The Main Sequence of Star-Forming Galaxies from CANDELS

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High redshift = $z > 2-3$

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What do we know?
The relation between SFR and $M_\star$ reveals interesting galaxy physics

- SFR-$M_\star$ can distinguish between star-forming, elliptical, and starburst galaxies
- The scatter about SFR-$M_\star$ can be due to
  - scatter in the net inflow rate of gas to fuel star formation
  - scatter in the galaxy formation time
What drives galaxies off the SFR-M$_\star$ relation? and with what uncertainties?

- Physical causes:
  - Starbursts, AGN
  - Stochastic SF histories
  - Star-formation quenching (mainly at low redshift)
  - M$_\star$ correlates strongly with UV dust attenuation (Panella+14). Thus, galaxies with the same amount of SF are less attenuated at higher redshift (it is hosted by a less massive, less metal rich galaxy).
What drives galaxies off the SFR-M\(^\star\) relation, and with what uncertainties?

- SED fitting methods
- Template assumptions
- Redshift uncertainties
- Sample selection
- SFR indicators

Whitaker+12
What can broadband photometry tell us?

- We use a Bayesian SED fitting procedure that calculates the posterior on each galaxy and marginalizes over nuisance parameters.
- UV SFRs calculated using an age-dependent Kenicutt 1998 conversion
- See Salmon+14 (arXiv 1407.6012) for details
What drives galaxies off the SFR-M$\star$ relation, and with what uncertainties?

- Right: an individual object’s 2D likelihood in the plane of SFR-M$\star$
- The scatter in determining a single object’s SFR or M$\star$ is orthogonal to the main relation (from age-dust degeneracies)
- These observational uncertainties contribute scatter to the SFR-M$\star$ plane, and must be accounted for with Monte Carlo simulations

Salmon+14 (arXiv 1407.6012)
What drives galaxies off the SFR-M\(\star\) relation, and with what uncertainties?

- We quantify our ability to derive SFR and M\(\star\) by comparing to the Somerville et al. SAMs.
- SAM fluxes are perturbed by CANDELS-like uncertainties, and used as inputs.
- The “best-fit” SED is less reliable at recovering SFR and M\(\star\) than using the median of the marginalized likelihood.
Result: Slope of SFR-M\textsubscript{★} remains un-evolving up to z\textasciitilde6

\[ \log(\text{SFR}) \approx \alpha \log(M\textsubscript{★}) \]

\( \alpha \) remains <1 (about \( \alpha=0.6 \) across all redshift)

Salmon+14 (arXiv 1407.6012)
Result: Slope of SFR-M\textsubscript{★} remains un-evolving up to z~6

- \( \log(\text{SFR}) \approx \alpha \log(\text{M}_\text{★}) \), \( \alpha \) remains <1 (about \( \alpha=0.6 \) across all redshift)

- Considering most observational uncertainties (purple), the “true” intrinsic scatter in SFR-M\textsubscript{★} is as much as 0.2-0.3 dex

Salmon+14 (arXiv 1407.6012)
Result: SFR-$M_\star$ is consistent with many theoretical models

- If SFR traces the net gas inflow, then the “true” scatter in the inflow rate is 0.2-0.3 dex.
- These observations favor smooth gas accretion over these redshifts and stellar masses

Salmon+14 (arXiv 1407.6012)
If SFR traces the net gas inflow, then the "true" scatter in the inflow rate is 0.2-0.3 dex.

- These observations favor smooth gas accretion over these redshifts and stellar masses
- Need ALMA to observe the gas-fraction scatter, thereby constraining the SFR efficiency

Result: SFR-M$_*$ is consistent with many theoretical models

Salmon+14 (arXiv 1407.6012)
How does the SFR evolve at these redshifts?

Does it match the observed SFR-M$_\star$ relation?

- A number-density selection can track the progenitor-to-descendant evolution across redshift.
- Objects were selected according to an evolving number density in stellar mass, as predicted by dark matter abundance matching (Behroozi+13b)
How does the SFR evolve at these redshifts?

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• A number-density selection can track the progenitor-to-descendant evolution across redshift.

• Objects were selected according to an evolving number density in stellar mass, as predicted by dark matter abundance matching (Behroozi+13b)

• We find a rising SF history at high redshift, as expected, with \( \text{SFR} = (t/\tau)^\gamma \) and \( \gamma = 1.4 \)

• Now, let’s feed this history into a stellar population synthesis model

Salmon+14 (arXiv 1407.6012)
Does the SFR evolution match the observed SFR-$M_\odot$ relation?

Salmon+14 (arXiv 1407.6012)
SFR-M ★ evolves little in slope, and decreases in scale over cosmic time

- At least since the first 800 Myr of the Universe, the scatter in SFR at a given mass is small (~0.2-0.3 dex after taking into account observational uncertainties).
- The SFH can be best described as a power law \( \text{SFR} = \left( \frac{t}{\tau} \right)^{\gamma} \), where \( \gamma = 1.4 \) at high redshift \((z>4)\).
SFR-M★ evolves little in slope, and decreases in scale over cosmic time

- At least since the first 800 Myr of the Universe, the scatter in SFR at a given mass is small (~0.2-0.3 dex after taking into account observational uncertainties).

- The SFH can be best described as a power law SFR = (t/τ)^γ, where γ=1.4 at high redshift (z>4).
ALMA: We need gas-mass fractions of high-z galaxies to constrain the SFR efficiency

- Theory predicts a rapidly evolving gas-mass fraction with redshift.
- CO emission can tell us dynamical mass, and therefore the gas-mass fraction. [CII] can tell us the dusty IR SFR, constraining the total UV+IR SFR
- ALMA can find the cause of the SFR-$M_\star$ scatter (is it SF efficiency or scatter in galaxy formation time?)

Salmon+14 (arXiv 1407.6012)
Summary

• The relation between SFR and $M_\star$ for star forming galaxies evolves little in slope, and declines in scale since the 1st Gyr of the Universe (Wuyts+11, Panella+14).

• The scatter in SFR at a given mass is small at all redshifts (~0.2-0.3 dex after taking into account observational uncertainties). If SFR traces the net gas inflow rate, then this result favors smooth, cosmological gas accretion.

• The SFH can be best described as a power law $SFR = (t/\tau)^\gamma$ at high redshift ($z>4$, $\gamma=1.4$), or a delayed-tau model across the age of the Universe (Salmon+14, arXiv 1407.6012)

• ALMA can constrain the gas-mass fraction, and place important limits on high-redshift SFR efficiency.
ALMA: We need gas-mass fractions of high-z galaxies to constrain the SFR efficiency
How does this relate to the Stellar Mass Function?

- Implies star formation evolves differently in galaxies of different masses.
- SFR-Mass slope cannot be <1 at all masses and redshifts

See Leja+14
What drives galaxies off the SFR-M★ relation, and with what uncertainties?

[Graphs showing scatter plots of various parameters vs. redshift, with annotations and data points indicated.]
What drives galaxies off the SFR-M relation, and with what uncertainties?