Semi-analytic forecasts: uncovering galaxy formation with joint constraints from wide and deep surveys

L. Y. Aaron Yung

Supervised by Rachel S. Somerville (Flatiron)

with thanks to collaborators:

Steve Finkelstein (UT Austin), Gergö Popping (MPIA), Romeel Davé (Edinburgh)
It fits! Can we all go home?

- these are predictions for stellar mass functions predicted by our model, great agreement with Duncan+14 & Song+16 between $z = 4 - 8$
- similar for SFRFs and UV LFs

see Paper I arXiv:1803.09761
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Not so fast!

- massive and low-mass objects are objects are degenerately affected by many physical processes.

- e.g. star formation physics / AGN feedback / dust attenuation / SNe feedback

- observations have large uncertainties and don’t fully agree with each other
SAM — a comprehensive galaxy factory

Physical / Empirical Parameters

- \( \mathcal{A}_{\text{SF}} \) - SF relation normalization
- \( N_{\text{SF}} \) - SF relation slope
- \( \tau_{*,0} \) - SF timescale

the list go on……

Physical Properties

(e.g. \( M^* \), SFR, …)

Recipies / Prescriptions

(e.g. star formation, stellar feedback, …)

Forward Model

Synthetic SED / JWST filters / Dust recipe, etc

Observables (e.g. \( M_{\text{UV}} \), \( m_{F200W} \))

calibrated once to \( z \sim 0 \) observations

semi-analytic model

DM halo merger trees

\[ \Sigma_{\text{SFR}} \propto \left( \Sigma_{M_{\text{gas}}} \right)^{\mathcal{A}_{\text{SF}}} \]
Efficiency is KEY! The semi-analytic approach

- **Semi-analytic Merger Trees** (Somerville & Kolatt 1999, Somerville+2008)
  - 1. grid of root halo masses → **large dynamic range** ($V_c = 20 – 500$ km/s)
  - 2. create Monte Carlo realizations of merging history based on Extended Press-Schechter (EPS) formalism
  - 3. trace merger history down to progenitor halos mass of $\sim 10^{10} M_\odot$, or 1/100th of the root halo mass, whichever is smaller.

  - Metallicty-based multiphase gas partitioning $M_{\text{cold}} \rightarrow M_{\text{H}_1} + M_{\text{H}_\text{II}} + M_{\text{H}_2}$ (Gnedin & Kravtsov 2010)
  - $\text{H}_2$-based star formation: $\Sigma_{\text{SFR}} \propto (\Sigma_{\text{H}_2})^{N_{\text{SF}}}$ (Bigiel+2008)
corner plots!

- This is an example showcasing our predictions for high-redshift (z = 6) galaxies.

- We show cross-correlation among
  - halo mass
  - stellar disc radius
  - cold gas metallicity
  - star formation rate
  - stellar mass
  - rest-frame UV luminosity
  - apparent magnitude in F200W filter

- We are hoping this serves as a quick lookup table for physical properties for both theorists and observers.

Look out for Paper II by the end of summer
Stellar Mass Functions

• SAM is capable of making predictions for large galaxy populations efficiently over a wide range of redshifts.

• Free parameters in our model is only calibrated at $z \sim 0$, and yet our results agreement with observations extremely well up to $z \sim 8$.

• Our model can efficiently sample halos over a wide mass range, covering galaxies forming in atomic cooling halos to the most massive halos forming at these epochs.

• Here we compare our results between $z = 4$ - 10 to observations from Duncan+14 and Song+16.
What can we learn?

- The SAM is so efficient that we can run multiple iterations while systematically changing the model parameters.

- The low-mass-/faint-end slope is sensitive to SNe feedback, as star formation activities are 'self-regulated'.

- Our current feedback model is $z$-independent, but still it may depend on other physical properties and effectively evolve as a function of $z$.

![Graph showing the effect of SNe feedback on galaxy properties](image)

\[ m_{out} = \epsilon_{SN} \left( \frac{V_0}{V_c} \right)^{\alpha_{th}} m_\ast \]

Legend:
- SC SAM (fiducial ($\alpha = 2.8$))
- Stronger Feedback ($\alpha = 3.6$)
- Weaker Feedback ($\alpha = 2.0$)
- Duncan et al. 2014
- Song et al. 2016

$z = 4$
What can we learn?

• On the other hand, the massive end is quite sensitive to the gas depletion time.

• Changing such quantity also affect other quantities such as metallicity and gas fraction.

\[
\Sigma_{\text{SFR}} = A_{\text{SF}} \left( \frac{\Sigma_{\text{H}_2}}{10 M_\odot \text{pc}^{-2}} \right) \left( 1 + \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{H}_2,\text{crit}}} \right)^{N_{\text{SF}}}
\]
Stellar Mass Functions

- SAM is capable of making predictions for large galaxy populations efficiently over a wide range of redshifts.

- Here we compare our results between $z = 4 - 10$ to observations from Duncan+14 and Song+16.

- Free parameters in our model is only calibrated at $z \sim 0$, and yet our results agree with observations extremely well up to $z \sim 8$.

- Our model can efficiently sample halos over a wide mass range, covering galaxies forming in atomic cooling halos to the most massive halos forming at these epochs.
What do we hope to learn from wide / deep surveys?

- **Cumulative number density (or counts) of galaxies over redshift**

- **Top-Panel**
  bright galaxies only. we show that star formation mechanism plays a major role in the formation of bright galaxies

- **Bottom-Panel**
  including faint galaxies. we show that strong stellar feedback has a major impact on the faint galaxy populations.

- **takeaway point**
  Galaxies of different masses are affected by different physical processes, and JWST will provide the necessary constraints for understanding them

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see Paper I arXiv:1803.09761
What do we expect from JWST?

- This plot shows the distribution function of apparent magnitudes in NIRCam filters.

- **Vertical lines:**
  detection limit for $\sim 10^4$ seconds exposure, with a detection limit $m \sim 28.5$

- **Horizontal lines:**
  $\sim 1$ object per NIRCam field-of-view (2.2’ x 2.2’)
  (assuming $\Delta z = 1.0$)

- Galaxy populations drop out in filters with shorter wavelength at higher redshifts.

- F200W would be a great nominal filter choice.

[Link to Paper I arXiv:1803.09761]
Reconstructed SMF

• Let’s focus on $z = 4$

• What if I only consider galaxies that are bright enough to be detected by a mock JWST wide survey (e.g. $m_{F200W} > 28$) and are prevalent to be found in the survey

• Objects that are too faint / too rare are excluded
What can we do with JWST

• Let’s focus on $z = 4$

• What happens when deep-, wide, and lensed-field surveys join forces

**JWST - F200W**

<table>
<thead>
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Improved as we go deeper

$L. Y. Aarom Yung$
And we need Euclid!!

- Let’s focus on $z = 4$
- What happens when deep-, wide, and lensed-field surveys join forces

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**Euclid - H band**

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L.Y. Aaron Yung
And with LSST

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**LSST - z band**

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L.Y. Aaron Yung
And with WFIRST

**JWST - F200W**

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**LSST - z band**

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**WFIRST - Y/J/H band**

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<td>Deep</td>
<td>J=29.0, H=28.2</td>
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Updated Thanks Ryan!
And with WFIRST

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Stellar Mass Functions

• This is our predictions for $z = 4 - 10$.

• Both wide and deep surveys are crucial to constraining the whole galaxy populations, especially at high redshift.
UV Luminosity Functions

• SAM is great for generating forecasts and mock catalogues for joint wide- and deep-field surveys given its great efficiency and wide dynamic range.

• Taking advantage of the SAM’s efficiency, we can systematically vary the physics and subgrid parameters within our physically motivated model to explore how this shapes the formation of galaxies over time.

• Both wide and deep surveys are crucial to fully constrain the physical processes that shape galaxy populations at high redshift, as well as their physical properties.

see Paper I arXiv:1803.09761

Look out for Paper II, III, & IV in the next couple of months!
Cosmic SFR / SFR Density

see Paper I arXiv:1803.09761
stellar-to-halo mass ratio

- This is our predictions for $z = 4 - 10$.
- Need future observations to distinguish these discrepancies between observations and models.

![Graph showing stellar-to-halo mass ratio vs redshift and halo mass](attachment:stellar_to_halo_mass_ratio.png)
Conclusion

- SAM is great for generating forecasts and mock catalogues for joint wide- and deep-field surveys given its great efficiency and wide dynamic range.

- Taking advantage of the SAM’s efficiency, we can systematically vary the physics and subgrid parameters within our physically motivated model to explore how this shapes the formation of galaxies over time.

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- SAM is great for generating forecasts and mock catalogues for joint wide- and deep-field surveys given its great efficiency and wide dynamic range.

- Taking advantage of the SAM's efficiency, we can systematically vary the physics and subgrid parameters within our physically motivated model to explore how this shapes the formation of galaxies over time.

- We find that massive galaxies are very sensitive to and are degenerately affected by star formation physics, gas depletion timescales, dust attenuation. Star formation in low-mass galaxies are `self-regulated' and is sensitive to strong stellar feedback.

- Both wide and deep surveys are crucial to fully constrain the physical processes that shape galaxy populations at high redshift, as well as their physical properties.

Future Projects

Mock Catalog / Predictions
- for joint JWST-Euclid observations
- for joint JWST-ALMA observations

Reionization / Intensity Mapping
- can galaxy reionize the Universe?
- ASK ME! / Talk to me offline!

Comprehensive SAM upgrade
- new merger trees code for ultrahigh z (z > 10)
- new physical recipes that captures physical processes that operates at these redshifts.

Contact: yung@physics.rutgers.edu
Data Release: www.physics.rutgers.edu/~yung

see arXiv:1803.09761
What do we expect from JWST?

- Performance of JWST in different surveys.
- Vertical lines - detection limits
  - HST: CANDELS-Wide,
  - JWST: CANDELS-Wide, HUDF, HUDF lensed (10x)
- Horizontal lines - volume estimate (~10 objects)
  - Yellow: HUDF (above)
  - Green: CANDELS-W (below)
- JWST will be able to detect large number of faint objects that weren’t detectable by HST
- Will constrain the faint end of UV LFs and test our simple assumption for SNe feedback.

see Paper I arXiv:1803.09761
Forward model for UV luminosity

- Model is calibrated only to $z \sim 0$ observations.
- We show the rest-frame UV luminosity functions between $z = 4 - 10$ from our fiducial model.
- **blue dashed**: intrinsic luminosity — no dust
  **blue solid**: with dust attenuation
- Turnover near $M_{UV} \sim -9$ corresponds to the cutoff in the atomic cooling function at $10^4$ K.
- Dust is estimated based on physical properties
  \[ \tau_{V,0} = \tau_{dust,0}(z) Z_{\text{cold}} m_{\text{cold}} / (r_{\text{gas}})^2 \]
  which the optical depth normalization is guided by observations. We invoked a $z$-dependent dust-to-metal ratio.

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Cosmological Tests

• We use an analytic reionization model to compute the reionization history and compare these to observations.

• e.g. ionizing photon emissivity, ionized hydrogen volume filling fraction, and the Thompson scattering optical for the CMB.

• The latest reionization constraints relax the tension between the budget of ionizing photons and constraints from Lyα forest observations.

• Assuming a mildly evolving UV escape fraction of 5 - 10%, we are able to simultaneously match these multi-probe observational constraints.

• Seems like we are in the right ballpark.

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Why do we care about this?

- Our models also show that the galaxies between $-16 < M_{UV} < -12$ are the powerhouse that generate these ionizing photons in the pre-reionization era, and galaxies between $-20 < M_{UV} < -16$ will gradually take over near $z \sim 10$.

- Most of these galaxies are not yet detected do-date…

- Assuming a $z$-dependent universal UV escape fraction, which does not depend on the physical properties. In reality we expect massive galaxies to contribute fewer ionizing photons at high redshifts.