Models for the Cosmic Evolution of Star Formation in Galaxies

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Cosmic SFRD in $\Lambda$CDM

QUENCHING: Galaxies above critical halo mass don’t form stars.

COSMIC DAWN: Halo growth above the filtering mass.

COSMIC NOON: Accretion ($\sim a_{\exp}^{-2.5}$) counters halo assembly.

Cosmic SFH reflects how halos assemble through the actively star-forming mass regime.

Madau+Dickinson 14
Halo mass range for active SF

What is the physics that picks out this mass range?

Efficient SF

shape change owing to dry mergers

Feedback from star formation

Feedback from AGN

Behroozi+13
Growing galaxies via the baryon cycle

Outflows

Cold accretion

IGM

Wind recycling

Galaxy

Circum-galactic medium

define: \( \eta = \text{outflow rate / SFR} \)

\( \zeta = \text{Fraction of inflow at } R_{\text{vir}} \text{ that gets into ISM} \)

\( t_{\text{rec}} = \text{typical time for outflow to recycle into ISM} \)

Keres+05
The Equilibrium Model

\[ \text{Inflow} = \text{SFR} + \text{Outflow} + \frac{d\text{Reservoir}}{dt} \]

- \( \text{SFR} = \left( \zeta M_{\text{grav}} + \dot{M}_{\text{recyc}} \right) / (1 + \eta) \)
- \( Z = y \frac{\text{SFR}}{\zeta M_{\text{grav}}} \)
- \( f_{\text{gas}} = (t_{\text{dep}} \text{sSFR}) \)

\[ \frac{\dot{M}_{\text{in-\text{grav}}}}{M_{\text{halo}}} = 0.47 f_b \left( \frac{M_{\text{halo}}}{10^{12} M_\odot} \right)^{0.15} \left( \frac{1 + z}{3} \right)^{2.25} \text{Gyr}^{-1} \]

\[ \text{Finlator, RD 08} \quad \text{RD+12} \quad \text{Mitra+14} \]
Baryon cycling parameters

- **Ejective feedback**
  \( \eta = \text{Outflow/SFR} \)

- **Preventive feedback**
  \( \zeta = \frac{\dot{M}_{\text{ISM}}}{\dot{M}_{\text{gas,halo}}} \)

- **Wind recycling time**
  \( t_{\text{rec}} = \text{time for outflow to return} \)

Each depends on \( M_{\text{halo}}, z \):
8 free parameters (after model selection).

\[
\eta = \left( \frac{M_h}{10^{10.98+0.62\sqrt{z}}} \right)^{-1.16},
\]
\[
t_{\text{rec}} = 0.52 \times 10^9 \text{yr} \times (1 + z)^{-0.32} \left( \frac{M_h}{10^{12}} \right)^{-0.45},
\]
\[
\zeta_{\text{quench}} = \text{MIN} \left[ 1, \left( \frac{M_h}{M_q} \right)^{-0.49} \right],
\]
where \( \frac{M_q}{10^{12}M_\odot} = (0.96 + 0.48z) \).

Mitra+15
The Best-Fit Equilibrium Model ($\chi^2 \sim 1.6$)

Mitra+15

M* - SFR

Somerville+RD 15

M* - SFR

Salim et al. (2007)
Speagle et al. (2014)

Schreiber et al. (2014)
Whitaker et al. (2014)
Speagle et al. (2014)

Mitra+15
Constraints on feedback

- Preventive feedback effective at $M_h < 10^{10}$ and $M_h > 10^{12} M_\odot$.

- Ejective feedback stronger at low mass, high redshift(?)

Mitra+15

Schroetter+16

Mitra+15
Scatter from inflow stochasticity

- If we assume scatter in halo inflow translates to scatter in SFR, then we get $\sigma \sim 0.2-0.25$ dex, approx indep of $M_*$ and $z$.

- Simulations also predict $\sigma \sim 0.25$ dex (RD+11, Sparre+15, ...), though larger at low-$M_*$ where feedback creates burstiness.

Mitra+16
see also Forbes+14
Outliers (starbursts)

Accretion fluctuations are not pure lognormal – tail to high SFR (~10%)
MS scatter via the sSFRF

- Specific SFR function in bins of stellar mass shows more detail than just $\sigma$: e.g. rapidity of quenching, starburst fraction, ...

Lines: MUFASA
Points: Ilbert+15

RD+17a
Extreme star-formers at high-z

- Most SMGs consistent with top end of main sequence; not in a burst phase. Still often interacting in dense environment.

RT using Powderday
Narayanan+15
Scatter is correlated!

- Inflow event -> decrease in $Z$ with increase in $f_{\text{gas}}$ -> increase in SFR.

- Correlated scatter reflects competition bet. consumption time $M_{\text{gas}}/sSFR(1+\eta)$ and accretion time $M_{\text{gas}}/(dM_{\text{in}}/dt)$.

- Probes response of galaxy to stimulus – new regime to test models.
Quantifying “second-order” galaxy growth

- Deviation plots: $\Delta[SFR, Z, f_{\text{HI}}, f_{\text{H}_2}]$ from their typical value at a given $M_*$, plotted against each other.
- Key test of galaxy response to inflow fluctuations; less sensitive to calibration issues.

RD+17a, MUFASA, z=0
Self-Regulated Star Formation

- Stellar and metal growth limited by cooling rate and conversion of gas into stars
- Ejective and preventive feedback
- Gas & metal content reflects “evolutionary state”
- Gas supply vs. processing rate
- Mergers drive galaxy evolution
- Are subdominant to cold streams for fueling
- Galaxies & IGM evolve independently
- Are connected by baryon cycling through CGM
Concluding remarks: Emission line galaxies as probes of the baryon cycle

- Cosmic star formation driven by stochastic halo growth, suppressed by preventive feedback at high & low masses, and modulated by outflows in between. What physics sets this?

- Emission lines provide an optimal way to probe such processes:
  - Balmer lines probe star formation, outflows
  - Metal lines probe metallicity, AGN content
  - CO, CII probe molecular fuel
  - HI-21cm probes gas in outskirts & CGM
  - Lyα probes low-mass early galaxies
  ...all of these can now be directly simulated

- Scatter around mean scaling relations is non-Gaussian and correlated, which offers new ways to test models and gain insights into how galaxies are impacted by baryon cycling.
Main sequence predictions among simulations are similar.

Cosmological sims predict $\sigma \sim 0.25$ dex.

Still too low at $z \sim 2$