Next Generation (Semi-)Empirical galaxy formation models

Matching individual galaxies

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Just occurred to me that this summer's #qnq2014 conference starts the morning after the World Cup final. Monday morning might be difficult.

Expand
Why (semi-)empirical models?

- Model observations in self-consistent cosmological framework
  - Build-up of stellar mass over time and relation to DM haloes
  - What determines galaxy mass and clustering properties
  - What sets the SFR? When/how is it triggered/quenched?
  - What does the stochasticity in GF depend on?

- Ab initio models: motivated by baryonic physics
  - try to predict statistical galaxy properties (e.g. SMF, CF, SSFR)
  - Hydro Sims: uncertain, unresolved physics, comp. expensive
  - SAMs: large parameter space, may not include all rel. physics

- Empirical Models: link stellar mass and halo mass statistically
  - put constraints on physical processes involved (SF, FB, ...)

Heidelberg, 14.07.2014
Abundance matching & parameterized linking

- Produce galaxy catalogue from observed SMF in same volume as halo catalogue
- Match galaxies-haloes by mass
- Optional: Use fitting-function to get $m^*(M_h)$

\[
m^*(M_h) = 2 R M_h \left[ \left( \frac{M_h}{M_1} \right)^{-\beta} + \left( \frac{M_h}{M_1} \right)^{\gamma} \right]
\]
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- Derive $m^*(M_h)$ individually for a set of redshifts

- Assume function for $m^*(M_h)$
- Populate haloes with galaxies
- Compute model SMF
- Fit parameters to observed SMF

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$$m^* (M_h) = 2 \times M_h M_1 + M_h M_1 \cdots$$
Evolving stellar-halo mass relation

- Evolving relation, but satellites are forced to follow the local one
- Inconsistency between different redshifts
- Assume redshift dependent parameters $M_1(z), N(z), \beta(z), \gamma(z)$
- Stellar-to-halo mass relation now depends on $M_{\text{infall}}$ and $z_{\text{infall}}$

- Fit $m_s(M_h,z)$ using all SMFs simultaneously using a MCMC
- SMFs can be fitted to high redshift
Inferred SFRs and accretion rates

- Identify all progenitors at previous snapshot
- SFR = total growth rate - accretion rate
- SFR peaks at some redshift and declines again
- Use derived SFR relation to predict SSFRs
- Model predictions are in excellent agreement

log $m^* = 9.5$
Scatter / Colour

- Expect haloes of same mass $M$ to have galaxies with different stellar masses (due to different formation history)
- To include that, scatter drawn from lognormal distribution (0.15-0.2 dex) is added to average $m_s$-$M_h$ relation
- SFR prediction only for average halo mass
  - no SFR / colour information for individual galaxies
- Difficult to include individual SSFRs in average models (but cf Hearin & Watson)
- Simple models cannot predict colour-dependence, e.g. for clustering…
• So far: stellar masses from average m*-M_h relation (no growth history)
• Now: parameterize SF efficiency as function of halo mass: \( \dot{m}^* / \dot{M}_h = \varepsilon (M_h, z) \)
• Stellar mass increases in one time-step as \( \Delta m^* = \varepsilon \cdot \Delta M_h = \varepsilon \dot{M}_h \Delta t \)

• Maximum SFR reached when \( M_h \sim 10^{12} M_{\odot} \)
• Afterwards SFR declines again
Satellite galaxies in individual haloes

- While host halo grows ➔ galaxy forms stars
- When host stops growing mass (loses mass) ➔ galaxy continues forming stars at current SFR with exponential decline on time-scale $\tau_1$
- After time-scale $\tau_2$ has passed ➔ SF is completely quenched (cf. Wetzel et al.)
- Time-scales can be constrained by fitting to quenched fractions vs stellar mass
While satellite orbits in a larger halo its subhalo loses mass

When subhalo mass has decreased sufficiently, satellite stars become unbound and galaxy is stripped

Model this effect by assuming satellite is stripped to ICM when halo mass is a fraction $f_s$ of its peak mass: $M_h = f_s M_{\text{peak}}$

Can be constrained with the 1-halo term of the galaxy CF

When subhalo finally merges (i.e. after dynamical friction time)

- 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

Is constrained by low $z$ stellar mass function (massive end)
Constraints on the model

- Stellar Mass Functions to $z \sim 8 \Rightarrow$ Constraints on $\varepsilon$ ($M_1, f_m$)
- Cosmic SFR density to $z \sim 9 \Rightarrow$ Constraints on $\varepsilon$'s normalization
- SSFRs to $z \sim 8 \Rightarrow$ Constraints on $\varepsilon$'s slopes ($\beta, \gamma$)
- Quenched Fractions $\Rightarrow$ Constraints on sat. quenching ($\tau_1, \tau_2$)
- 1-halo term of galaxy CF $\Rightarrow$ Constraints on sat. stripping ($f_s$)
Constraints and Predictions

- Empirical models can be particularly helpful for:
  - Constrain models with more detailed baryonic physics e.g. cooling, star formation, feedback…
    Now we can also compare to individual zoom-simulations
  - Making predictions without many uncertain assumptions on baryonic physics:
    e.g.
    - high z clustering
    - GRB delay times
    - galaxy merger rates
Galaxy merger rates

- Mean halo merger rates have a power-law dependence on mass
- Enhanced likelihood for major mergers for massive galaxies
- Low mass galaxies rarely experience major mergers

\[
\text{Preliminary}
\]
Merger rates for SF/quenched centrals

- Divide merger rates into two samples: SF/quenched central
- For low mass: SF galaxies are more likely to have a merger
- For high mass: Quenched and SF galaxies show similar merger rates
Conclusions

• Self-consistent cosmological framework using constraints from the observed SMFs to connect galaxies to dark matter haloes

• SFR of massive galaxies peaked at high redshift (z~2) and is quenched afterwards ➞ growth only through accretion

• Haloes can also be modelled individually by parameterizing the star formation efficiency

• Satellite quenching and stripping can be constrained with additional observations (quenched fractions, 1-halo term of CF)

• Possible to divide computed galaxy statistics into SF/non-SF

• Next steps: include colours, gas, metallicity, etc…