On the Origin and Evolution of the Galaxy Stellar Mass Function

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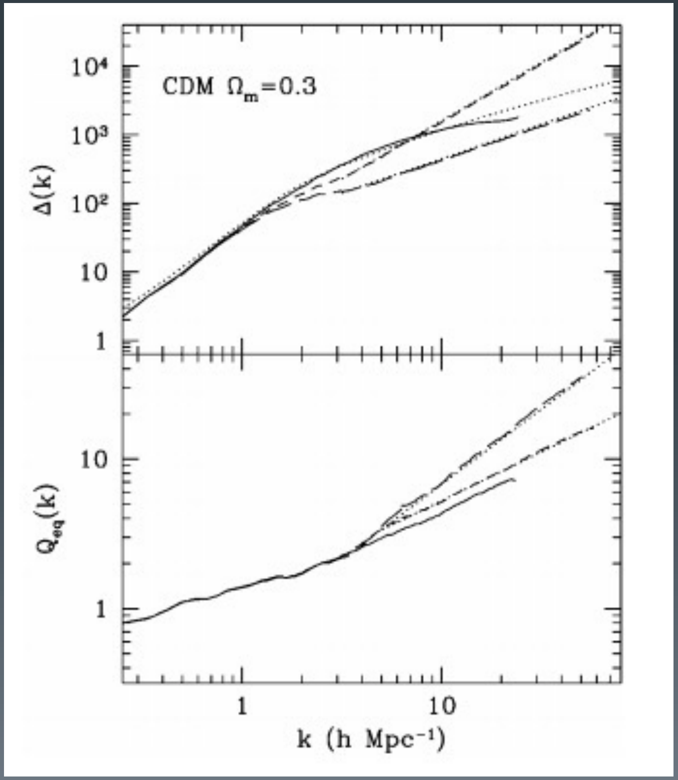
ABSTRACT

Here we explore the evolution of galaxy ensembles at early times by writing the *in situ* stellar mass growth of galaxies purely as a stationary stochastic (e.g., quasi-steady state) process. By combining the mathematics of such processes with Newtonian gravity and a mean local star formation efficiency, we show that the stellar mass evolution of galaxy ensembles is directly related to the average acceleration of baryons onto dark matter halos at the onset of star formation, with explicit dependencies on initial local matter densities and halo mass. The density term specifically implies more rapid average rates of growth in higher density regions of the universe compared to low density regions, i.e., assembly bias. With this framework, using standard cosmological parameters, a mean star formation efficiency derived by other authors, and knowledge of the shape of the cosmological matter power spectrum at small scales, we analytically derive (1) the characteristic stellar masses of galaxies (M^*), (2) the power-law low-mass slope (α) and normalization (ϕ^*) of the stellar mass function, and (3) the evolution of the stellar mass function in time over $12.5 \geq z \gtrsim 2$. Correspondingly, the rise in the cosmic star formation rate density over these epochs, while the universe can sustain unabated fueling of star formation, also emerges naturally. All of our findings are consistent with the deepest available data, including the expectation of $\alpha \approx -7/5$; i.e., a stellar mass function low-mass slope that is notably shallower than that of the halo mass function, and with no systematic deviations from a mean star formation efficiency with density or mass, nor any explicit, additional feedback mechanisms. These derivations yield a compelling richness and complexity but also show that very few astrophysical details are required to understand the evolution of cosmic ensemble of galaxies at early times.

Inputs

- Cosmological Parameters
- Mean star formation efficiency
- Cosmological matter power spectrum



Outputs

- M* - characteristic stellar mass
- α - Power law slope for low mass
- φ* - normalization of SMF
- Evolution of SMF from

$12.5 \geq z \geq 2$

Ma, C.-P., & Fry, J. N. 2000, ApJ, 531, L87

Methods and Goals

- Statistical mechanics approach
- Start with few astrophysical phenomena
- Derive analytical framework
  - "equations of motion" for galaxy ensembles
  - Examine dependence on initial conditions
  - Shape and normalization of SMF

Galaxy evolution

=

"a stochastic, cosmological, jostling of ensembles of quasi-steady state systems"

Terminology

Stochastic

- Discontinuous function with no definable derivative
- Characterize discontinuities
  - Brownian motion
- Use CLT to get probability distribution of f(t)

$$f'(t) \cong \frac{f(t + \Delta t) - f(t)}{\Delta t}$$

Ensembles behave deterministically while individual components do not

Terminology

Stationary

- Consider ensemble of galaxies with unique SFH’s
- Arithmetic mean of discontinuities is identically zero
- Steady state equilibrium not required

Little's Law

If…

$$t_{baryon} \ll t_{stochastic}$$

or

$$t_{baryon} \gg t_{stochastic}$$

$$L = \lambda \cdot W$$

Little, J. D. C.; Graves, S. C. 2008. Building Intuition 115. 81.

Terminology

Markovian vs. Non-Markovian

- Correlation of discontinuities in SFH
- “long-term memory”
- Hurst parameter, H
  - Spectrum of covariance
  - H=1

May expect high H with density fluctuations on scales relevant to galaxy evolution

Early Mass Growth

$$\dot{M}_{i,t} \equiv \frac{M_{i,t+\Delta t} - M_{i,t}}{\Delta t}$$

(Rate of stellar mass growth)

$$X_{i,T+1} = \dot{M}_{i,T+1} - \dot{M}_{i,T},$$

(Change to growth rate,
 a.k.a. second derivative)

$$\dot{M}_{i,T+1} = \sum_{T=0}^{T+1} X_{i,T}.$$

General picture of SFH's

Early Mass Growth

$$\mathrm{E}[X_{i,T+1}] = \frac{1}{N}\sum_{i=1}^{N} X_{i,T+1}$$

First moment (mean)

$$\mathrm{E}[X_{i,T+1}] = 0.$$

(Stationarity)

$$\mathrm{E}[\dot{M}_{i,T+1}] = \dot{M}_{i,T}$$

$$\overline{\sigma}_{i,T} = \left(\frac{1}{T}\sum_{j=1}^{T} \sigma_{i,j}^2\right)^{1/2}$$

RMS of galaxy SFR

Results

$$\mathrm{E}[M_{I,T}] = \frac{1}{\sqrt{2\pi}} \frac{t^{H+1}}{H(H+1)} \overline{\sigma}_{I,T} + M_{I,0},$$

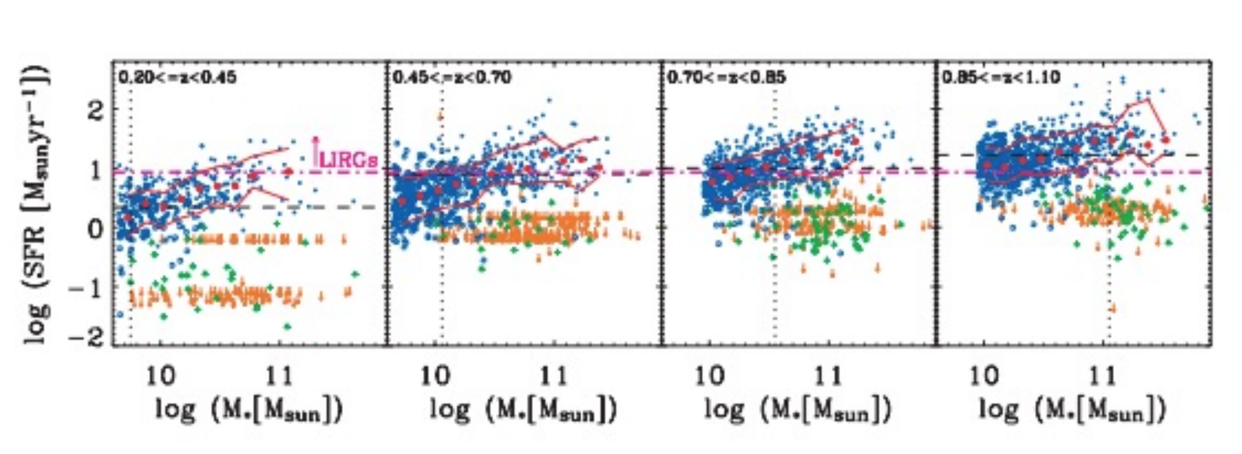
Mean stellar mass

$$\mathrm{E}[\dot{M}_{I,T}] = \frac{1}{\sqrt{2\pi}} \frac{t^{H}}{H} \overline{\sigma}_{I,T}$$

Mean SFR

$$\mathrm{E}\left[\frac{d^2 M}{dt^2}\right]_I = \frac{\overline{\sigma}_{I,t}}{\sqrt{2\pi}} \left(1 + t \frac{d \ln \overline{\sigma}_{I,t}}{dt}\right),$$

Derivative of mean SFR



Star Forming Main Sequence

$$\langle \mathrm{sSFR} \rangle \propto \mathrm{E}[\dot{M}_{I,T}/M_{I,T}] = \frac{H+1}{T}$$

$$H = 0.98 \pm 0.06$$

$$\mathrm{Sig}[\dot{M}_{I,T}/M_{I,T}] = H^{1/2}\mathrm{E}[\dot{M}_{I,T}/M_{I,T}]$$

$$Mean[SSFR] \approx \frac{4}{t}$$

Noeske, K. G., Weiner, B. J., Faber, S. M., et al. 2007, ApJ, 660, L43

Stochastic Accretion

- Dark matter/baryon accretion serves to
  - Supply fuel for stellar mass growth
  - Stochastically alter SFR's
  - Correlate those changes through matter spectrum

- Assumption valid only while "the universe can support unabated fueling of galaxy growth"

Stochastic Accretion

- Case 1: isotropic accretion;
- Case 2: accretion onto individual halos through surface areas proportional to individual halo surface area;
- **Case 3: accretion onto individual halos through a mean surface area that is uncorrelated with halo mass or local density.**
  - **3 streams with cross section radius of 1 kpc, eff=0.015**

Key Results

$$\bar{\sigma}_{I,z_{\rm start}} = \sqrt{2\pi}\left(\frac{4\pi}{3}\right)^{2/3} N_s \pi r_s^2 \gamma \epsilon_* f_b \times G M_{h,I,z_{\rm start}}^{1/3} \rho_{h,I,z_{\rm start}}^{5/3} .$$

$$\bar{\sigma}^* = \left(\frac{\epsilon_{\rm ff}}{0.015}\right)\left(\frac{\gamma}{2}\right)\left(\frac{f_b}{0.16}\right)\left(\frac{N_s}{3}\right)\left(\frac{r_s}{1\ {\rm kpc}}\right)^2 \times \left(\frac{1+z_{\rm start}}{1+12.5}\right)^5 \left(\frac{M^*_{h,z_{\rm start}}}{1\times 10^9\ {\rm M_\odot}}\right)^{1/3} (2.9\times 10^{-7}\ {\rm M_\odot\ yr^{-2}}) .$$

$$M^*_{h,z} \sim 10^9 M_\odot$$

Key Results

$$M^*(t) \sim 4 \times 10^{10} \mathrm{M}_\odot \times \left(\frac{t}{\mathrm{Gyr}}\right)^2 .$$

*

Time evolution of characteristic stellar mass

Key Results

$$P(\bar{\sigma}) \sim \bar{\sigma}^{-7.5} \rightarrow \alpha = -7.5$$

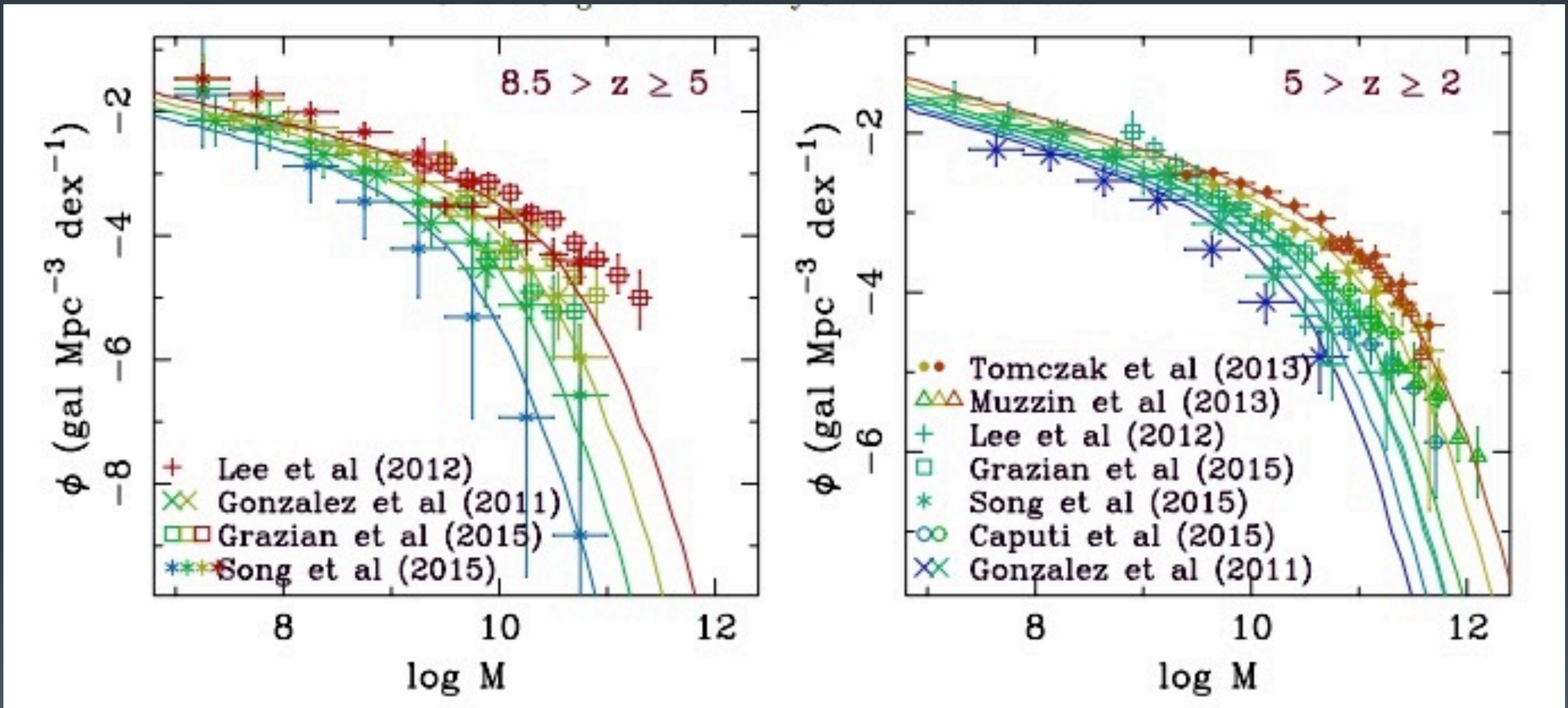
Power law slope (SMF) for low sigma

$$P(\overline{\sigma}_h) = \frac{3\phi_h(M_h)}{\Gamma\left(-\frac{7}{5}+1, 10^{-\frac{5}{3}\log[178(1+z_{start})^3]}\right)}$$

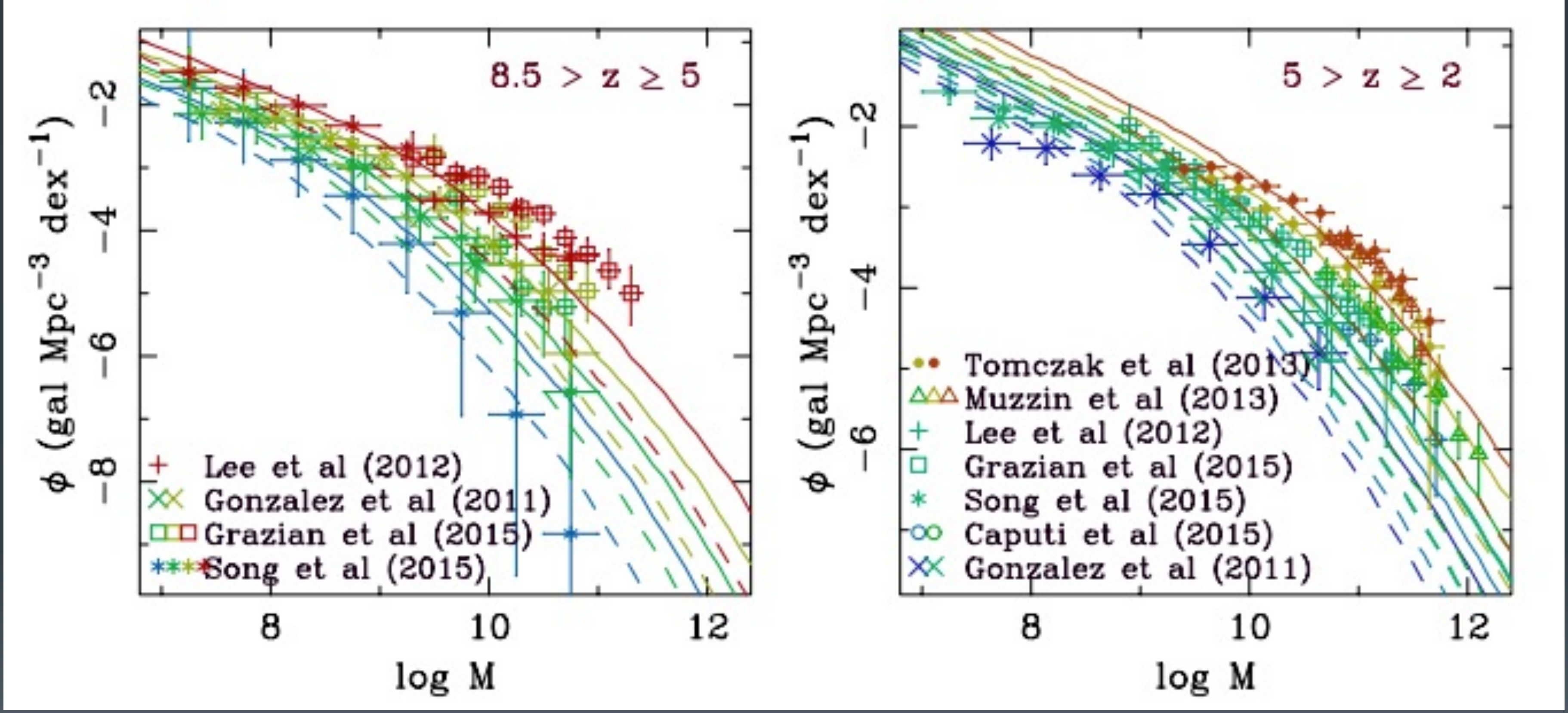
$\rightarrow$

$$P(\bar{\sigma}) = 3 * 10^{-4} * \phi_h(M_h)\ at\ z \sim 10$$

$$\sim 10 \frac{DMH}{Mpc^3}\ for\ z \sim 10 - 15$$



8.5 > z ≥ 5
φ (gal Mpc^-3 dex^-1)
log M
Lee et al (2012)
Gonzalez et al (2011)
Grazian et al (2015)
Song et al (2015)
5 > z ≥ 2
Tomczak et al (2013)
Muzzin et al (2013)
Lee et al (2012)
Grazian et al (2015)
Song et al (2015)
Caputi et al (2015)
Gonzalez et al (2011)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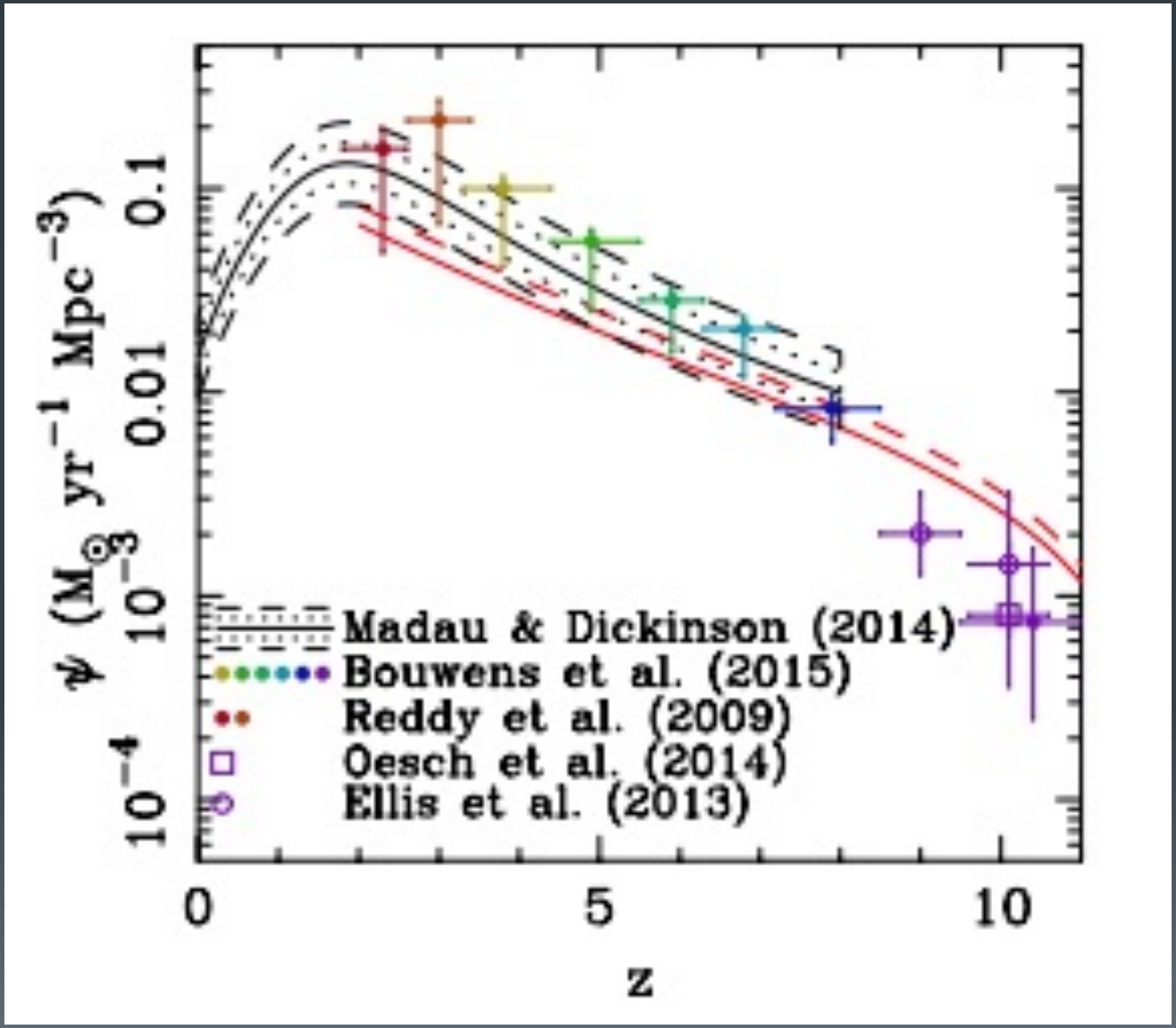

ψ ($M_\odot$ yr^{-1} Mpc^{-3})
0.1
0.01
10^{-3}
10^{-4}
0
5
10
z
Madau & Dickinson (2014)
Bouwens et al. (2015)
Reddy et al. (2009)
Oesch et al. (2014)
Ellis et al. (2013)

Conclusions

- Galaxy seeds begin growing around z = 10-15
- Star-formation proportional to second derivative of baryon accretion (which are determined by local matter density)
- *In situ* mass growth proceeds according to stationarity
- Changes to SFR are stochastic but correlated over long timescales

References

- Ma, C.-P., & Fry, J. N. 2000, ApJ, 531, L87
- Little, J. D. C.; Graves, S. C. 2008. Building Intuition 115. 81.
- Noeske, K. G., Weiner, B. J., Faber, S. M., et al. 2007, ApJ, 660, L43
- Kelson, D., Benson, A., Abramson, L., 2016,

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