Empirical galaxy formation models:

Constraints for simulations

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Modelling Galaxy Formation

Self-consistent cosmological framework

- Build-up of stellar mass from dwarfs to clusters?
- What sets galaxy properties and scatter?
- What sets the SFR?
- How are galaxies distributed in the cosmic web?

Wuyts+11
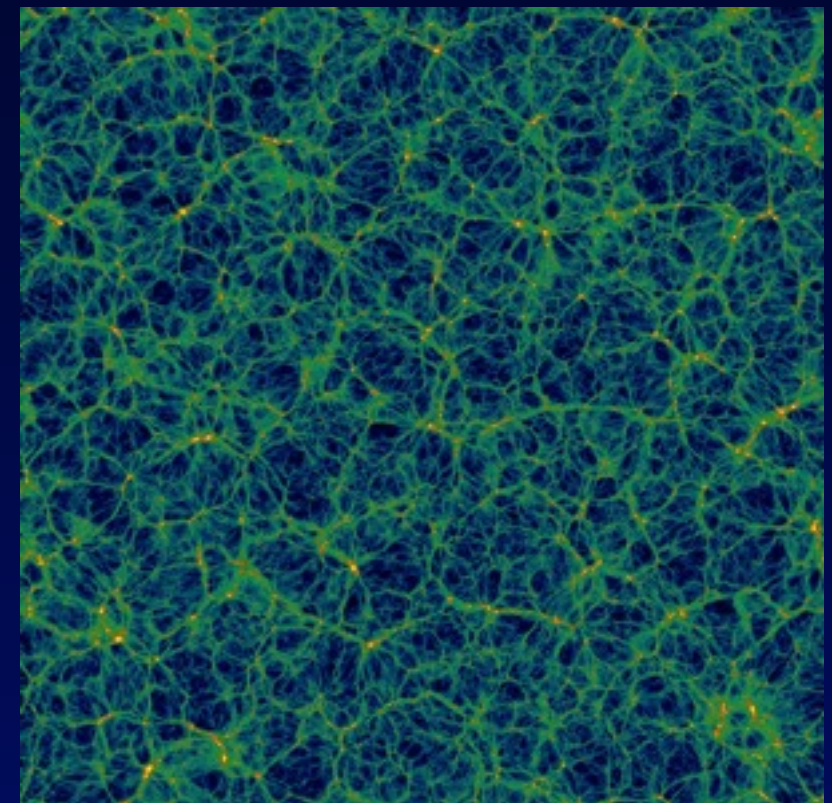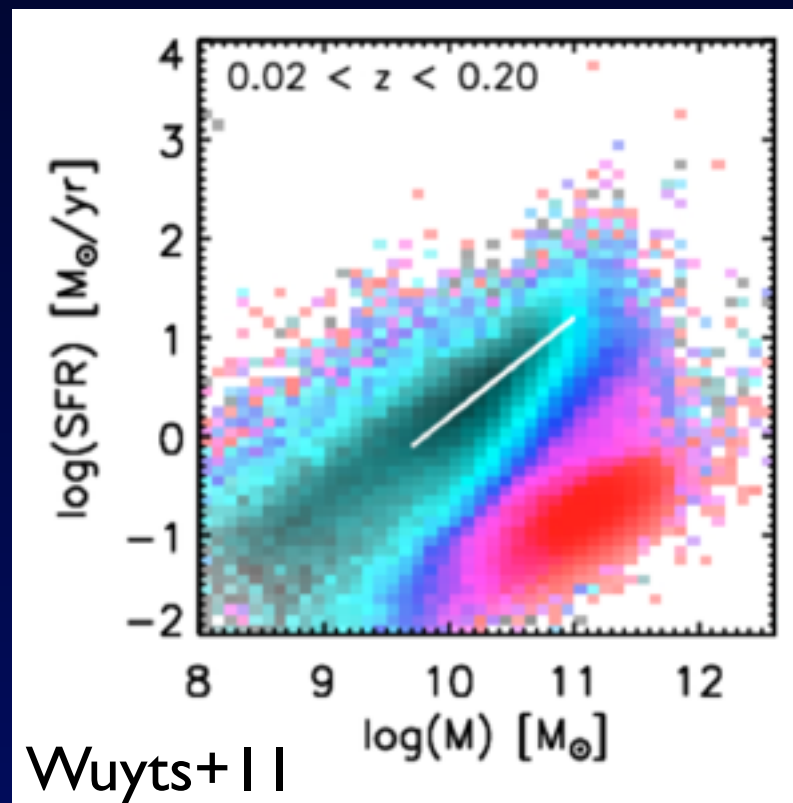
Hydrodynamical Simulations

- Evolve ICs according to all physical processes we think are important
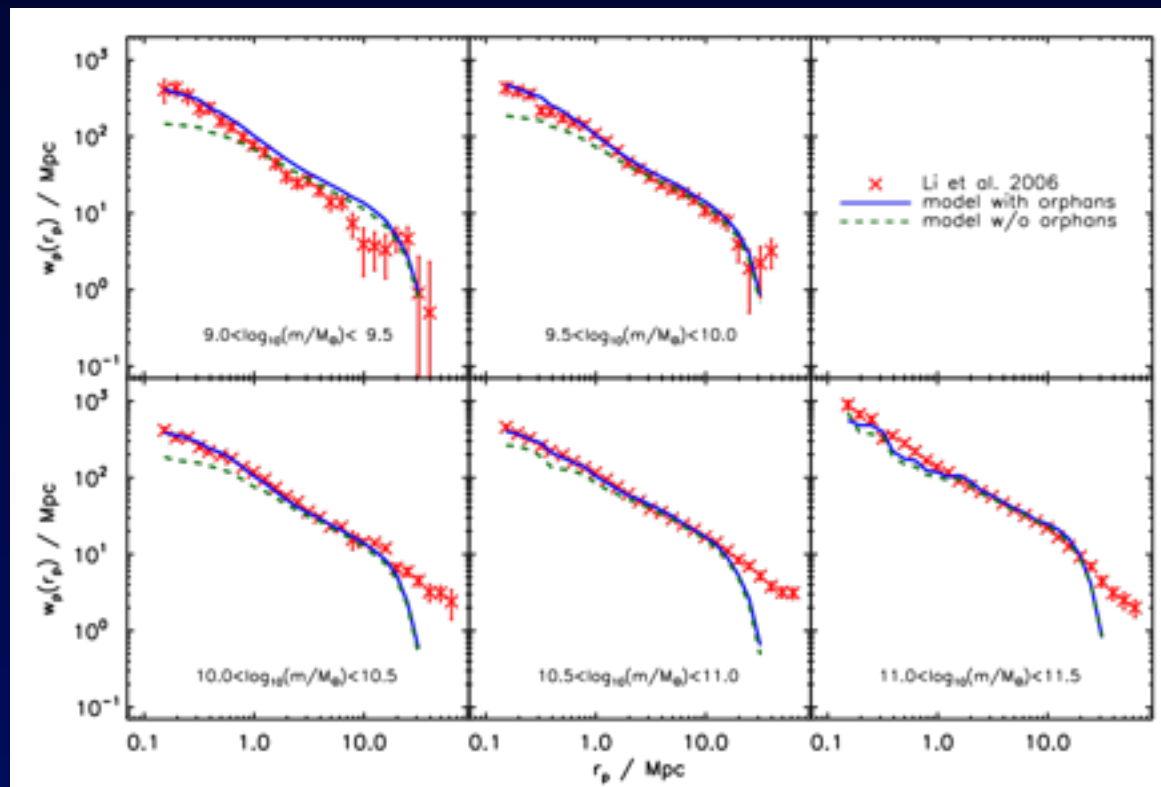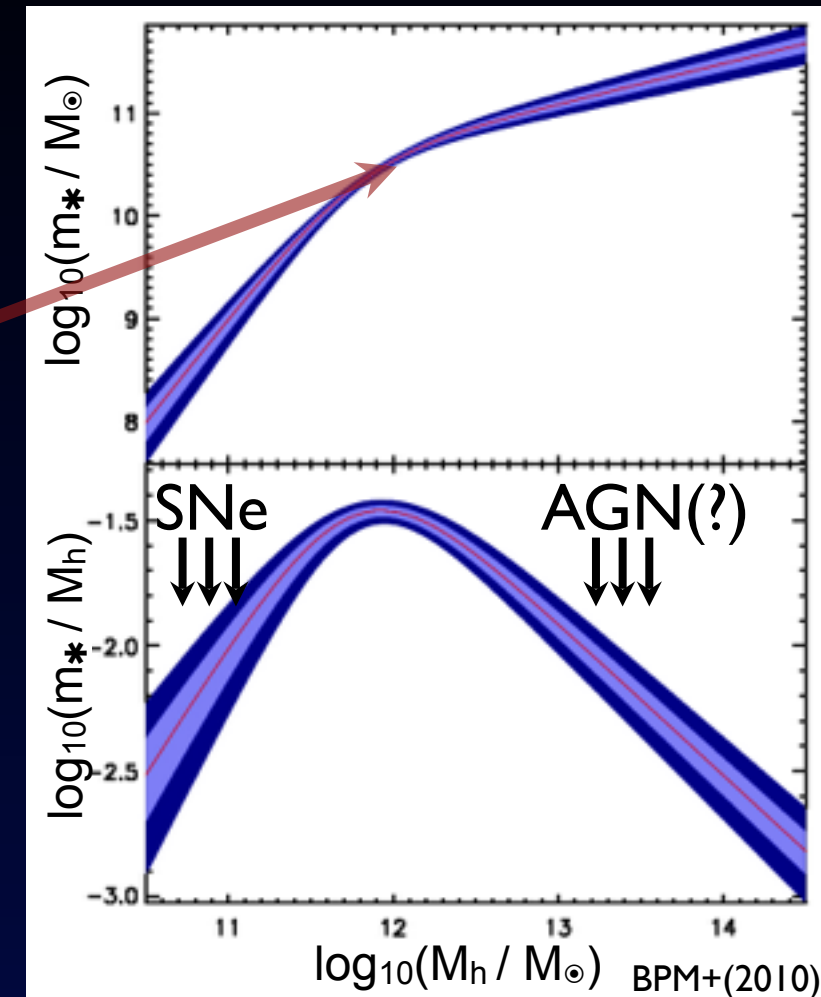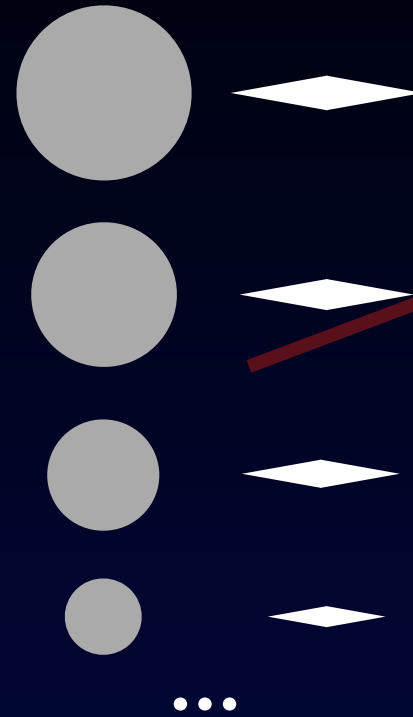
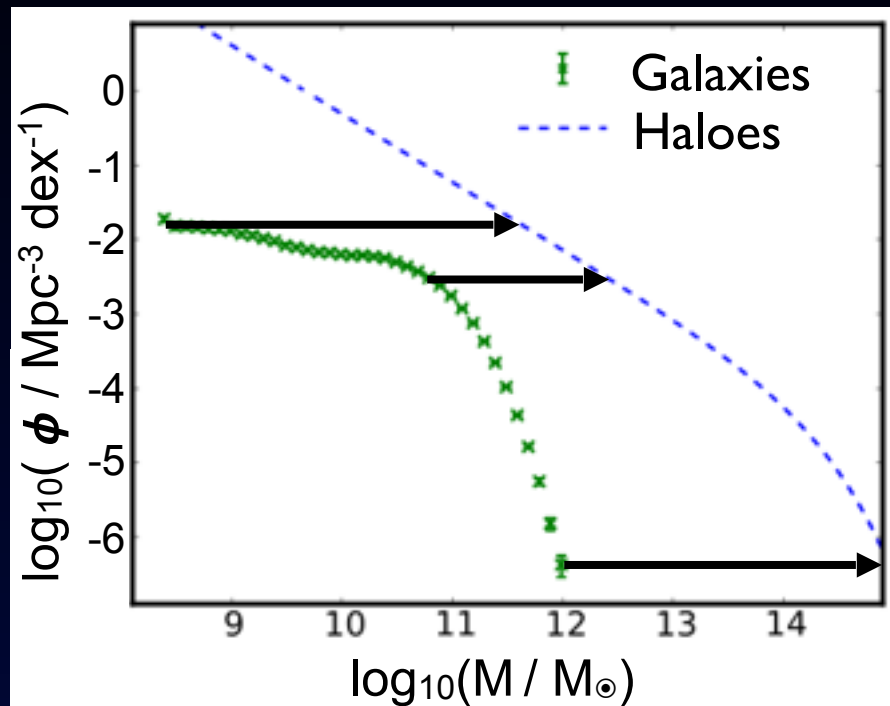- Compare results to observations

- Repeat and learn…

- Unresolved physics: subgrid models
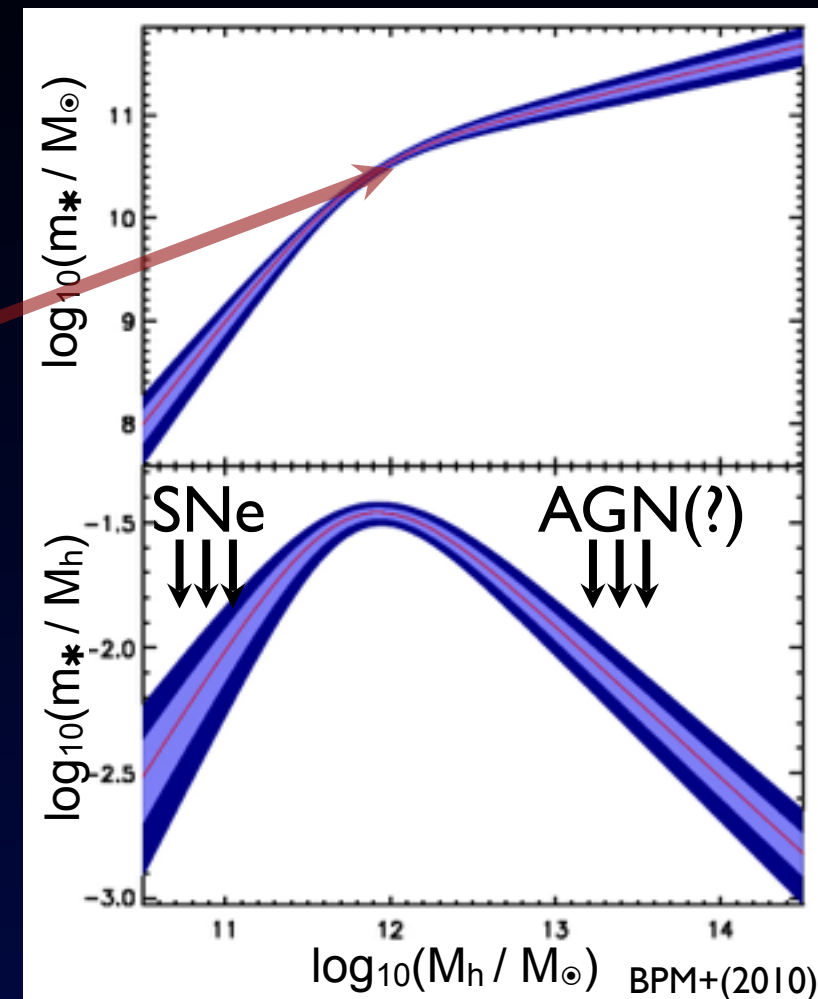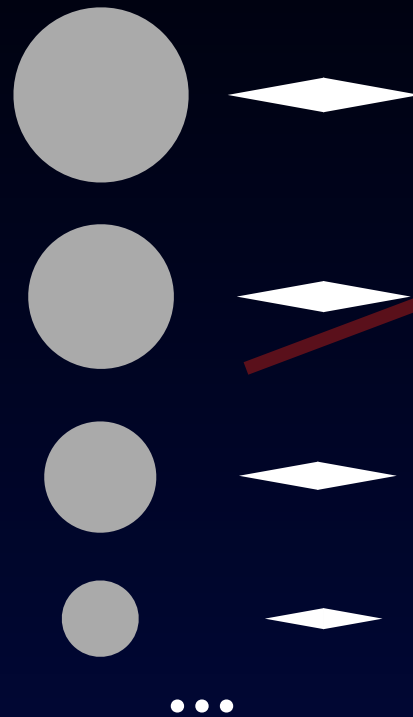 Different implementations
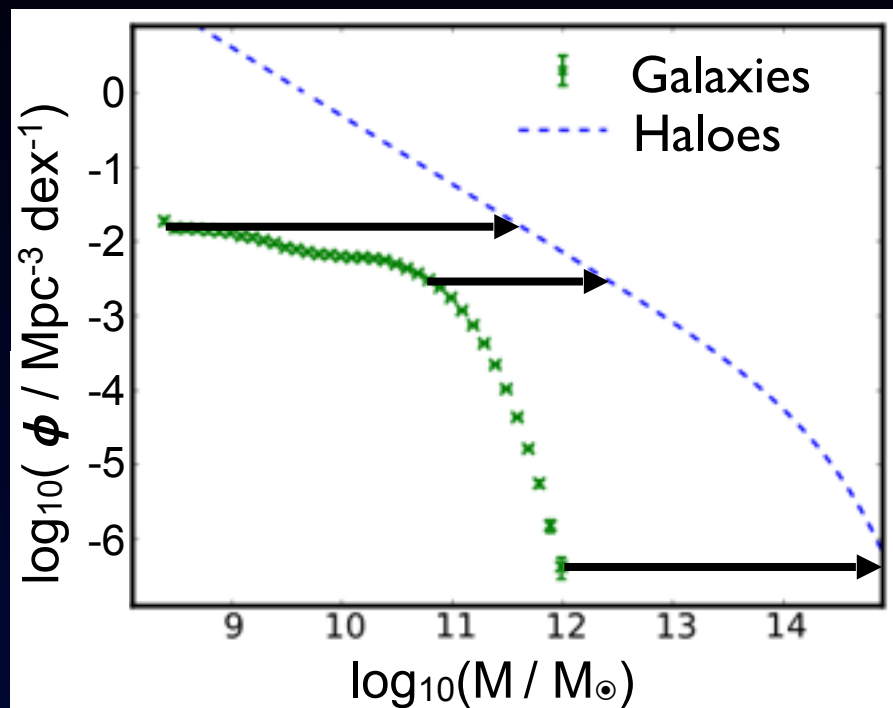 ➤ different results

- Empirical Models: link galaxies and haloes statistically
  ➤ follow galaxy populations through time
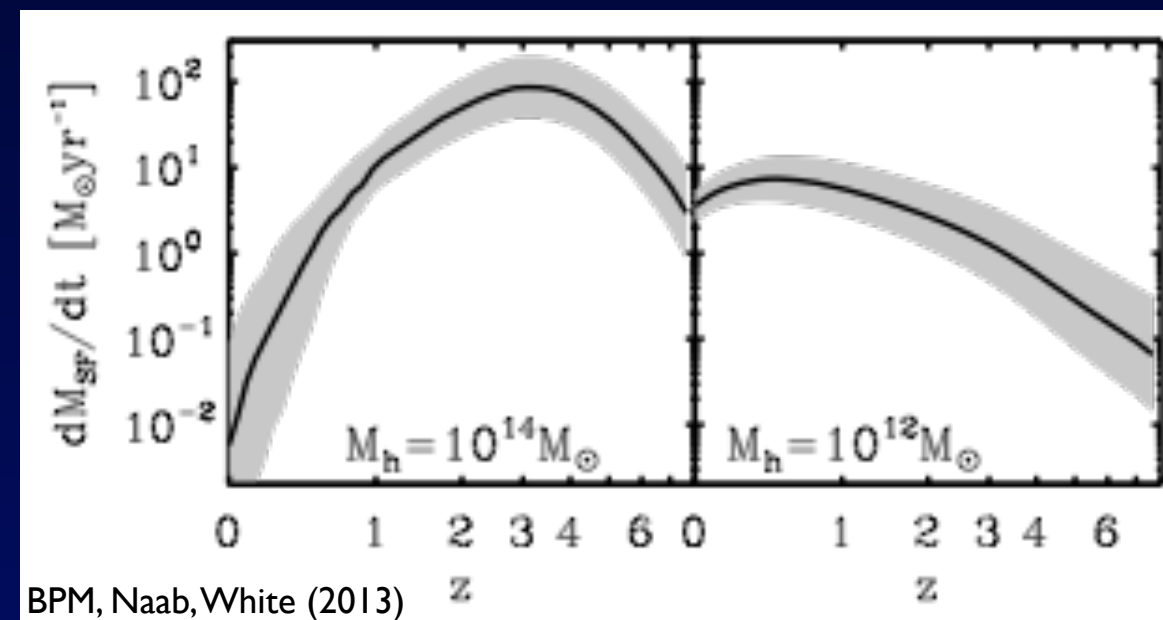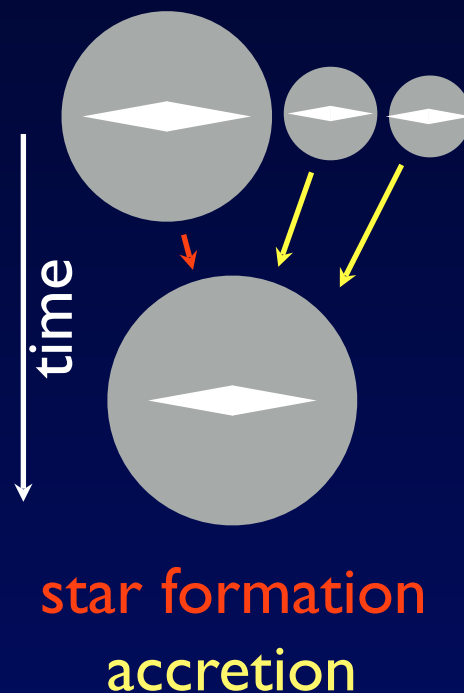 ➤ put constraints on physical processes involved

Factor 10 {

$\times$ Li & White (2009)

— Simulations

$\log_{10}(\phi$ / Mpc^{-3} dex^{-1})

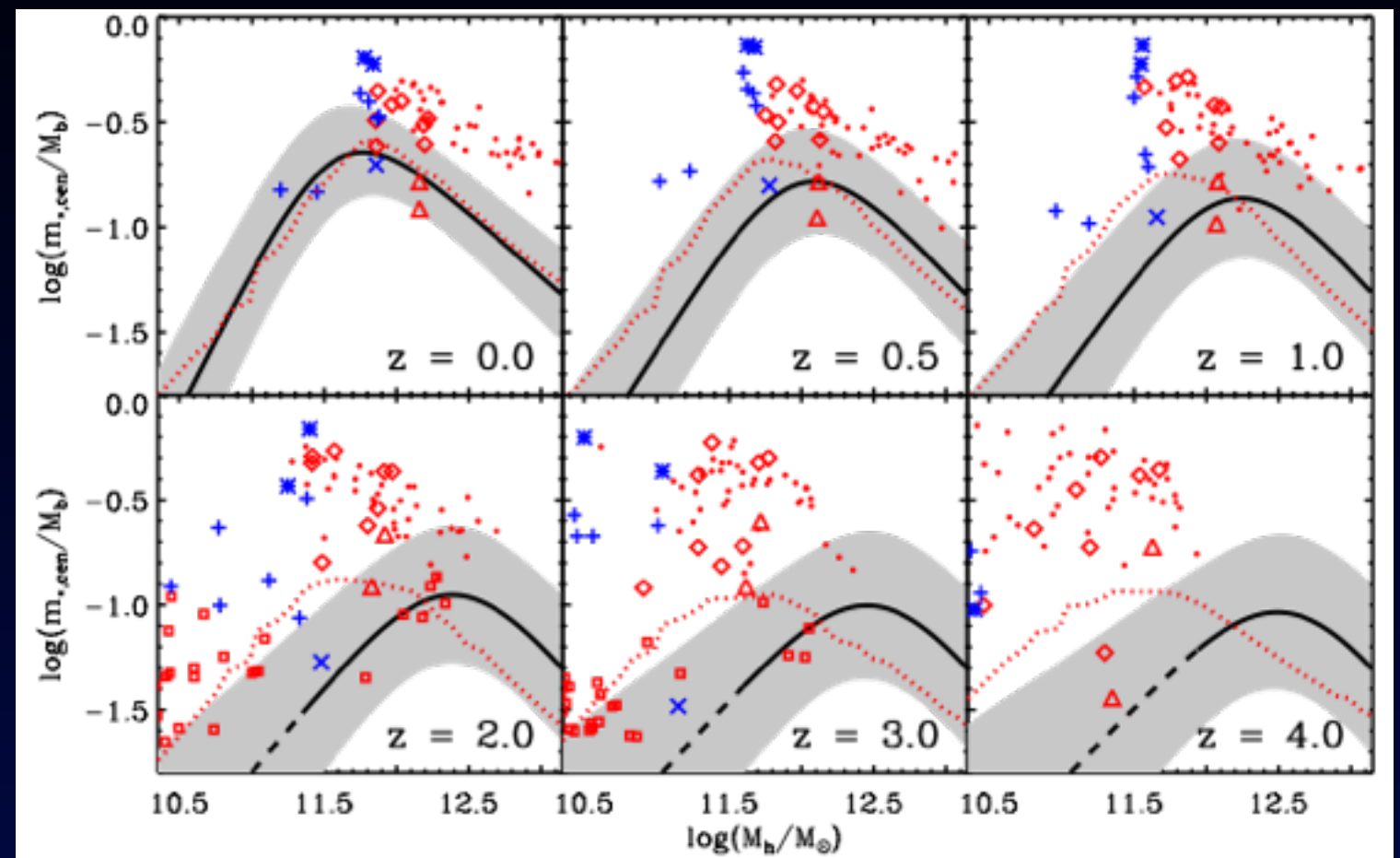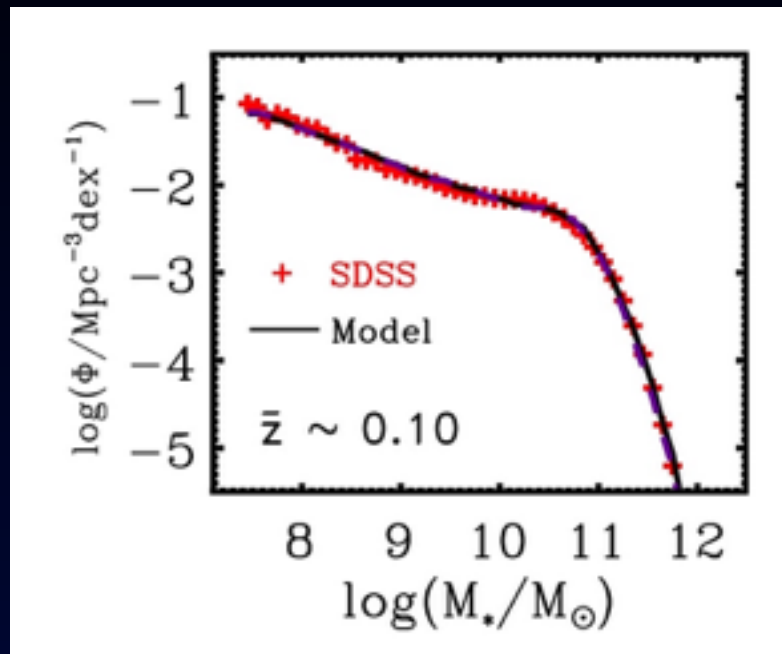$\log_{10}(m_* / M_\odot)$
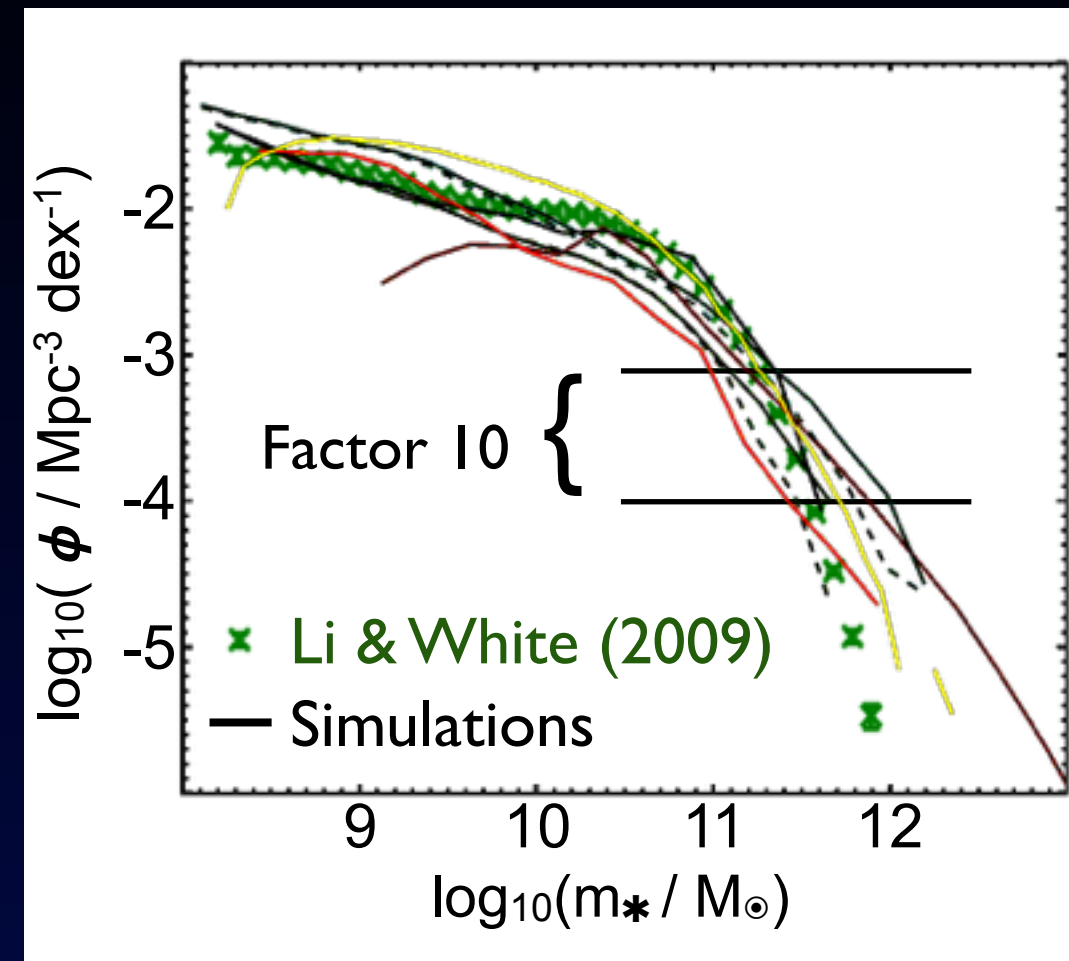
Abundance matching

Abundance matching

- Populate halo merger trees

- infer SF & accretion rates

star formation
accretion

time

SNe   AGN(?)

$\log_{10}(m_* / M_\odot)$
$\log_{10}(m_* / M_h)$
$\log_{10}(M_h / M_\odot)$ BPM+(2010)

$\log_{10}(\phi$ / Mpc^{-3} dex$^{-1})$
$\log_{10}(M / M_\odot)$

Galaxies
Haloes

dM_{SF}/dt [$M_\odot yr^{-1}$]
$M_h = 10^{14} M_\odot$ $M_h = 10^{12} M_\odot$
z z
BPM, Naab, White (2013)

Constraints for dwarf galaxies?

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Benjamin Moster   Constraints from empirical models   Ringberg, 12.05.2016
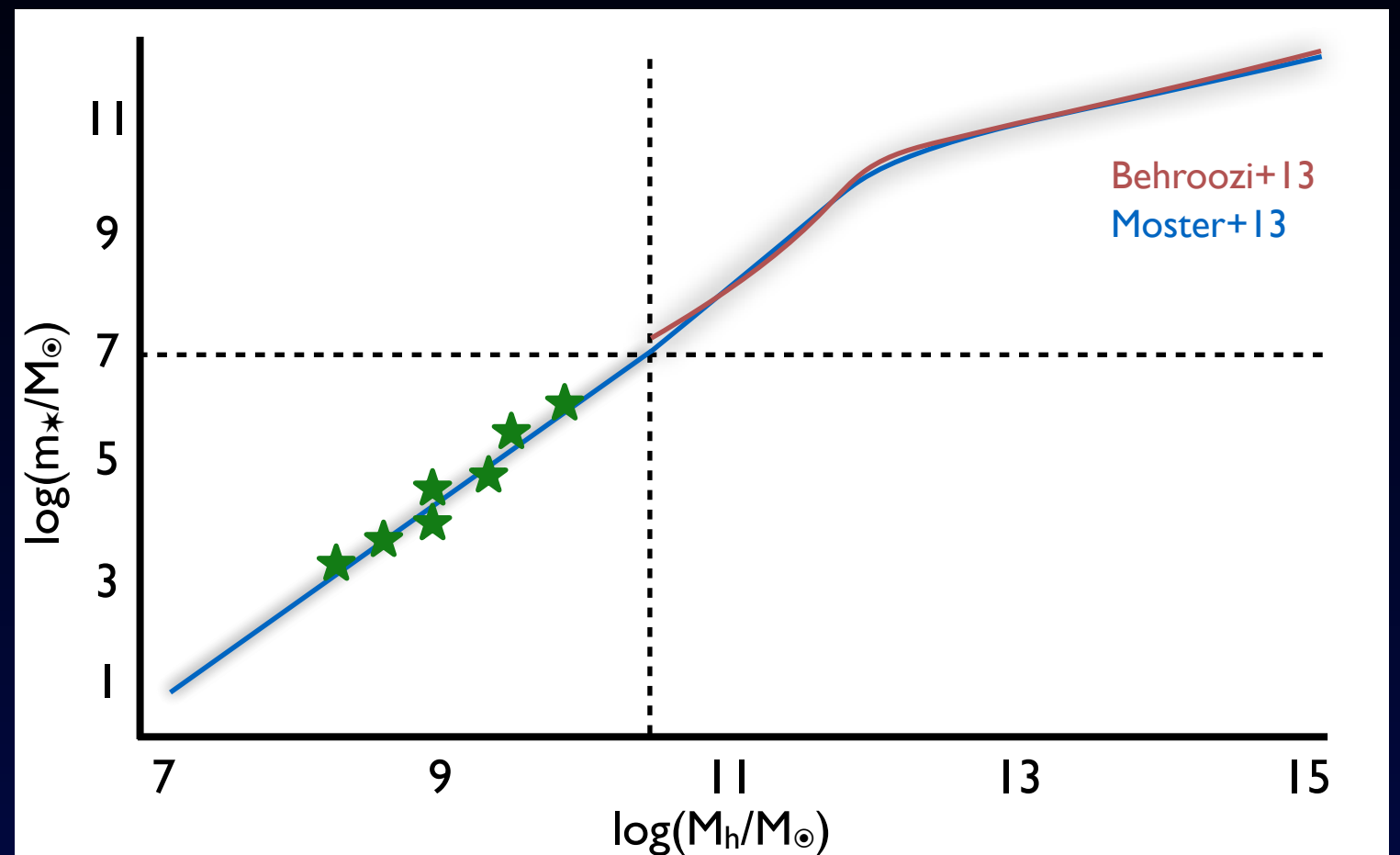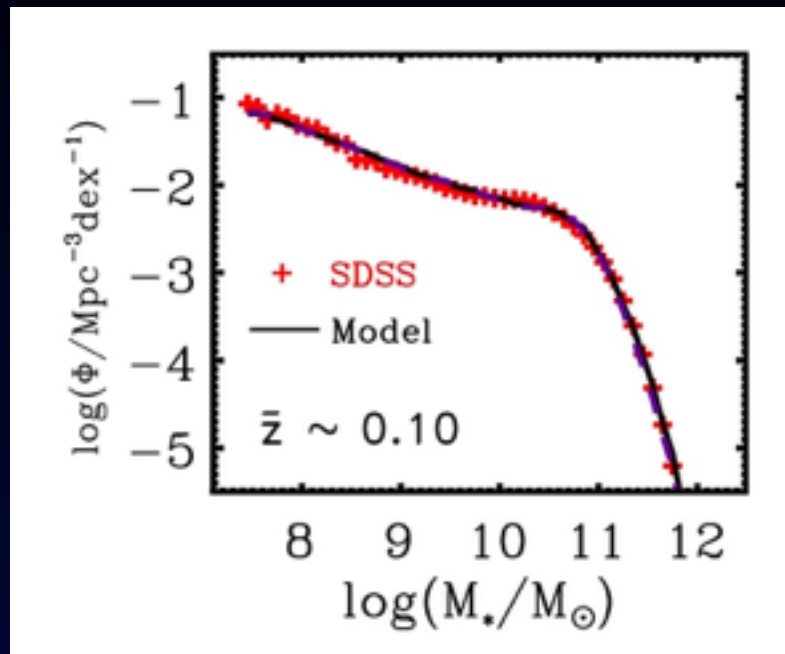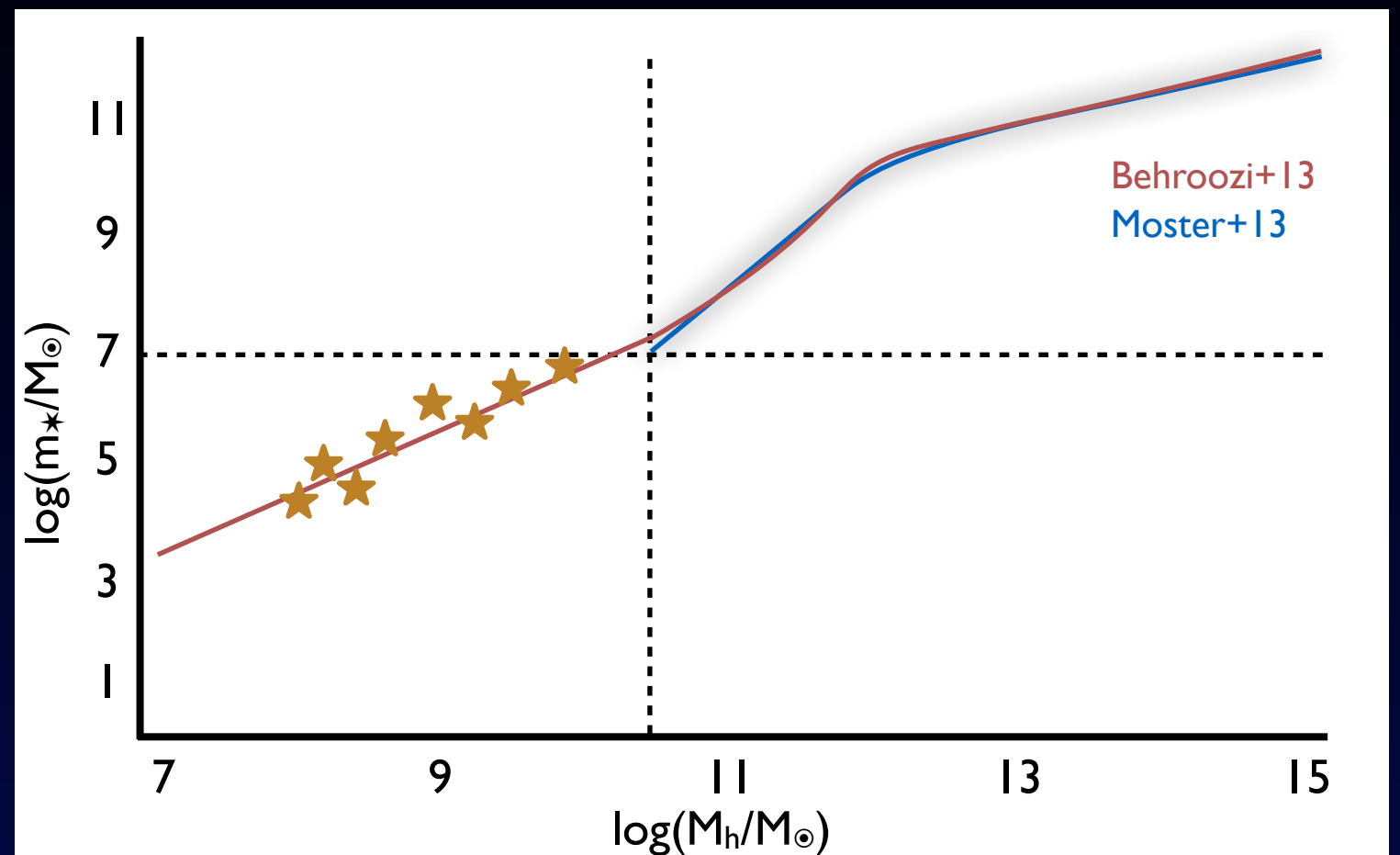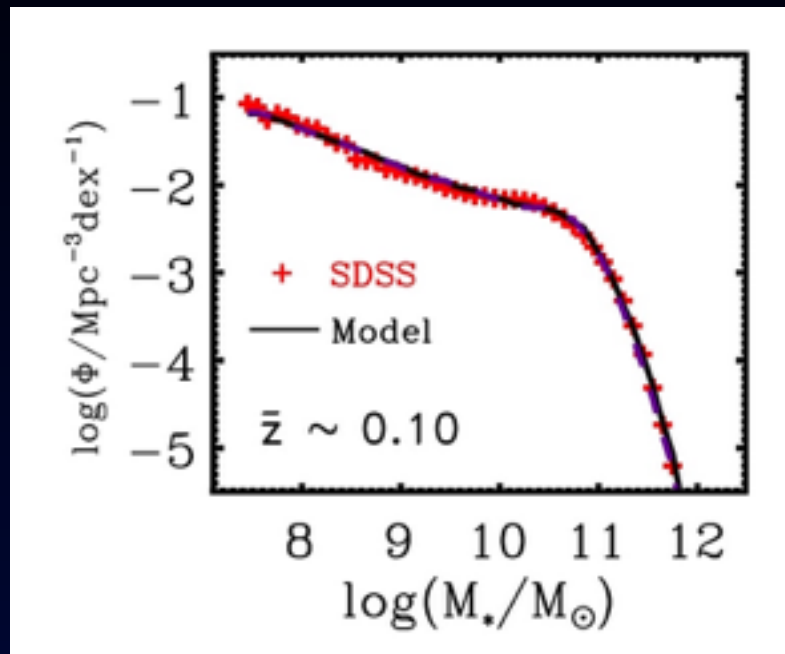
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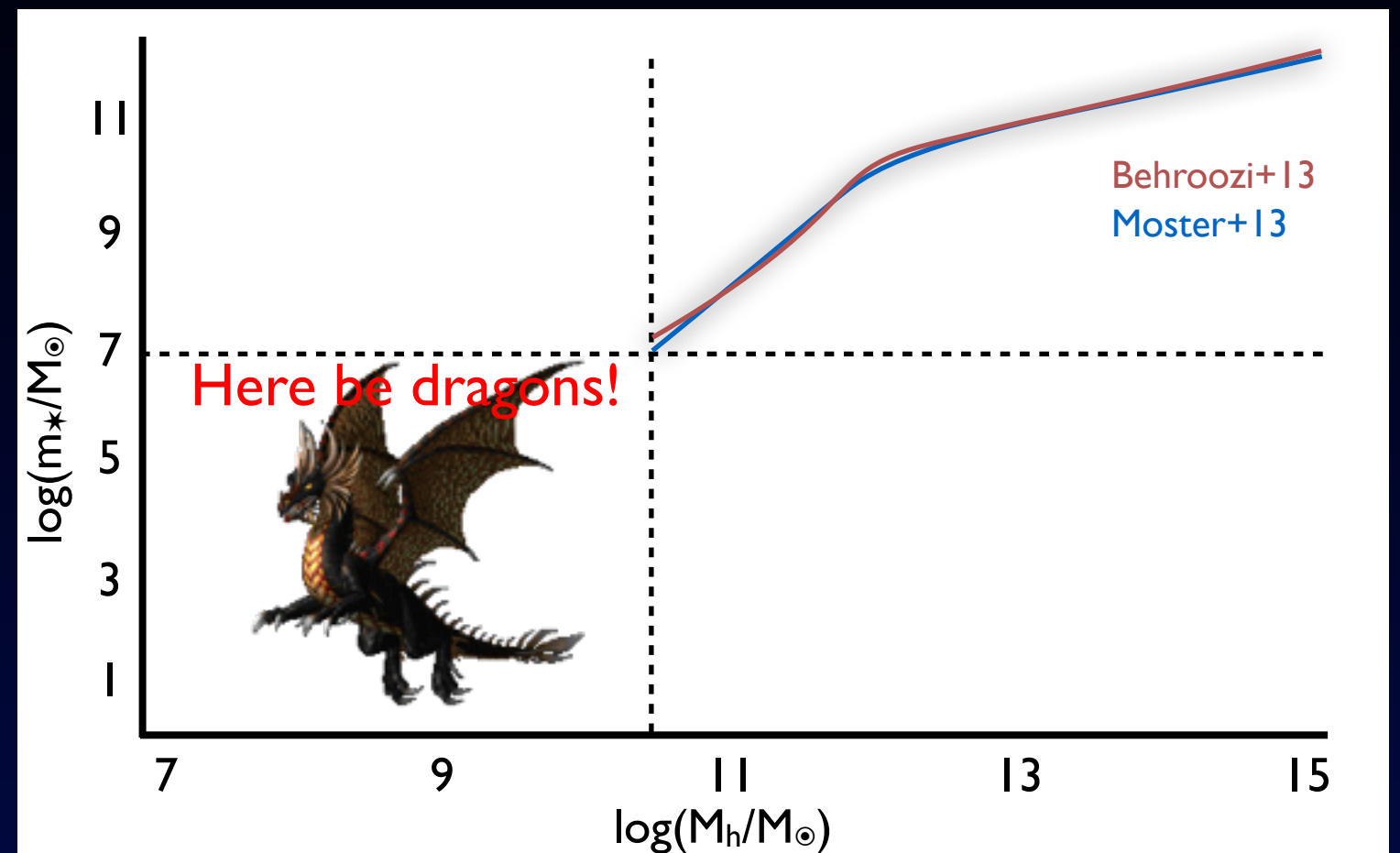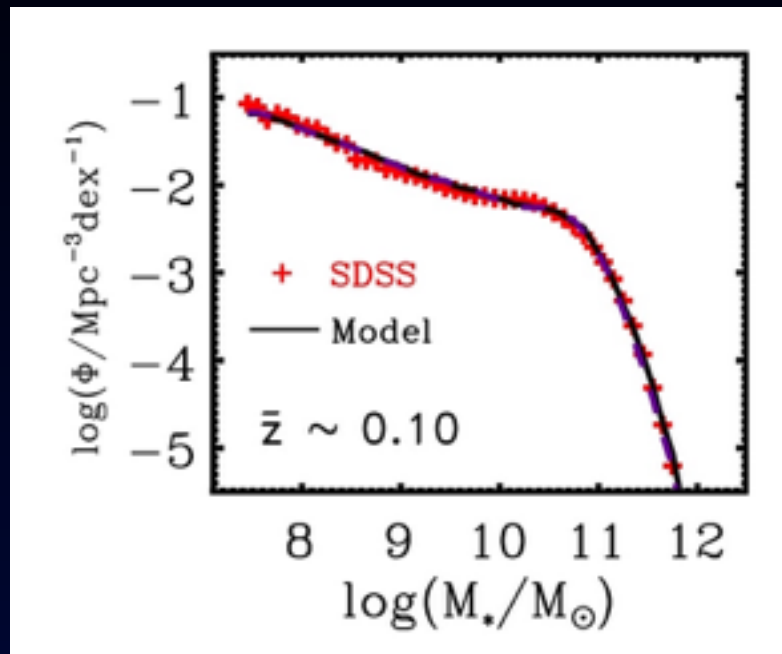
- Extrapolation is dangerous

- Some subhaloes might be dark (cf. Sawala+15)
- The physics dominating galaxy formation at $M_h \approx 10^{11} M_\odot$ don't necessary apply the same at $M_h < 10^{10} M_\odot$
- No independent confirmation of model (e.g. clustering)

Scatter & Colours

- So far: constant scatter (typically 0.15 - 0.2 dex)

- SFR only for average halo mass
  ➙ no SSFR or colour information

    for individual galaxies

- Cannot predict colour-dependence

  - Bimodality

  - Clustering

  - Conformity
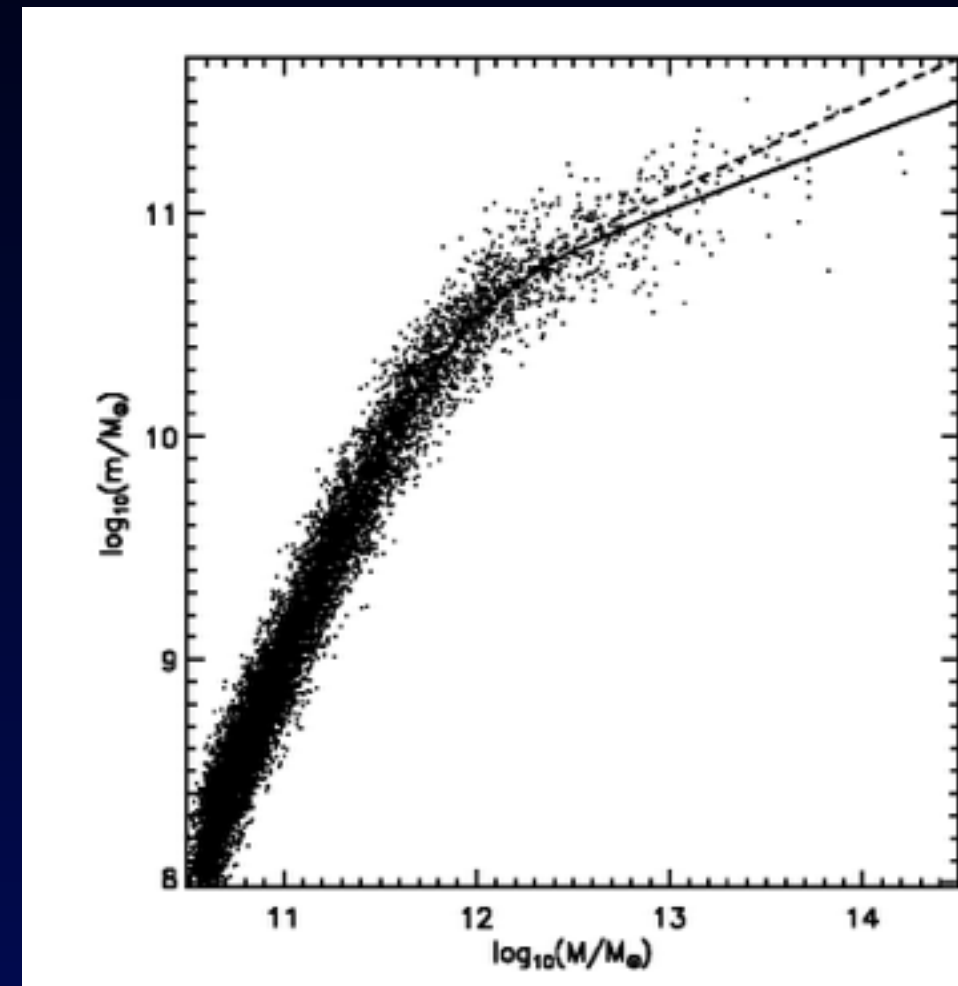
Models for individual haloes

- So far: average m_*-M_h relation
  Now: individual growth histories
  $m_* / M_h = \varepsilon_{integr}\ (M_h, z)$

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Models for individual haloes

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  Now: individual growth histories

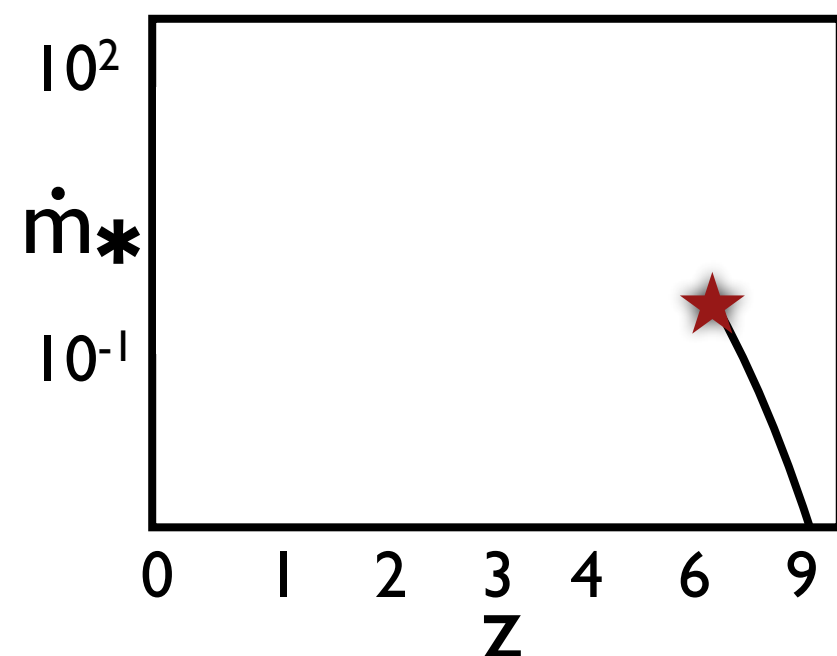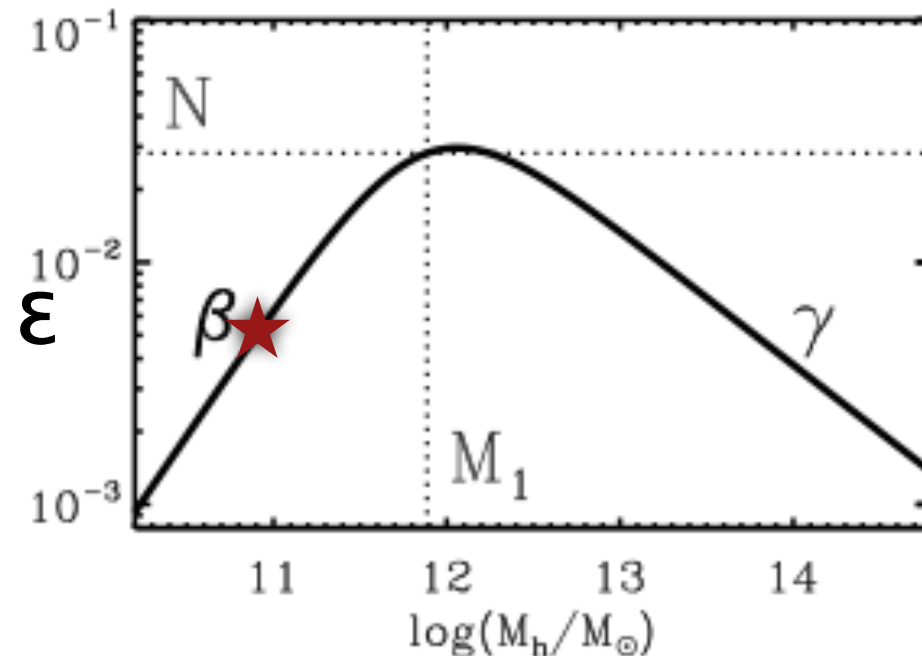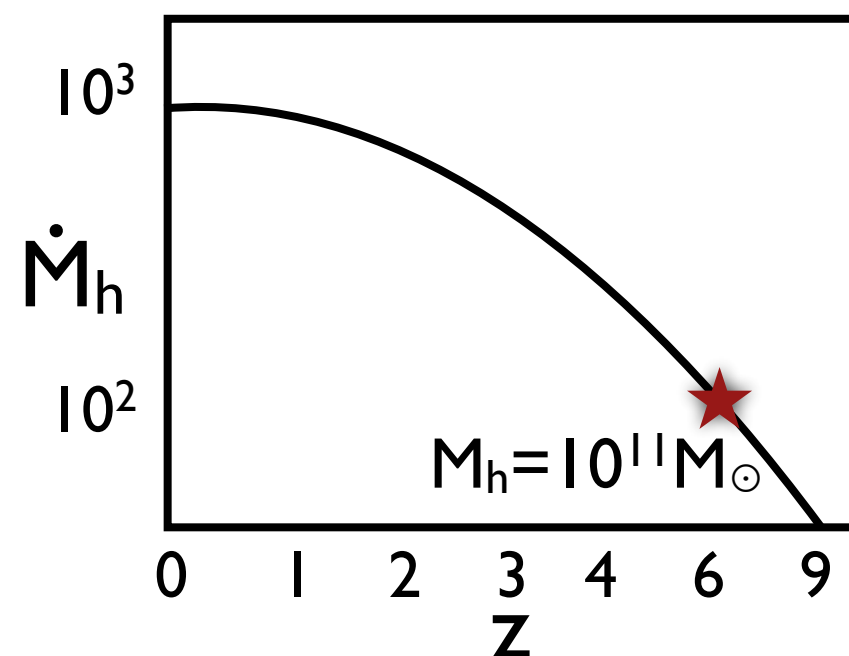 $\dot{m}_* / \dot{M}_h = \varepsilon_{instant}(M_h, z)$

  Material becoming available

  Conversion efficiency

- Stellar mass increases as

  $\Delta m_* = \boxed{\varepsilon} \cdot \boxed{\Delta M_h} = \varepsilon \, \dot{M}_h \, \Delta t$

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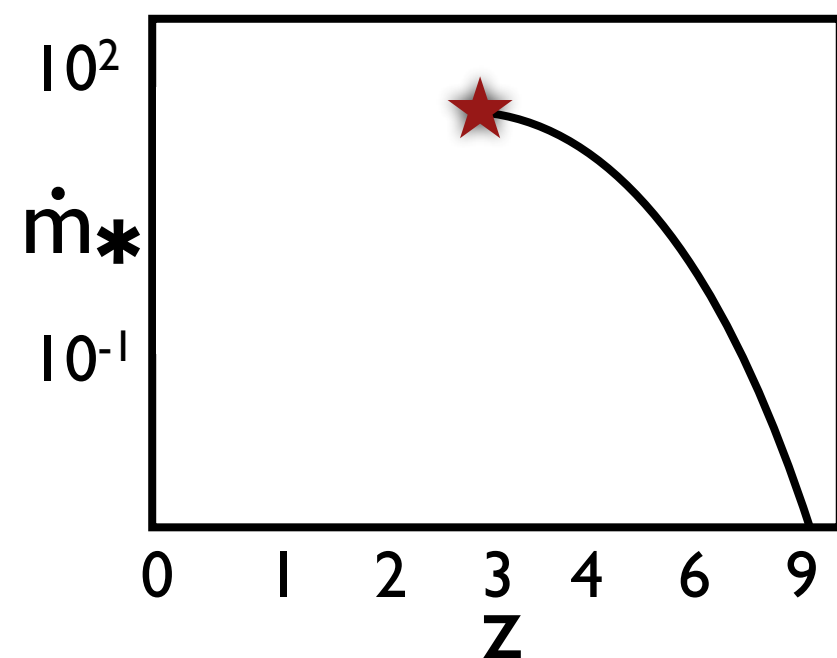 $\dot{m}_* / \dot{M}_h = \varepsilon_{instant} (M_h, z)$

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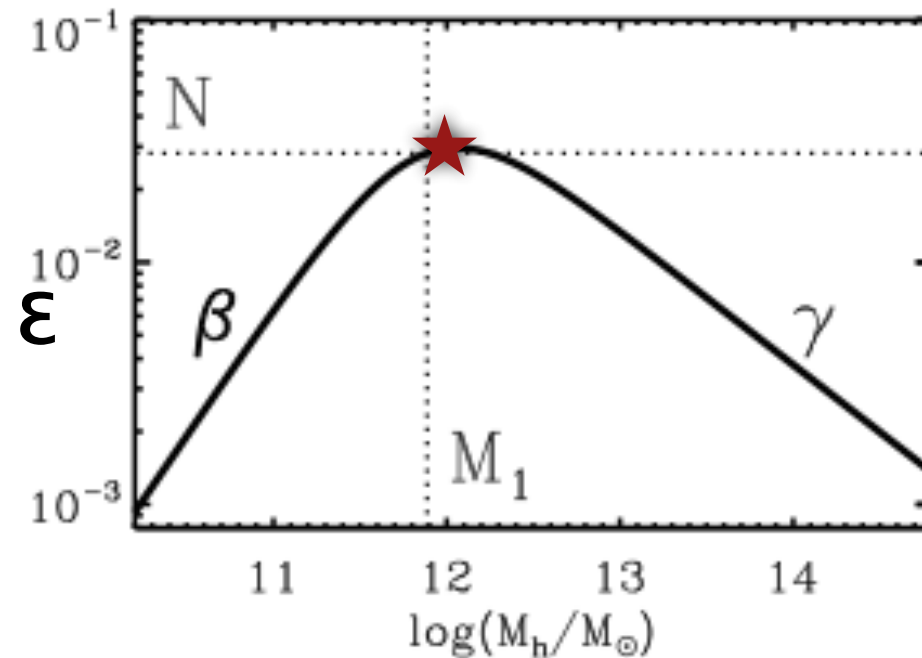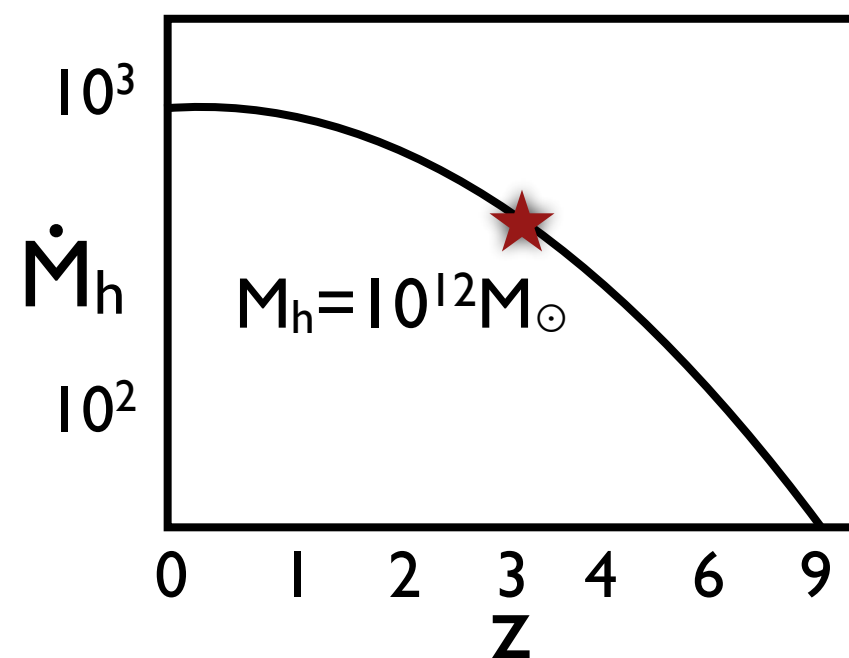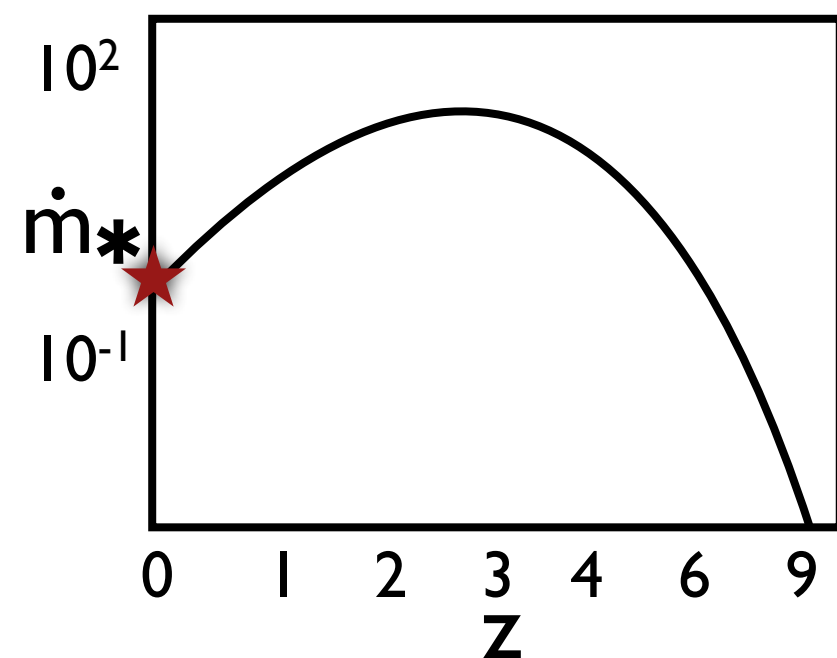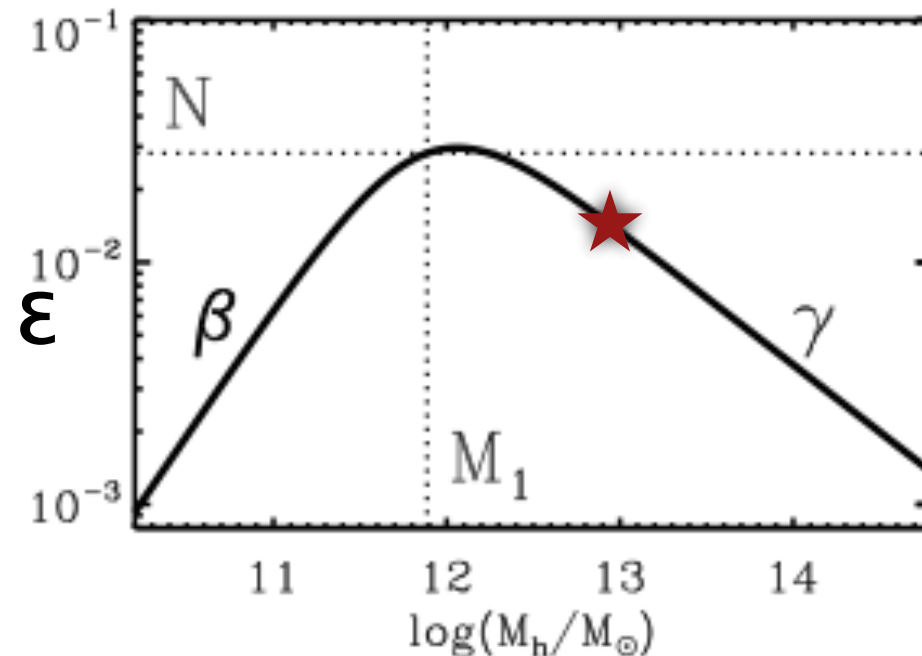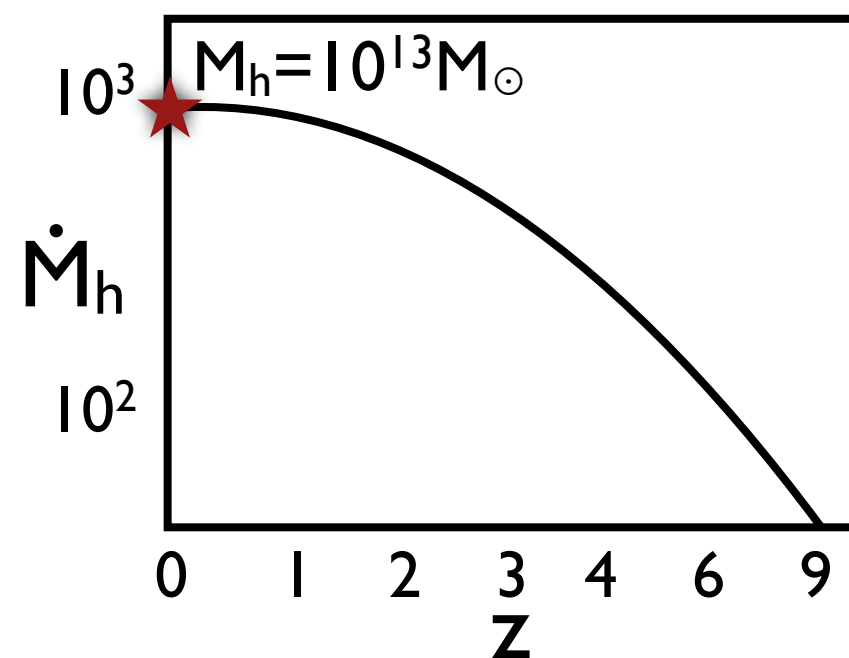- So far: average $m_* - M_h$ relation
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Satellite galaxies

- Quenching:

Halo stops growing ➤ SF at current rate

τ after halo stop growing ➤ SF quenched

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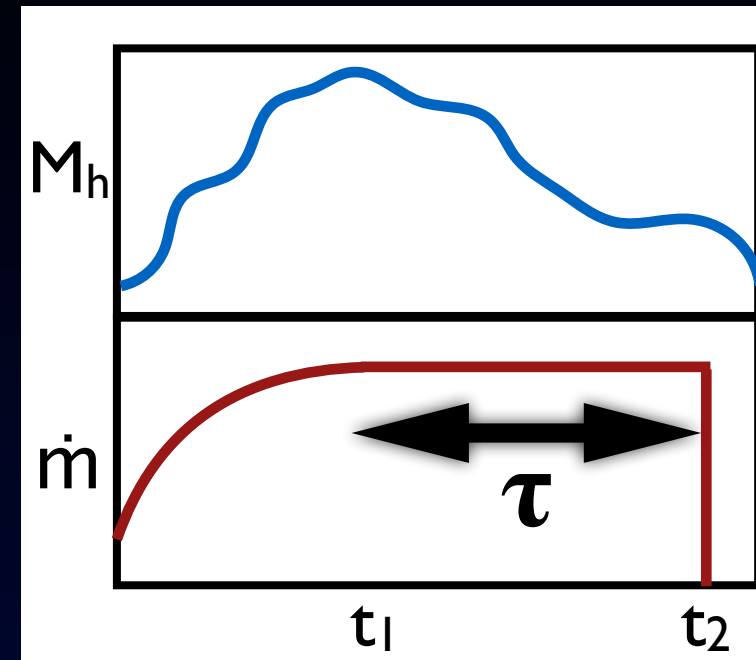Benjamin Moster   Constraints from empirical models   Ringberg, 12.05.2016

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Satellite galaxies

- Quenching:

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  τ after halo stop growing ➤ SF quenched

- Stripping:

  Subhalo mass decreased sufficiently ➤ stars become unbound

  Halo mass falls below threshold $M_h = f_s M_{peak}$ ➤ stars stripped

- Merging:

  ➤ fraction f_m of the satellite mass is ejected to the ICM

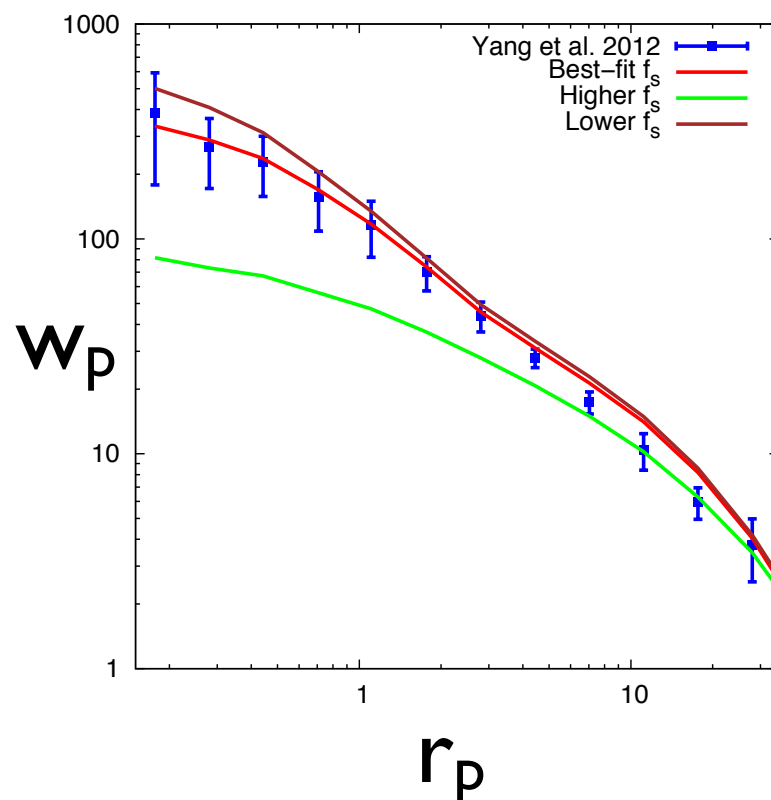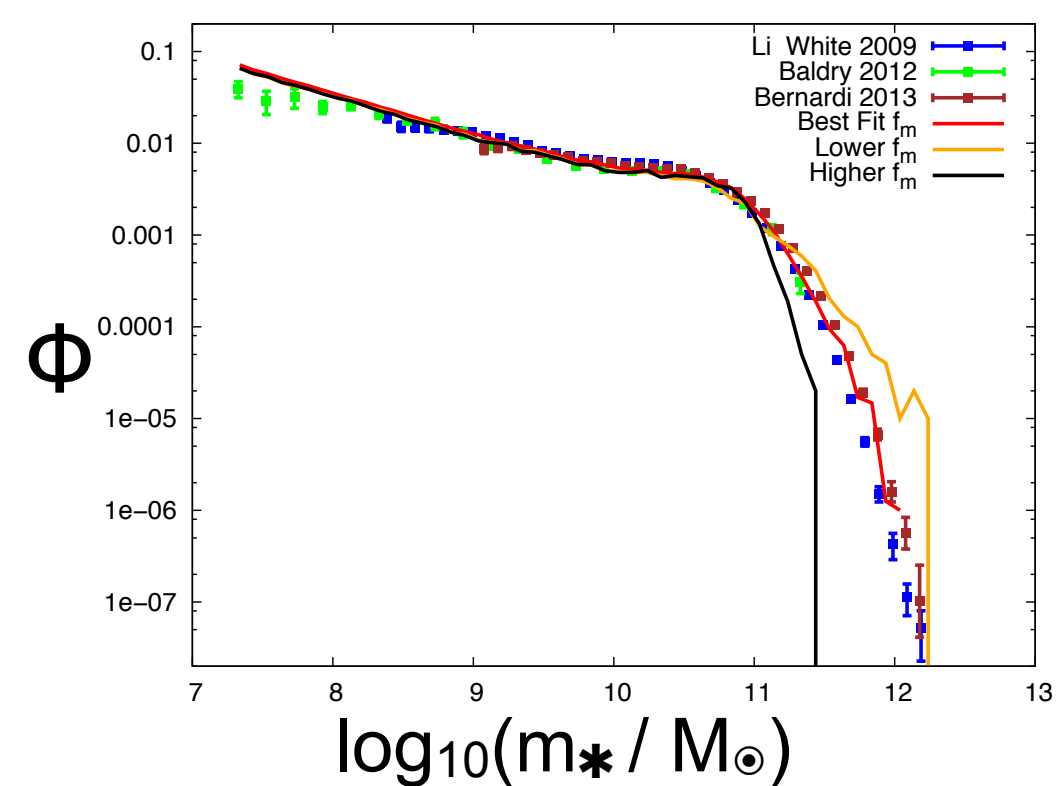 ➤ the rest $(1-f_m) \cdot m_s$ is added to the central galaxy
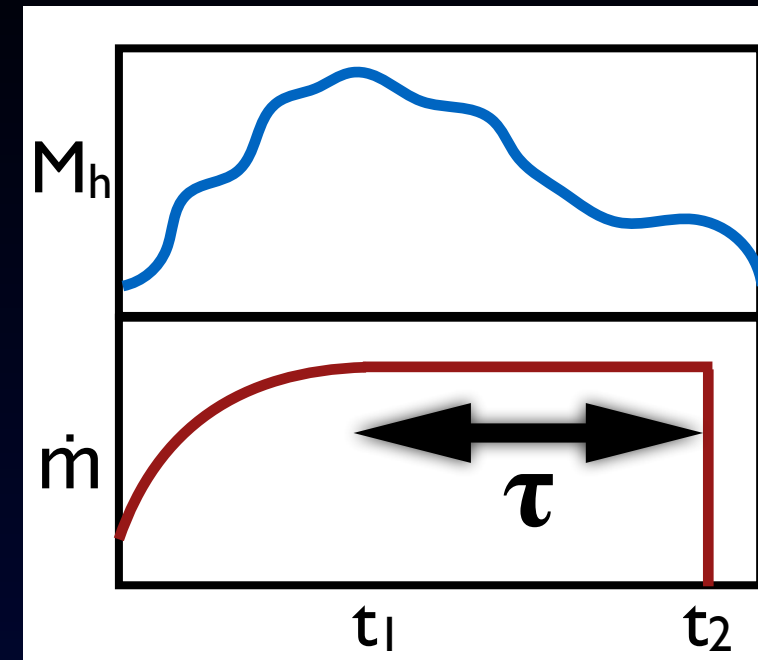
Constraints on the model

- Each model parameter is constrained by one observation

- Use MCMC to fit parameters and get uncertainty

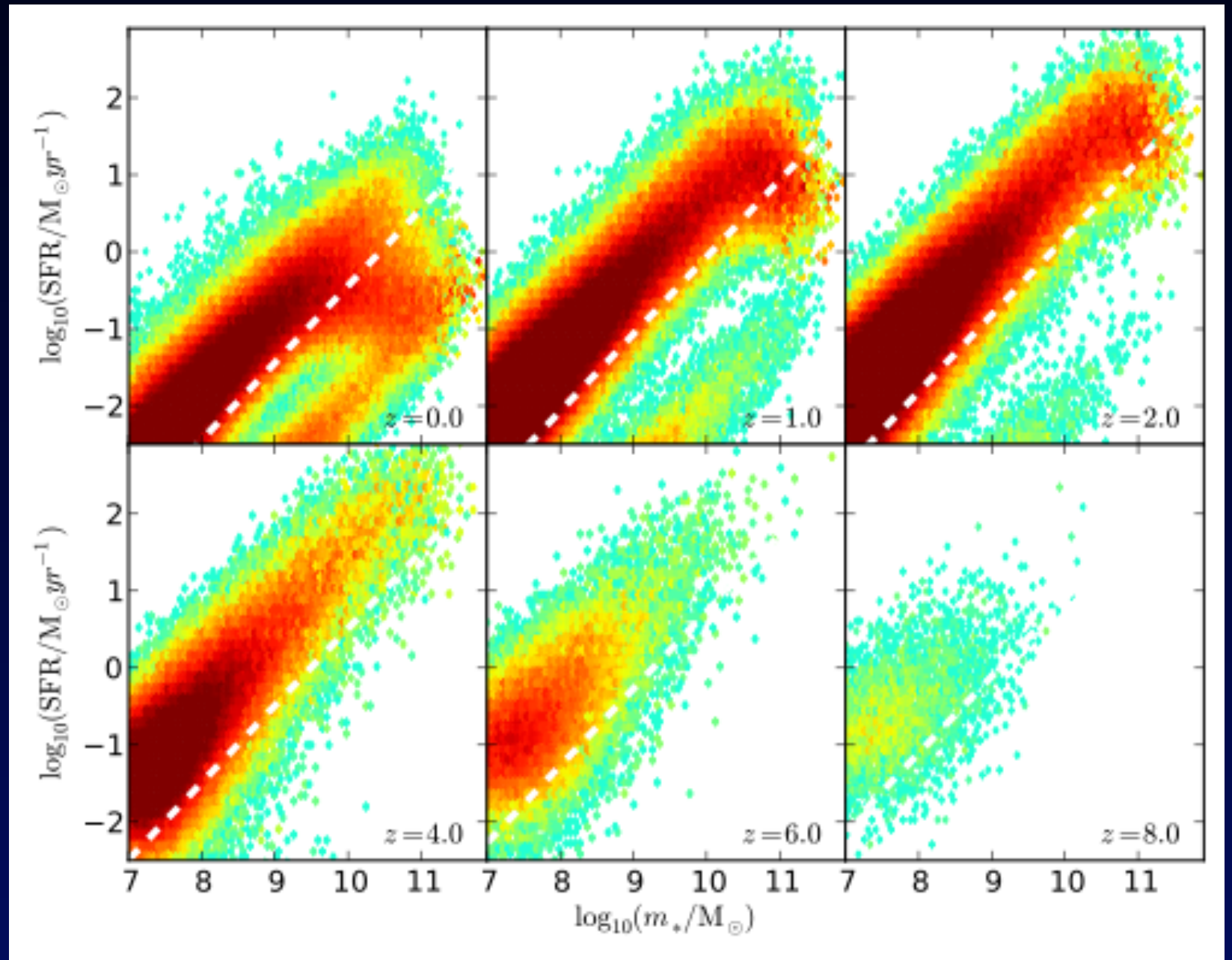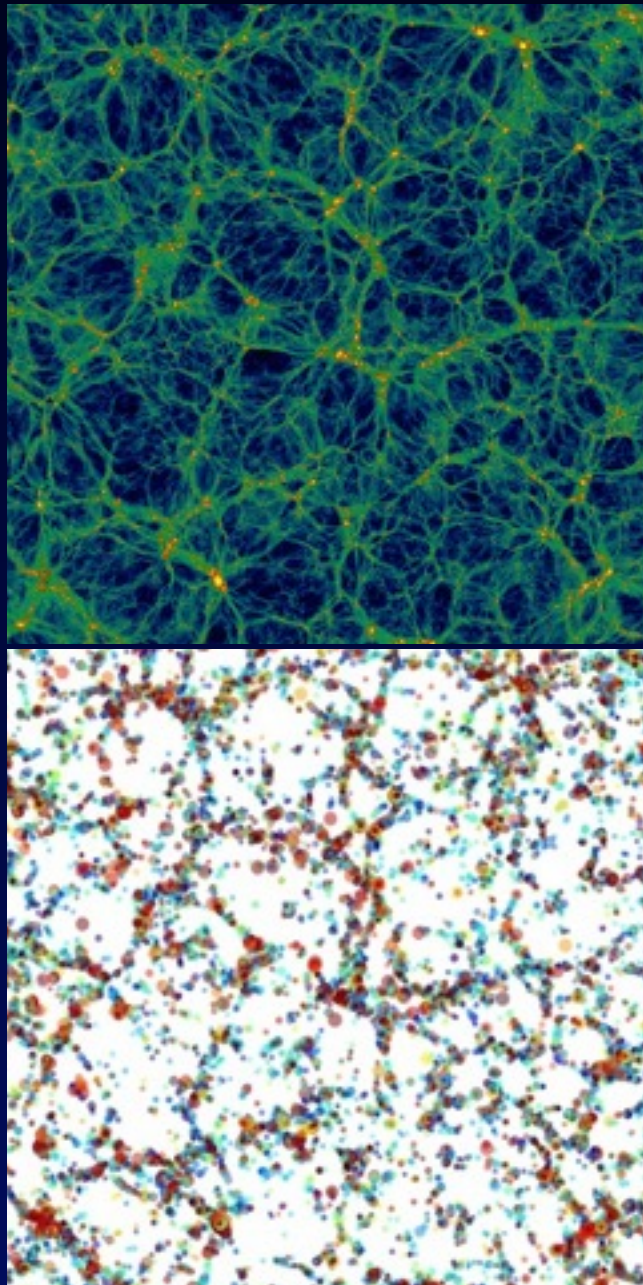- Bayes Factors ➡ Keep model as simple as possible
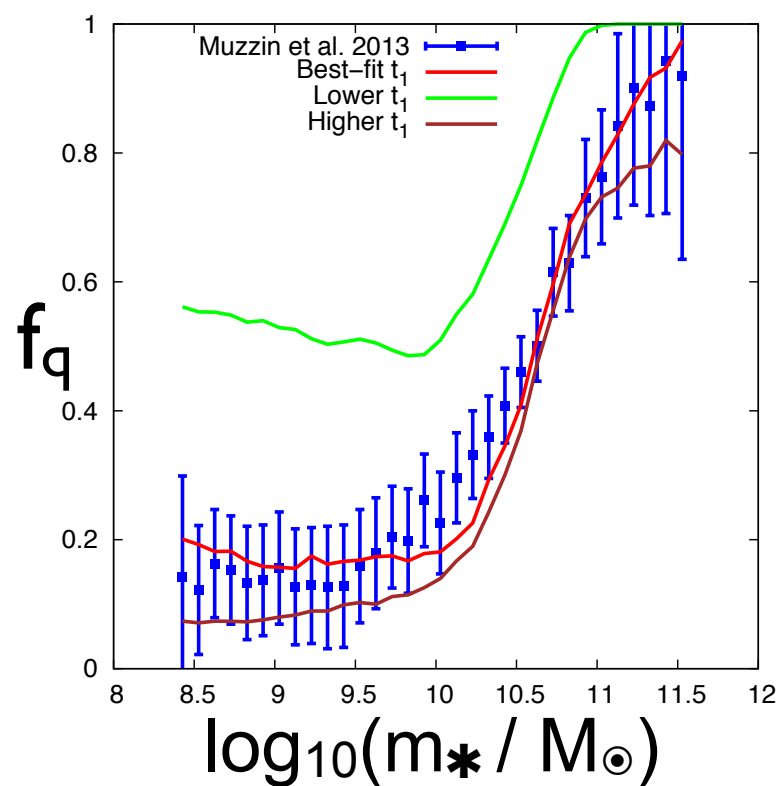
➡ Quenching   ➡ Stripping   ➡ Merging

Statistical galaxy properties

- Galaxies have a wide range of color / SFRs

- Model reproduces large number of observations up to high z

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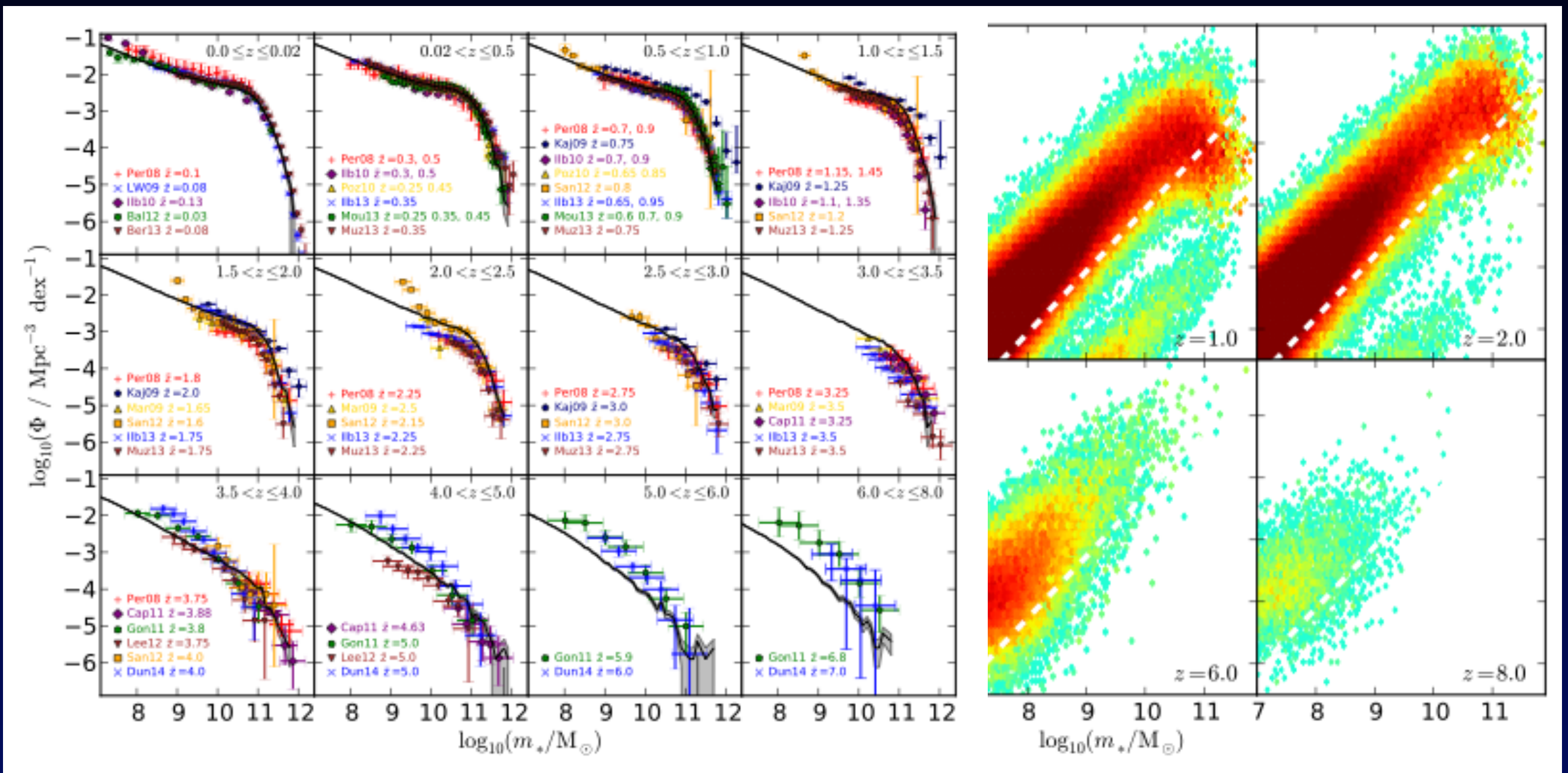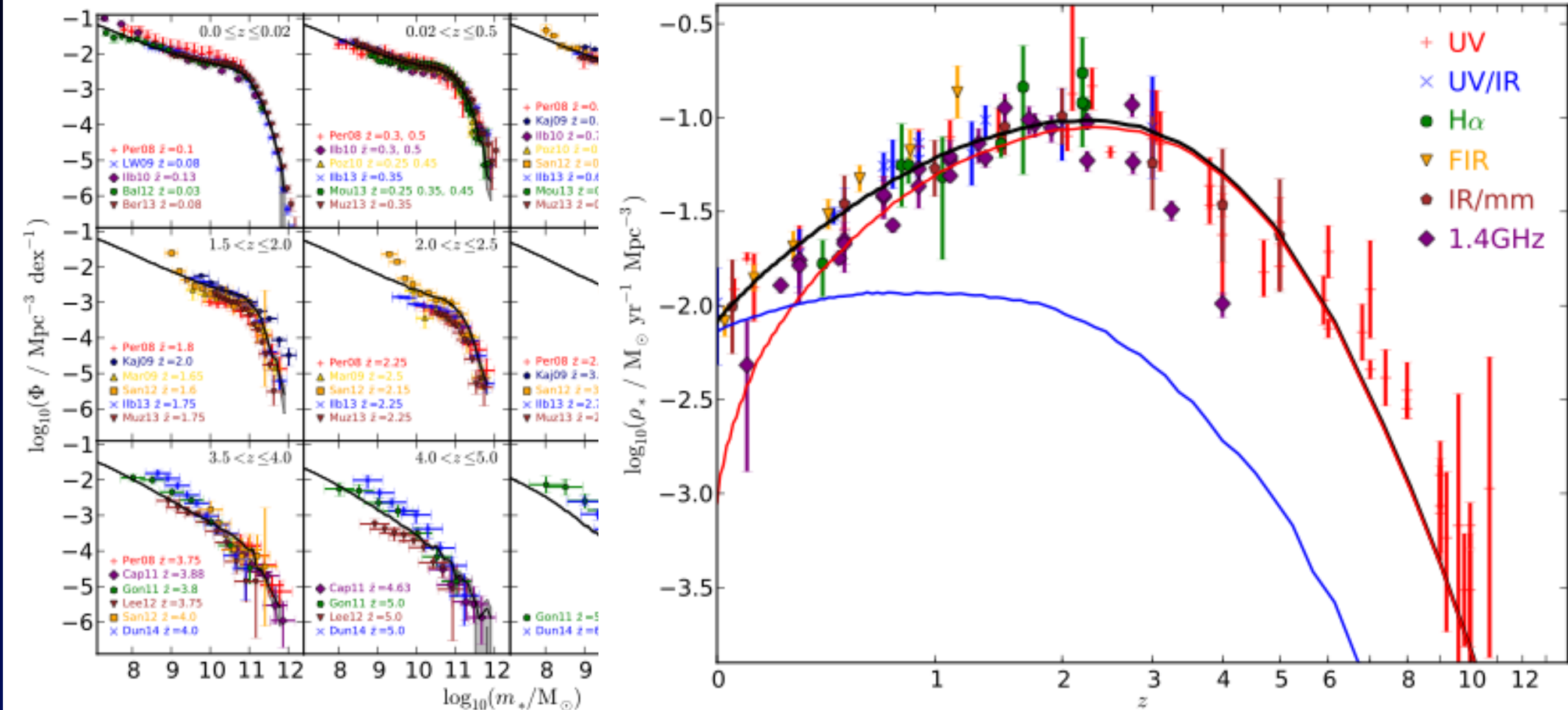
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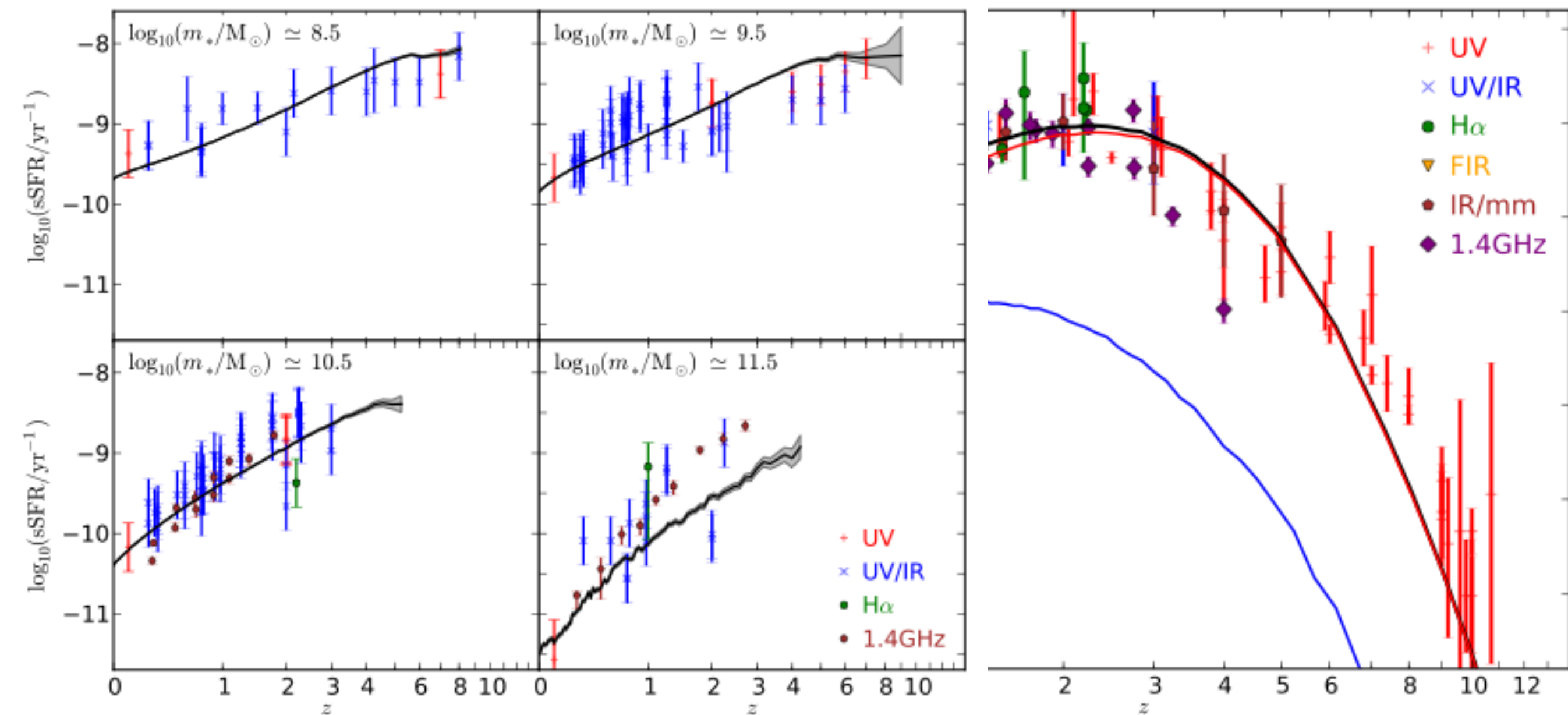- Model reproduces large number of observations up to high z

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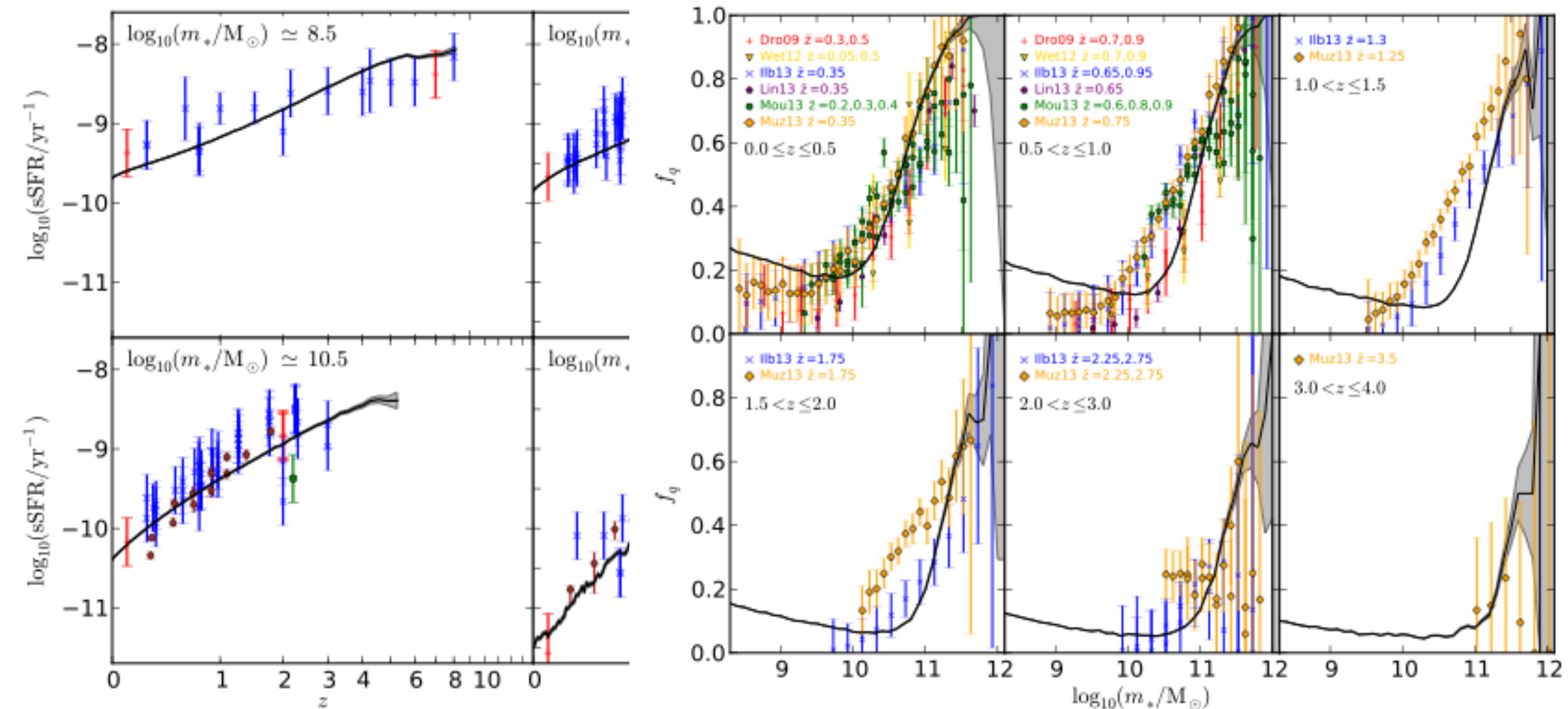- Model reproduces large number of observations up to high z

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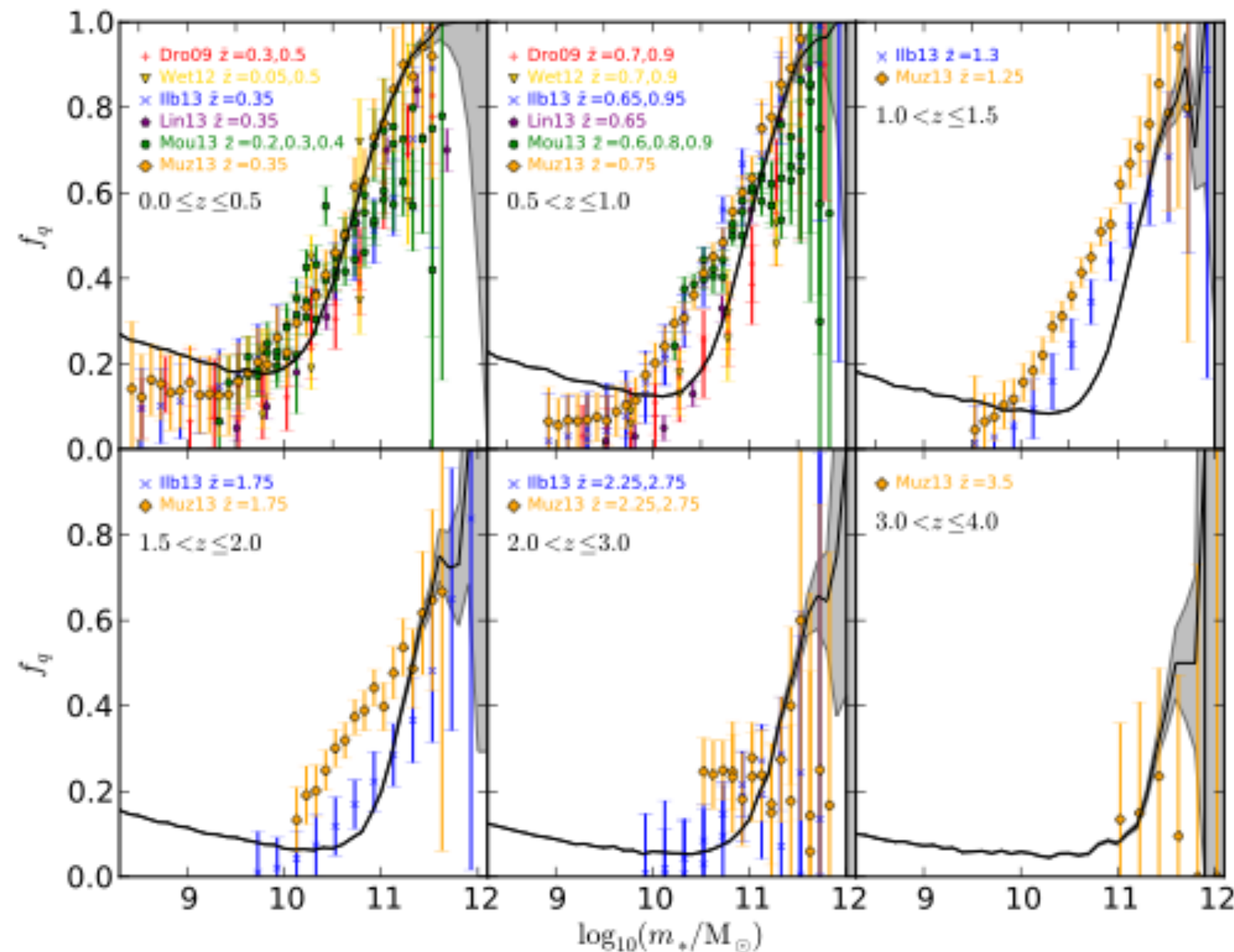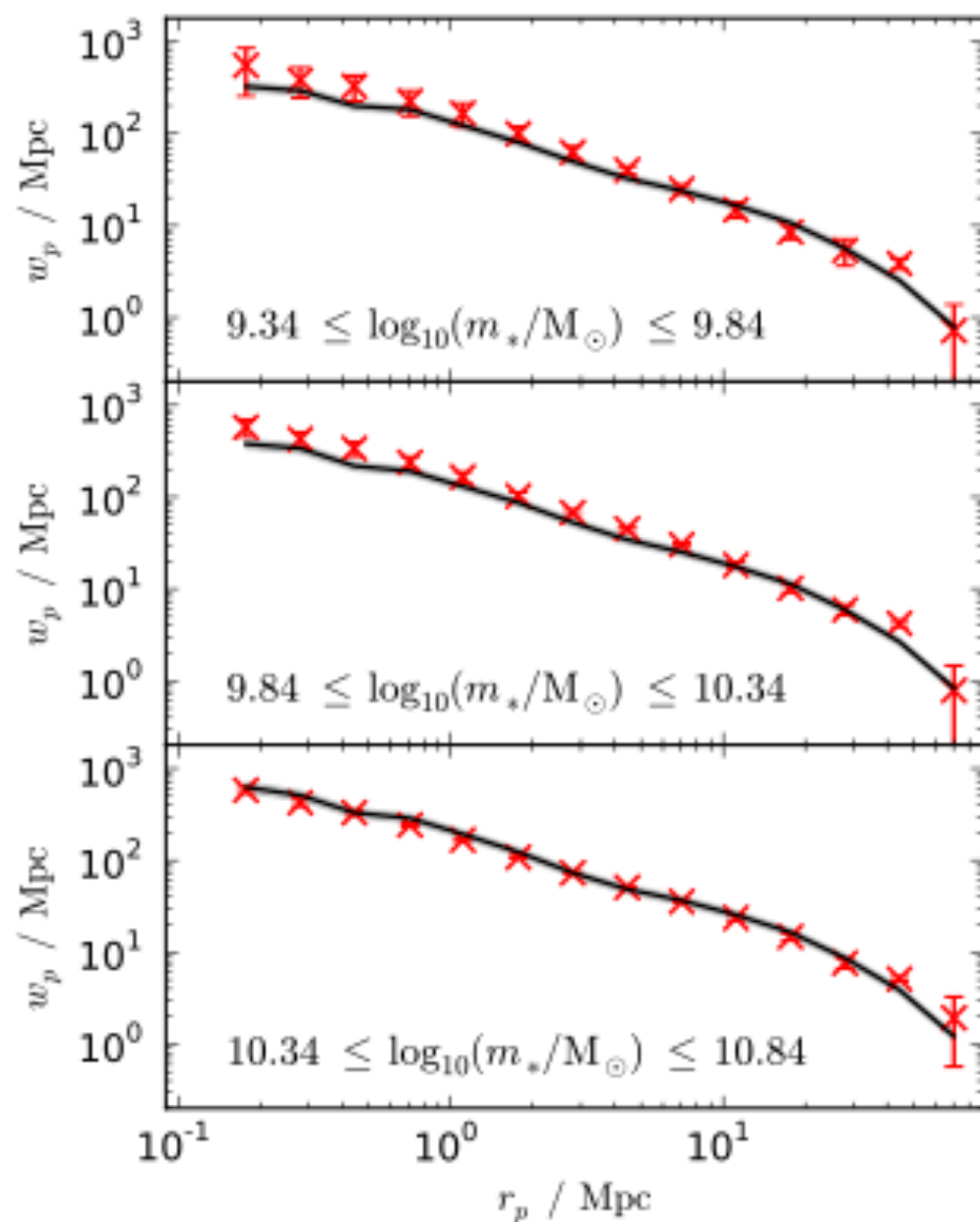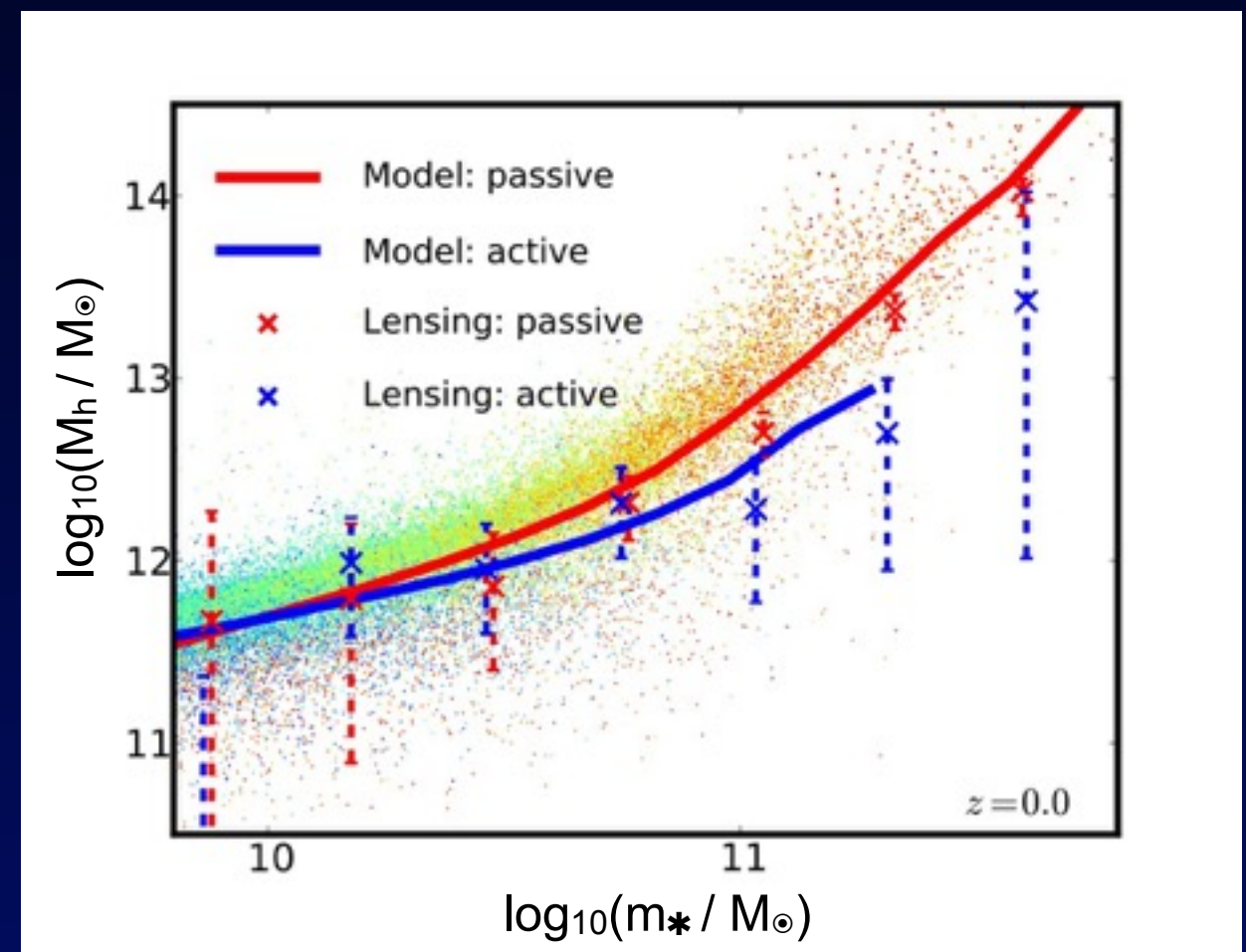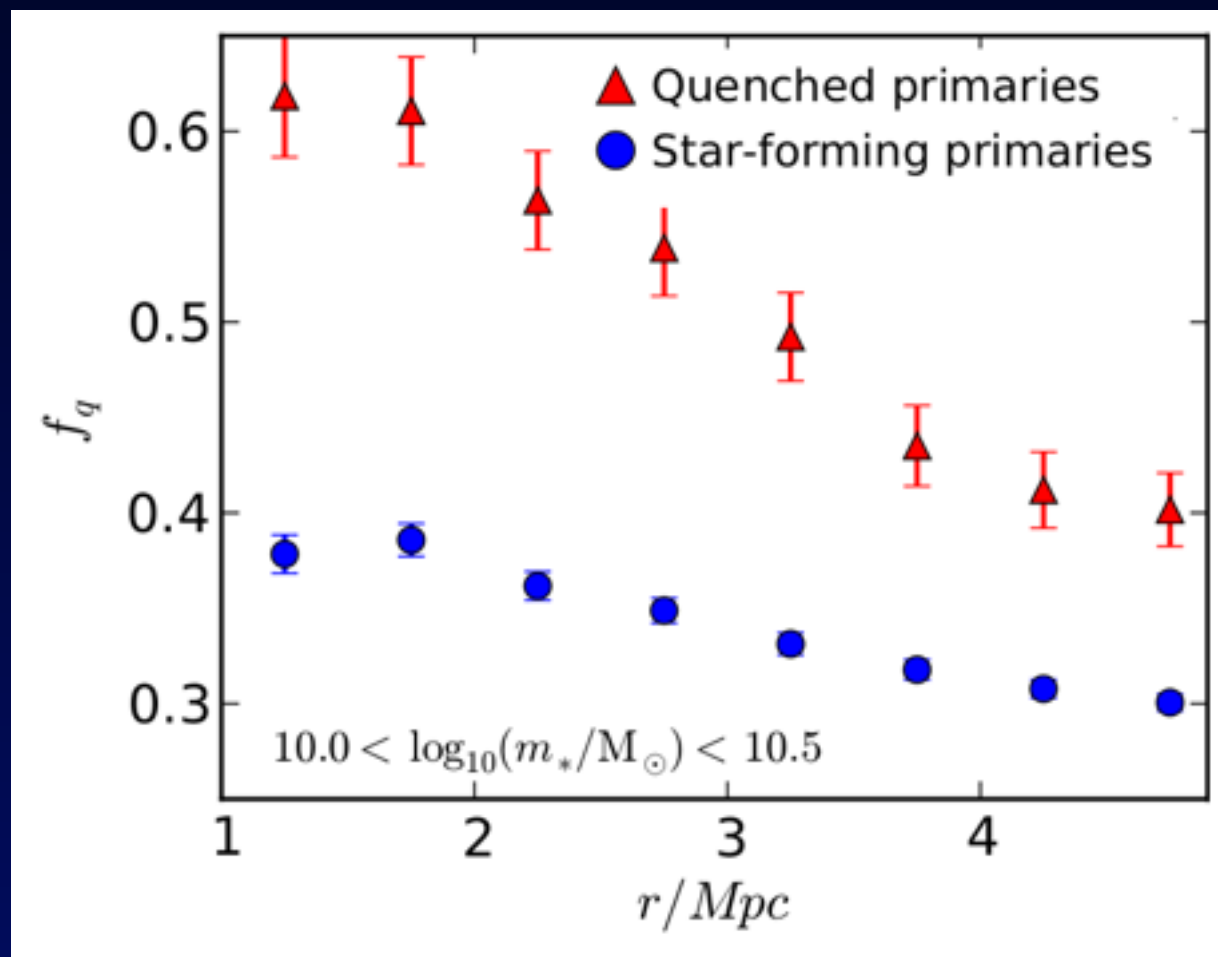- Model reproduces large number of observations up to high z

Conformity and m∗(Mh) for red/blue
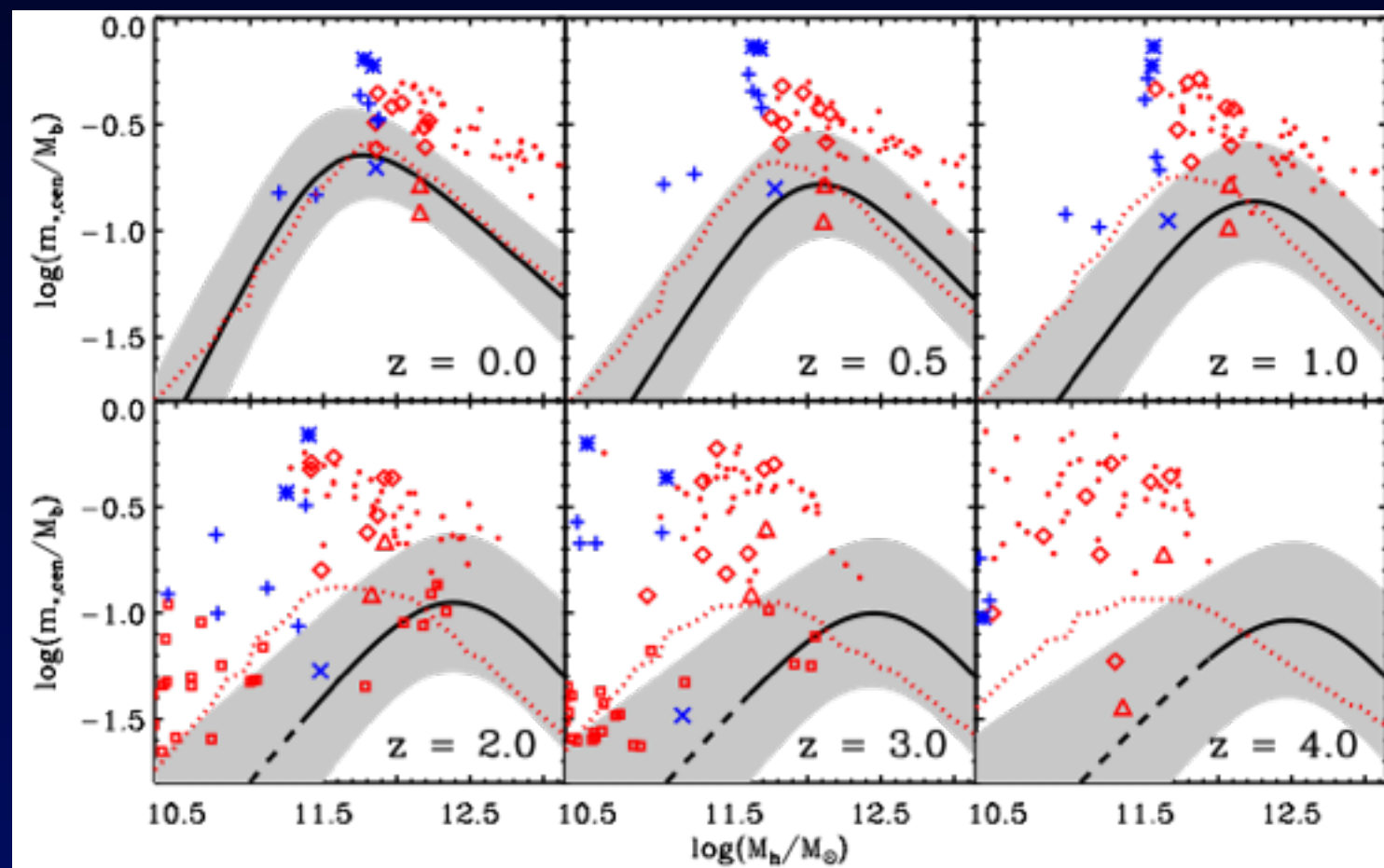
- SFR directly connected to halo growth rate

  Halo conformity ➙ Galaxy conformity

- Passive galaxies live in more massive haloes

Constraints and Predictions

- Empirical models helpful for:

    - Predictions unbiased by assumptions on baryonic physics

    - Testing the cosmological framework on new data

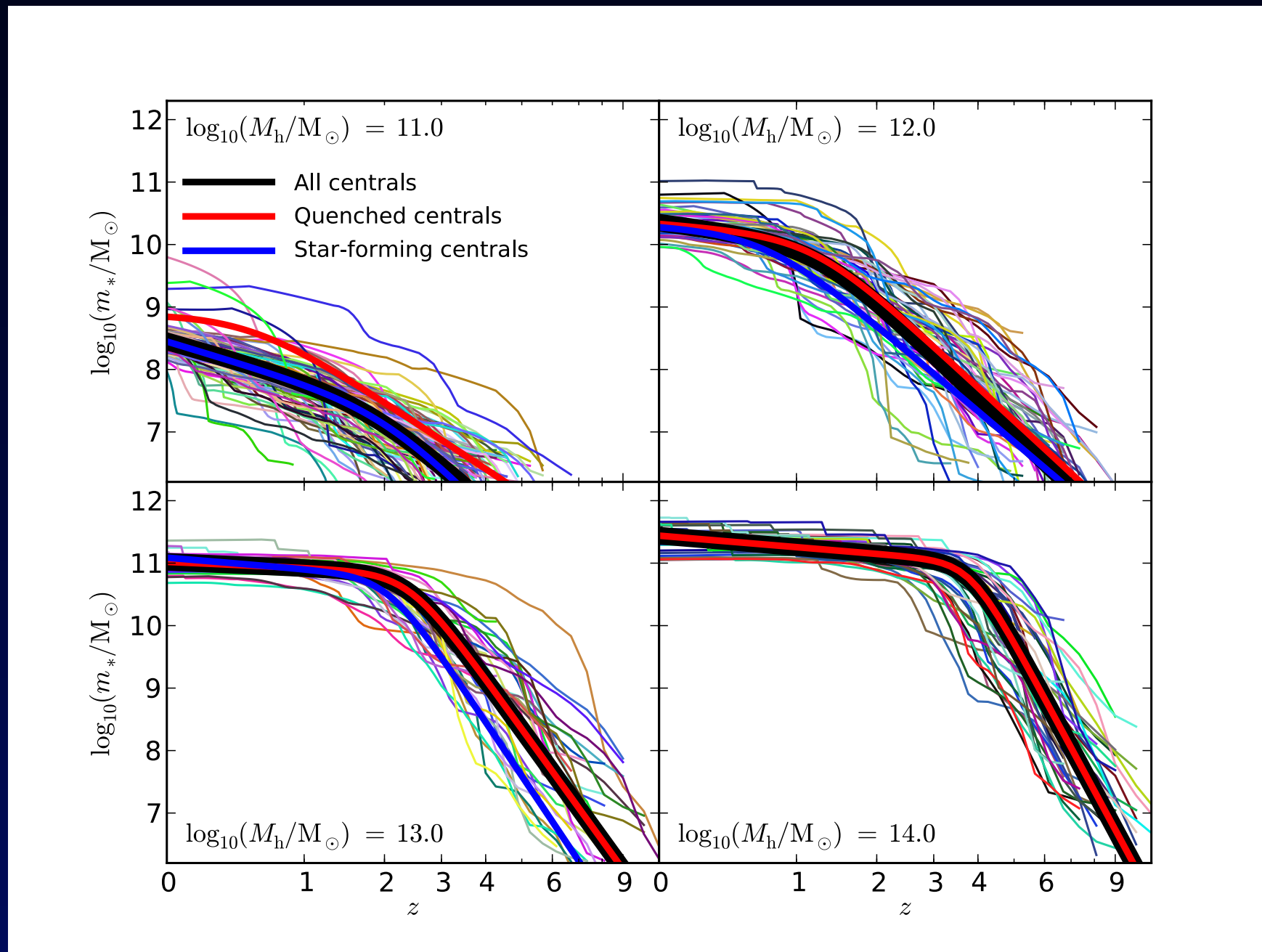   - Constraining models with detailed baryonic physics

Growth of individual galaxies

- Each galaxy now has its own growth history (depends on halo mass and environment)
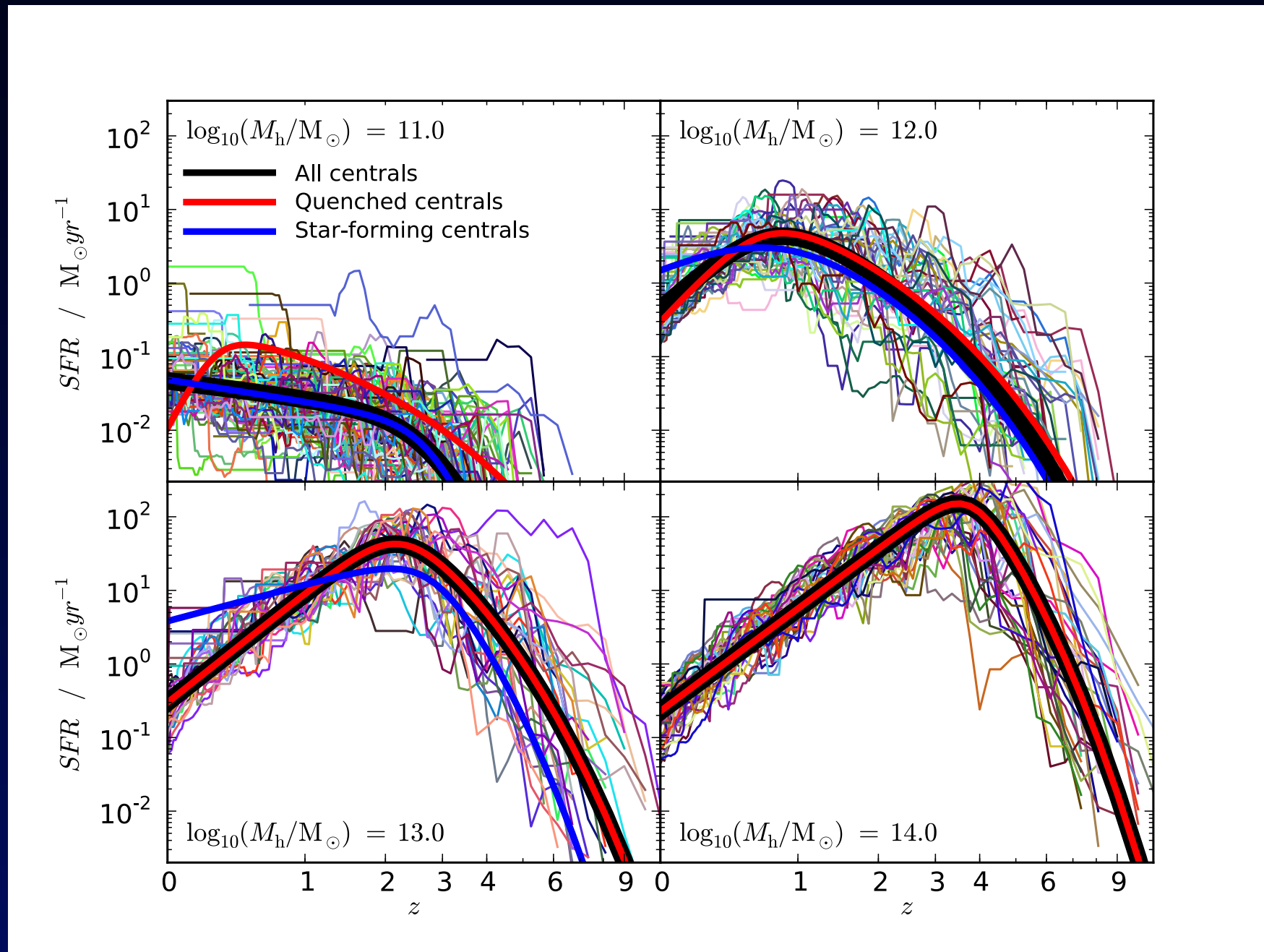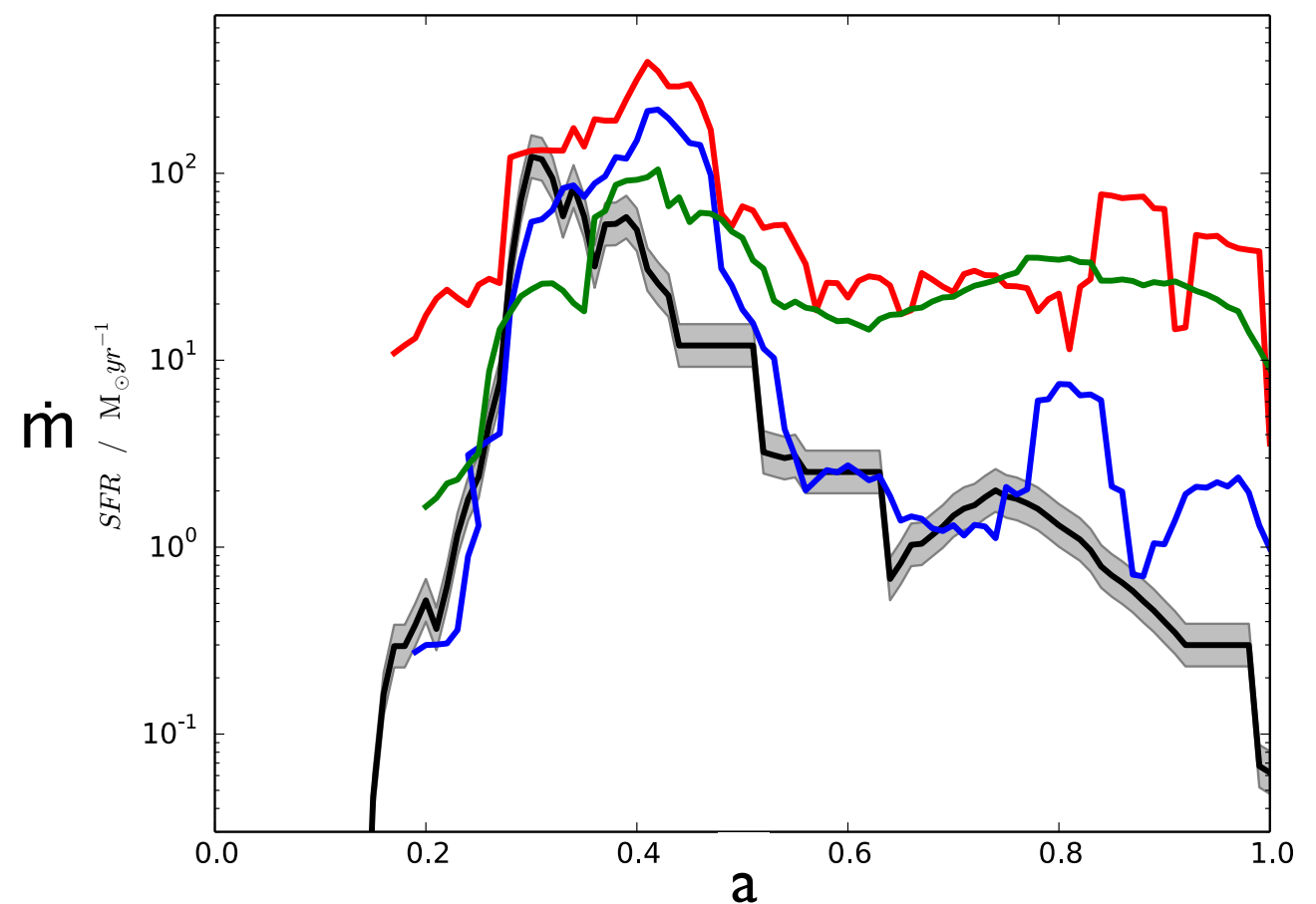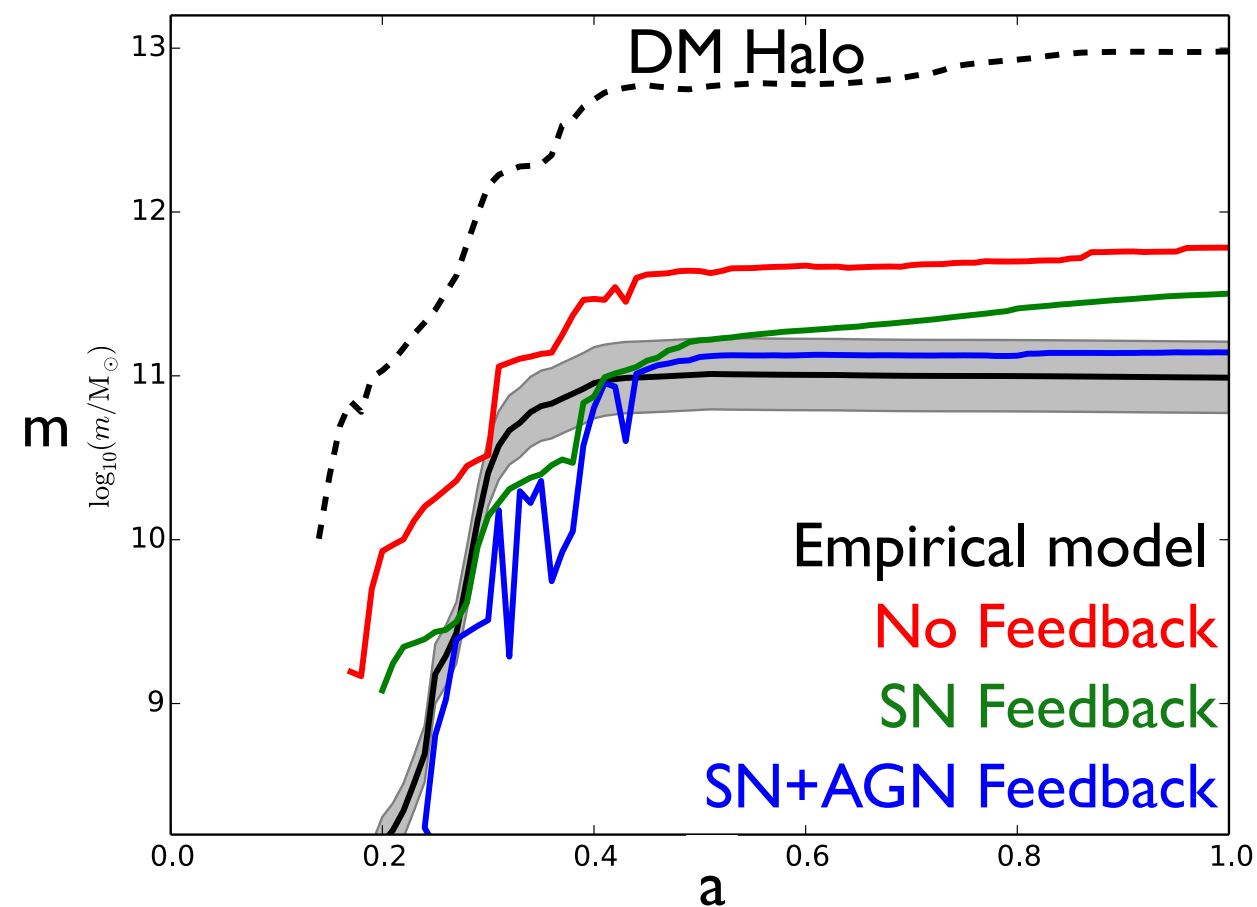
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Direct comparison to zoom simulations

- Can now compare empirical prediction for each individual halo

- Run empirical model on DM-only run

- Compare SFR, m_*, etc directly to runs with different physics

The massive end of the SMF

- Bernardi+13 find shallower slope for SMF when fitting Sersic

- Kravtsov+14 perform abundance matching and conclude:
  "feedback in massive halos should be weaker than assumed in most of the current simulations"
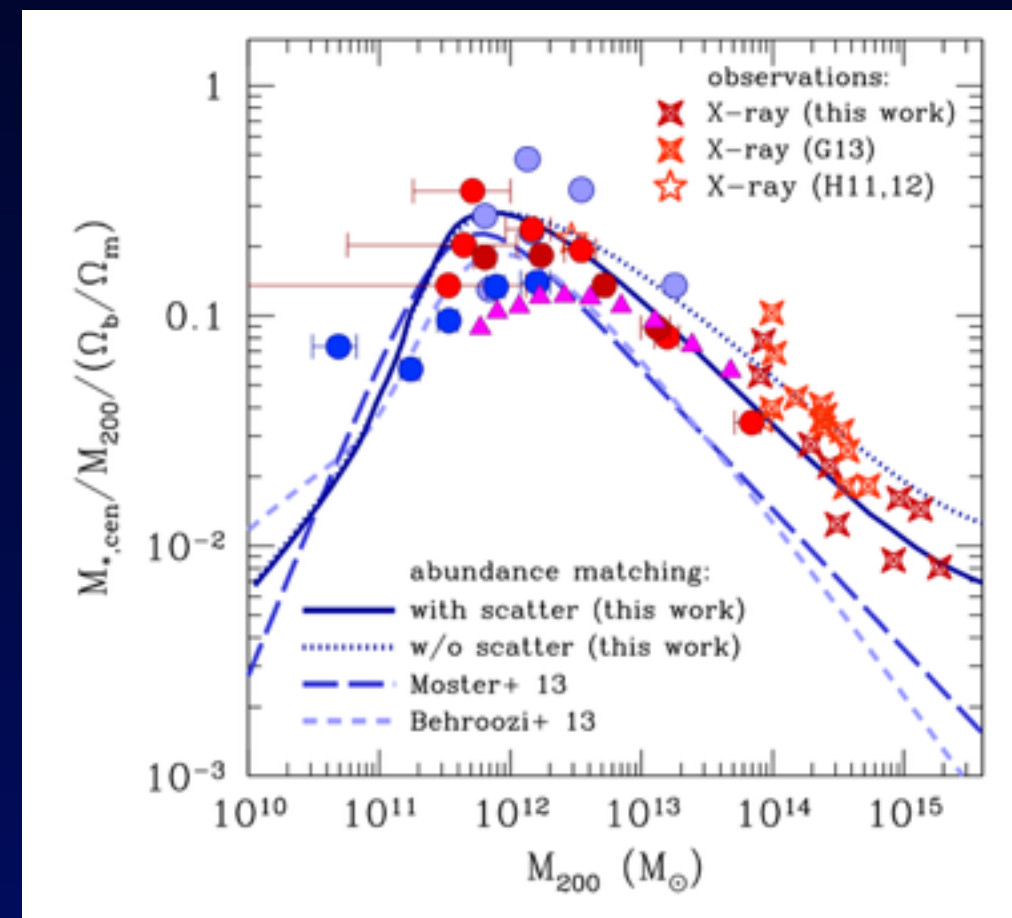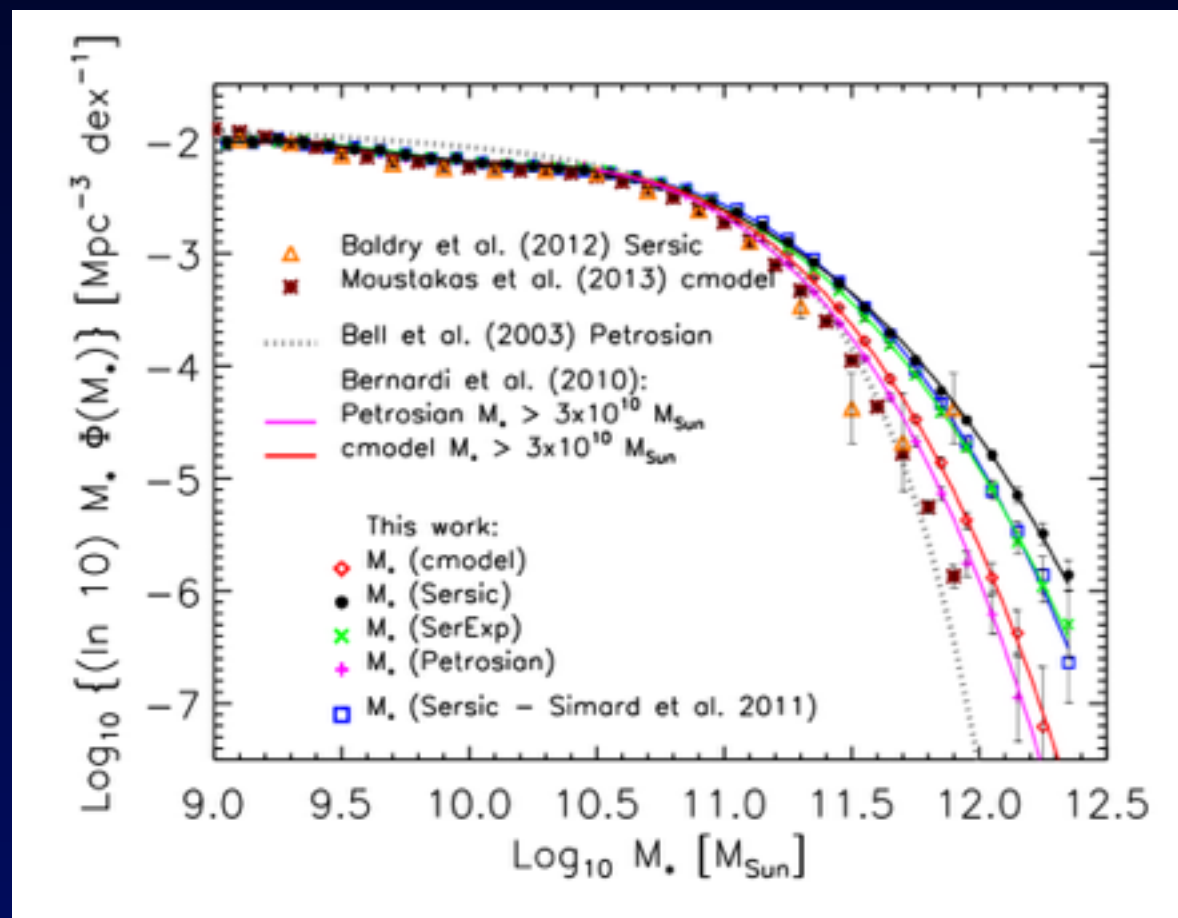
The massive end of the SMF

- Problem: fitting Sersic captures lots of light/mass from outskirts Most of this mass has been accreted (Oser+10, Hilz+13)

- SFRs are not changed same strong feedback

- Growth is achieved by adding less stars to ICM

- Mass / SMF depends on what you call 'galaxy'

- Make sure you compare apples with apples!
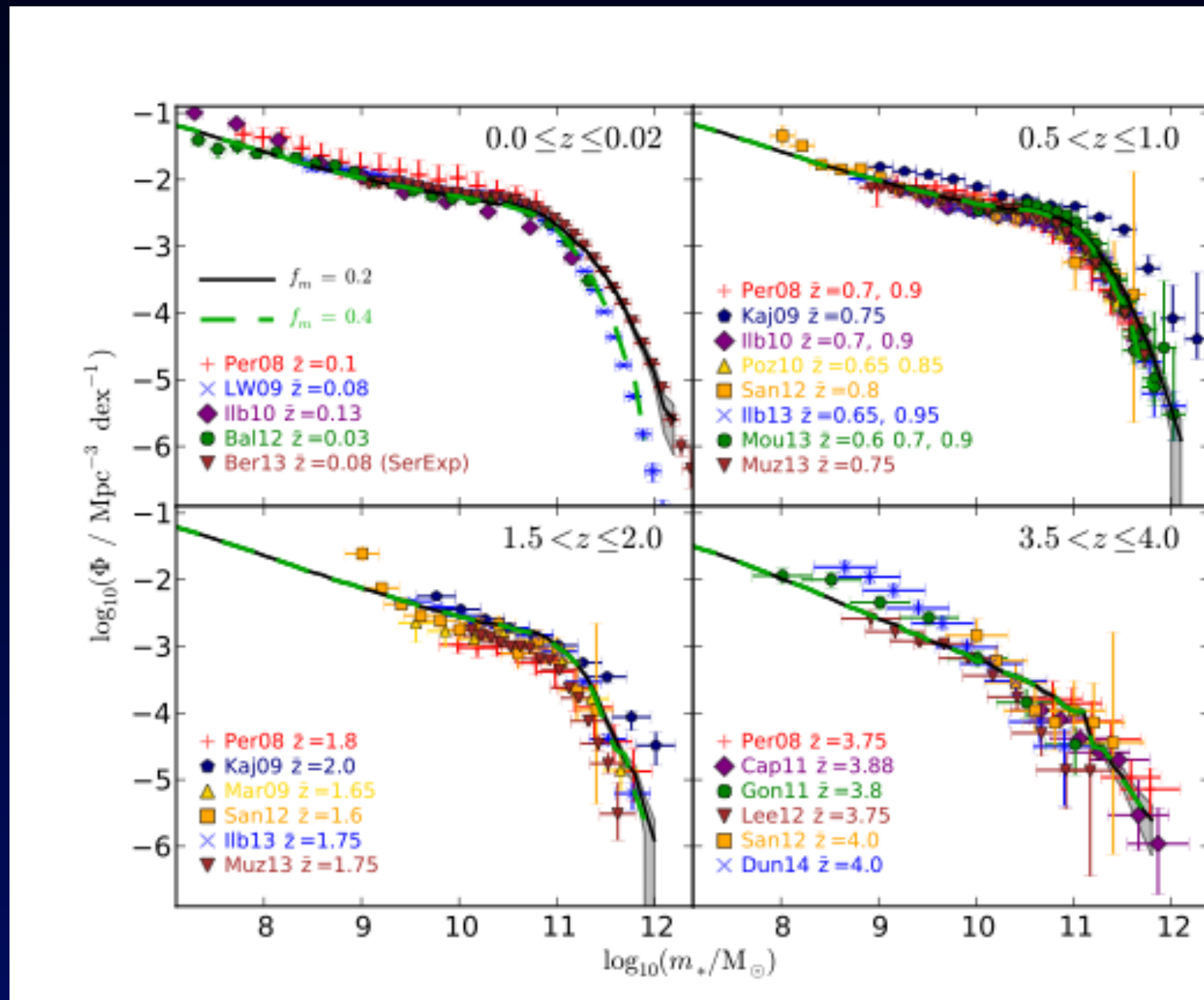
Conclusions

- Self-consistent cosmological framework
  - ➜ connect observed galaxies to simulated DM haloes

- Model individual haloes/galaxies with conversion efficiency
  - ➜ Possible to divide galaxies into SF/non-SF

- M_h-m_* relation at low masses ($m_* < 10^7 M_\odot$) unconstrained

- Strong feedback still needed at the massive end

- Next steps:
  - colours
  - gas
  - metallicity
  - black holes
  - size
  - morphology