Semi-Analytic Forecasts for JWST
high-redshift galaxy demographics & implications for reionization

L. Y. Aaron Yung
Supervised by Rachel S. Somerville

special thanks to key collaborators:
Romeel Davé (Edinburgh)
Harry Ferguson (STScI)
Steve Finkelstein (UT Austin)
Gergö Popping (MPIA)
Some Promising Predictions

- The Santa Cruz semi-analytic model (SC SAM) has been shown to reproduce observations at low redshifts (z < 6)

- These predictions are made with model parameters only calibrated to z ~ 0 observations

- goal of this project: examine the predictions of these models for high redshift galaxy physical and observable properties (4<z<15), and study the implications for reionization

see Paper I [arXiv:1803.09761]
Paper II [arXiv:1901.05964]
SAM — a comprehensive galaxy factory

Physical Parameters

- $A_{SF}$ - SF relation normalization
- $N_{SF}$ - SF relation slope
- $\tau_{SF}$ - SF timescale
- etc...

Physical Properties

(e.g. $M^*$, SFR, ...)

Recipes / Prescriptions

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

Forward Model

Synthetic SED / JWST filters

Observables

(e.g. $M_{UV}$, $m_{F200W}$)

calibrated only to $z \sim 0$ observations

semi-analytic model

DM halo merger trees

$\Sigma_{SFR} \propto (\Sigma_{\text{cold}})^{N_{SF}}$

$\Phi_{M_*}$

$\Delta z = 6$

$\phi_*$

$\Phi$

$z = 6$

$\phi_*$

$\Phi$

Rest-frame UV magnitude

Forward Model

Synthetic SED / JWST filters

Dust recipe, etc
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 \((V_c = 20 – 500 \text{ km/s})\)
  - 2. create Monte Carlo realizations of merging history based on Extended Press-Schechter (EPS) formalism
  - 3. trace merger history down to progenitor halo mass of \(\sim 10^{10} M_\odot\), or 1/100th of the root halo mass, whichever is smaller.

  - Metallicity-based multiphase gas partitioning
    \(M_{\text{cold}} \rightarrow M_{\text{H}_1} + M_{\text{H}_2} + M_{\text{H}_2}\) (Gnedin & Kravtsov 2010)
  - \(\text{H}_2\)-based star formation:
    \(\Sigma_{\text{SFR}} \propto (\Sigma_{\text{H}_2})^{N_{\text{SF}}}\) (Bigiel+2008)
Comparison with other models

- Baseline: SAM Fiducial vs. Song et al.
- SAM vs. numerical simulations
  - pretty good agreement
- SAM vs. (semi-)empirical models
- larger dispersion between ‘a priori’ and (semi-)empirical models
Comparison with other models

• Baseline: SAM Fiducial vs. Song et al.

• SAM vs. numerical simulations
  - pretty good agreement

• SAM vs. (semi-)empirical models
  - larger dispersion between 'a priori' and (semi-)empirical models
Fraction of galaxies detectable in wide, deep, and lensed JWST surveys from $z = 4$–$10$ calculated using a sliding boxcar filter of width $\Delta M^* = 0.2$ in stellar mass. The dotted and dot-dashed lines show detection fractions of 90% and 50%.

make sure you explain why the mass at a given completeness is lower at high redshift (counterintuitive)
**JWST detection limit**

- Let’s use $z = 4$ as an example
- **Vertical lines:** 50% completeness for a given detection limit
- **Horizontal lines:** where ~1 object is expected per survey volume
- **do not account for survey geometry / field-to-field variance**

**JWST - F200W**

Table 1. Summary of assumed detection limits for the NIRCam F200W filter and survey areas for representative *JWST* surveys.

<table>
<thead>
<tr>
<th>Survey Type</th>
<th>Detection Limit</th>
<th>Survey Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide-field</td>
<td>28.6</td>
<td>$\sim 100$ arcmin$^2$</td>
</tr>
<tr>
<td>Deep-field</td>
<td>31.5</td>
<td>$2 \times 2.2^2$ arcmin$^2$</td>
</tr>
<tr>
<td>Lensed-field</td>
<td>34.0</td>
<td>$\frac{1}{15} (2 \times 2.2^2)$ arcmin$^2$</td>
</tr>
</tbody>
</table>
**JWST detection limit**

- Let’s use $z = 4$ as an example
- **Vertical lines:** 50% completeness at detection limit
- **Horizontal lines:** where ~1 object is expected per survey volume
- ** do not account for survey geometry / field-to-field variance

**JWST - F200W**

**Table 1.** Summary of assumed detection limits for the NIRCam F200W filter and survey areas for representative *JWST* surveys.

<table>
<thead>
<tr>
<th>Survey Type</th>
<th>Detection Limit</th>
<th>Survey Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide-field</td>
<td>28.6</td>
<td>$\sim 100$ arcmin$^2$</td>
</tr>
<tr>
<td>Deep-field</td>
<td>31.5</td>
<td>$2 \times 2.2^2$ arcmin$^2$</td>
</tr>
<tr>
<td>Lensed-field</td>
<td>34.0</td>
<td>$\frac{1}{15}(2 \times 2.2^2)$ arcmin$^2$</td>
</tr>
</tbody>
</table>
Predictions for the low-mass-end of SMFs

- Current SNe feedback model:

\[ \dot{m}_{\text{out}} = \epsilon_{\text{SN}} \left( \frac{V_0}{V_c} \right)^{\alpha_{\text{rh}}} \dot{m}_* \]

- no guarantee that these parameters are a good representation of the physical scaling laws at different cosmic epochs

- important to explore sensitivity of model predictions to parameter values

- future JWST observations will be able to help constrain modeling of stellar-driven outflows
z = 6

Paper II [arXiv:1901.05964]
Paper III: intrinsic productivity of LyC radiation

- We extended our predicted UV LFs to $z \sim 15$ (use with caution!! **)
- For now, let’s consider UV escape fraction as a “population-averaged” quantity

$f_{\text{esc}}$ is treated as a free parameter such that the ionizing photon emissivity ($\dot{n}_{\text{ion}}$) and CMB optical depth match observations.
**new** Paper III: intrinsic productivity of LyC radiation

- Steve Wilkins found $\xi_{\text{ion}}$ is highly dependent on the SSP models

- may produce up to a factor of ~2 to ~3 difference compare to previously assumed values

- Now we estimate $\xi_{\text{ion}}$ based on synthetic SED that account for Z and stellar age

- may vary and evolve among the galaxy populations due to their physical properties

(Wilkins+2016)
Paper IV: Implication on reionization and $f_{\text{esc}}$

- We use a simple analytic reionization model (e.g. Kuhlen & Faucher-Giguere 2012)

- We show that assuming a redshift dependent mean $f_{\text{esc}}$, our galaxies can reionize the Universe while matching both IGM and CMB constraints!
what if we change the stellar feedback model…

• weaker feedback means a lower $f_{esc}$ is required, or the Universe reionizes earlier

• converse for stronger feedback — becomes in possible tension with observations

![Graph showing the relationship between $\tau_{CMB}$ and $z_{ion}f_{esc}$ for different redshifts (z = 11, 12, 13, 14) with various feedback models (fiducial, $\alpha_n = 2.0$, $\alpha_n = 2.4$, $\alpha_n = 3.2$, $\alpha_n = 3.6$, Planck 2016).]
We also tried a physically motivated model

• We assume \( f_{\text{esc}} \) is proportional to the optical depth of dust, with no explicit dependence on redshift (qualitatively consistent with observed trends at lower redshift)

• it naturally suppresses the overproduction of ionizing photons that would otherwise happen with a non-evolving \( f_{\text{esc}} \) — but not quite enough
Fraction of all ionizing photons responsible for by galaxies grouped by luminosities.

Fraction of all ionizing photons responsible for by galaxies detectable by JWST surveys.
Summary & Conclusions

- SAMs are an efficient method for generating forecasts and mock catalogues for joint wide- and deep-field surveys. Predictions agree well with hydrodynamic simulations with similar physical ingredients.

- 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.

- The predicted galaxy populations in our fiducial model are consistent with observational constraints on reionization from the IGM and CMB, assuming reasonable escape fractions.

- Project summary and all data products available at https://www.simonsfoundation.org/semi-analytic-forecasts-for-jwst/
bkup slide: Dust Model

V-band, face-on extinction optical depth of the diffuse dust

\[ \tau_{V,0} = \tau_{\text{dust},0} \ Z_{\text{cold}} \ m_{\text{cold}} / r_{\text{gas}}^2 \]

Dust attenuation in the V-band for a galaxy with inclination \( i \)

\[ A_v = -2.5 \log_{10} \left[ \frac{1 - \exp[-\tau_{V,0} / \cos(i)]}{\tau_{V,0} / \cos(i)} \right] \]

\( A_{UV} \) starburst attenuation curve (Calzetti et al. 2000)