Semi-analytic bubbles - probing high redshift reionization sources with mock deep *Roman* surveys

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Background: Reionization & *Roman*

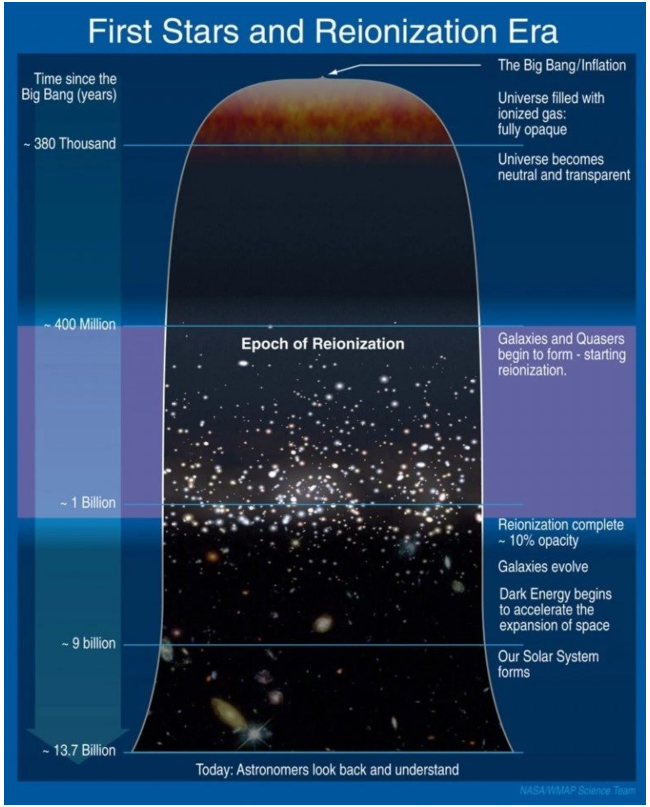
Epoch of Reionization – when the intergalactic medium (IGM) transformed from neutral to ionized hydrogen

Sources of reionization: first stars, galaxies, quasars

Reionization gives us the observable universe!

Roman: large footprint + mid-infrared filters = reionization constraints

Need to build predictive models for future surveys!



Project: Objective and Goals

Problem –

Need wide and large volume IGM simulations to characterize reionization. Incredibly time intensive + computationally expensive (capturing multi-scale physics)

Objective –

Use semi-analytic model galaxy formation simulations to do fast reionization simulations for making predictions for *Roman Space Telescope*

Procedure –

1) Calculate ionizing photon production per galaxy from star formation histories
2) Create IGM reionization maps with variable escape fraction
3) Calculate ionization bubble statistics

The Santa Cruz semi-analytic model (SC-SAM)

Lightcone created using SC-SAM
(**Yung et. al 2023**)

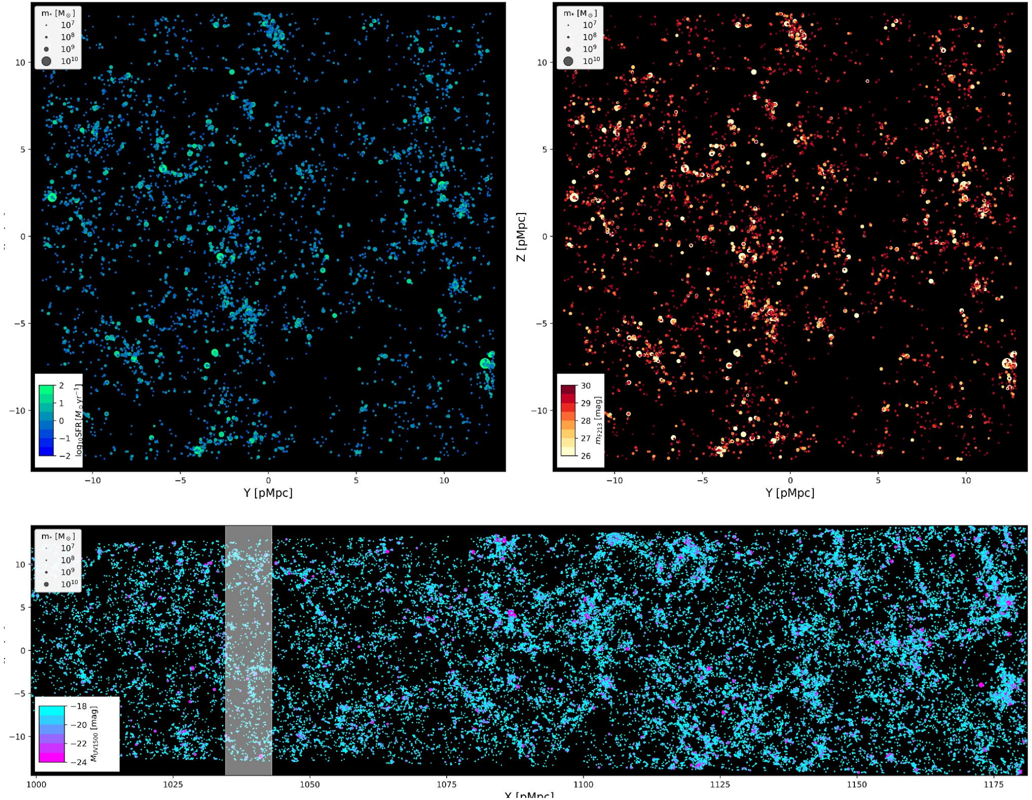
Resolution details –

redshift: $0 < z < 10$

mass: $m_{halo} > 10^{10}\ M_{\odot}$, $m_{star} > 10^{7}\ M_{\odot}$

footprint: 2 deg^2

Data products: galaxy + halo catalogs, star formation histories



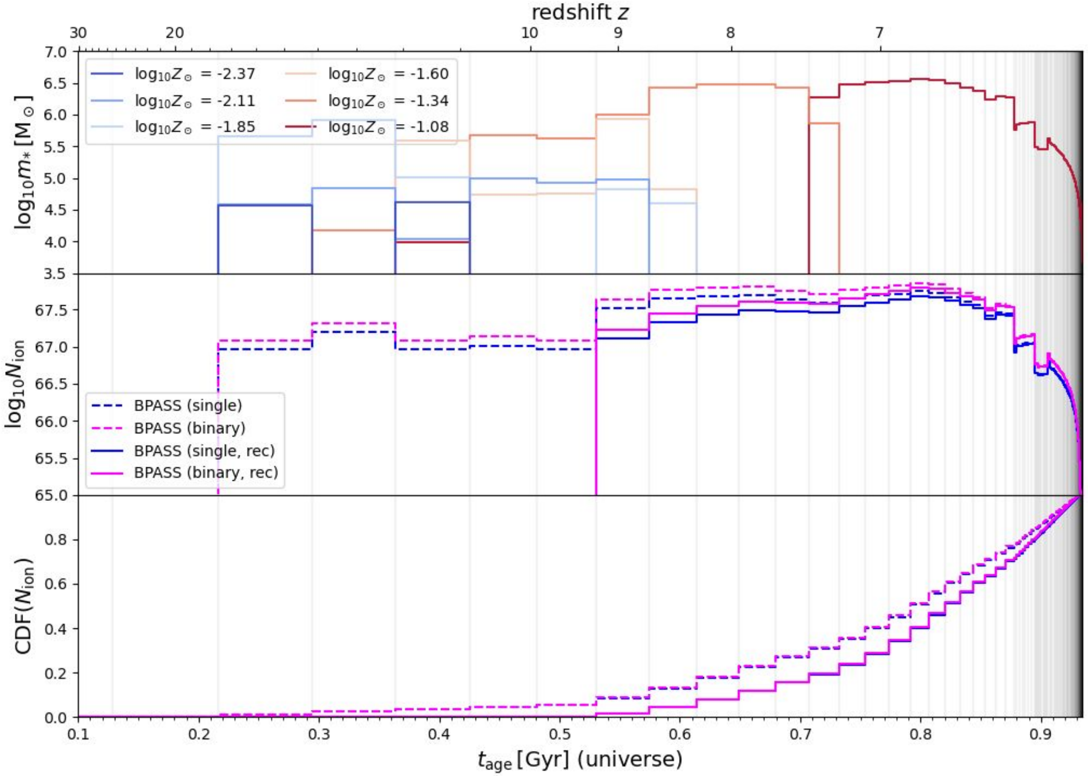
SC-SAM data product: star formation histories

SAM SFHs: 12 metallicity bins x 197 age bins

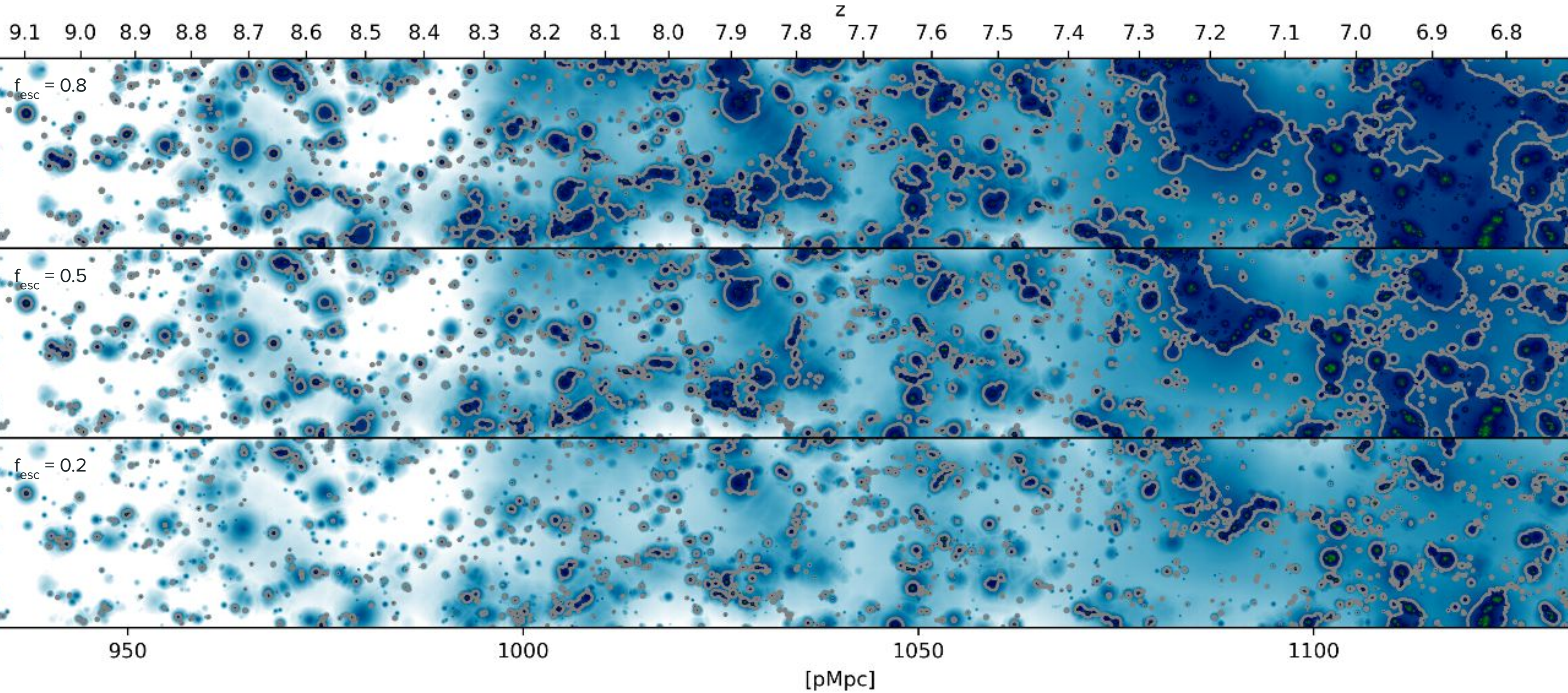
Age bins inherited from BC03, semi-log spacing

Using the **BPASS SPS model**, can calculate ionizing photon production for single / binary star populations

Factoring in **hydrogen recombinations** per age bin



Bubble simulations: qualitative visualization across redshift



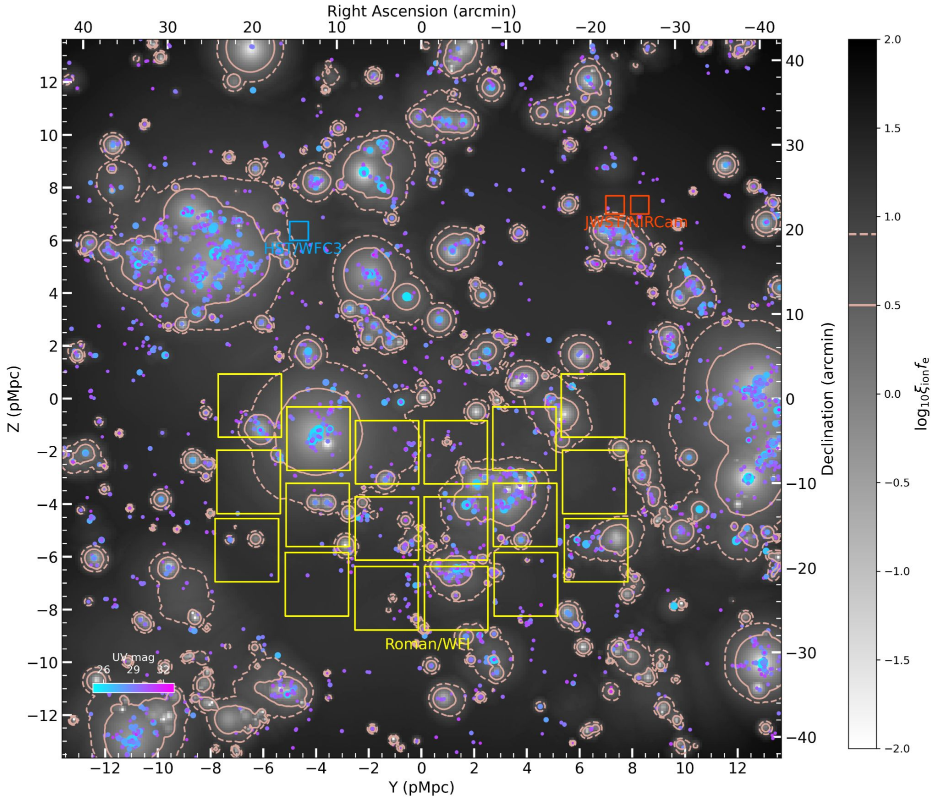
Bubble simulations: footprint visualization

Runtime: 2 days on Macbook Air M2 for 150 redshift slices (numba, no parallelization)

Telescope footprints: HST/WFC3, JWST/NIRCam, and Roman/WFI

Escape fraction f_{esc} left as free parameter. Tells us what is our observable universe

Roman will be able to capture both small and large bubbles + their bright sources



Bubble statistics: extracting bubbles from maps

Inspiration: Friends-of-Friends algorithm in 2D

1.) Identify local minima cell candidates in map and add to list
2.) Search a minima's cell neighbors to see if they are ionized
    a.) If ionized, link cell to minima, add cell's neighbors to also search
    b.) If not ionized, ignore cell
3.) Repeat until all neighbor cells are exhausted. Move onto next minima

Result: Bubble catalogs and bubble segmentation map!

Can back out **effective bubble radius**, $r_{eff} = (A_{bubble} / \pi)^{1/2}$

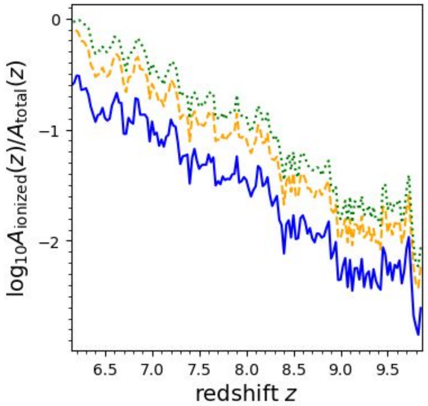
Bubble statistics: ionization area and effective radii

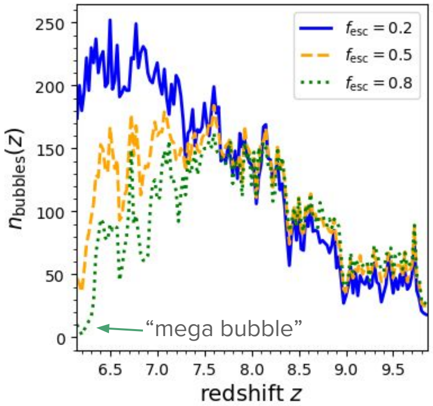
Three different escape fraction scenarios: f_{esc} = 0.2, 0.5, 0.8.

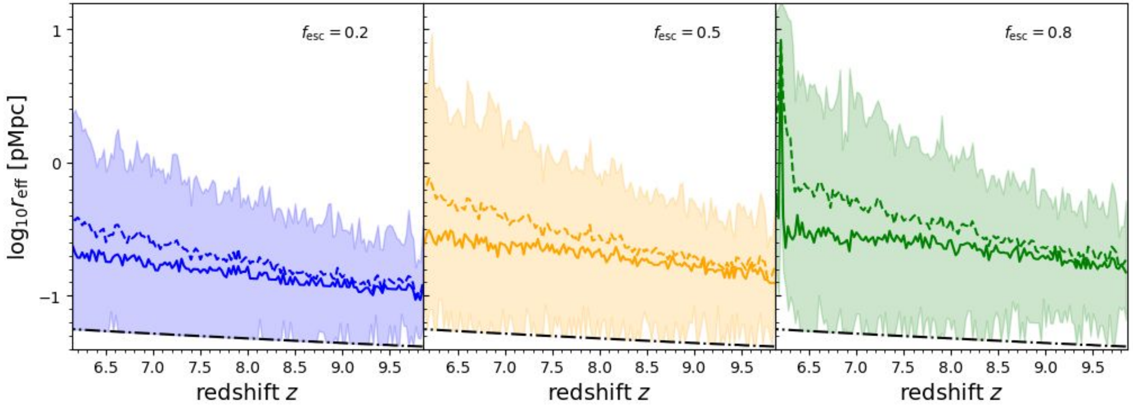
97% of lightcone area reionized at z = 6.2 for f_{esc} = 0.8

Can see in different scenarios where small bubbles start collapsing into “mega bubbles”

Late reionization in our simulation







Caveats & Considerations

Missing low mass halos ($m_{halo} < 10^{10}\ M_\odot$), which are a significant contribution to reionization history. Need high $f_{esc} = 0.8$ to achieve full reionization in simulation

Similar conditions to THESAN-HIGH-2 (Kannan+22), does not fully reionize universe until $z = 5.5$

Assuming very simplistic, uniform (redshift dependent) IGM model.

Need to factor in line-of-sight calculations for survey predictions

Conclusions:

Using SAM with star-formation histories and recombination allows us to see the **spatial structure of reionization** over large areas efficiently.

There is significant structure over large scales in mid-zone reionization, making **wide field observations with Roman essential**.

Without low mass galaxies, the f_{esc} has to be ramped to 80% to achieve reionization by z = 7, consistent with observations, underscoring **the importance low mass haloes**.

Next steps – assigning galaxies to bubbles (mapping photometry) for Roman survey predictions

Questions? Answers!

Extra: Bubble simulations: calculations

Our method for calculating the state of the IGM:

1. Consider a sheet centered at some z. Assume redshift-dependent but uniform IGM density. Divide up sheet into a 2D grid.

2. Subsample lightcone for galaxies living in $z \pm 0.15$ volume centered on z to isolate possible reionization sources (including bright ones)

3. For each grid cell, consider the contribution from the volumetric ionizing photon production efficiency of each galaxy in the subsample

Extra: Bubble statistics: cumulative distribution functions

What can we say about our bubbles? How rare are they at different points in time?

Evolution of different cumulative distributions across redshift

At lower redshifts, dominated by a single "mega bubble" and many smaller ones