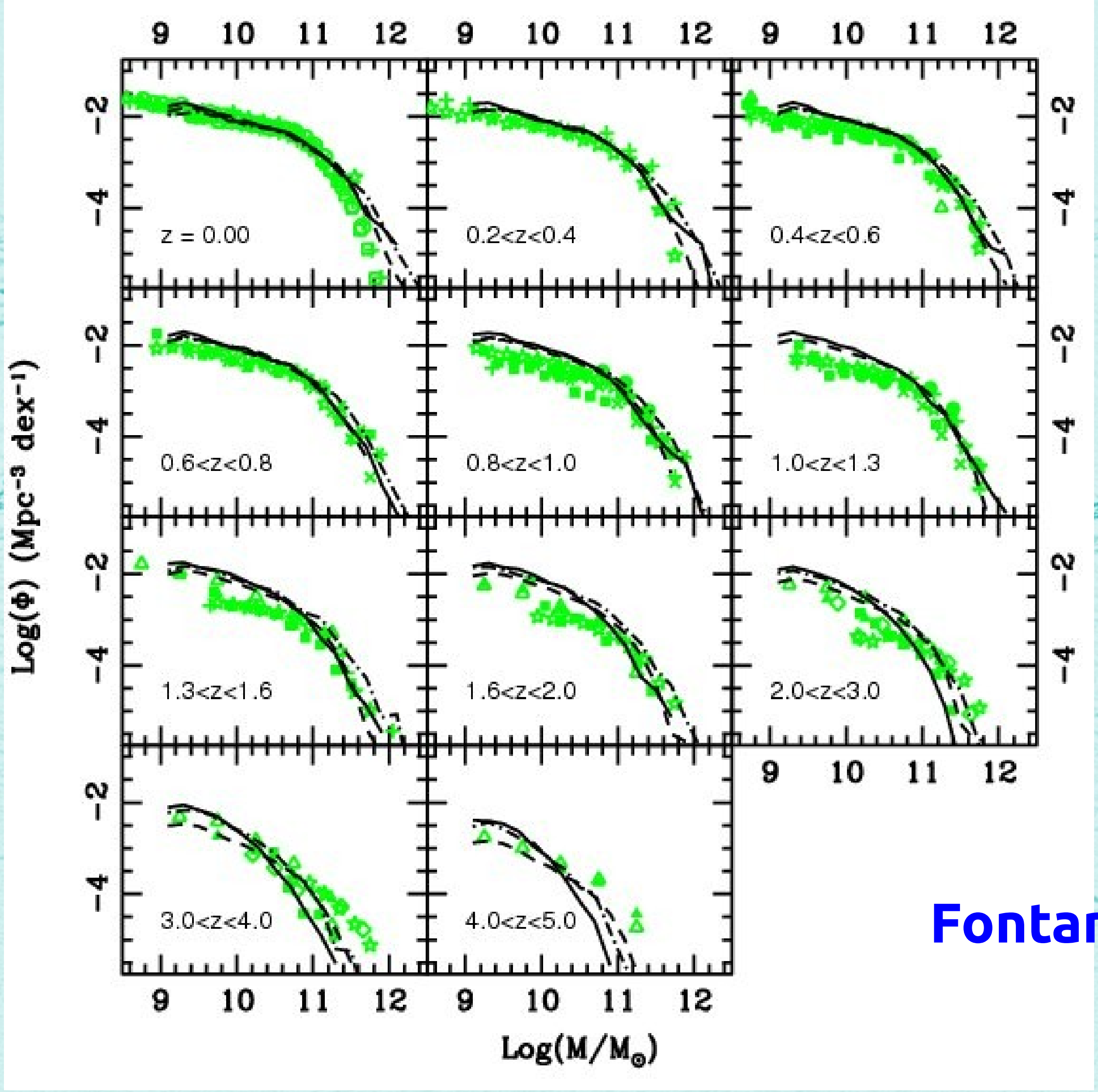
- Detailed Chemical Enrichment De Lucia+14
- Updated treatment of stellar feedback

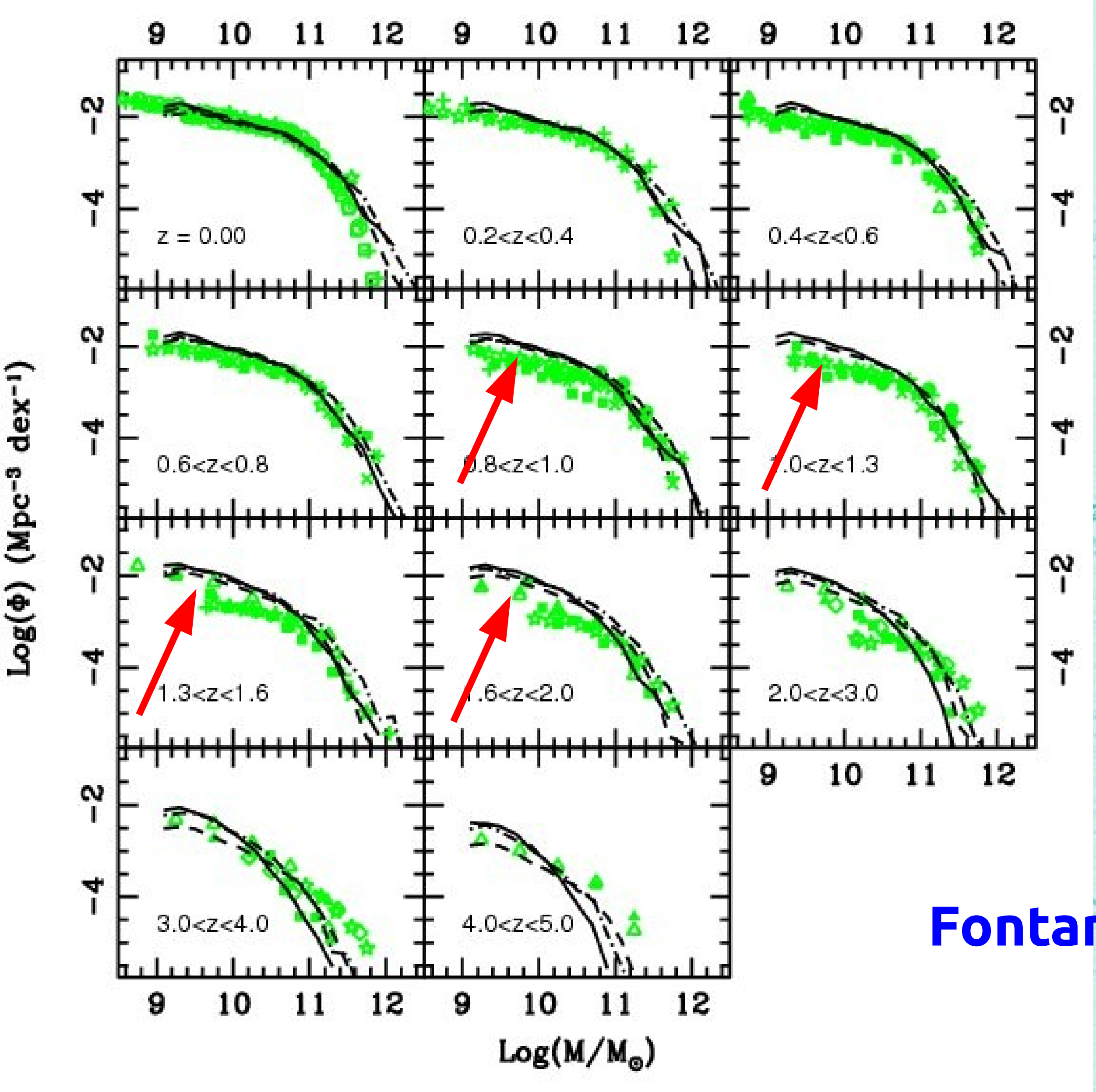
  Hirschmann De Lucia & Fontanot 2016

GSMF



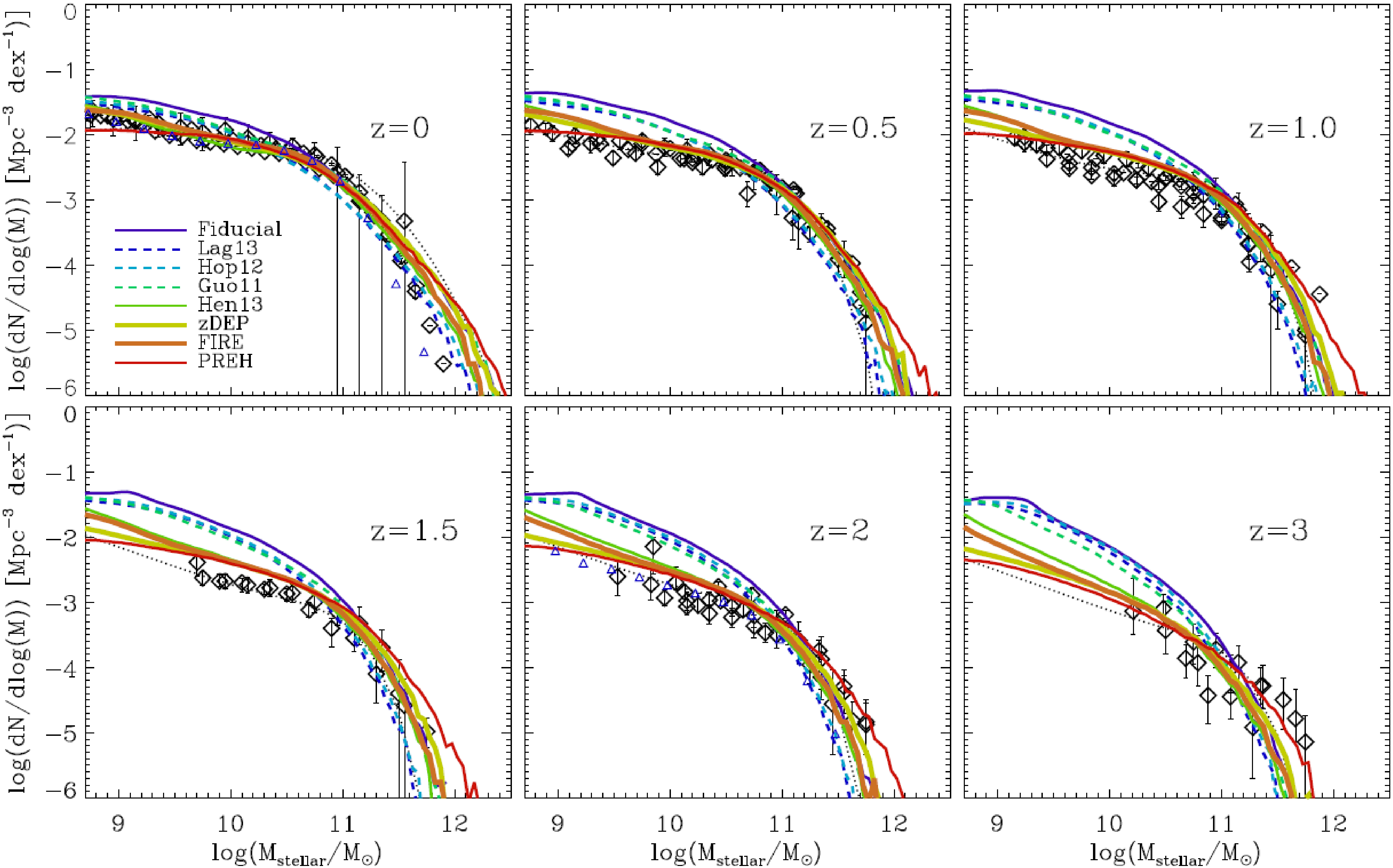
Fontanot+09

GSMF



Fontanot+09

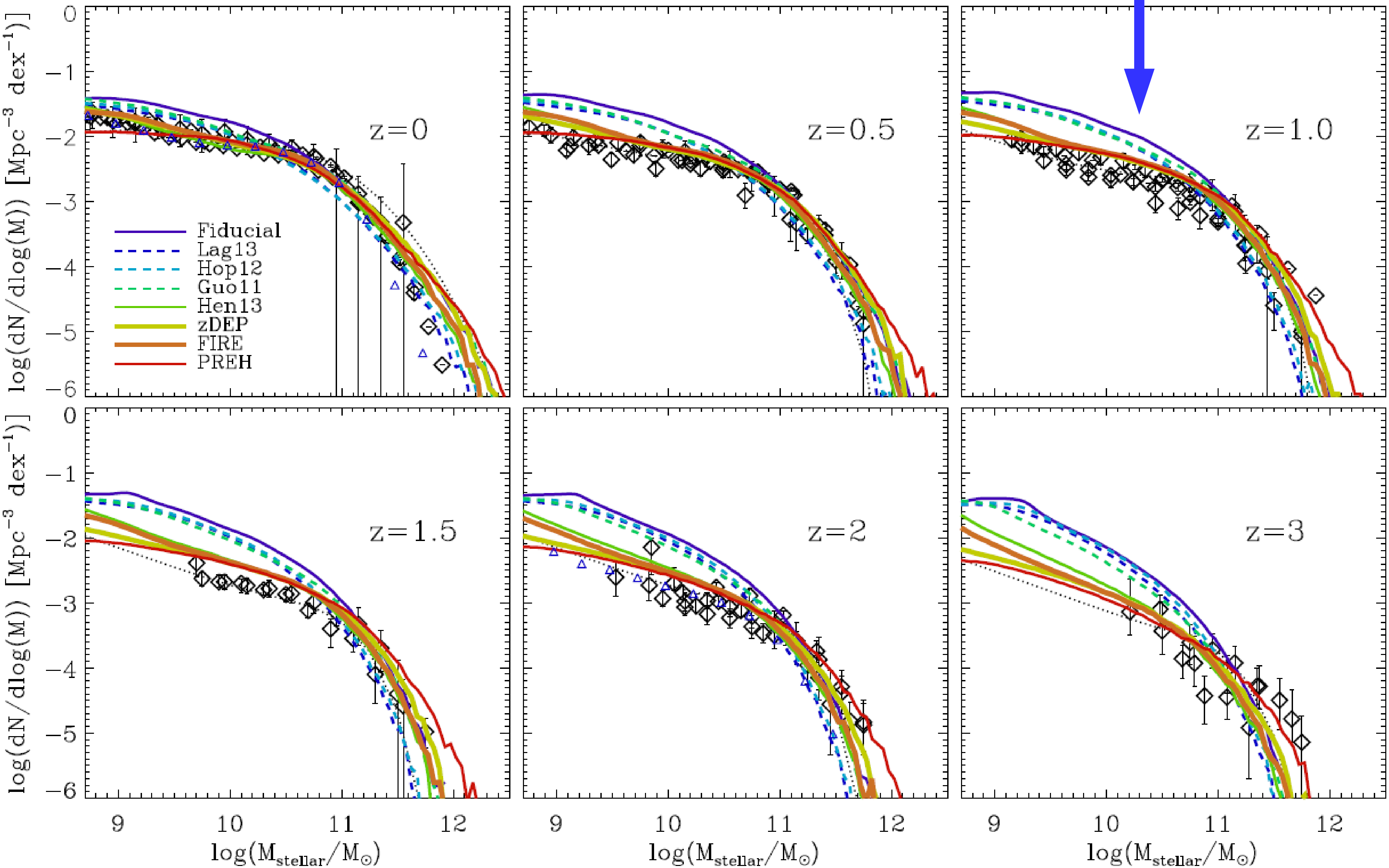
GSMF



Hirschmann, De Lucia & Fontanot 2016 (see also Henriques+13 or White+14)

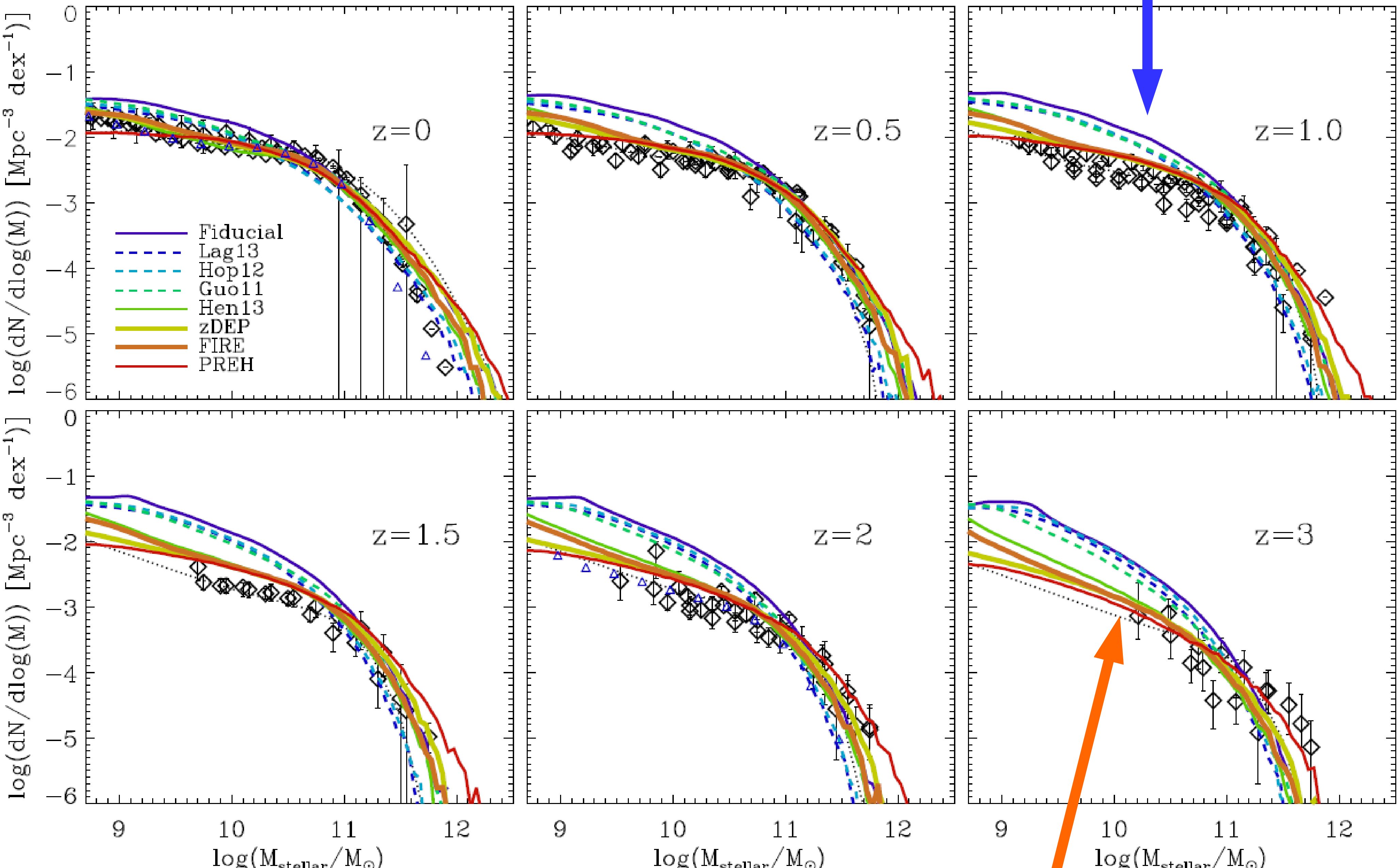
GSMF

“Old” feedback schemes



GSMF

"Old" feedback schemes



Ejective/Preventive feedback

GAEA

- Evolution of the De Lucia & Blaizot 2007 SAM
- Detailed Chemical Enrichment De Lucia+14
- Updated treatment of stellar feedback =>
  Ejective (or preventive) feedback (H16F)

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- Updated treatment of stellar feedback =>

  Ejective (or preventive) feedback (H16F)

  - Modelling Reheating

$$\dot{M}_{\rm reheat} = \epsilon_{\rm reheat}(1+z)^{1.25}\left(\frac{V_{\rm max}}{60\,{\rm km\,s^{-1}}}\right)^{\alpha} \times \dot{M}_{\rm star}$$

"FIRE" simulations
Muratov+15

GAEA

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"FIRE" simulation suite
Muratov+15

  - Modelling Ejection

$$\dot{E}_{\rm FB} = \epsilon_{\rm eject}(1+z)^{1.25}\left(\frac{V_{\rm max}}{60\ {\rm km\,s^{-1}}}\right)^{\alpha} \times 0.5\dot{M}_{\rm star}V_{\rm SN}^{2}$$

→

$$\dot{M}_{\rm eject} = \frac{\dot{E}_{\rm FB} - 0.5\dot{M}_{\rm reheat}V_{\rm vir}^{2}}{0.5V_{\rm vir}^{2}}$$

As in Guo+11

GAEA

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  Ejective (or preventive) feedback (H16F)

  - Modelling Reheating

$$\dot{M}_{\rm reheat} = \epsilon_{\rm reheat}(1+z)^{1.25}\left(\frac{V_{\rm max}}{60\ {\rm km\,s^{-1}}}\right)^{\alpha} \times \dot{M}_{\rm star}$$

"FIRE" simulation suite
Muratov+15

  - Modelling Ejection

$$\dot{E}_{\rm FB} = \epsilon_{\rm eject}(1+z)^{1.25}\left(\frac{V_{\rm max}}{60\ {\rm km\,s^{-1}}}\right)^{\alpha} \times 0.5\dot{M}_{\rm star}V_{\rm SN}^2 \longrightarrow \dot{M}_{\rm eject} = \frac{\dot{E}_{\rm FB} - 0.5\dot{M}_{\rm reheat}V_{\rm vir}^2}{0.5V_{\rm vir}^2}$$

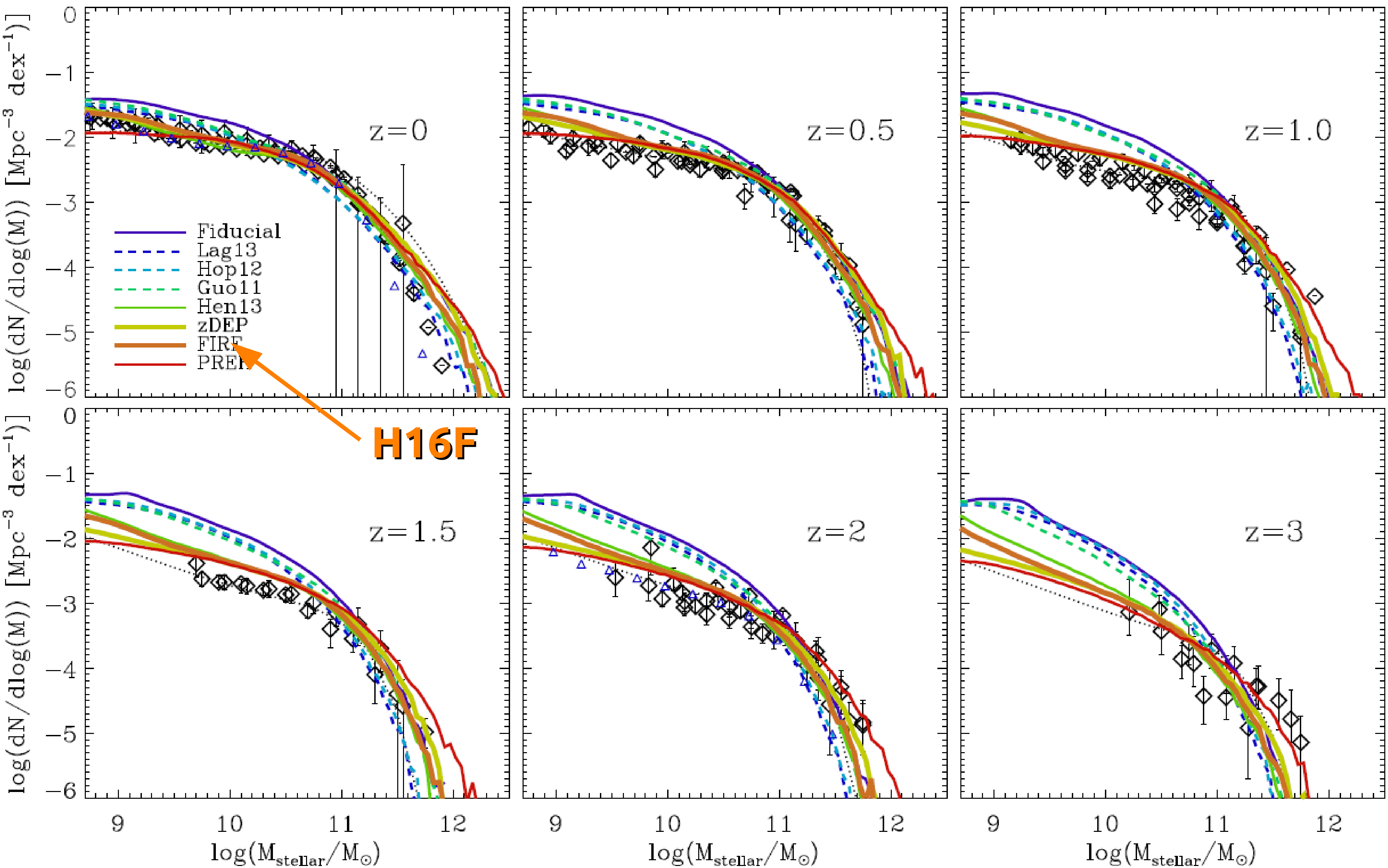
As in Guo+11

  - Mass dependent reincorporation

$$M_{\rm reinc} = \gamma\frac{M_{\rm eject}}{t_{\rm reinc}},\ \ {\rm with}\ t_{\rm reinc} = \frac{10^{10}\,{\rm M}_\odot}{M_{\rm vir}} \times yr$$

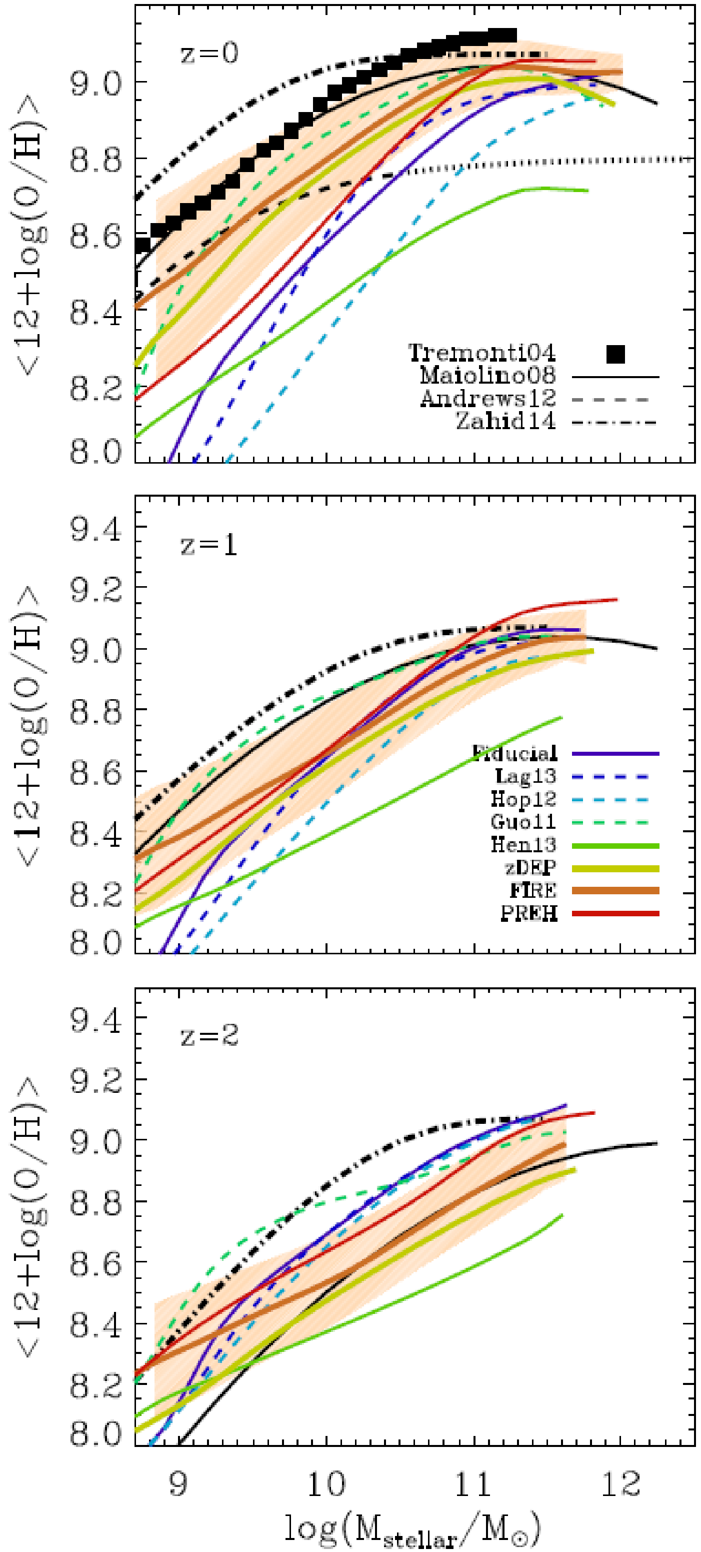
As in Henriques+13

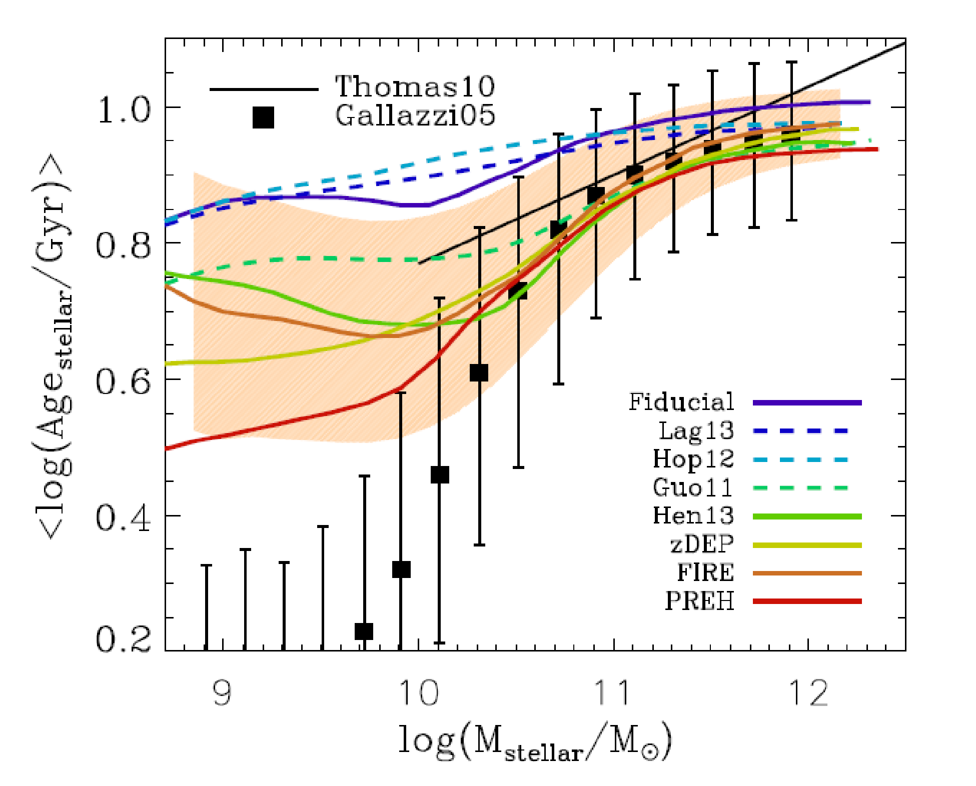
GAEA



Hirschmann, De Lucia & Fontanot 2016 (see also Henriques+13 or White+14)

GAEA

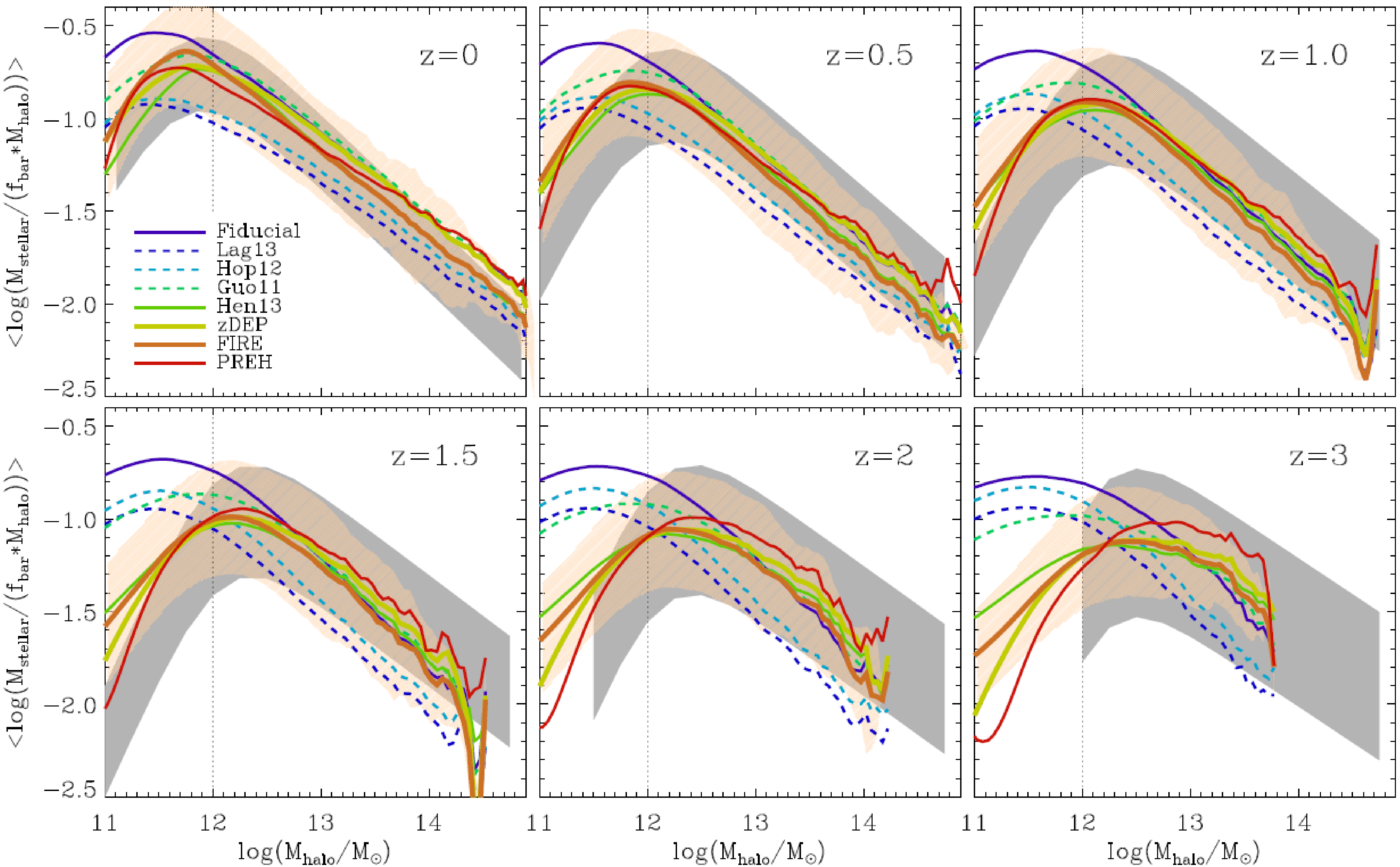


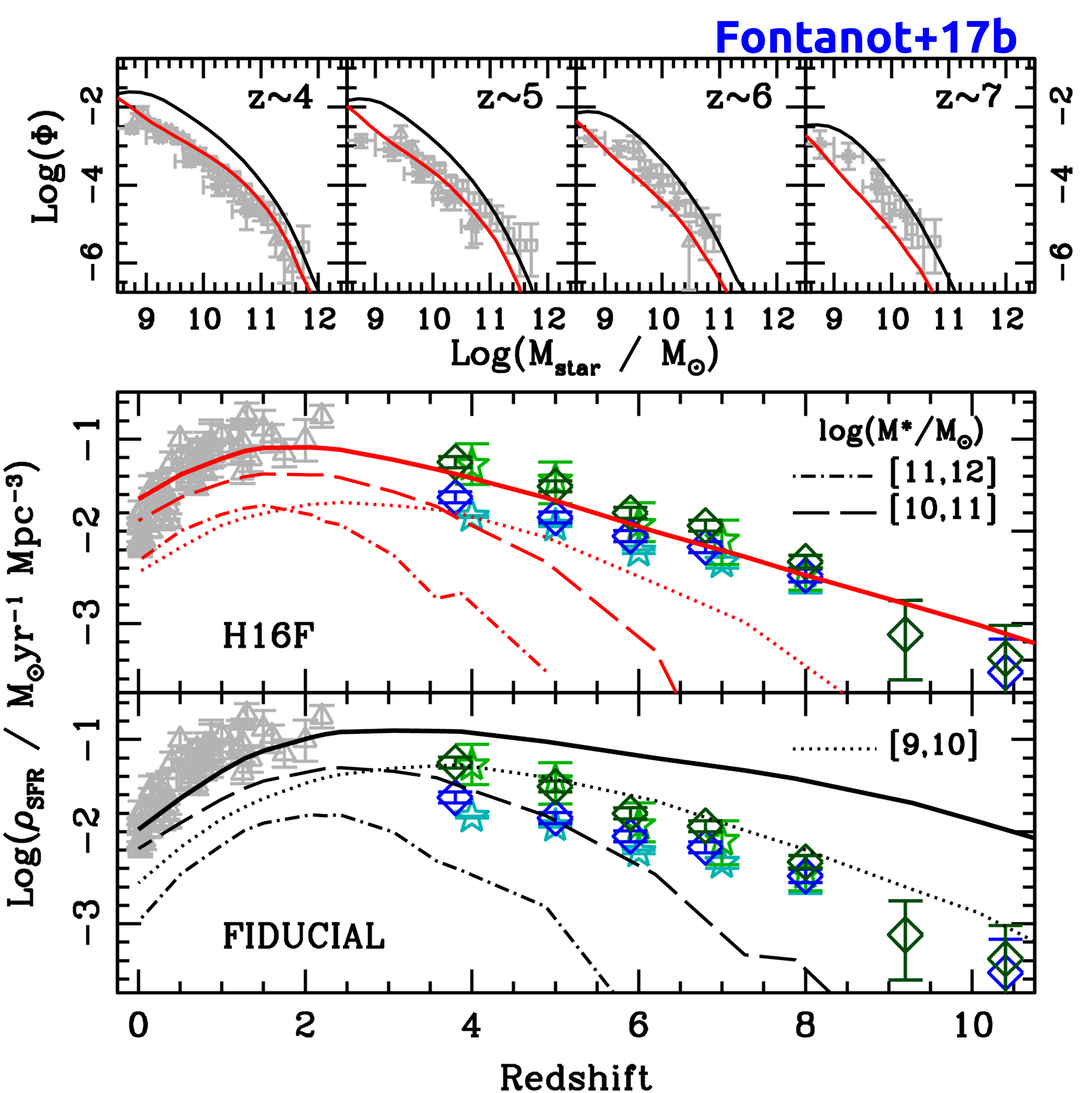


Hirschmann, De Lucia & Fontanot 2016

GAEA

Hirschmann, De Lucia & Fontanot 2016




Fontanot+17b
z~4
z~5
z~6
z~7
Log(Φ)
Log(M_star / M_⊙)
log(M*/M_⊙)
[11,12]
[10,11]
[9,10]
H16F
FIDUCIAL
Log(ρ_SFR / M_⊙yr⁻¹ Mpc⁻³)
Redshift

GAEA

- Evolution of the De Lucia & Blaizot 2007 SAM
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- Updated treatment of stellar feedback

  Hirschmann De Lucia & Fontanot 2016

- Other projects

GAEA

- Evolution of the De Lucia & Blaizot 2007 SAM
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- Other projects
  - H2-based star formation prescriptions Xie+17

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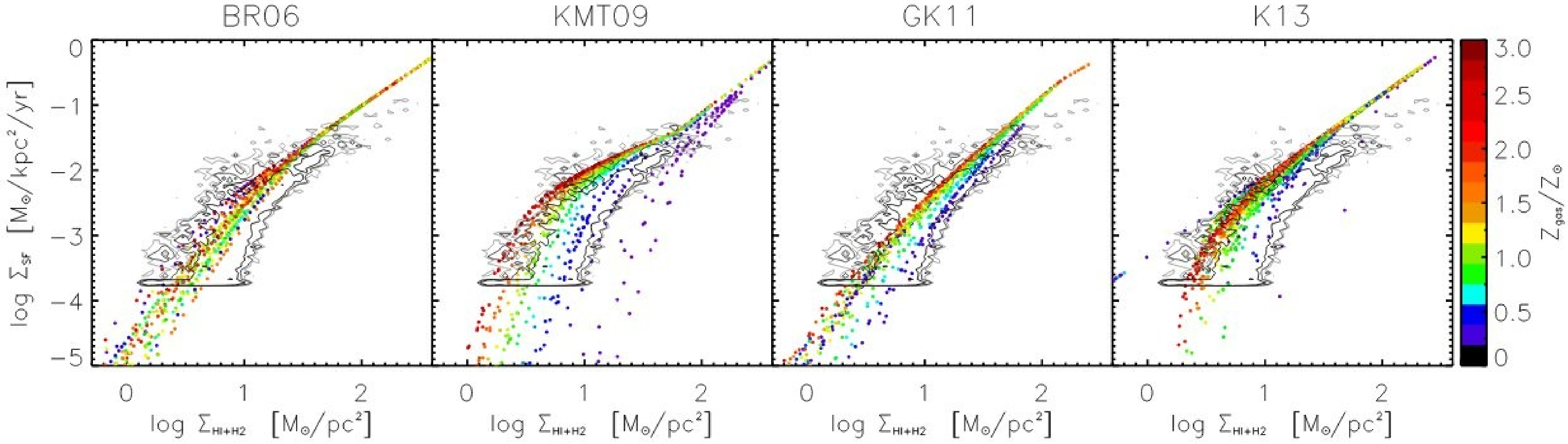

GAEA

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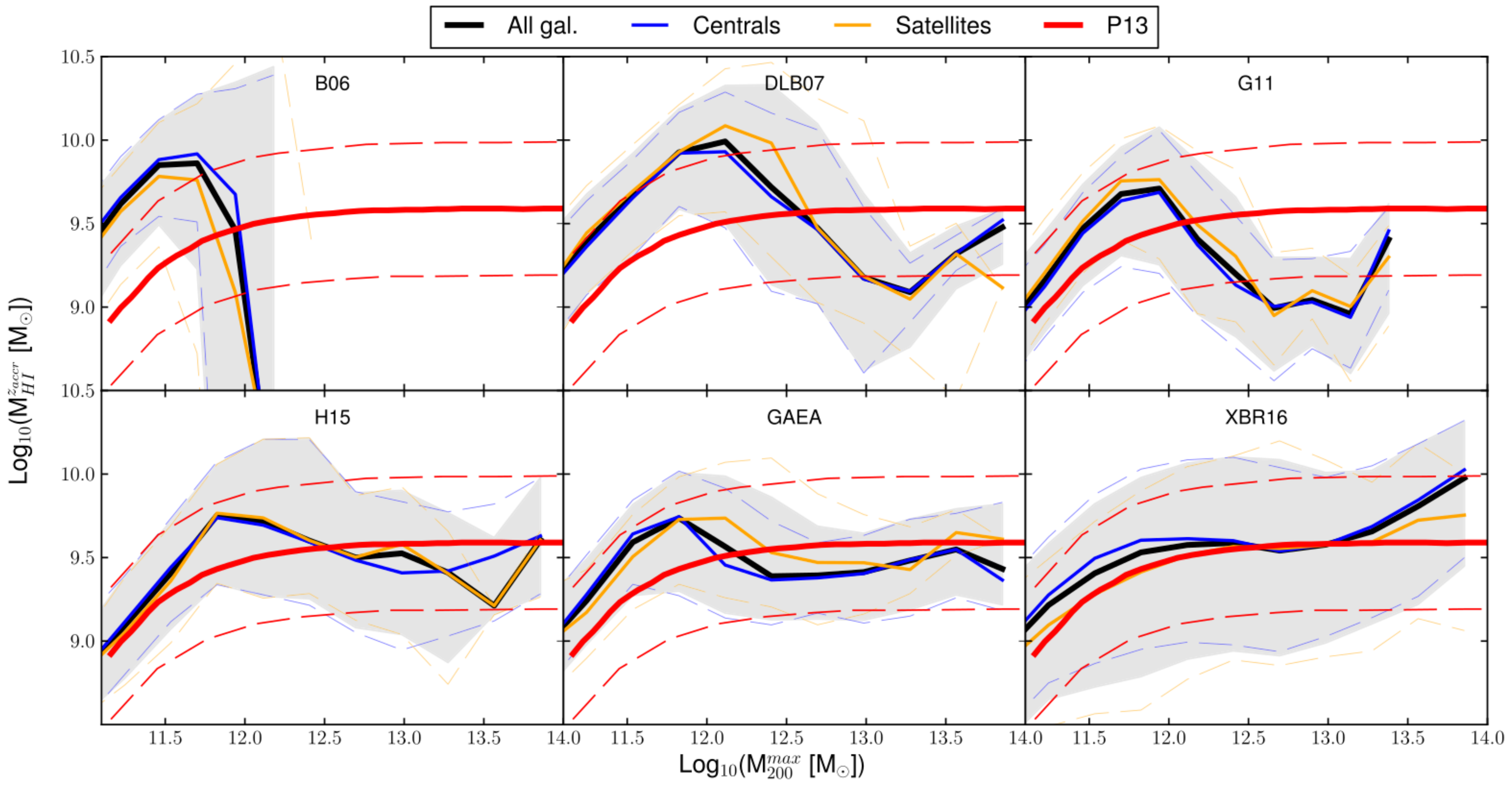
- Other projects
  - H_2-based star formation prescriptions Xie+17
  - HI content of DMHs Zoldan+17

HI content of DM haloes



Zoldan+17

Light-cone Generator

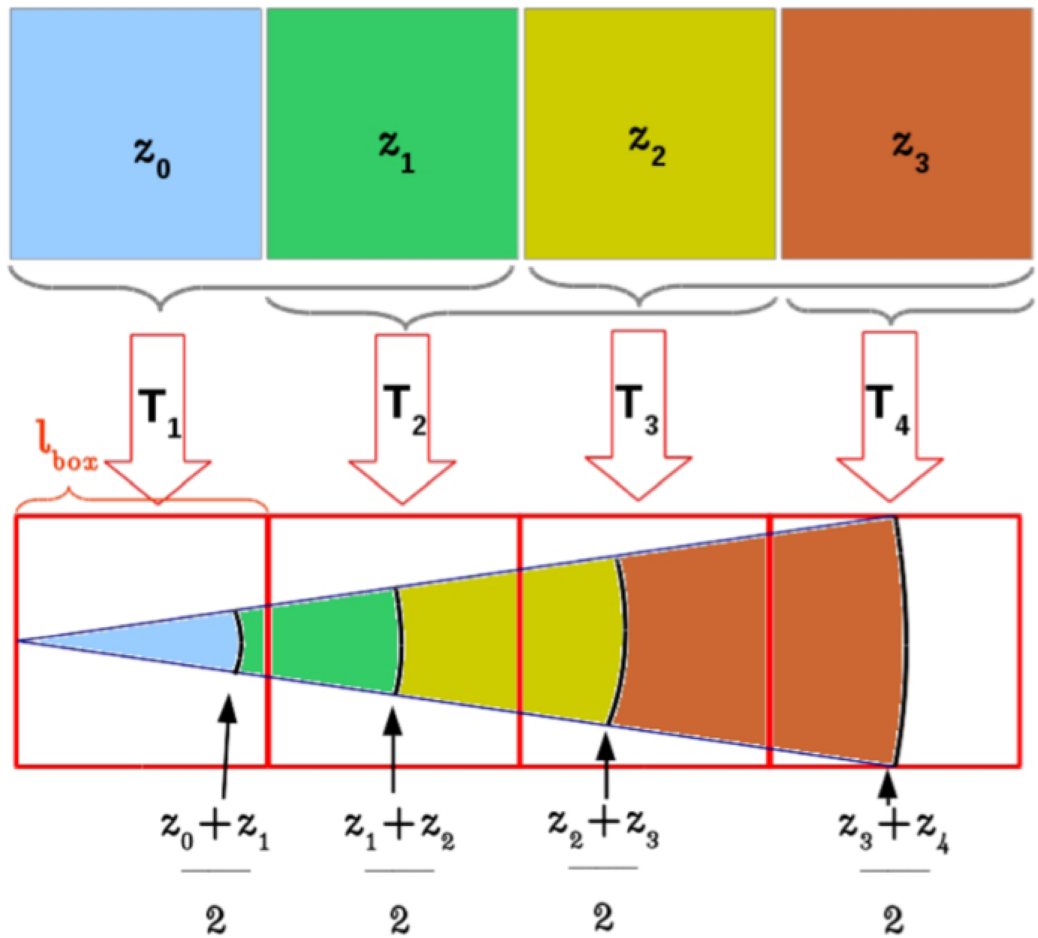


Figure 1. A schematic illustration of our light-cone construction algorithm: a grid of cubic boxes with size length l_{box} (red) is built over the cone, and galaxies inside each box of the grid are randomly shifted/rotated/inverted depending on the specific box they end up in. Galaxies are extracted from the simulation output with redshift closest to the comoving distance to the observer.

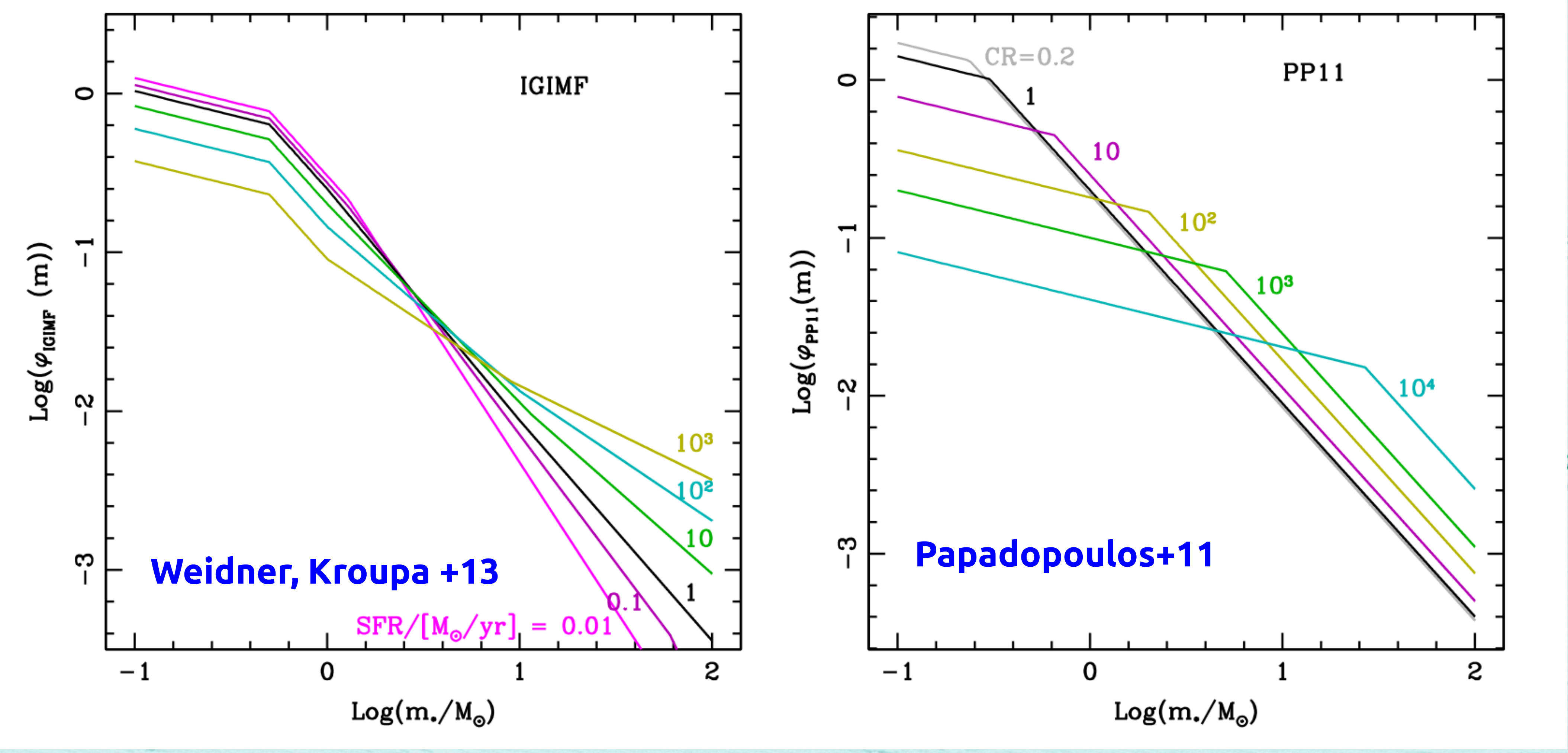
Zoldan+17

GAEA

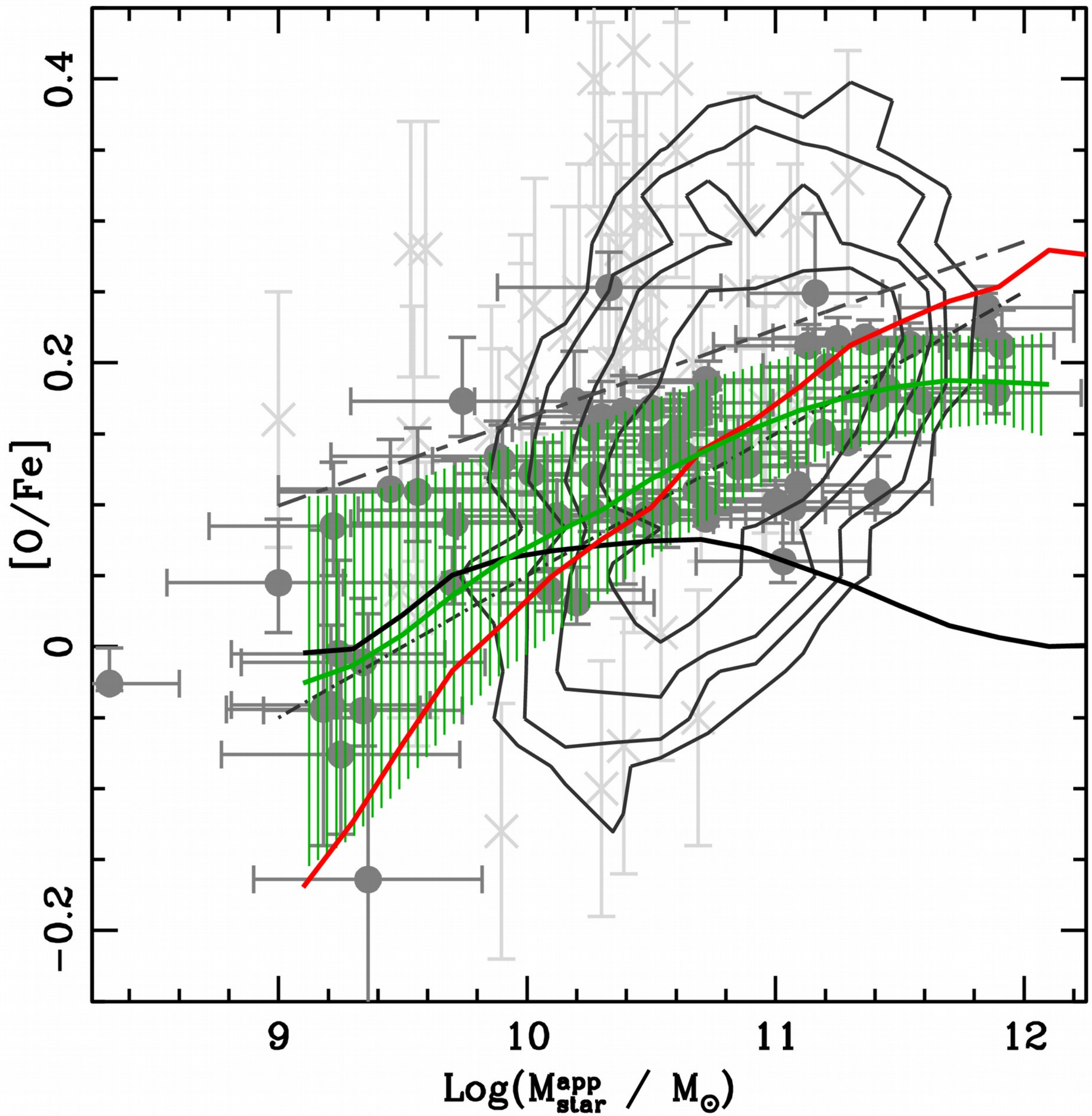
- Evolution of the De Lucia & Blaizot 2007 SAM
- Detailed Chemical Enrichment De Lucia+14
- Updated treatment of stellar feedback

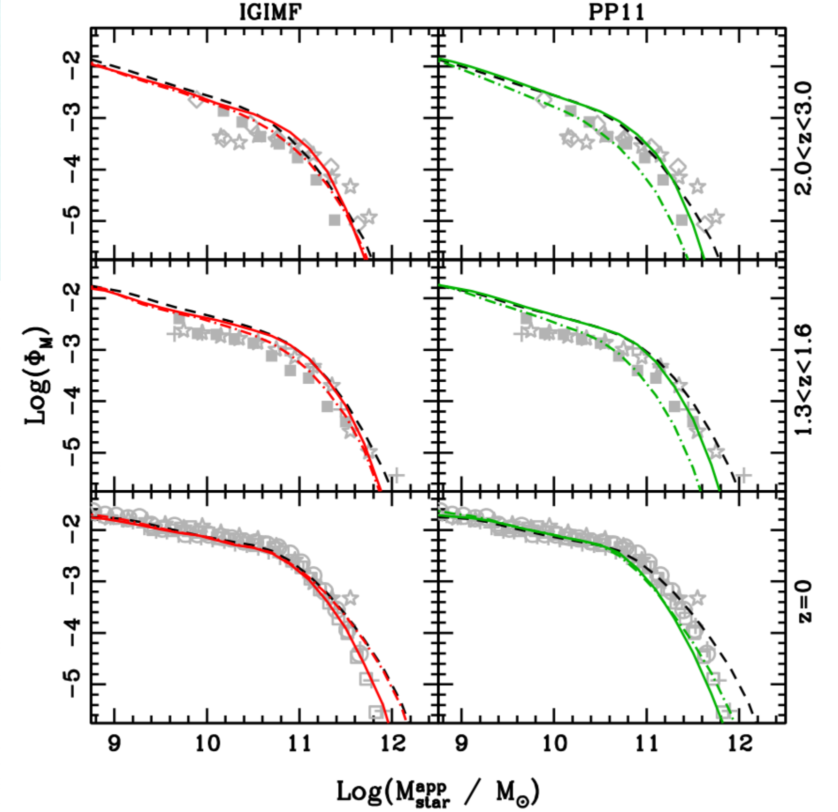
  Hirschmann De Lucia & Fontanot 2016
- Other projects
  - H_2-based star formation prescriptions Xie+17
  - HI content of DMHs Zoldan+17
  - Variable IMF Fontanot+17,18

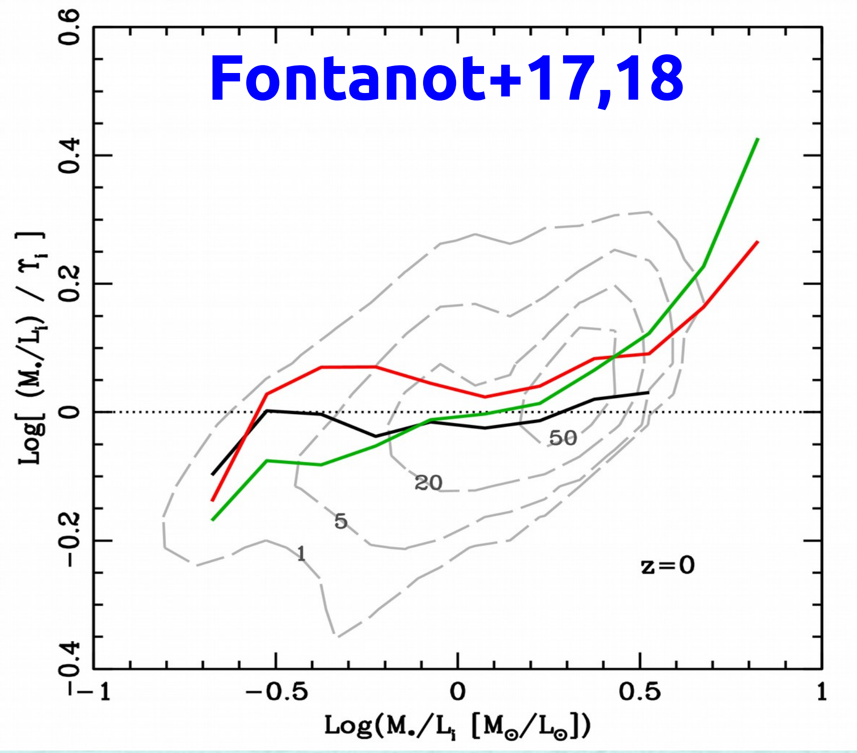
Variable IMF



Variable IMF







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  Hirschmann De Lucia & Fontanot 2016

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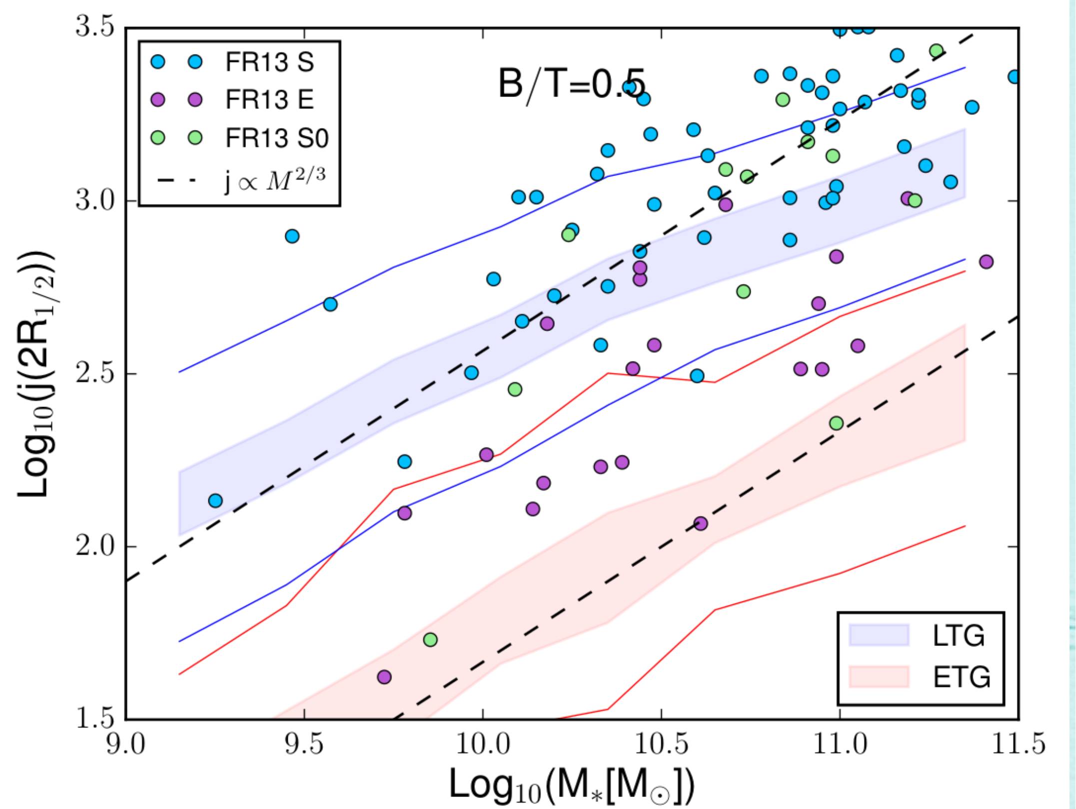
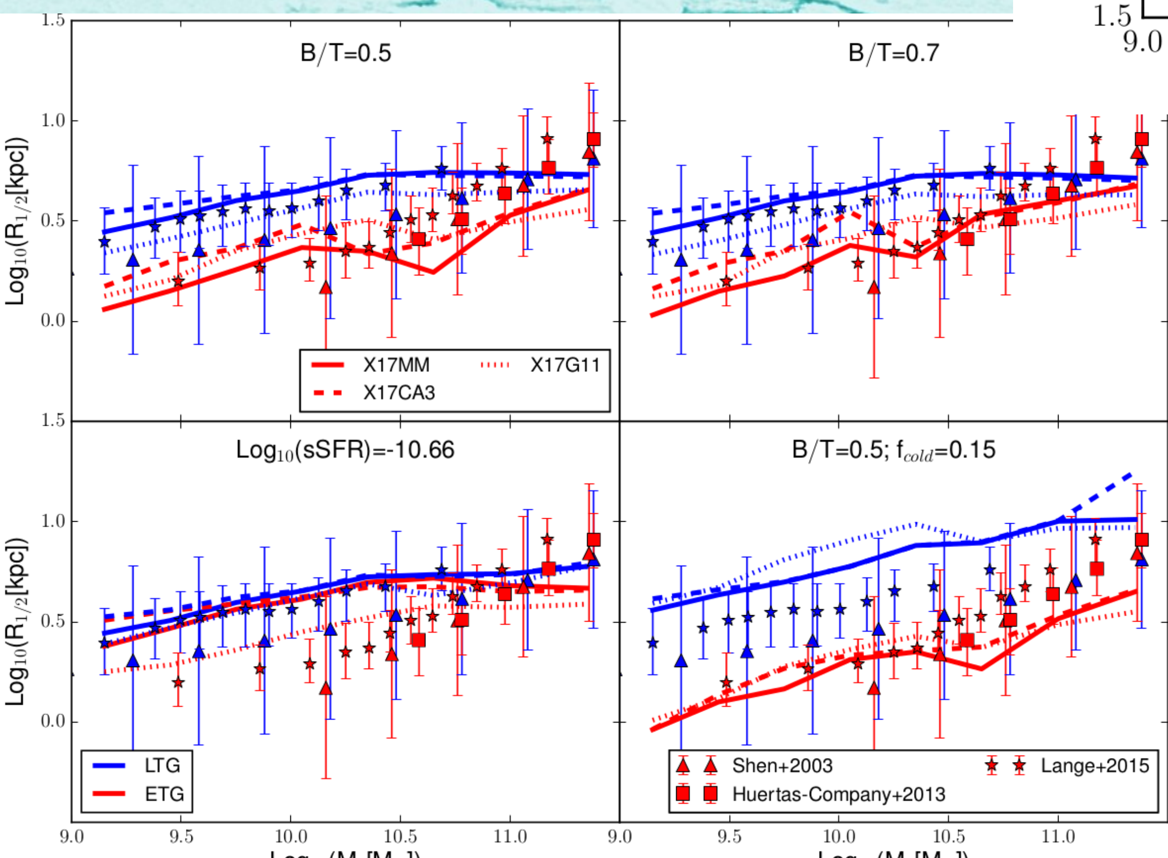
  - HI content of DMHs Zoldan+17
  - Variable IMF Fontanot+17,18
  - Scaling Relations Zoldan+18

Sizes & Ang. Momenta



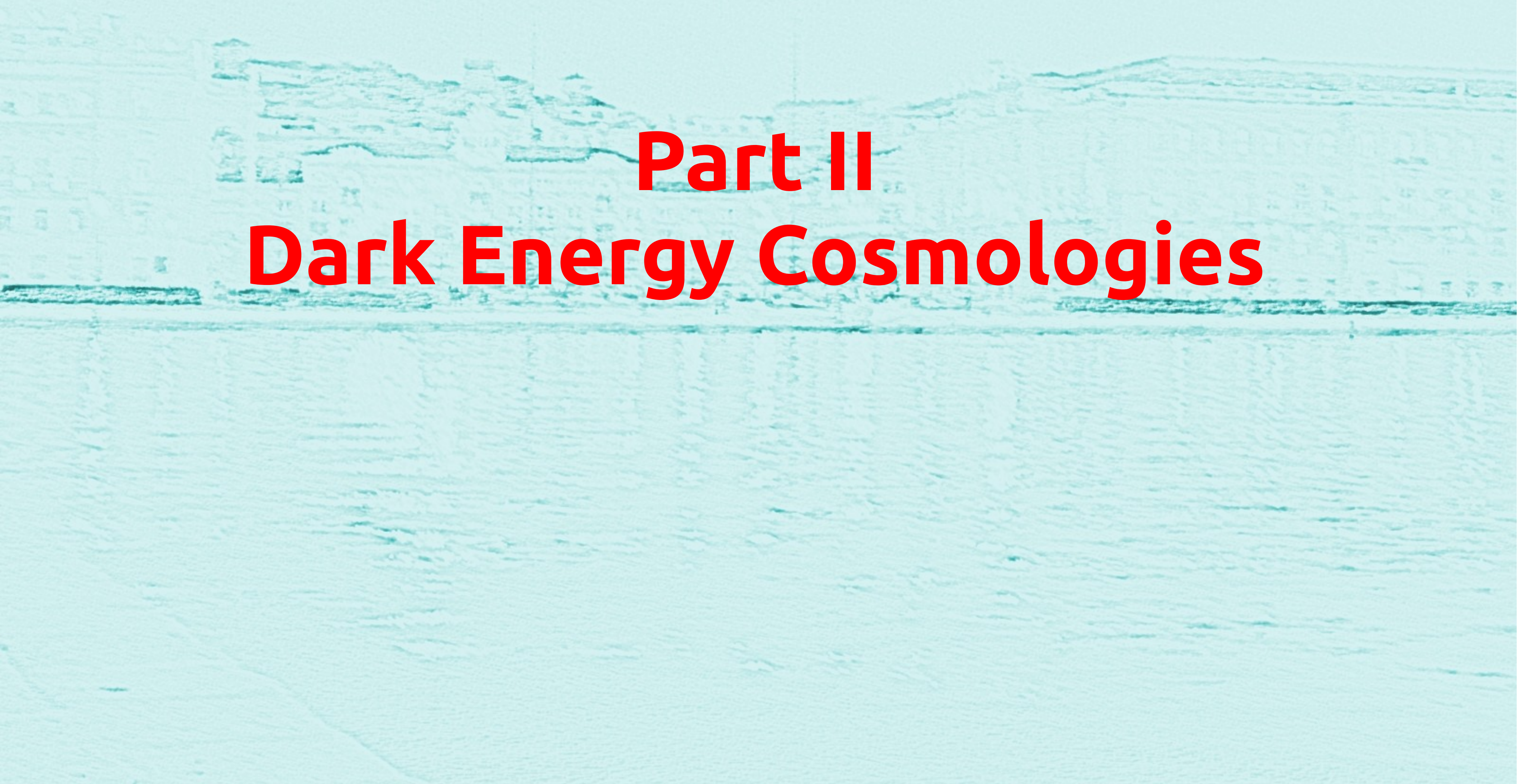


Zoldan+18 (submitted)

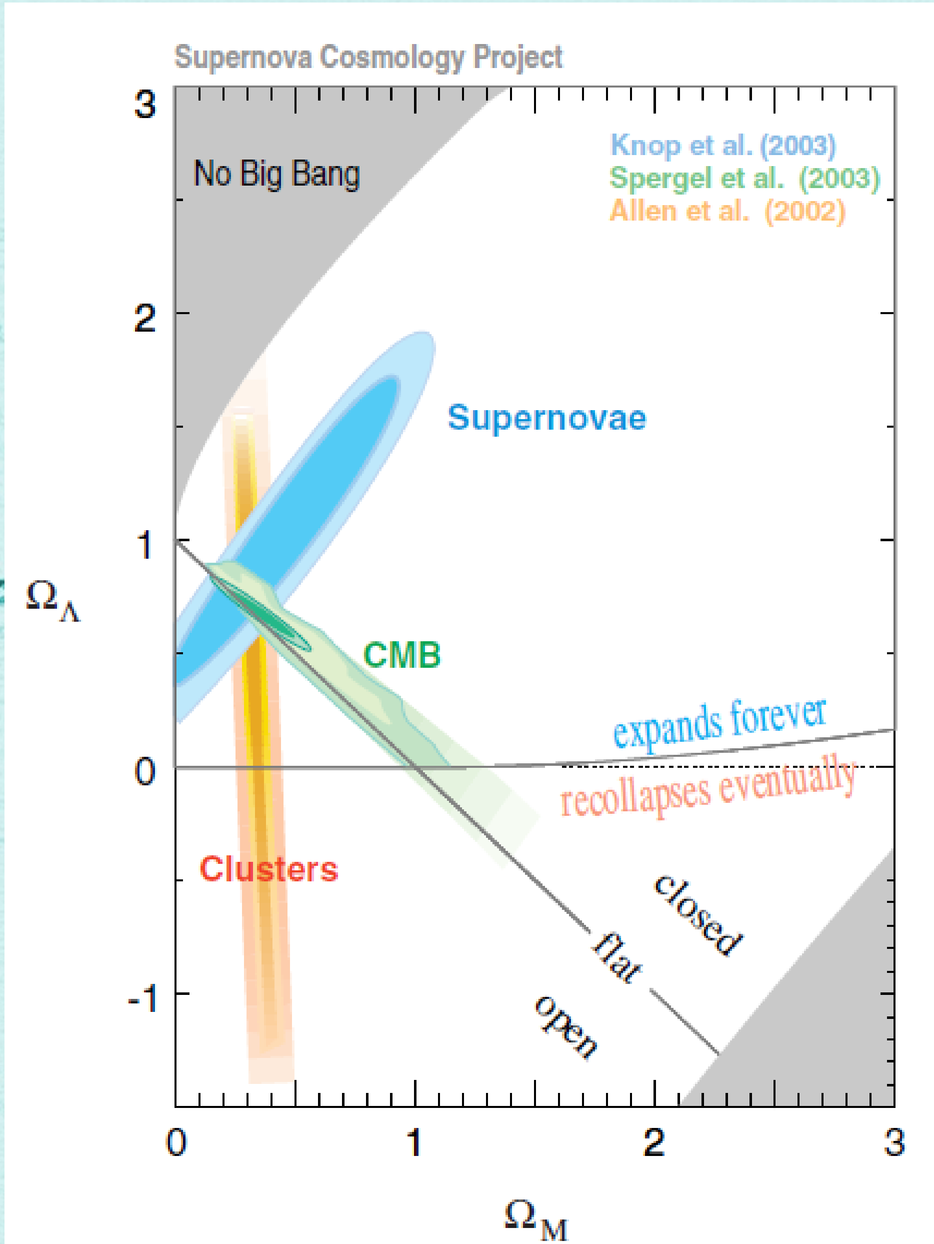
Conclusions I

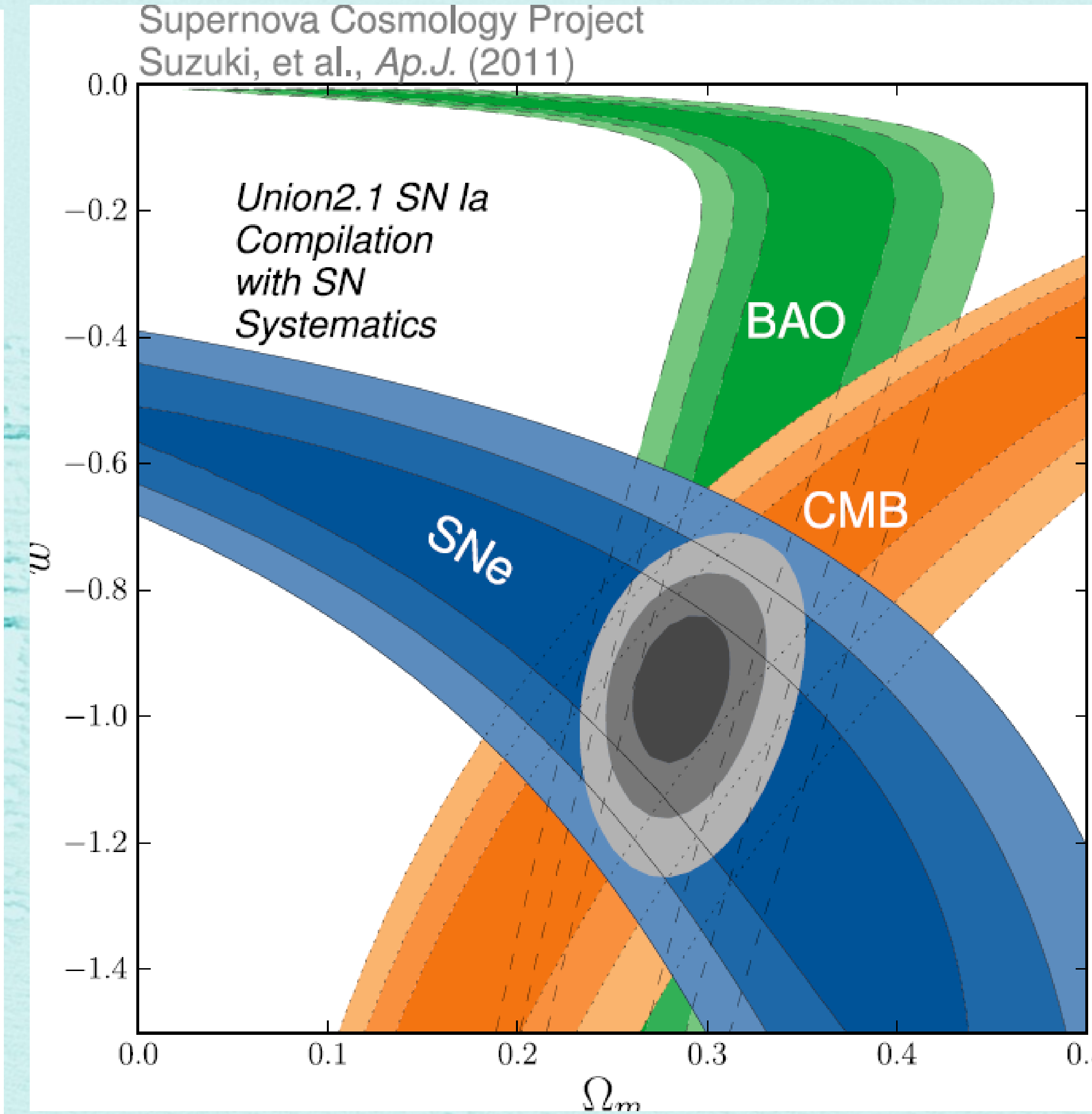
- GAEA state-of-the-art SAM including chemical enrichment and updated stellar feedback schems
  - Strong stellar-driven outflows coupled with mass-dependente re-accretion timescales are able to recover the evolution of the stellar mass function, rest-frame UV and optical LFs
- GAEA provides a self consistent picture of galaxy evolution at z<10

Part II
Dark Energy Cosmologies



Combination of independent evidencies





Dark Energy scenarios

- Cosmological constant
  - "fine tuning" problem **Weinberg89**

Dark Energy scenarios

- Cosmological constant
- Early Dark Energy & Quintessence **Wetterich88**
  - Non-negligible DE contribution at early times
  - Simulations **Grossi & Springel09**
- Modified Gravity **Hu&Sawicki07**
  - Chamaleon, Symmetron, Dylaton
  - Simulations **PuchweinSpringel13**
- "Coupled" DE **Wetterich95**
  - Interaction of scalar field with DM or baryons
  - Simulations **Baldi12**
- Massive Neutrinos
  - Suppression of the matter power spectrum on small scales
  - Simulations **Villescusa-Navarro14**

Dark Energy scenarios

- Cosmological constant
- Early Dark Energy & Quintessence
  - Non-negligible DE contribution at early times
  - SAM module Fontanot+12
- Modified Gravity
  - Chamaleon, Symmetron, Dylaton
  - SAM module Fontanot+13
- “Coupled” DE
  - Interaction of scalar field with DM or baryons
  - SAM module Fontanot+15b
- Massive Neutrinos
  - Suppression of the matter power spectrum on small scales
  - SAM module Fontanot+15a

Strategy

- Simulations of DE cosmologies (~100^3 Mpc^3)
  - Extracting Merger Trees
  - Reference LCDM (same ICs)
- Developing modules for L-Galaxies Guo+11
  - No recalibration of model parameters wrt LCDM
- Comparing Galaxy properties in DE cosmo with reference LCDM
- Intra-SAM variance in LCDM runs using Croton+06 DLB07

Early Dark Energy

Fontanot et al. (2012)

Early Dark Energy (EDE)

- DE an observable fraction of the total energy density at the time of matter-radiation equality
  - earlier formation of structures (for an equal amplitude of the present-day clustering)
  - lowered value of the critical linear density contrast needed for collapse Bartelmann+06
  - slower evolution of the halo population than the standard cosmology

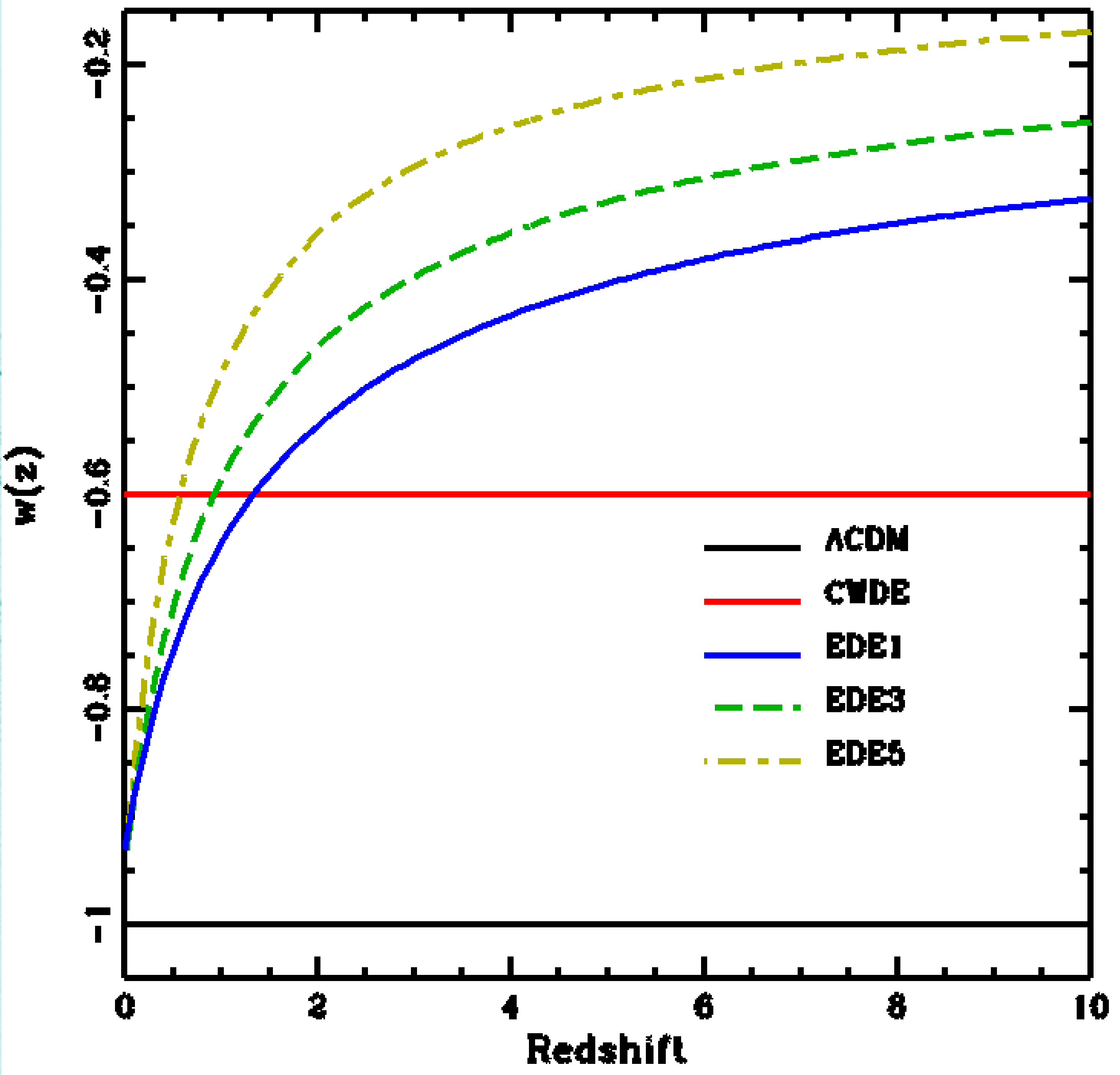
Early Dark Energy (EDE)

- Simulations by Grossi & Springel 09
- Equation of state parametrization following Wetterich04

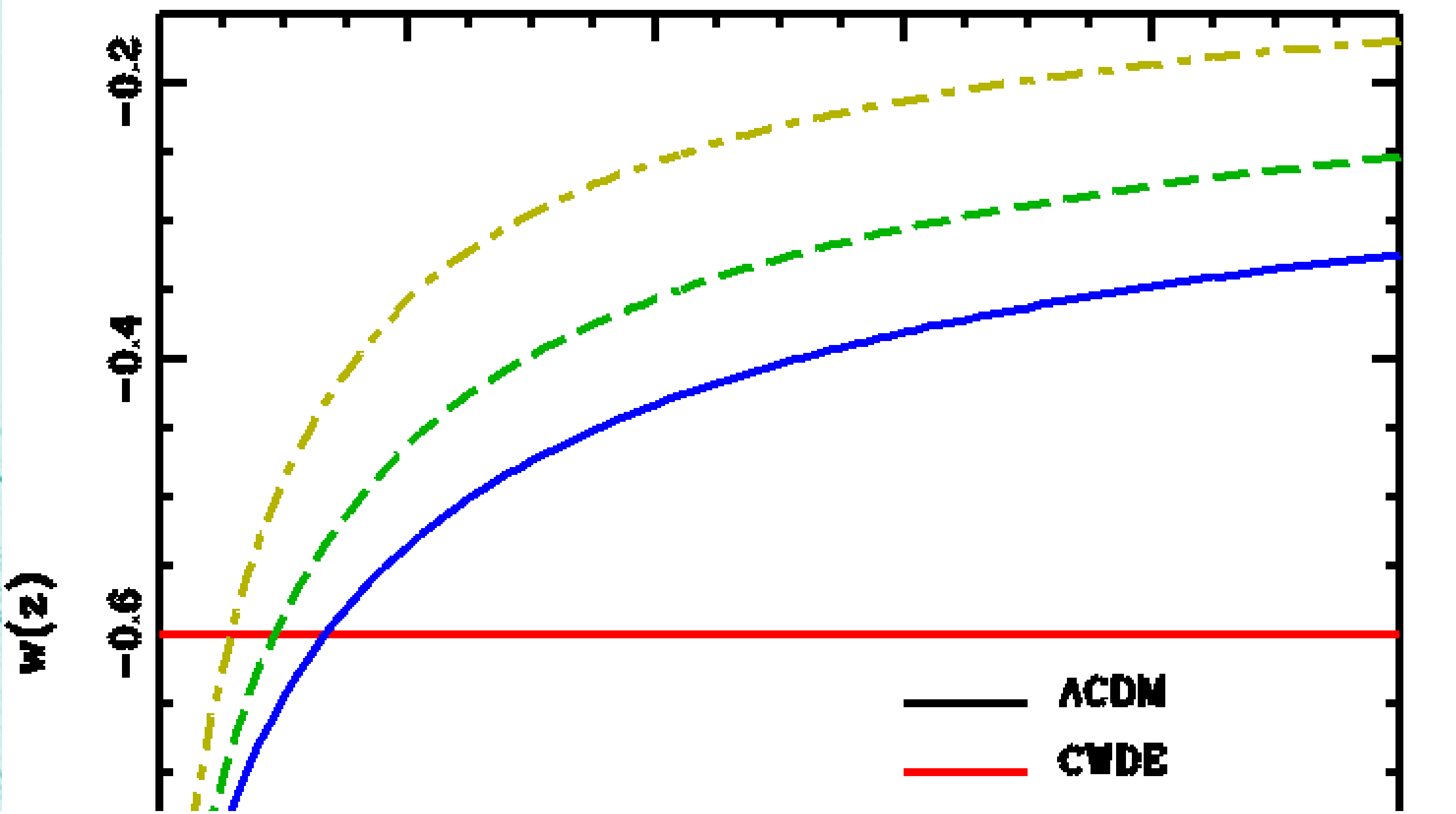
$$w(z) = \frac{w_0}{1 + b \ln^2(1+z)},$$

where

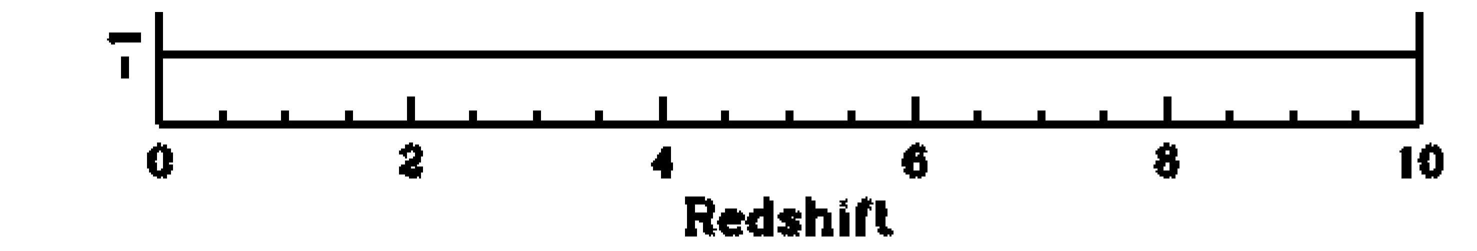
$$b = -\frac{3\, w_0}{\ln\left(\frac{1-\Omega_{\rm de,e}}{\Omega_{\rm de,e}}\right) + \ln\left(\frac{1-\Omega_{\rm m,0}}{\Omega_{\rm m,0}}\right)}.$$

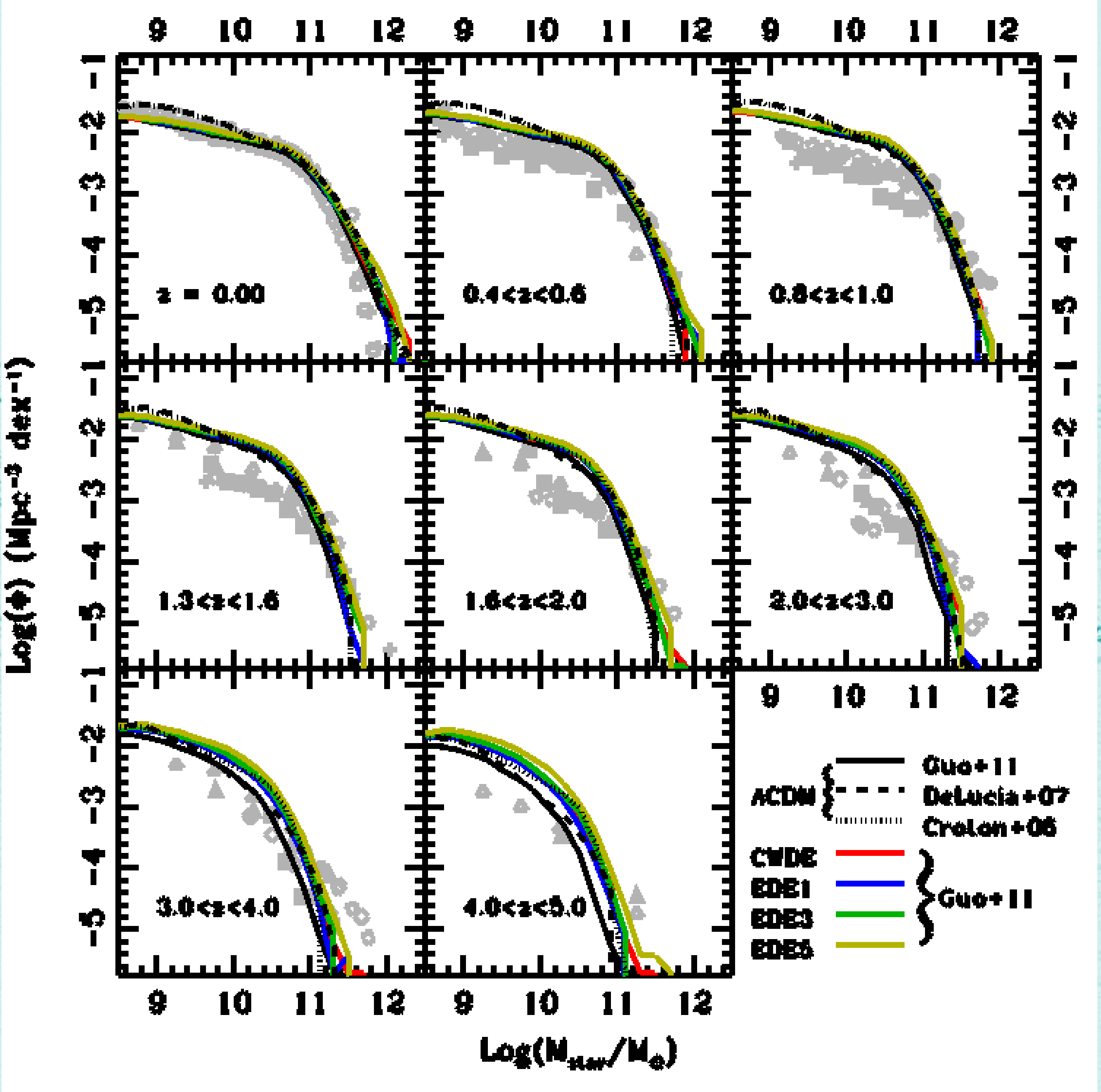


w(z)
-0.2
-0.4
-0.6
-0.8
-1
0
2
4
6
8
10
Redshift
ΛCDM
CWDE
EDE1
EDE3
EDE5

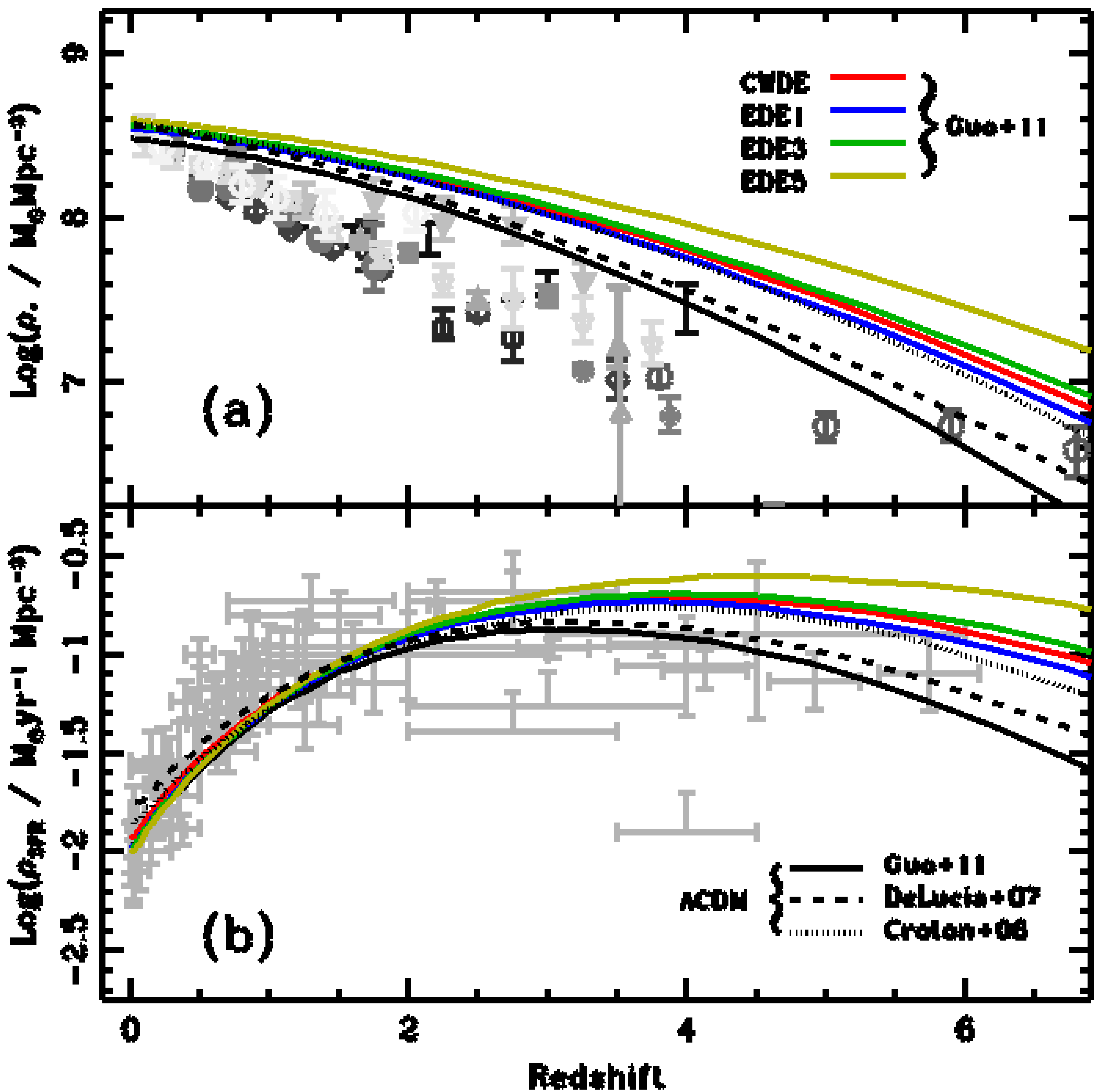


$$H(a) = H_0 \sqrt{\frac{\Omega_{\mathrm{m},0}}{a^3} + \Omega_{\mathrm{de},0}\, e^{-3\int [1+w(a)]\, d\ln a}}.$$

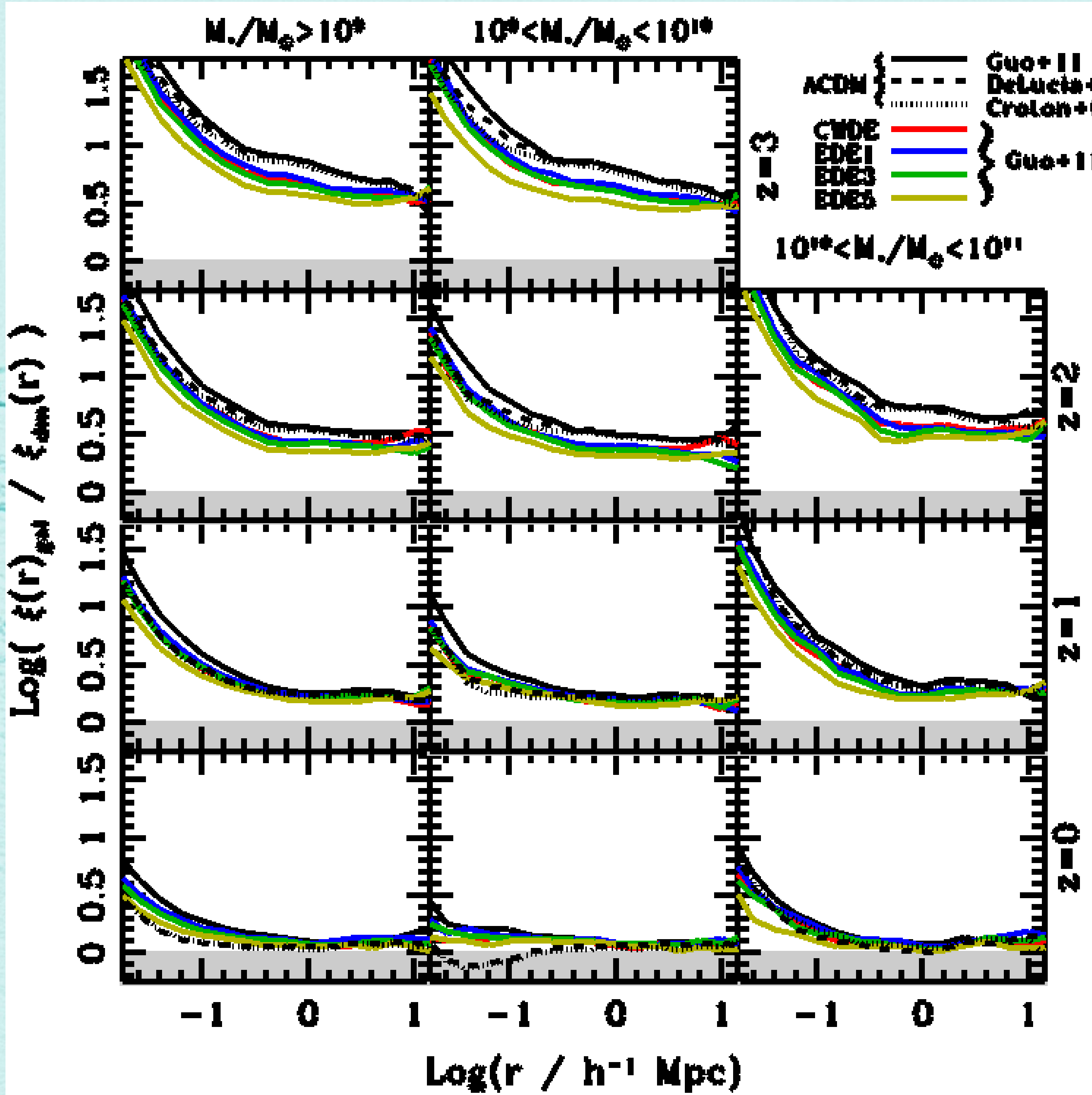




z = 0.00
0.4<z<0.6
0.8<z<1.0
1.3<z<1.6
1.6<z<2.0
2.0<z<3.0
3.0<z<4.0
4.0<z<5.0
Log(Φ) (Mpc⁻³ dex⁻¹)
Log(M_star/M_⊙)
ΛCDM
Guo+11
DeLucia+07
Croton+06
CWDE
EDE1
EDE3
EDE5
Guo+11



CWDE
EDE1
EDE3
EDE5
Guo+11
(a)
Log(ρ* / M☉Mpc⁻³)
9
8
7
Log(ρSFR / M☉yr⁻¹ Mpc⁻³)
−0.5
−1
−1.5
−2
−2.5
(b)
ΛCDM
Guo+11
DeLucia+07
Croton+06
0
2
4
6
Redshift



Guo+11
ΛCDM
CWDE
EDE1
EDE3
Guo+11
z=3
z=2
z=1
z=0
Log(r / h⁻¹ Mpc)

Modified Gravity

Fontanot et al. (2013)

Modified Gravity

- Modification of Einstein equation via addition of non-linear function of Ricci Scalar to mimic cosmic acceleration
  - Extra degree of freedom and "5th-force"
  - GR robust against local tests of gravity
  - Screening mechanisms
    - Field became massive in high-density environments (small Compton wavelength): Chamaleon effect
    - Weak coupling with matter in high density environments: Symmetron model

f(R) - gravity

- Simulations by **PuchweinSpringelBaldi 2013**
- Modification of Einstein equation

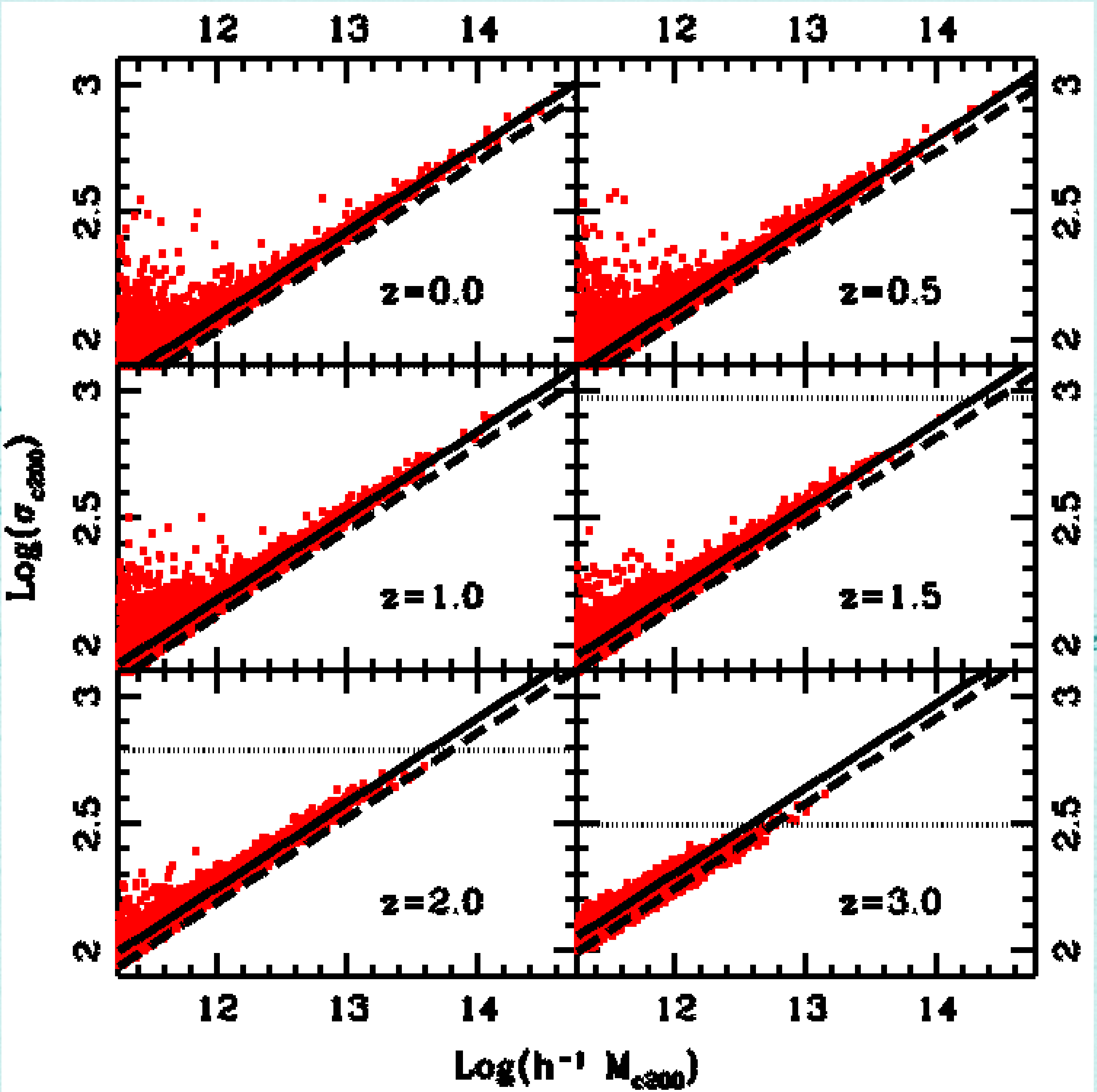
$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{R + f(R)}{16\pi G} + \mathcal{L}_\mathrm{m} \right]$$

- Parametrized Equation for f(R) **HuSawicki07**

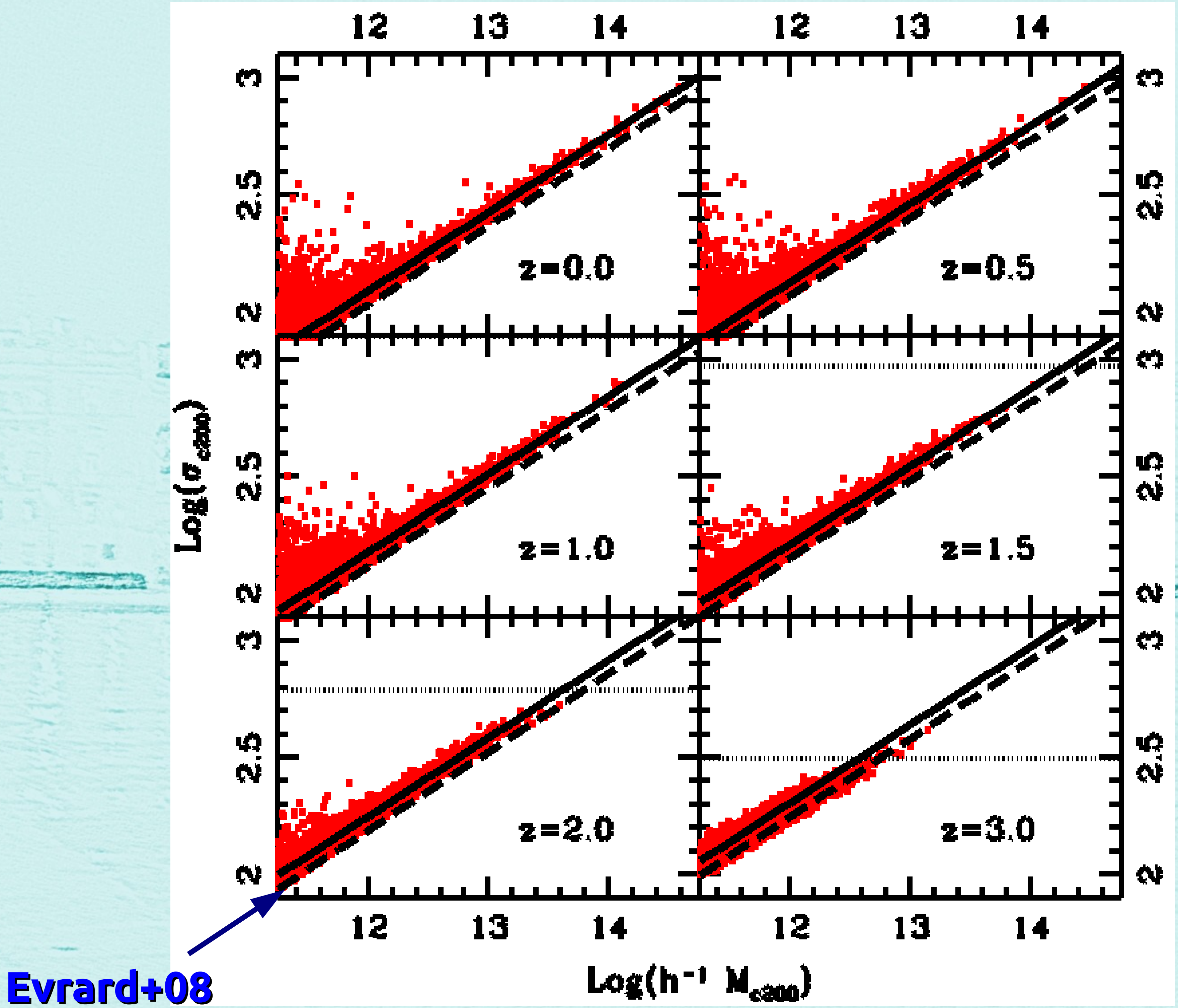
$$f(R) = -m^2 \frac{c_1 (R/m^2)^\eta}{c_2 (R/m^2)^\eta + 1}$$

$$f_R = \frac{\mathrm{d}f(R)}{\mathrm{d}R} = -\eta \frac{c_1}{c_2^2} \left(\frac{m^2}{R} \right)^{\eta+1}$$

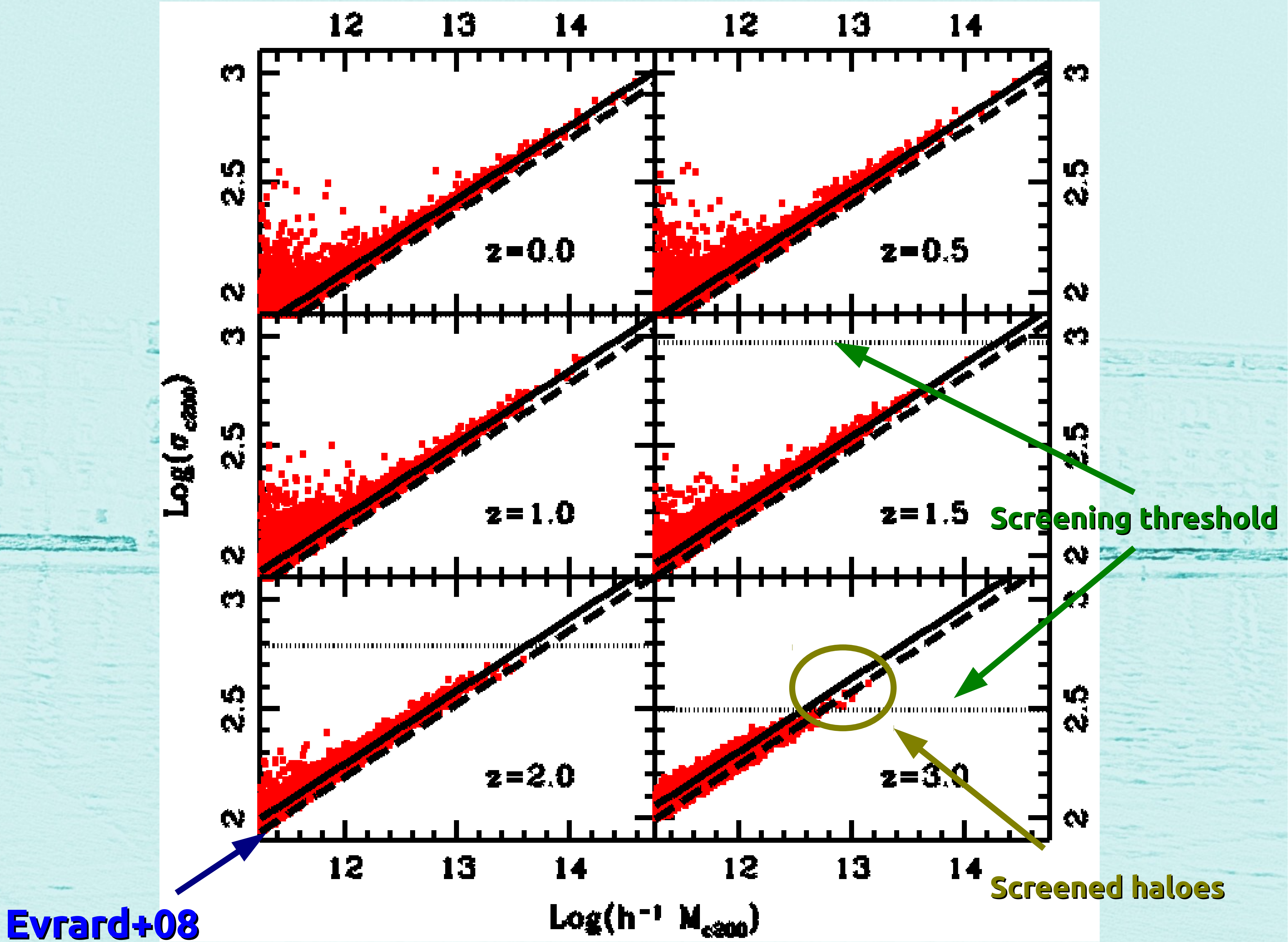
$$\frac{c_1}{c_2} \approx 6 \frac{\Omega_\Lambda}{\Omega_\mathrm{m}}$$



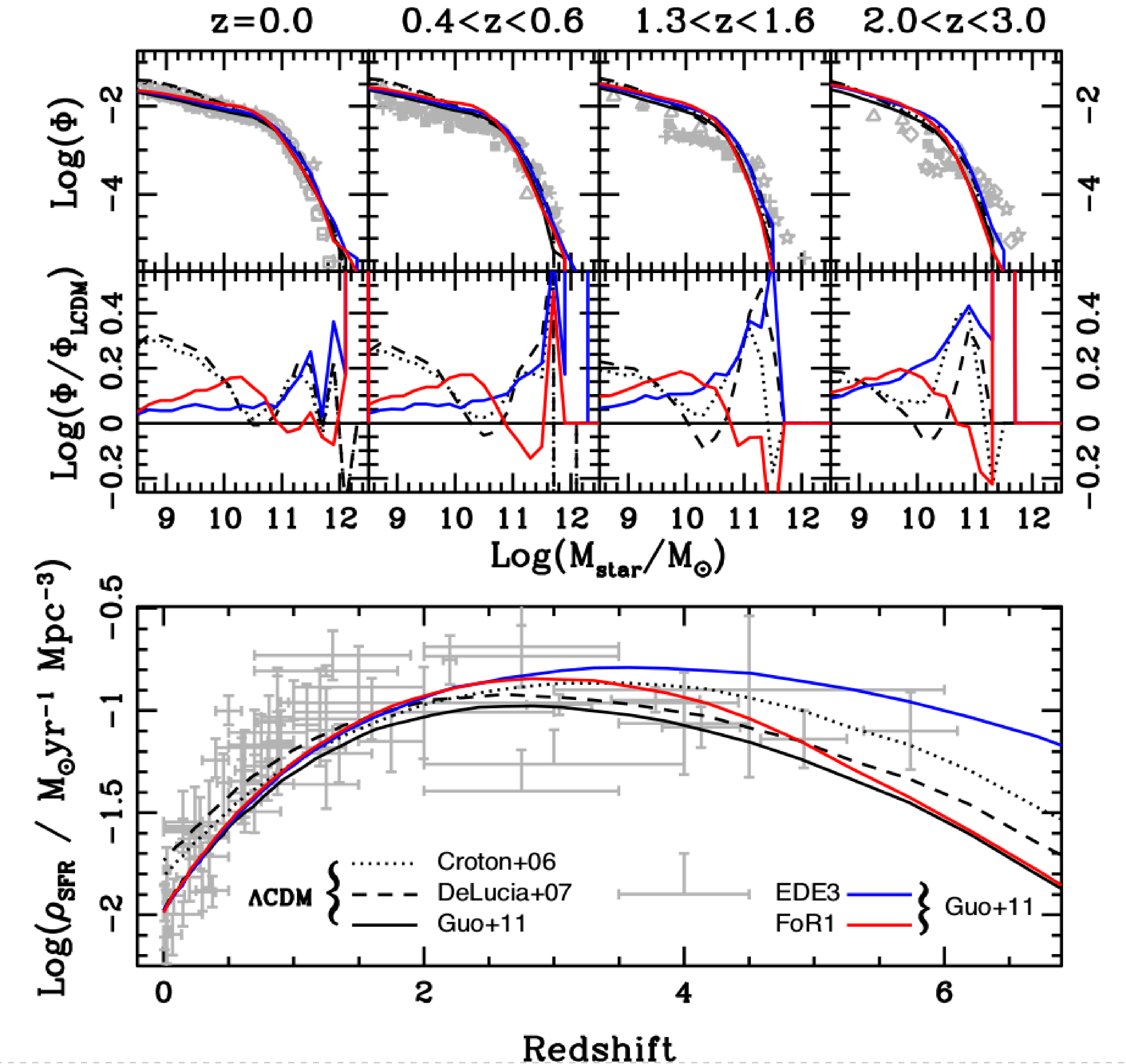
z=0.0
z=0.5
z=1.0
z=1.5
z=2.0
z=3.0
12
13
14
2
2.5
3
Log(σ_c200)
Log(h⁻¹ M_c200)



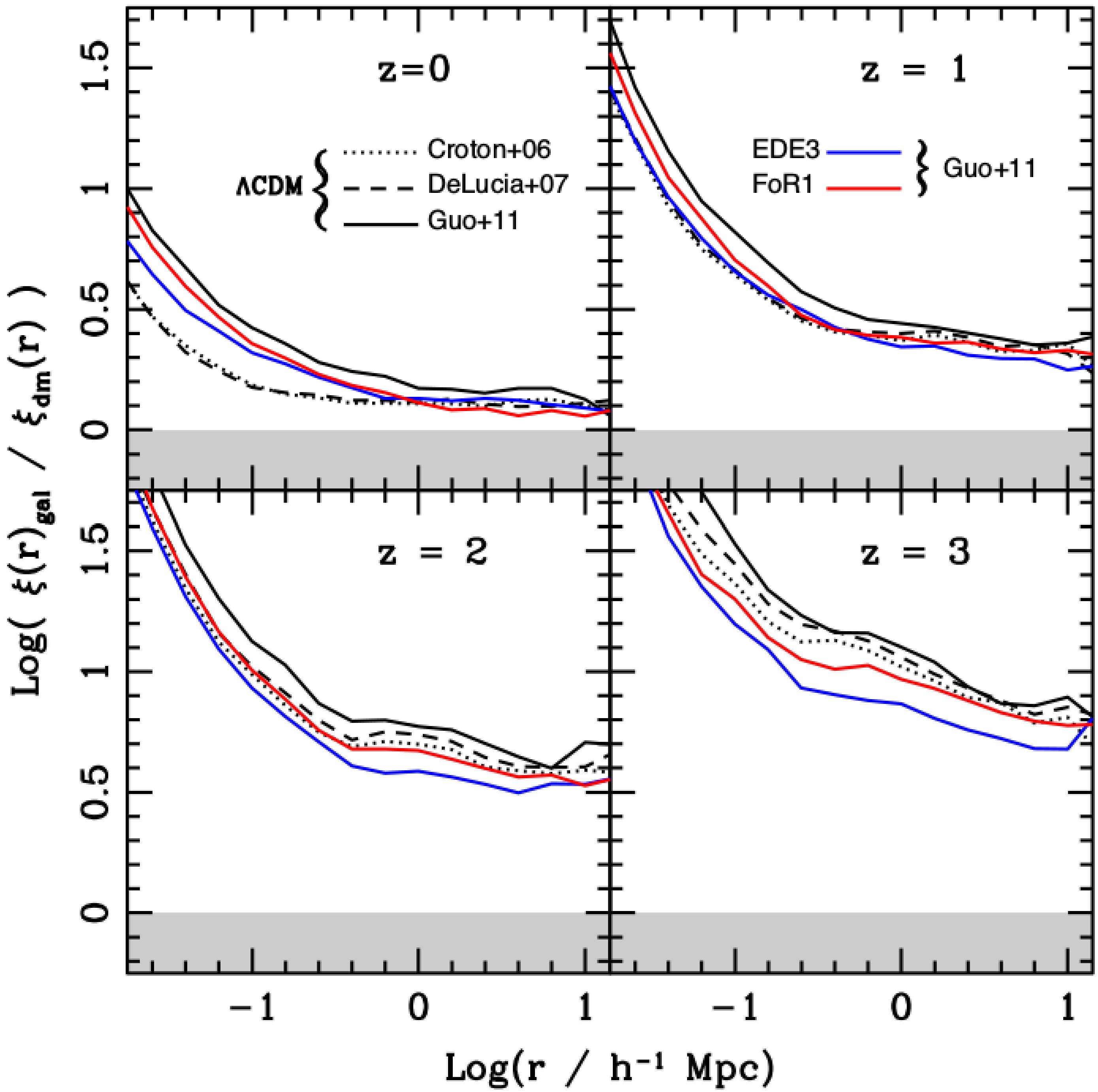
z=0.0
z=0.5
z=1.0
z=1.5
z=2.0
z=3.0
Log(h⁻¹ M_c200)
Log(σ_c200)
Evrard+08

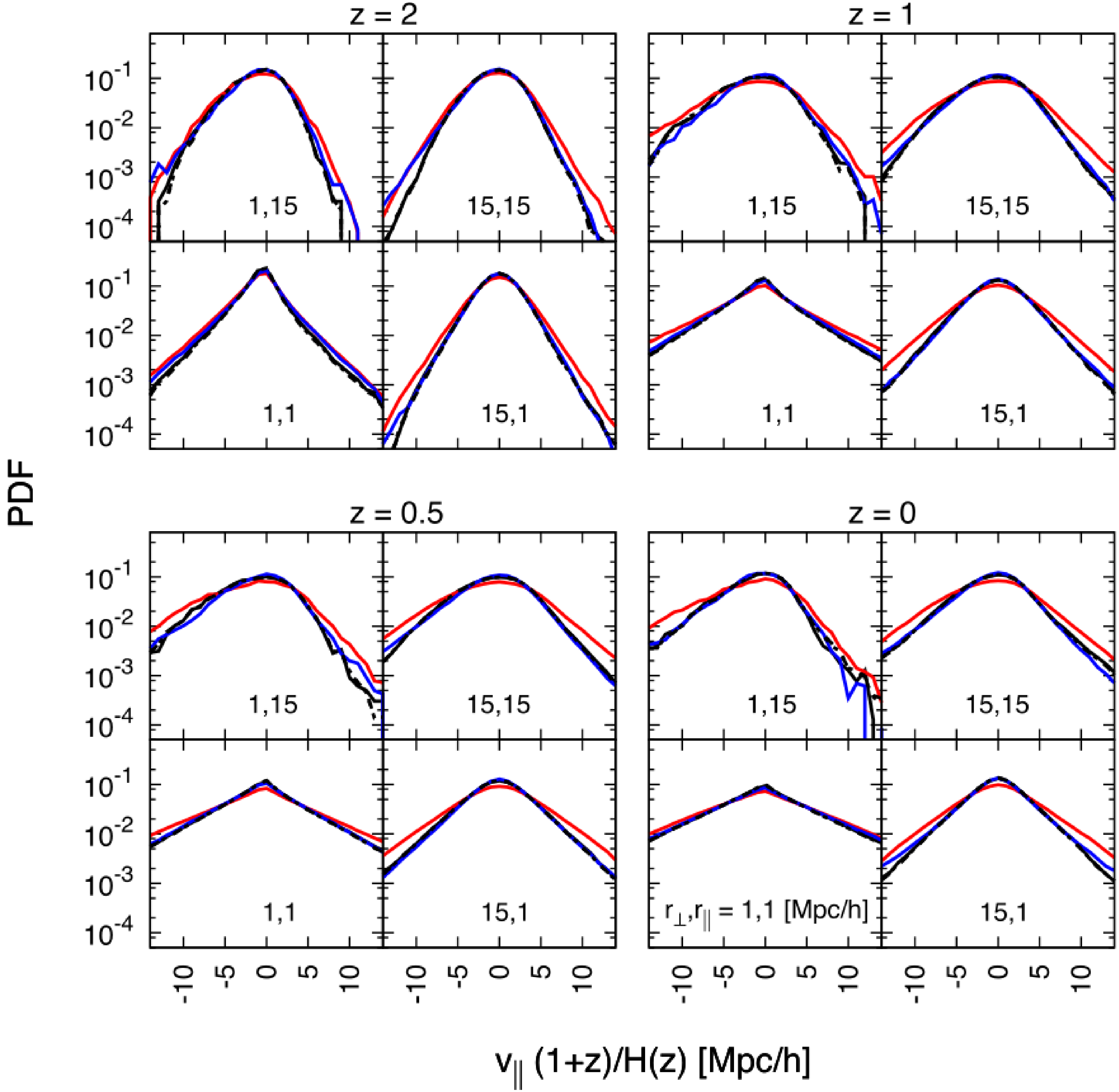


z=0.0
z=0.5
z=1.0
z=1.5
z=2.0
z=3.0
Log(σ_{c200})
Log(h^{-1} M_{c200})
Screening threshold
Screened haloes
Evrard+08



z=0.0
0.4<z<0.6
1.3<z<1.6
2.0<z<3.0
Log(Φ)
Log(Φ/Φ_LCDM)
Log(M_star/M_⊙)
Log(ρ_SFR / M_⊙yr^-1 Mpc^-3)
Redshift
ΛCDM
Croton+06
DeLucia+07
Guo+11
EDE3
FoR1
Guo+11


z=0
z = 1
z = 2
z = 3
ΛCDM
Croton+06
DeLucia+07
Guo+11
EDE3
FoR1
Guo+11
Log(ξ(r)gal / ξdm(r))
Log(r / h⁻¹ Mpc)
-1
0
1
-1
0
1
0
0.5
1
1.5
0
0.5
1
1.5


z = 2
z = 1
z = 0.5
z = 0
PDF
1,15
15,15
1,1
15,1
r⊥,r∥ = 1,1 [Mpc/h]
v∥ (1+z)/H(z) [Mpc/h]

Coupled Dark Energy

Fontanot et al. (2015b)

Coupled Dark Energy

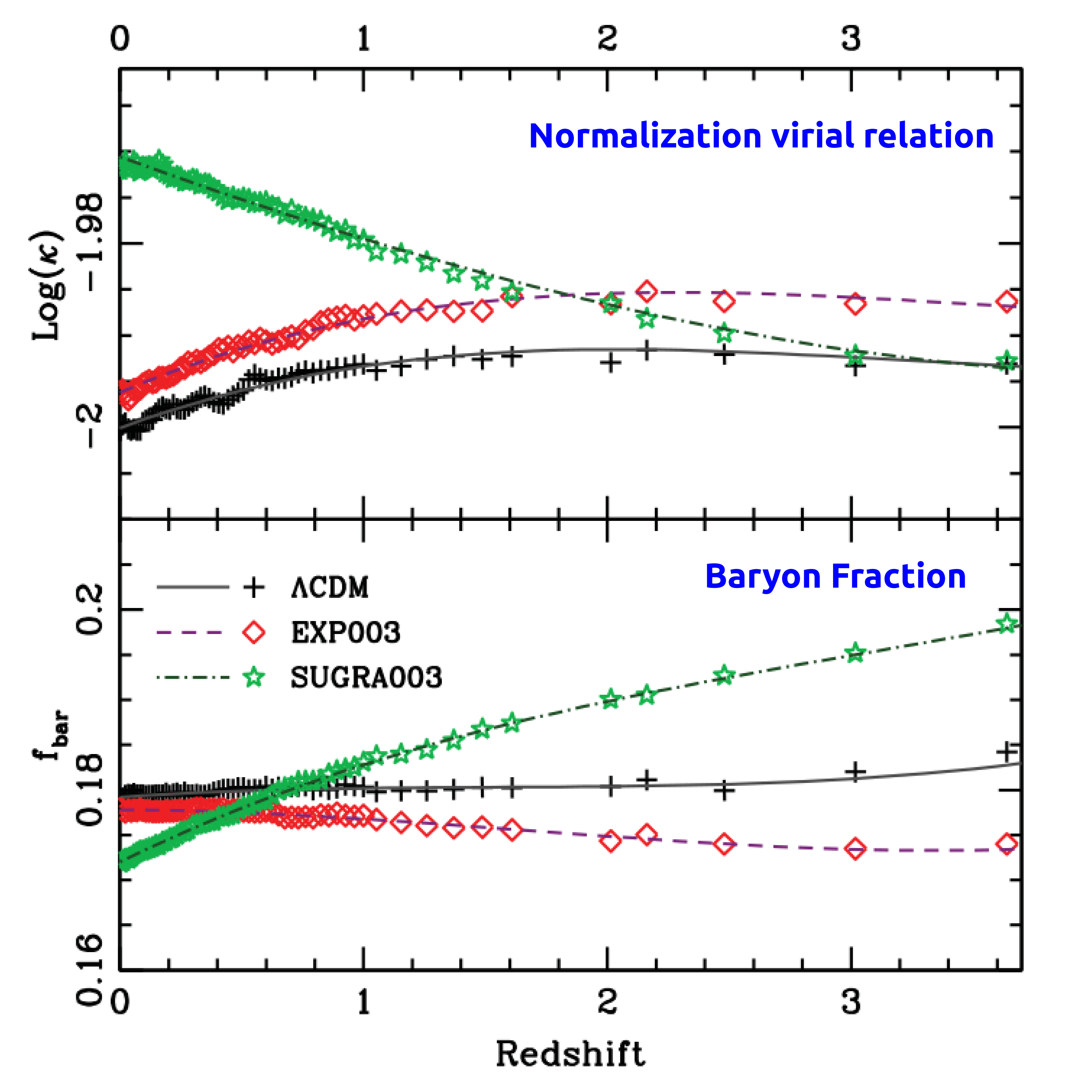
- Dynamical evolution of scalar field (DE) with interactions between the DE scalar field and CDM particles **Wetterich95**
  - "Fitfh-force"
    - no constraints from local test of gravity
    - Constraints from CMB – crosscorrelation between CMB and LSS
    - DM and Baryons feel "different gravity"
  - Classified on the basis of the coupling (constant – variable - "bouncing")

Coupled Dark Energy

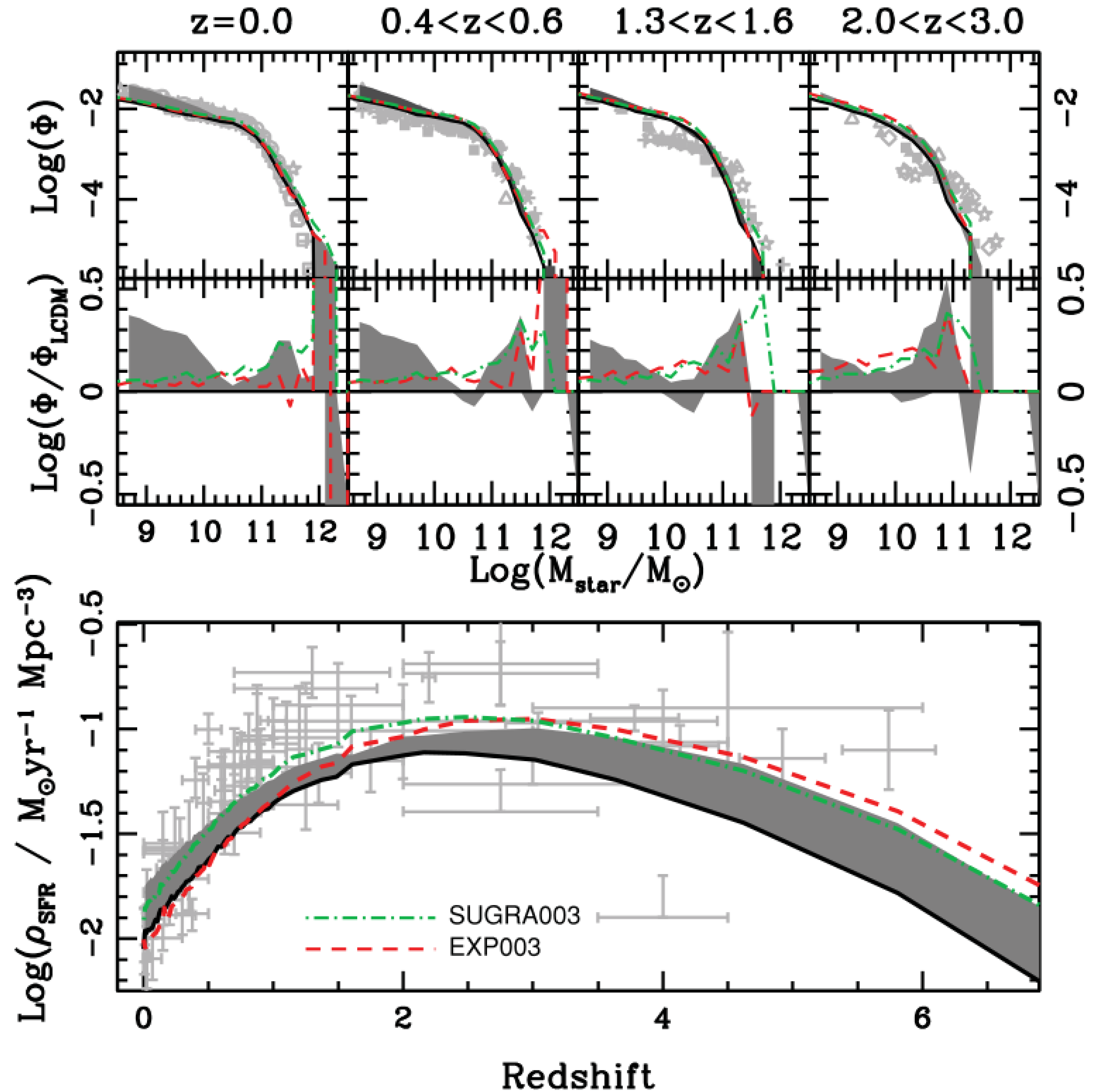
- N-Body simulations from CoDECS project
  Baldi12
- DE scalar field potential
  - Exponential $V(\phi) = A\phi e^{-\alpha\phi}$
  - SUGRA (supersymmetric gravity) $V(\phi) = A\phi^{-\alpha} e^{-\phi^2/2},$
  - Dynamical equations including the interaction between the scalar field and CDM particles

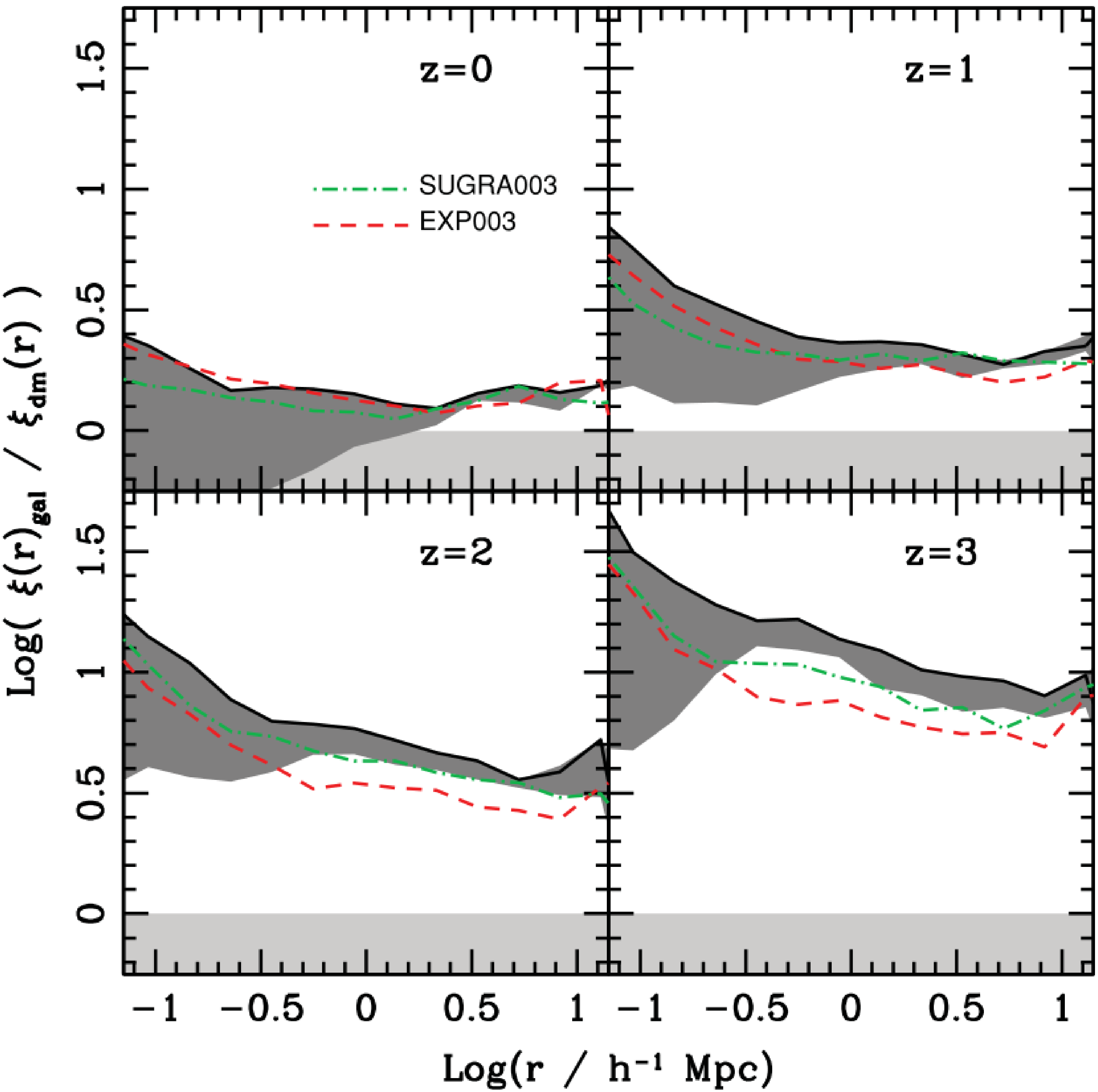
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = \sqrt{\frac{16\pi G}{3}}\beta(\phi)\rho_c$$

$$\dot{\rho}_c + 3H\rho_c = -\sqrt{\frac{16\pi G}{3}}\beta(\phi)\rho_c\dot{\phi},$$

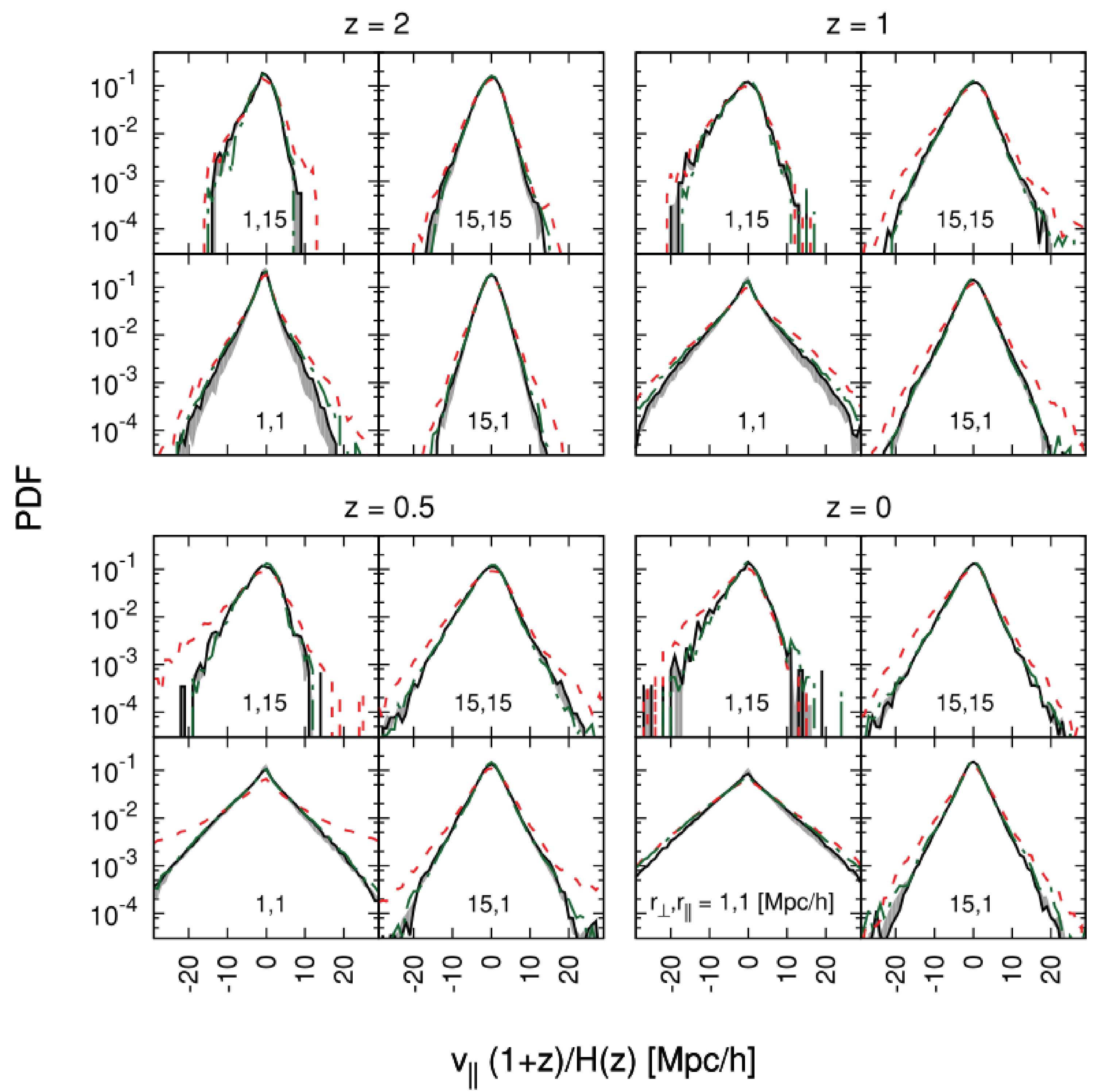


Normalization virial relation
Baryon Fraction
Log(κ)
−1.98
−2
f_{bar}
0.2
0.18
0.16
0
1
2
3
ΛCDM
EXP003
SUGRA003
Redshift


z=0.0
0.4<z<0.6
1.3<z<1.6
2.0<z<3.0
Log(Φ)
Log(Φ/Φ_LCDM)
Log(M_star/M_⊙)
Log(ρ_SFR / M_⊙yr^-1 Mpc^-3)
Redshift
SUGRA003
EXP003



z=0
z=1
z=2
z=3
SUGRA003
EXP003
Log(ξ(r)gal / ξdm(r))
Log(r / h⁻¹ Mpc)
1.5
1
0.5
0
−1
−0.5
0
0.5
1

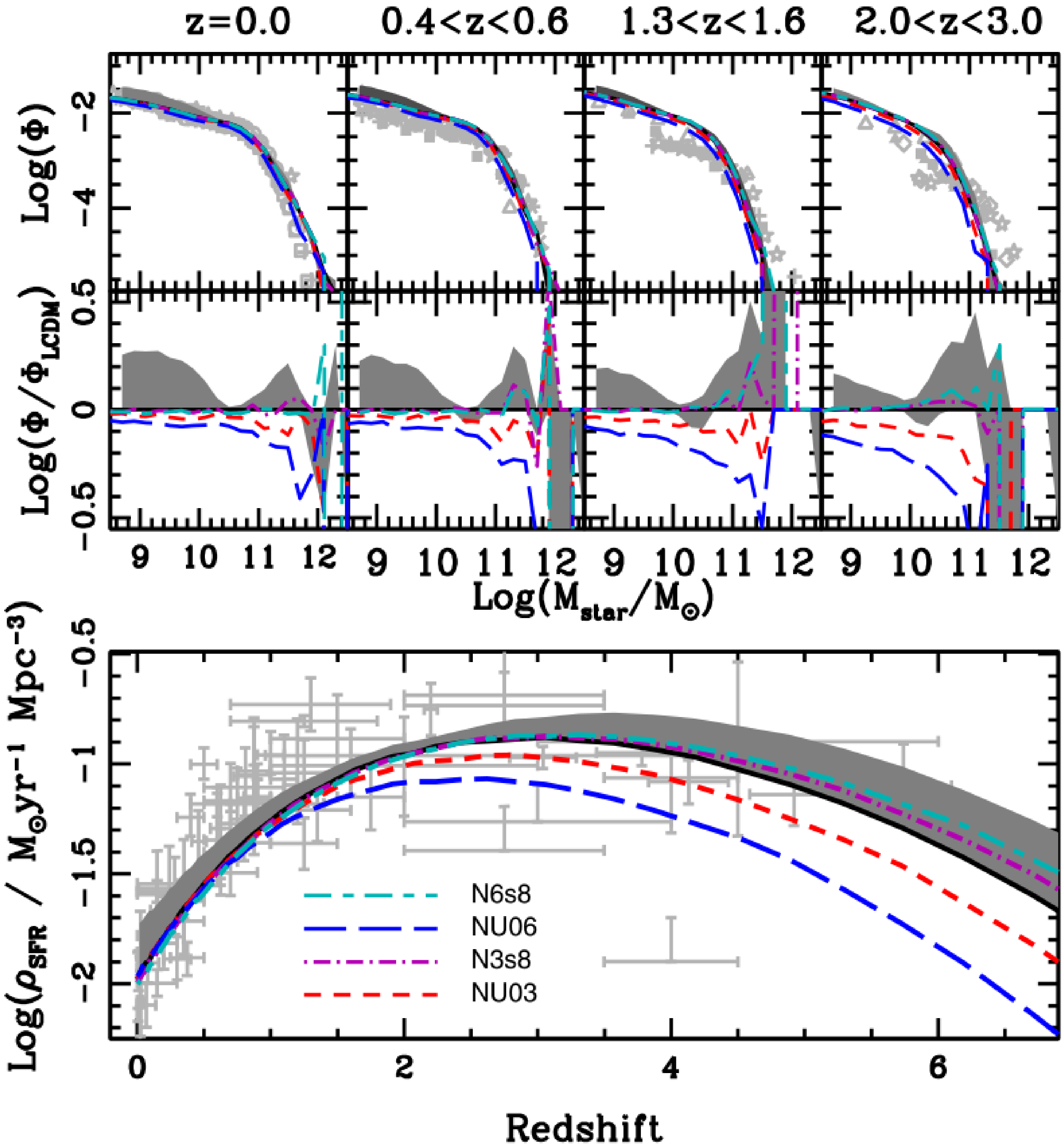

z = 2
z = 1
z = 0.5
z = 0
PDF
10^-1
10^-2
10^-3
10^-4
1,15
15,15
1,1
15,1
r⊥,r|| = 1,1 [Mpc/h]
-20
-10
0
10
20
v|| (1+z)/H(z) [Mpc/h]

Massive Neutrinos

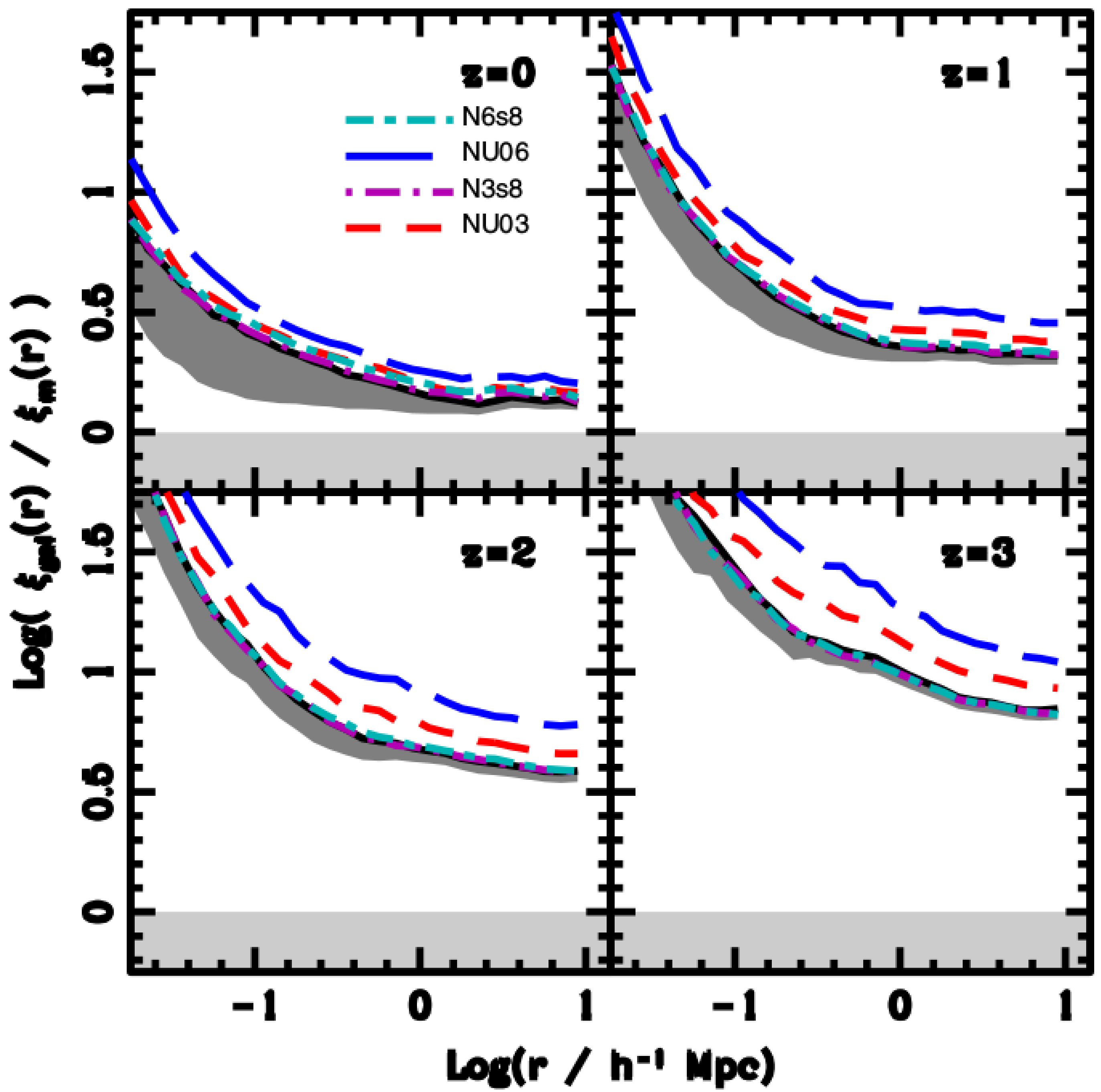
Fontanot et al. (2015a)

Massive Neutrinos

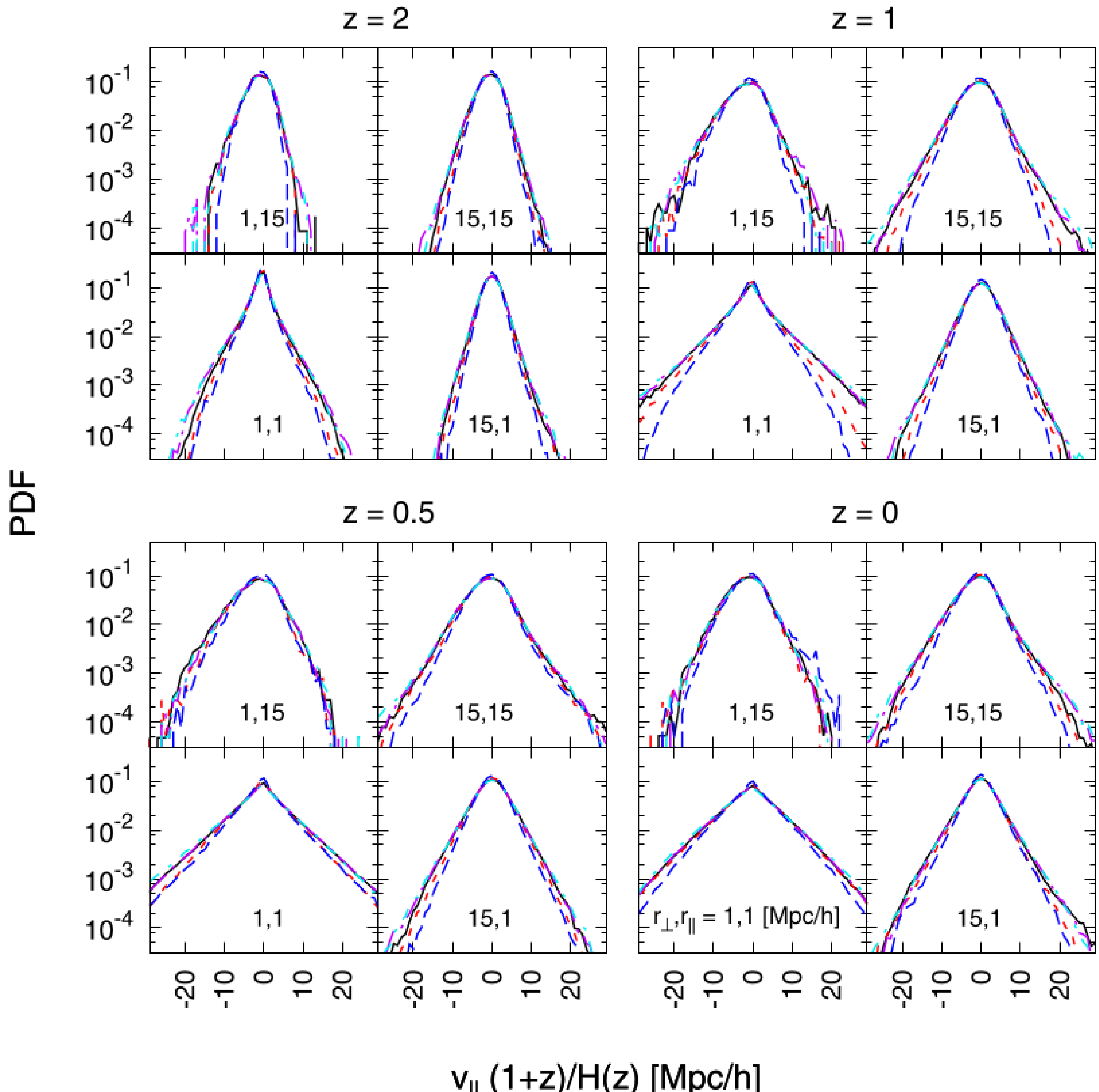
- Neutrino oscillation probe neutrinos have mass
- Affect the growth of LSS at different scales
  - Suppress mass power spectrum at small scales
  - Induce a scale dependent bias on large scales
- Mimicked by a different σ_8



z=0.0
0.4<z<0.6
1.3<z<1.6
2.0<z<3.0
Log(Φ)
Log(Φ/Φ_LCDM)
Log(M_star/M_⊙)
Log(ρ_SFR / M_⊙yr^-1 Mpc^-3)
Redshift
N6s8
NU06
N3s8
NU03



z=0
z=1
z=2
z=3
N6s8
NU06
N3s8
NU03
Log(ξgm(r) / ξm(r))
Log(r / h⁻¹ Mpc)



z = 2
z = 1
z = 0.5
z = 0
PDF
1,15
15,15
1,1
15,1
r⊥,r|| = 1,1 [Mpc/h]
v|| (1+z)/H(z) [Mpc/h]

Conclusions II

- Modifications in galaxy properties induced by Dark Energy cosmologies are of the same order of magnitude as intra-SAM variations
- When independent information on the underlying properties of host dark matter haloes is included, SAM predictions may provide important clues on the expansion history and the equation-of-state evolution

- Galaxy Bias for EDE
- Velocity PDF for modifications of gravity
- Massive Neutrinos should be taken into account