Georgia Tech Center for Relativistic Astrophysics
College of Sciences

FIRST LIGHT

Exploring the Spectra of Galaxies in the Early Universe

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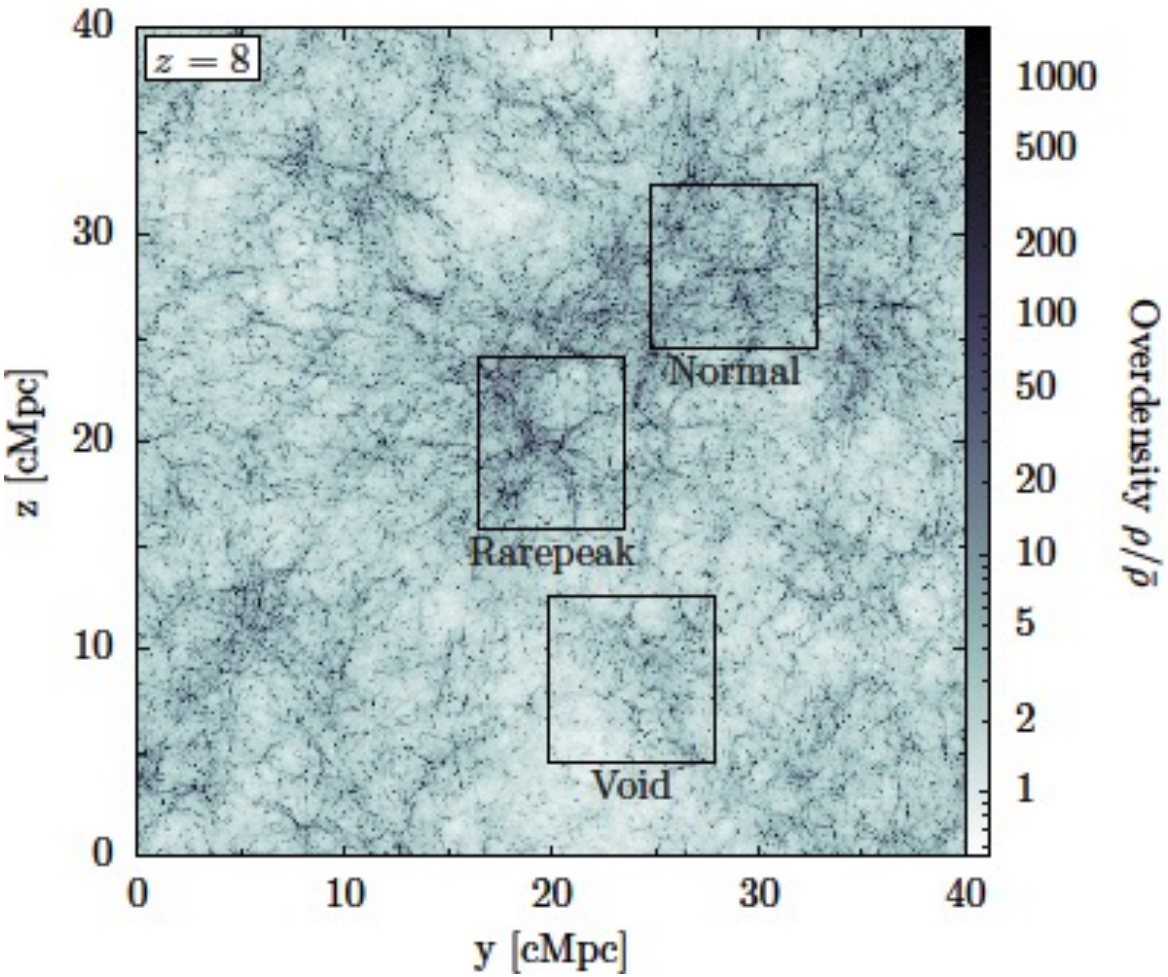
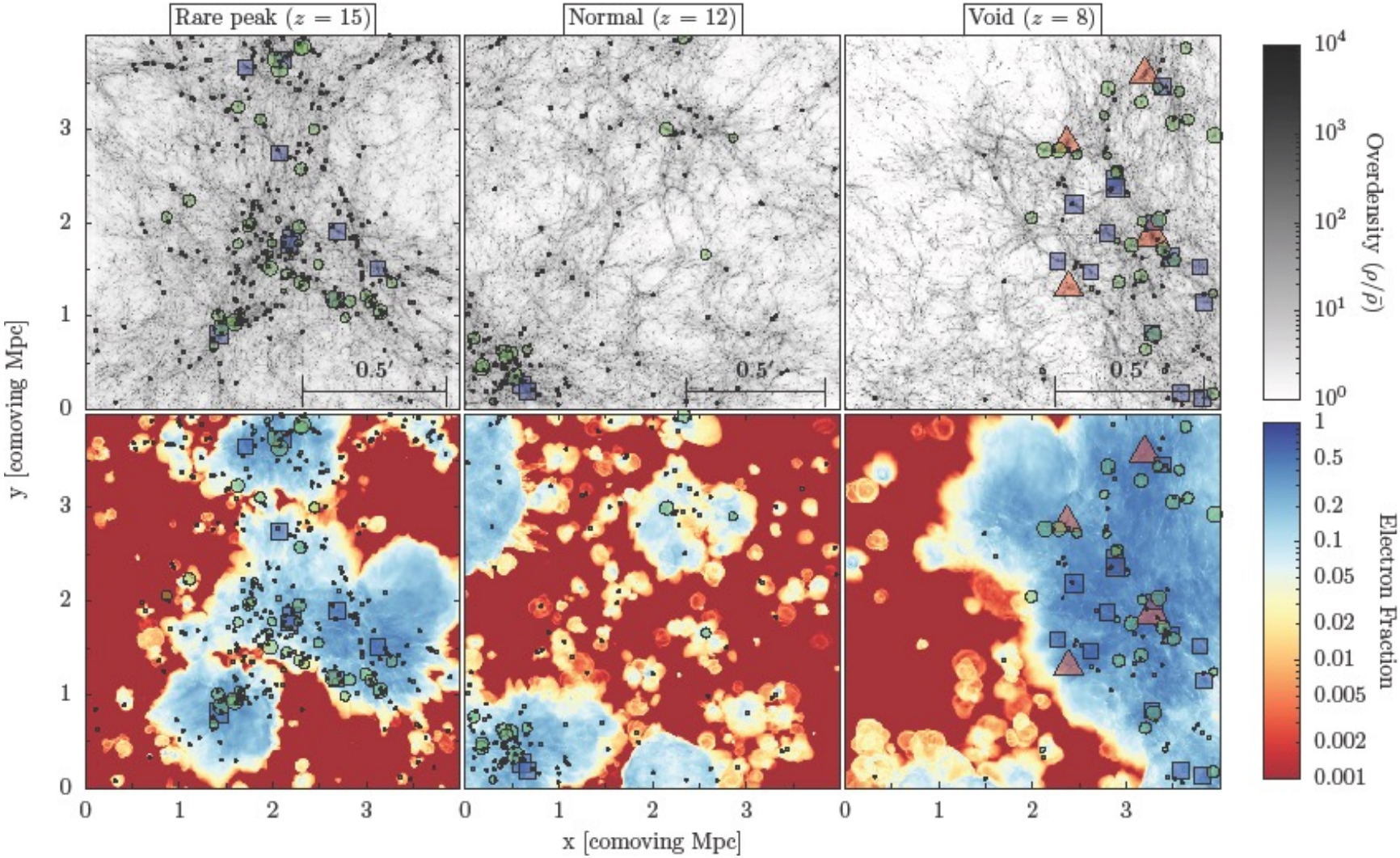
Renaissance Simulations



- $(40\ \mathrm{Mpc})^3$
- 29,000 $M_\odot$ DM Resolution
- $(5\ \mathrm{Mpc})^3$ zoom-in regions
- 9-species chemical solving
- Radiating stellar clusters
- Population III and metal-enriched star formation
- ray-tracing
- Supernovae feed back

Xu et al. (2013, 2014, 2016abc), Chen et al. (2014), O'Shea et al. (2015), Ahn et al. (2015)

Renaissance Simulations

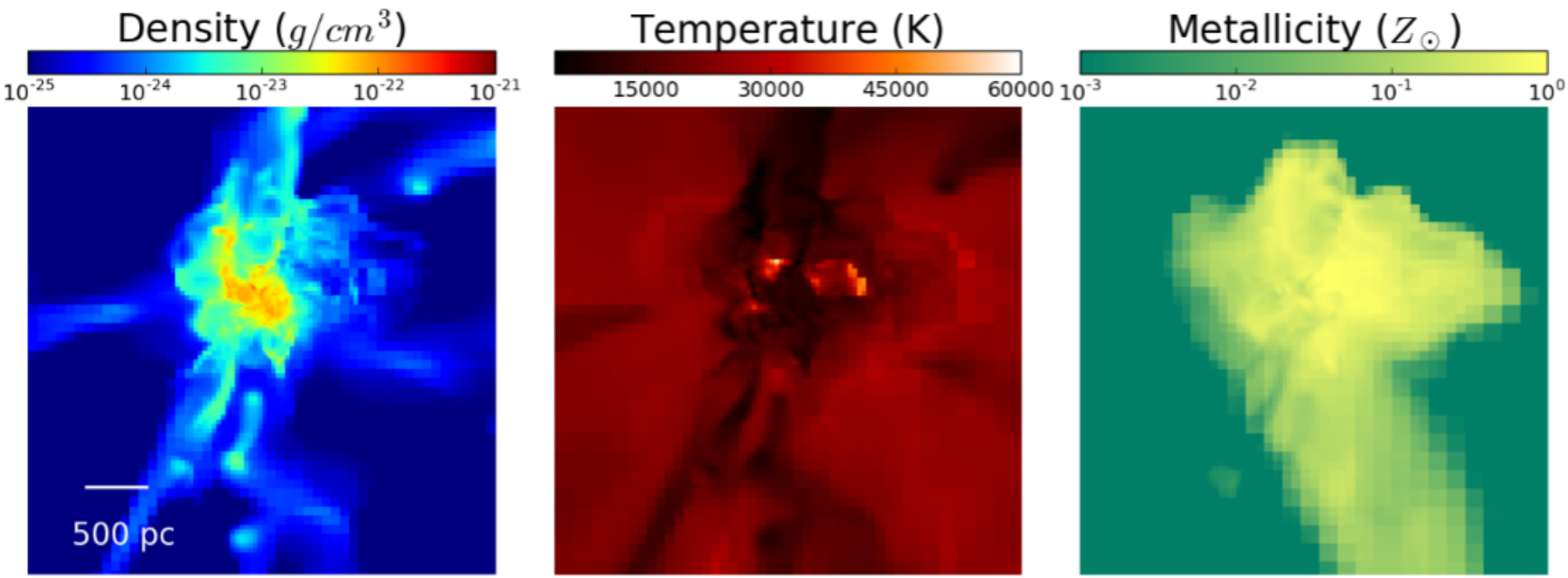


O'Shea et al. (2015)

Renaissance Simulations

Mass:	$10^{9.02}$ $M_\odot$
Stellar Mass:	$10^{7.31}$ $M_\odot$
Gas Mass Fraction:	0.164
Metallicity:	0.410 $Z_\odot$
Virial Radius:	4.426 kpc

- High Metallicity
- Anisotropic
- Third Most Massive Halo
- Multiple Recent Mergers
- Recent Star Formation

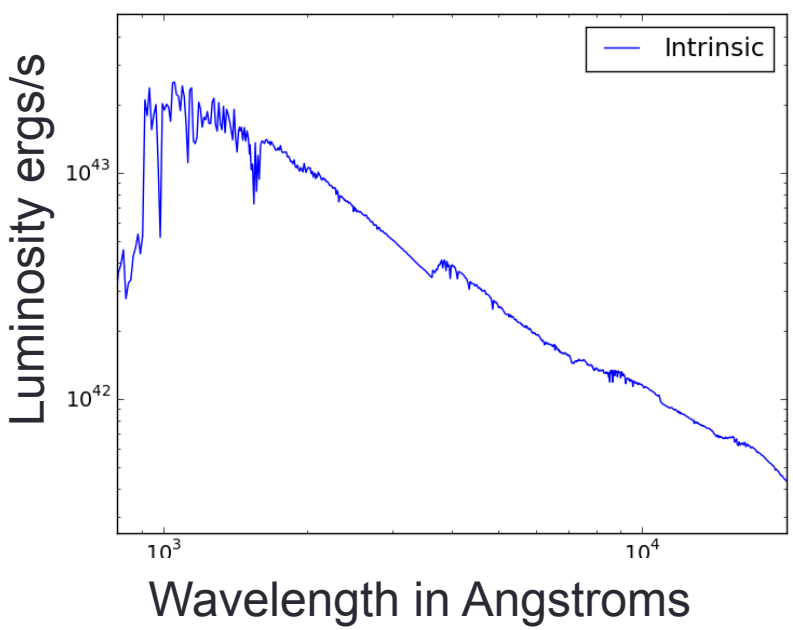


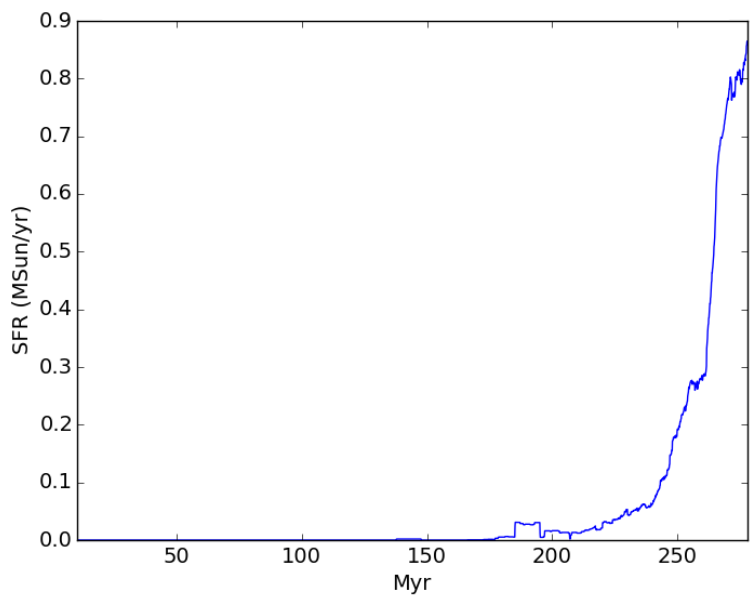
Joining the Two

Cosmological Simulations → Hubble/JWST Observables

First Ingredient: Stars

- Flexible Stellar Population Synthesis (FSPS) (Conroy, Gunn, & White 2009)
- Uses metallicity and age and outputs spectra/Msun based on HR. (FORTRAN)

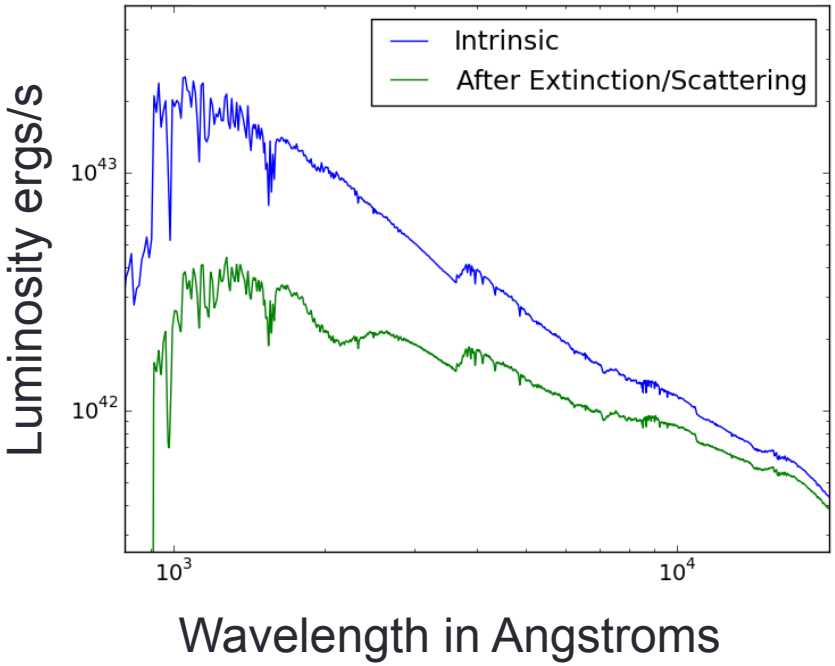




Second Ingredient: Dust and Gas

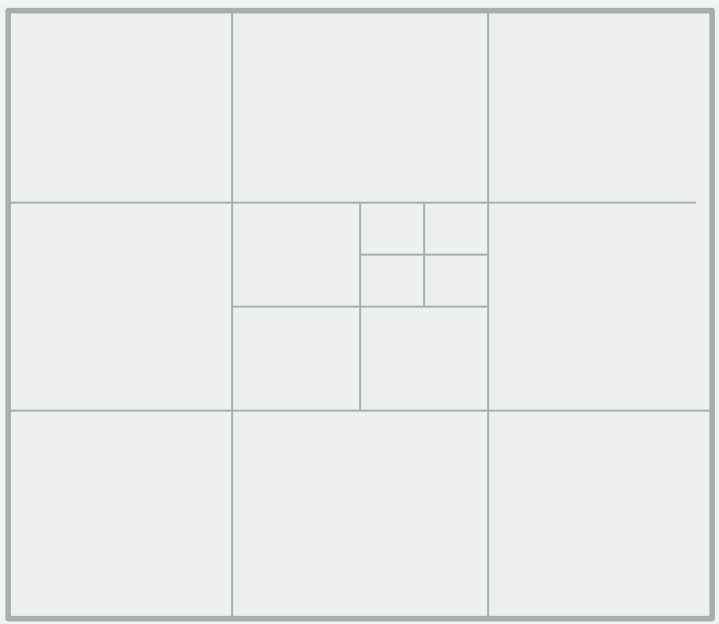
- Hyperion Monte Carlo ray-tracing code (Robitaille, 2011)
- Takes a 3-D arrangement of gas, dust, and stars and traces 100,000,000 photons using the FSPS spectra as sources

- Draine 2003 for dust model where dust is assumed to scale with metallicity with Milky Way abundance
- Hydrogen albedos and opacities applied to the gas



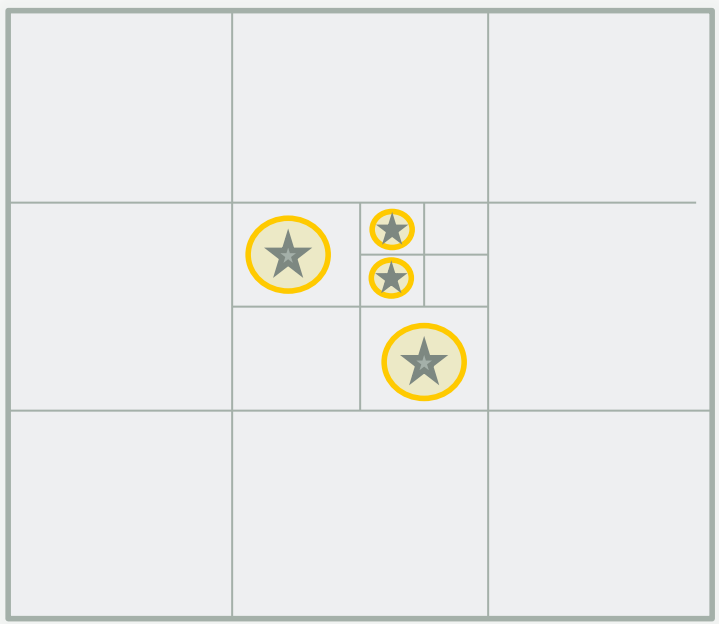
Third Ingredient: Nebular Emission Lines

- Cloudy chemistry and radiative transfer solver (G. J. Ferland et al 2013)
- Each Halo is subdivided into an AMR grid



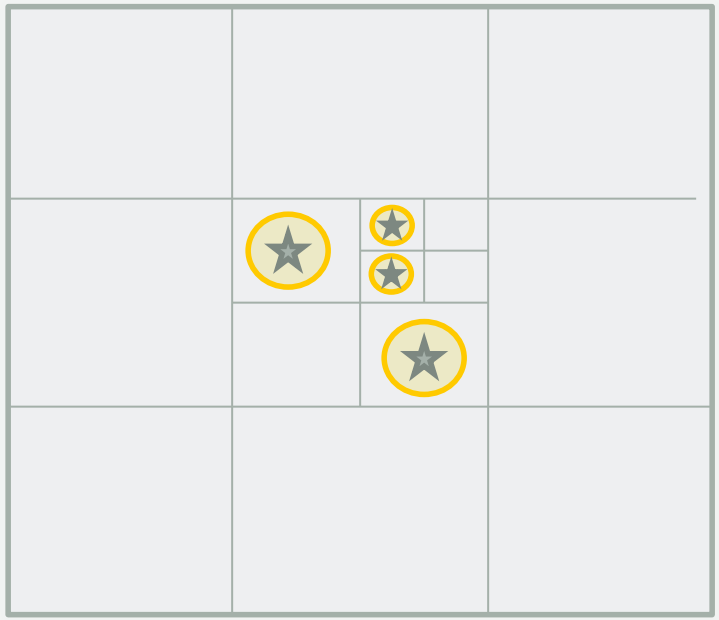
Third Ingredient: Nebular Emission Lines

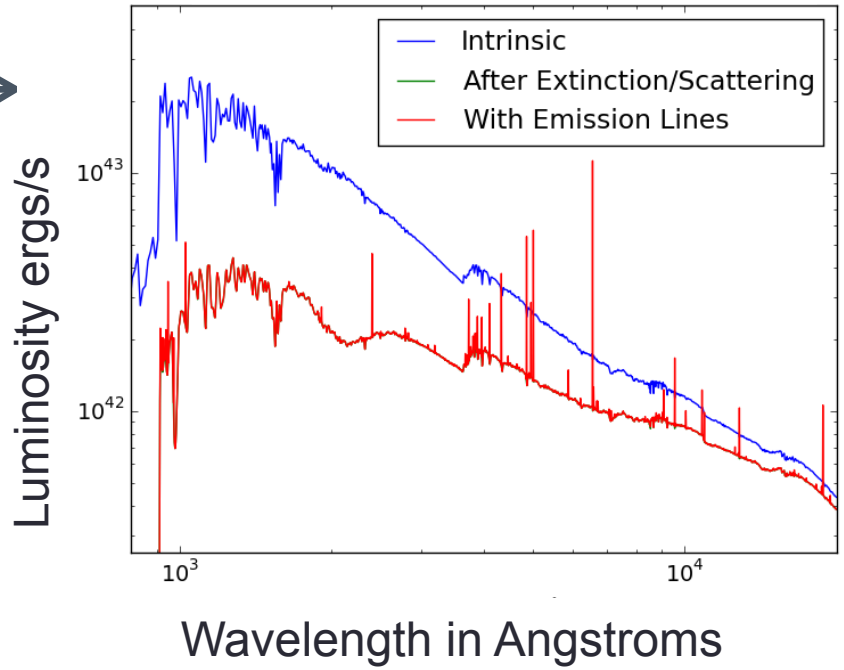
- For each cell containing a star, Cloudy simulates the emission lines using the central star particles as the source and gas properties imported from Enzo.



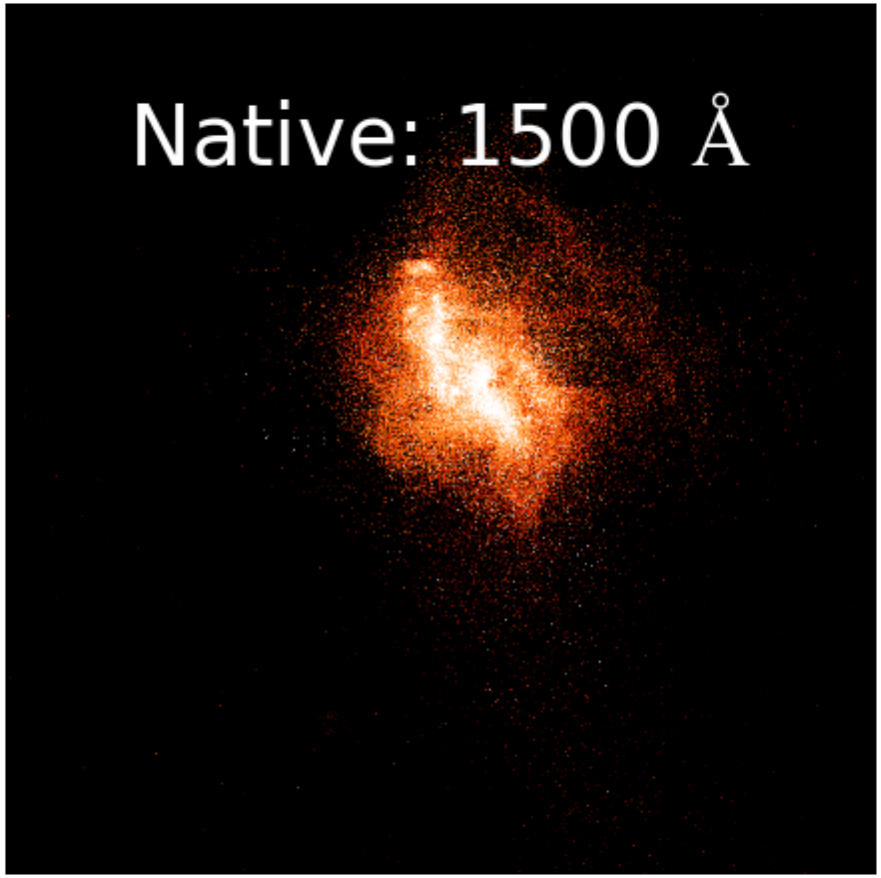
Third Ingredient: Nebular Emission Lines

- The resulting emission lines are added to the Hyperion spectra assuming the same extinction ratio.



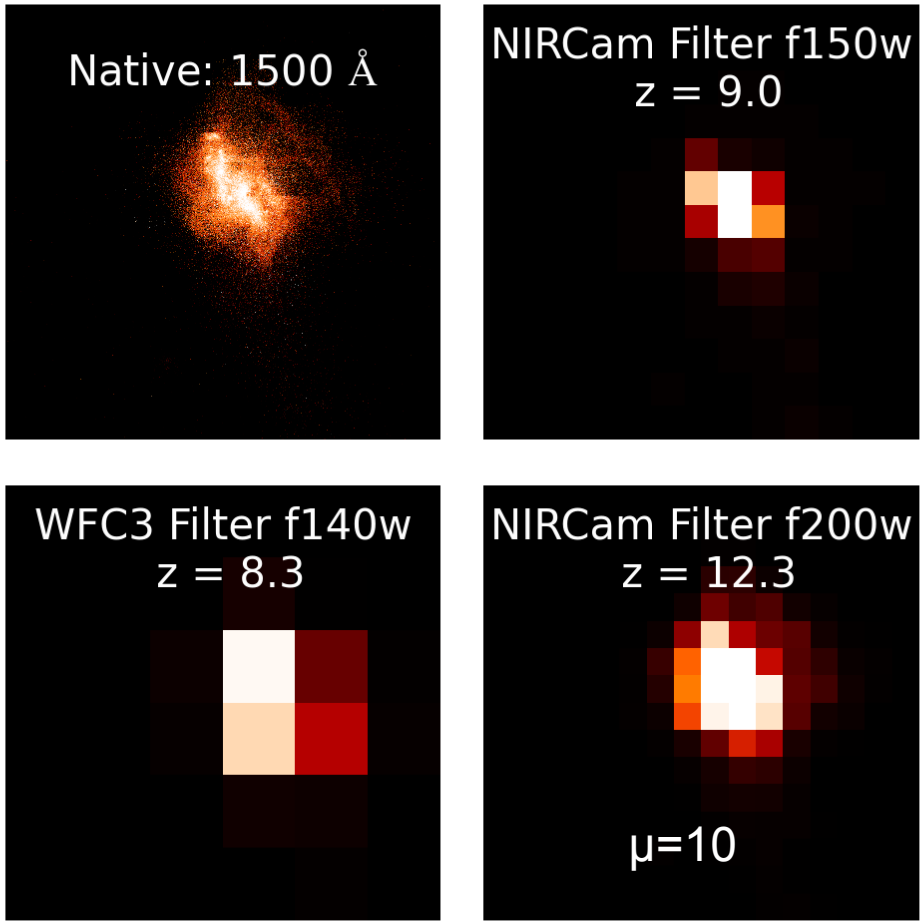


Turning Spectra Into Images

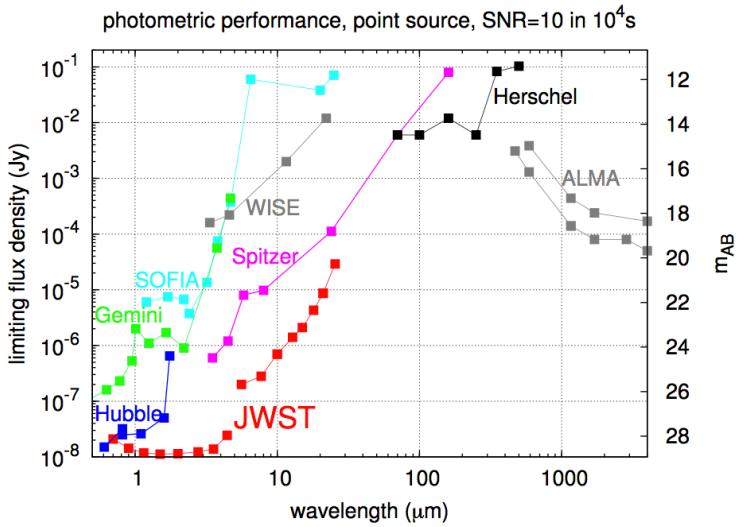


- The Monte Carlo Process is fully 3-D, so the opportunity exists to create single-wavelength images of a halo
- Contrast increased to show frequency-dependent dust and gas scattering.
- Fixing the Hubble filter, these images are translated into redshift

What We See

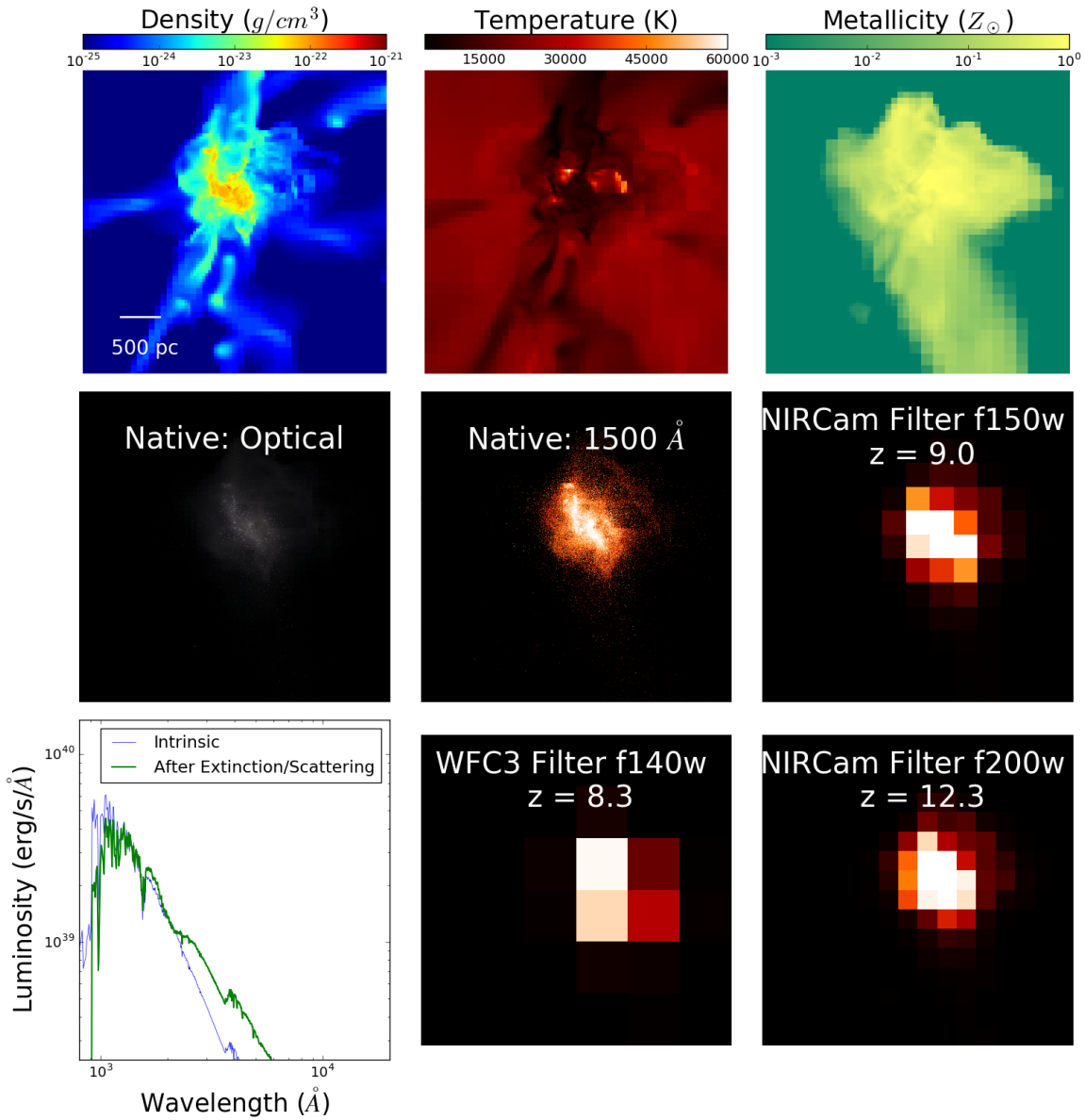


(Source: JWST website)

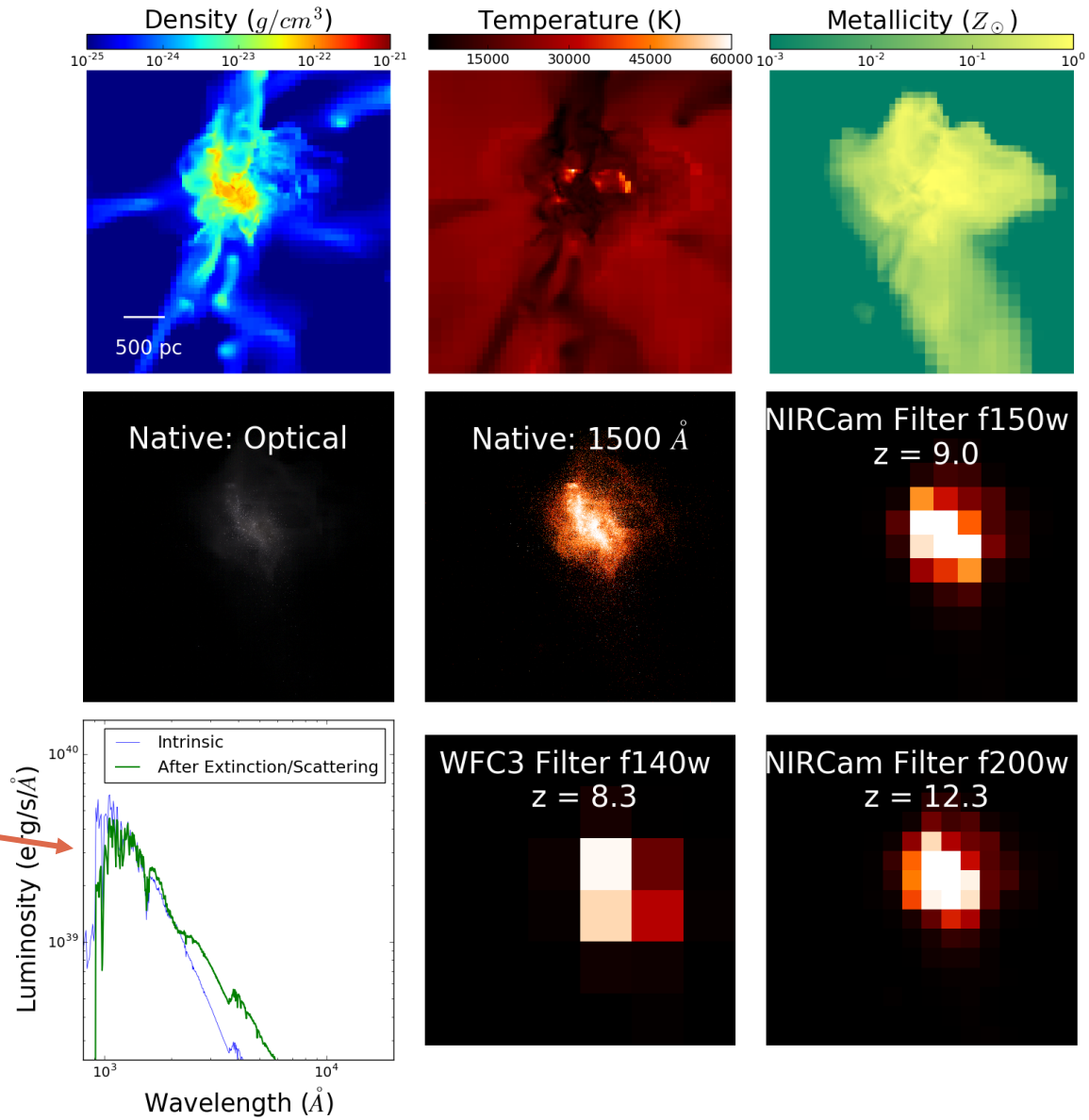


- Applied light distance, angular distance, noise, telescope blur (Gaussian) and pixel binning to the rest frame images
- Not included: IGM (z=14 not visible)
- 10 X gravitational lensing applied to flux.
- Hubble and JWST visible through redshift 11.3 with a SNR > 10 after a 10^6s (11.6 day) exposure

Visualizing Halos

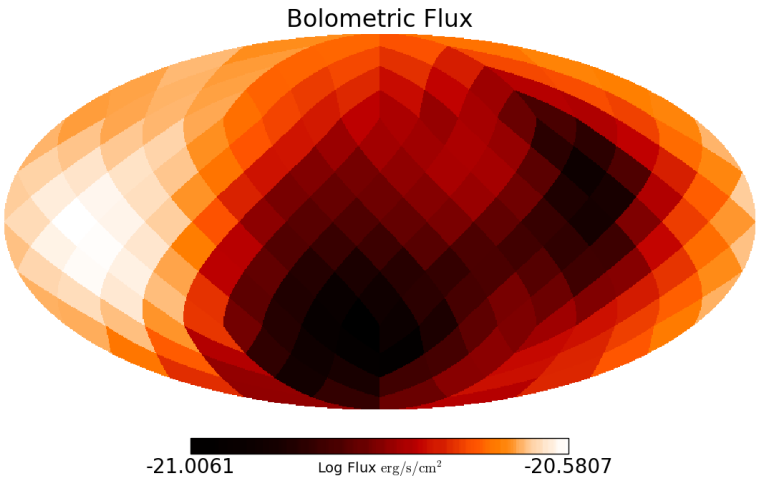


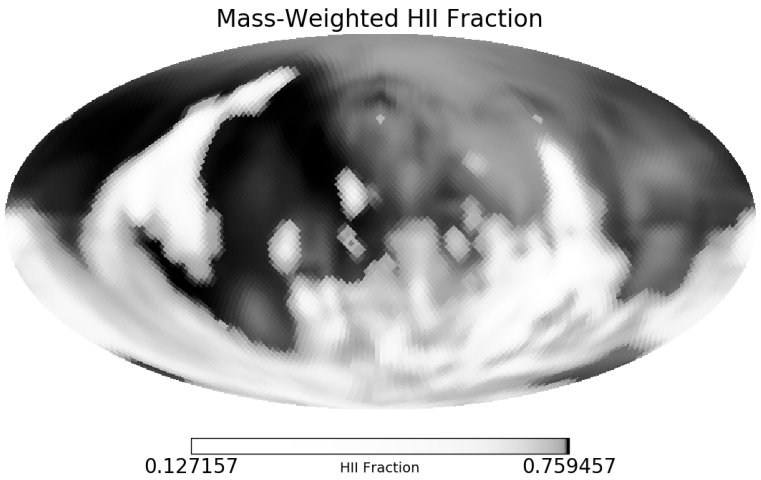
Visualizing Halos

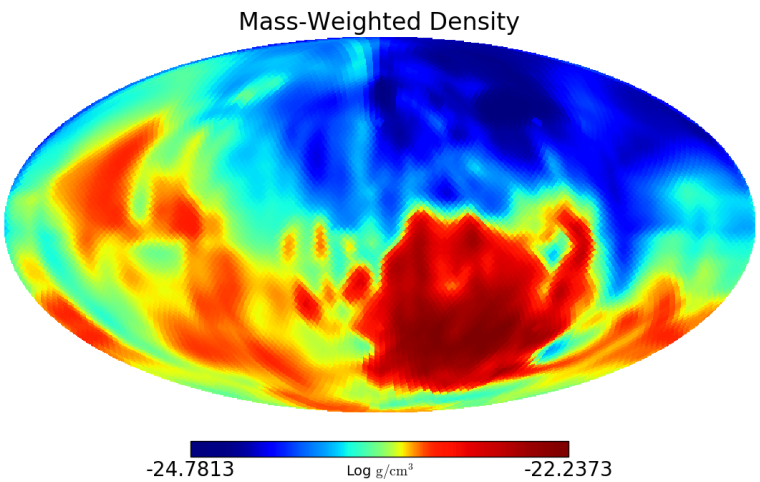


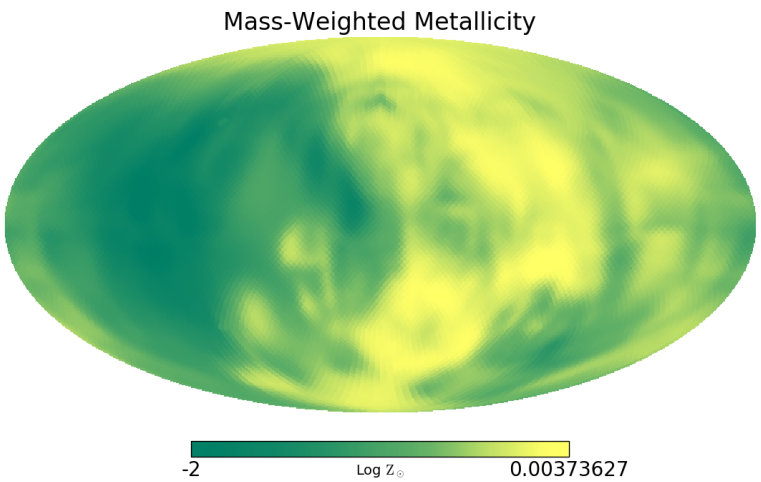
Processed intrinsic spectra shows attenuation at UV and optical wavelengths and strong emissions at IR wavelengths

Visualizing Halos

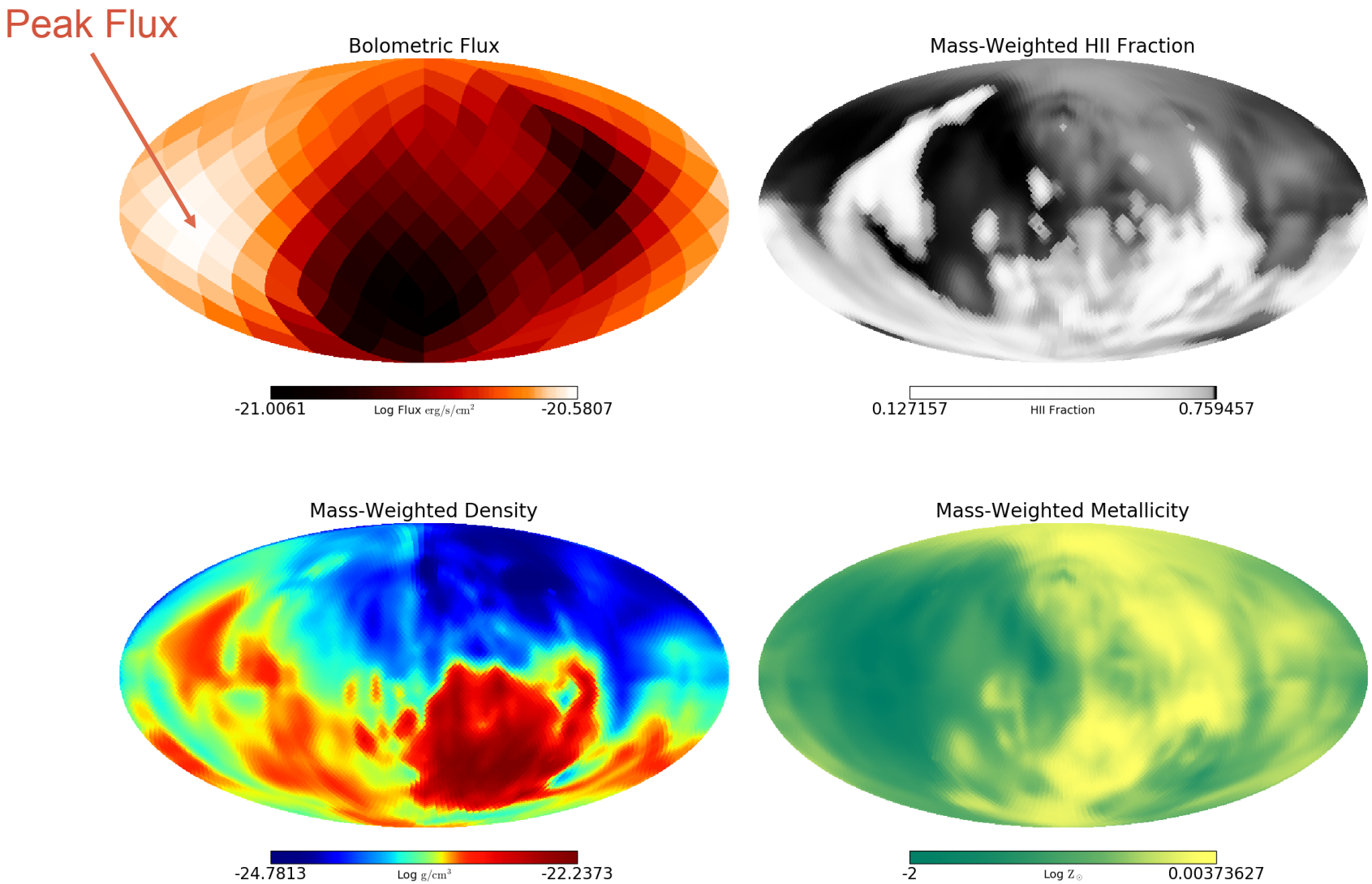




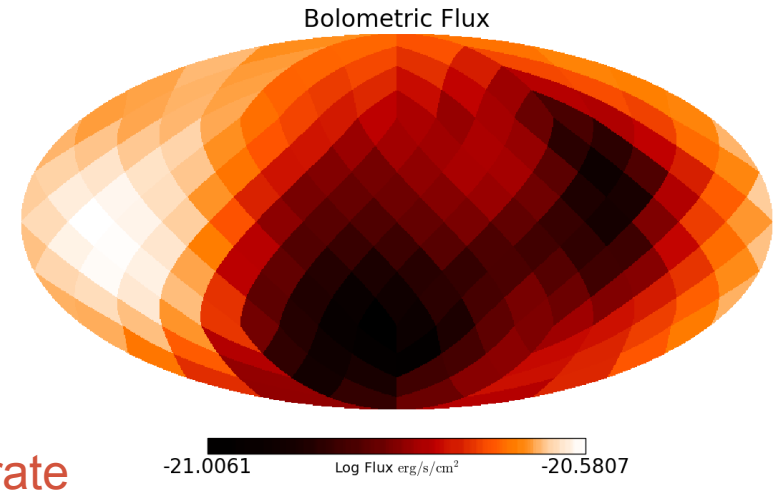


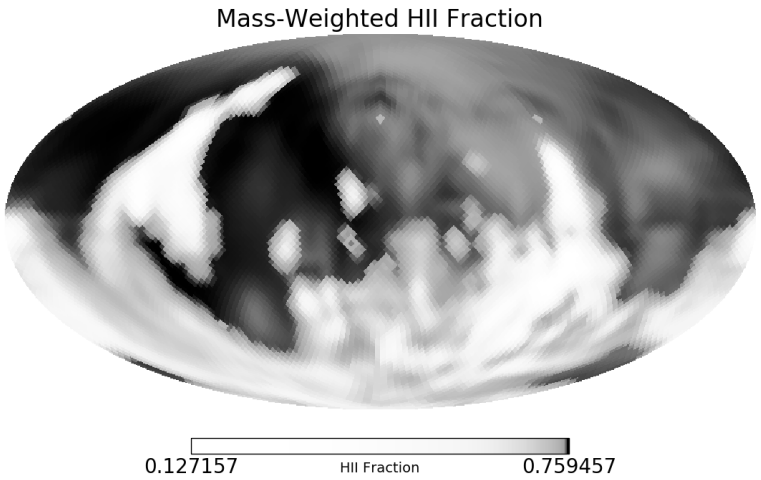


Visualizing Halos

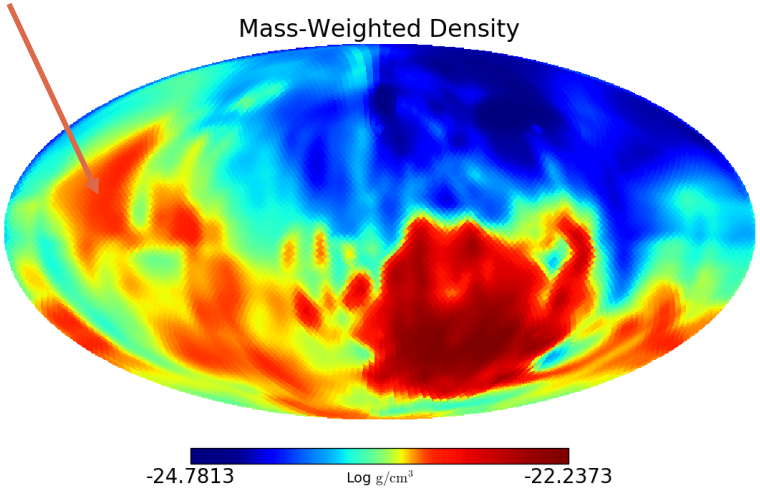


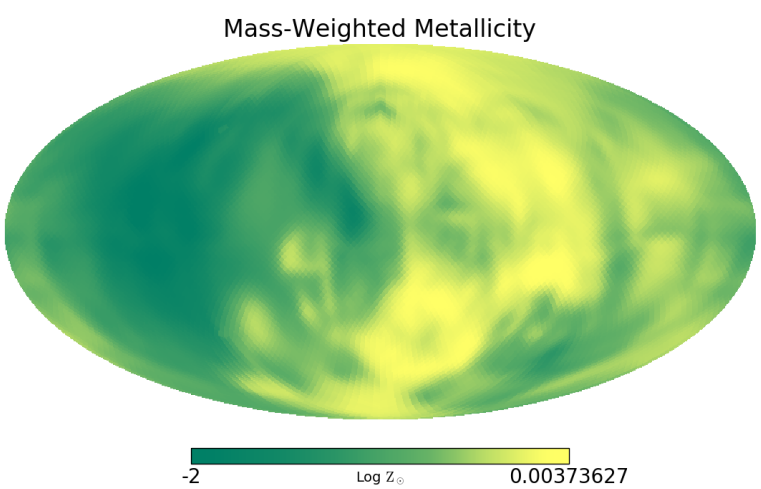
Visualizing Halos



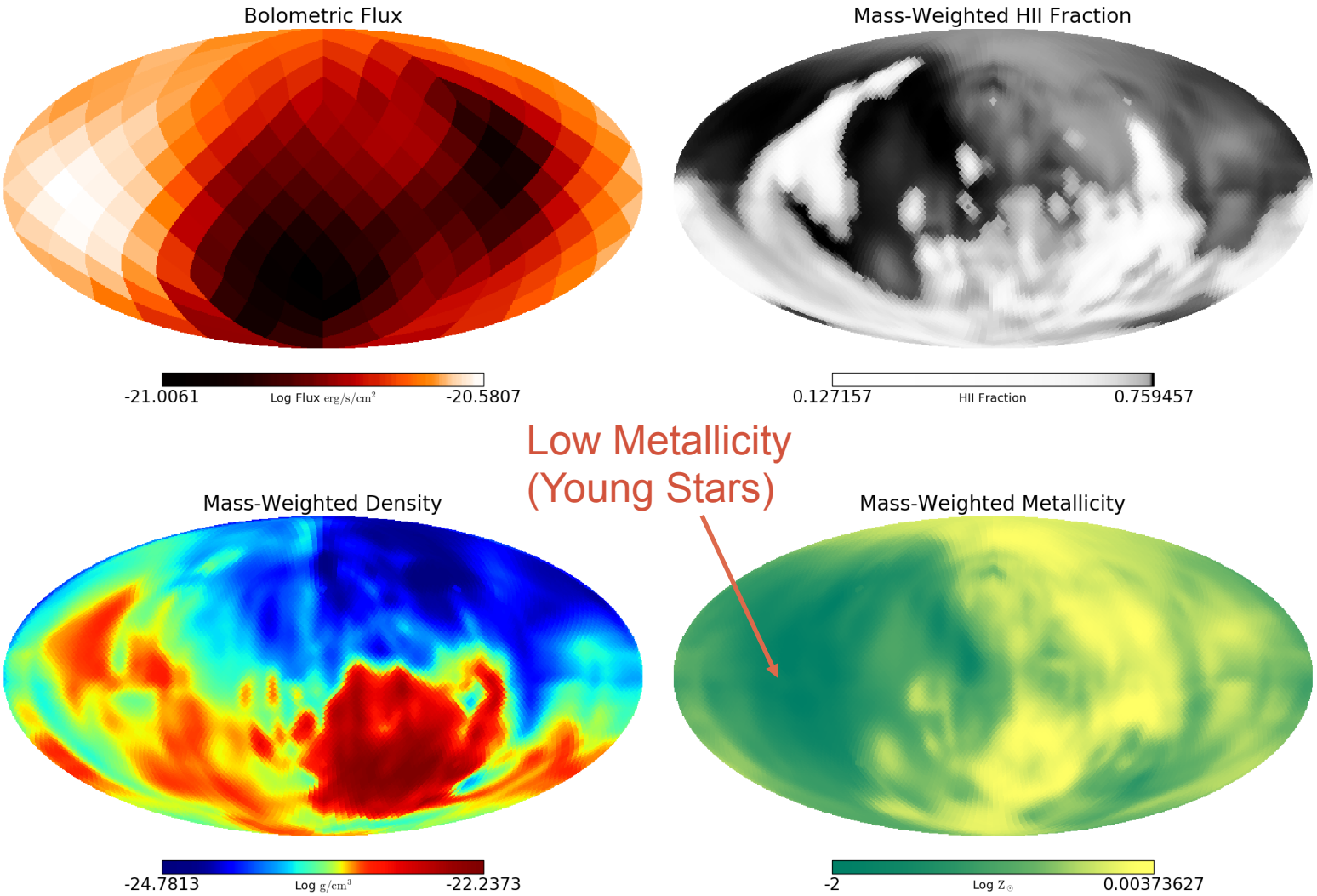


Moderate Column Density



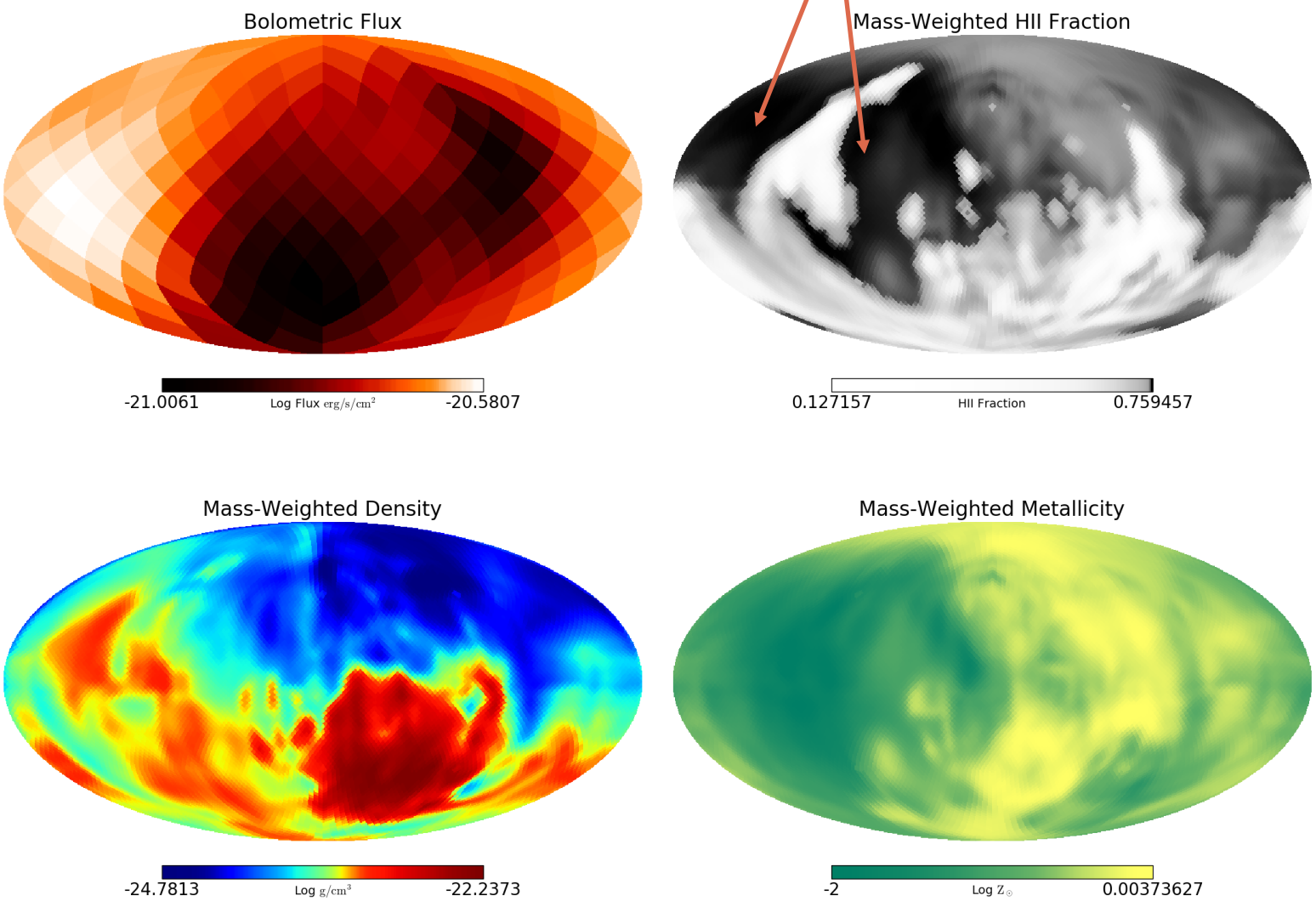


Visualizing Halos

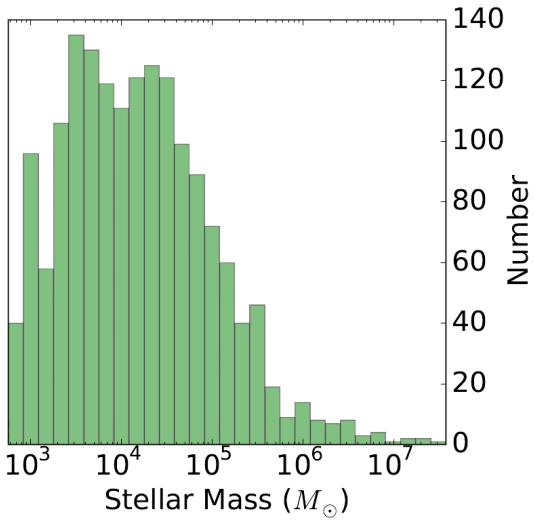


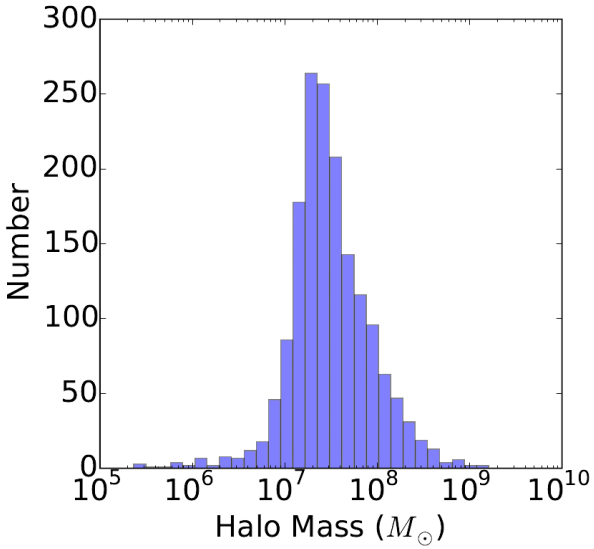
Visualizing Halos

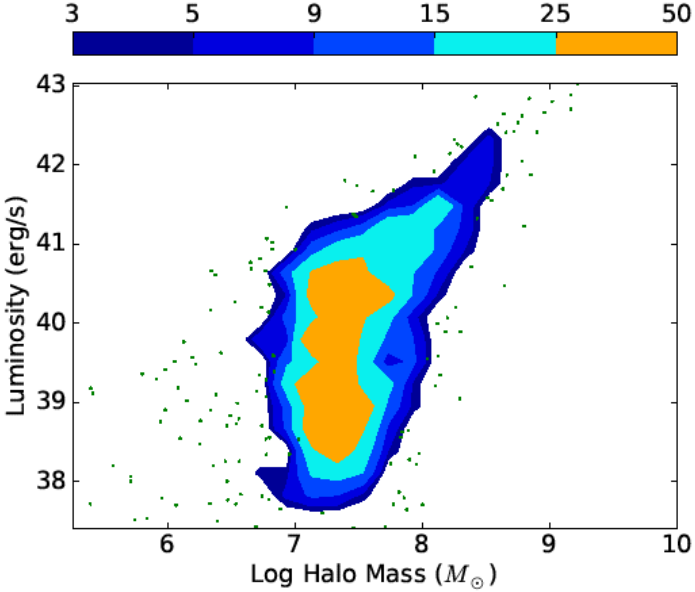
Channels of ionized gas

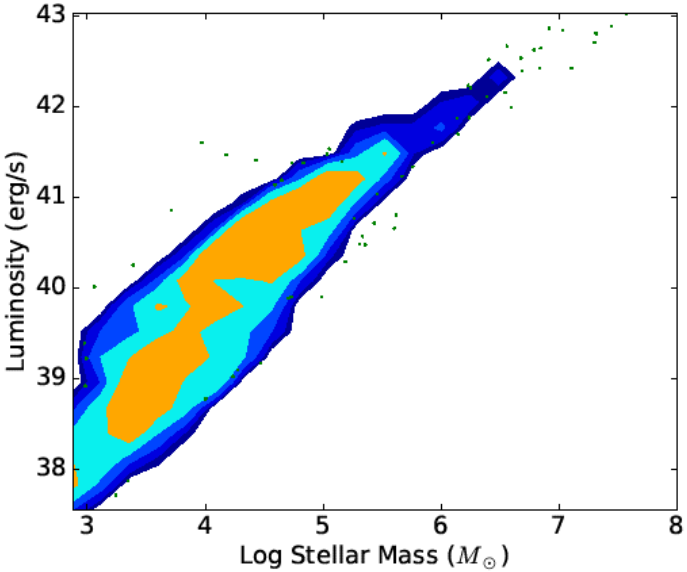


Sample of Galaxies

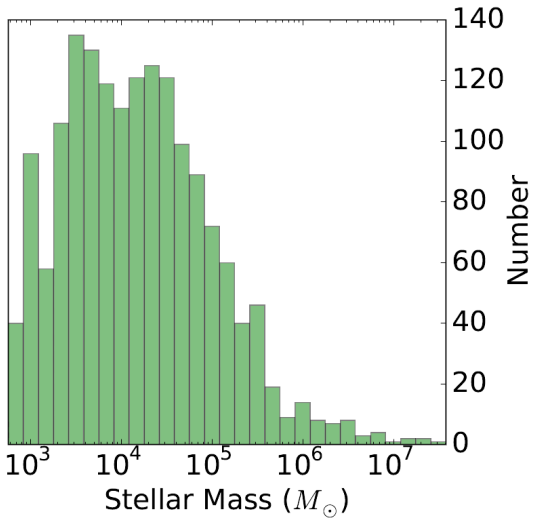


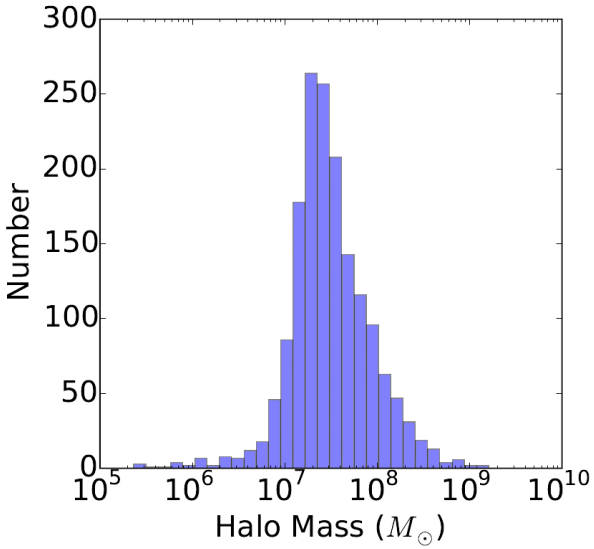


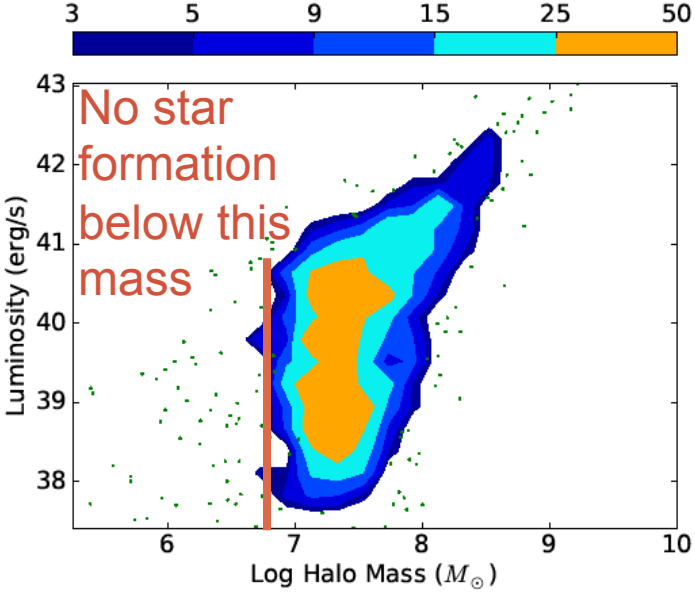


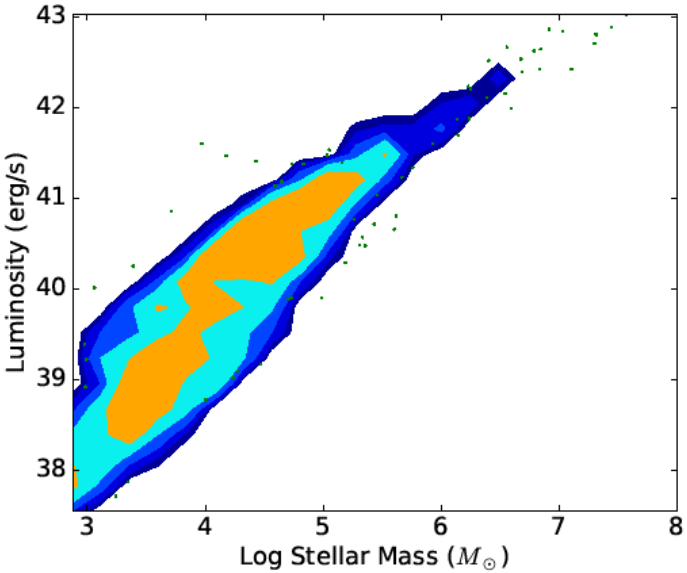


Sample of Galaxies

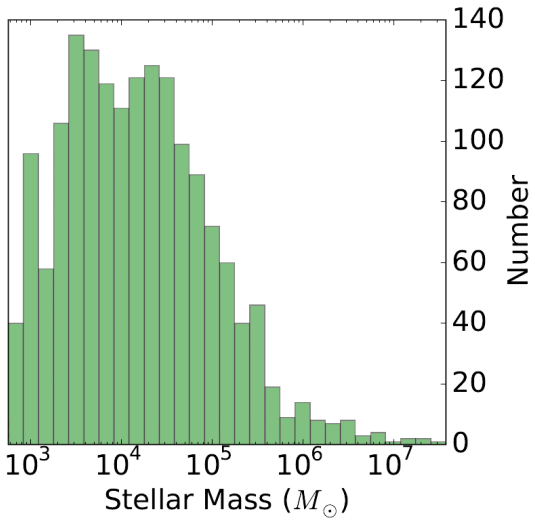


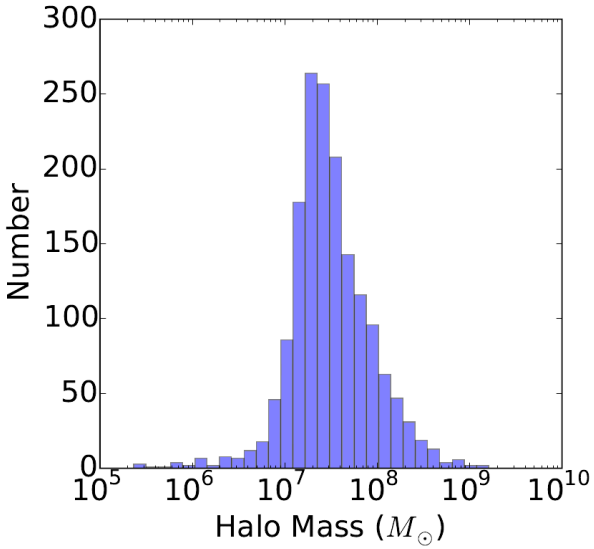


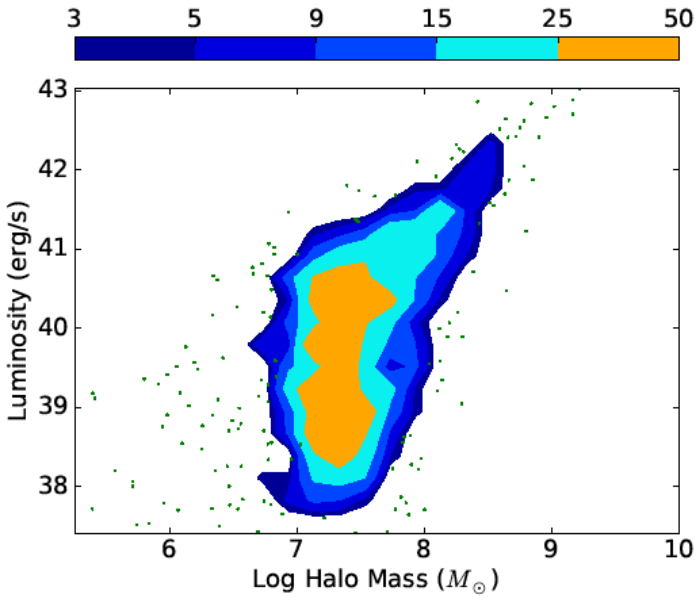


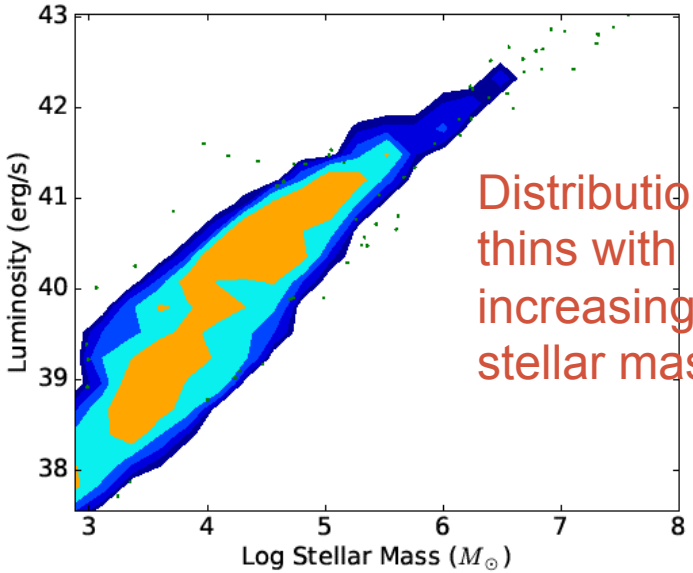


Sample of Galaxies



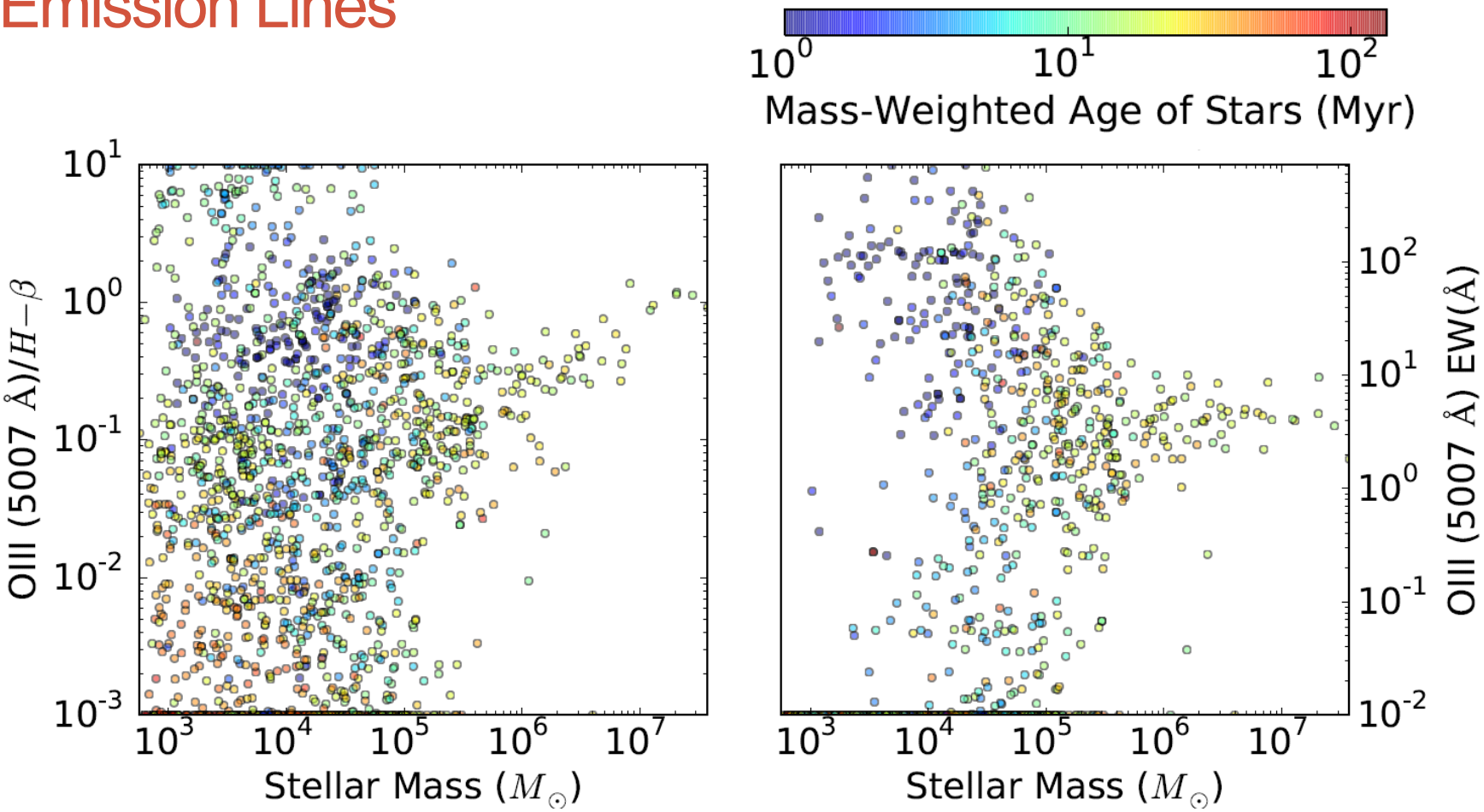




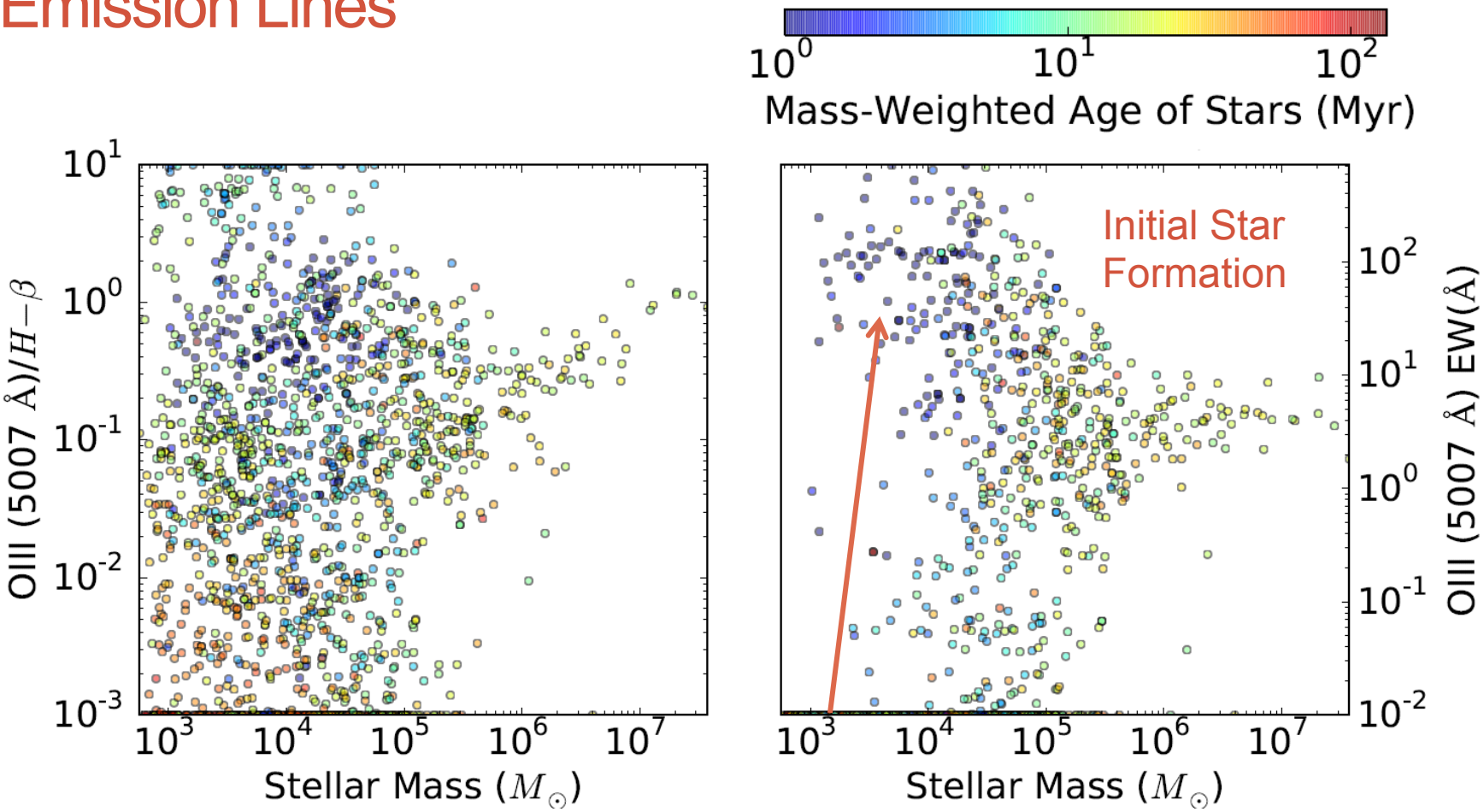


Distribution thins with increasing stellar mass.

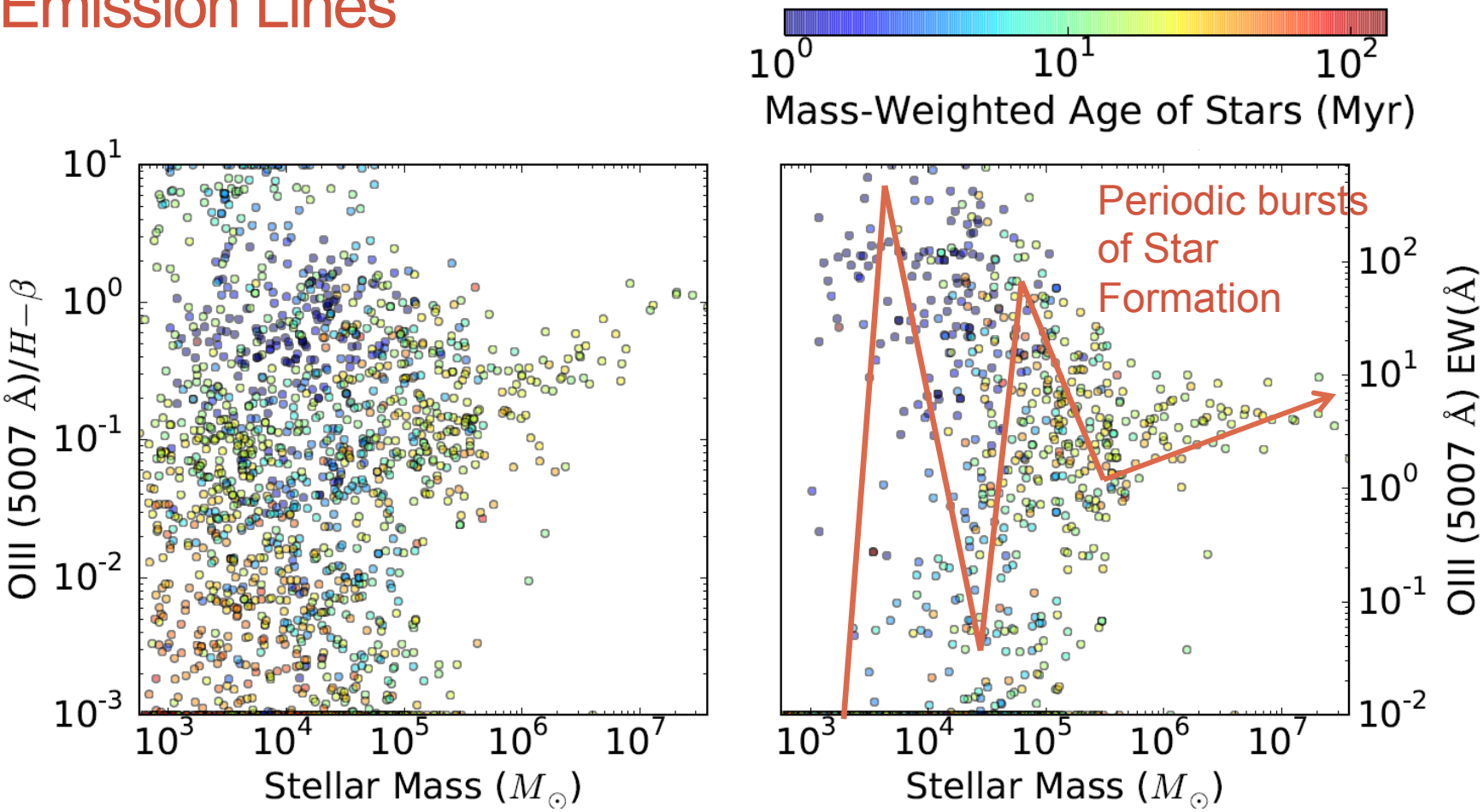
Emission Lines



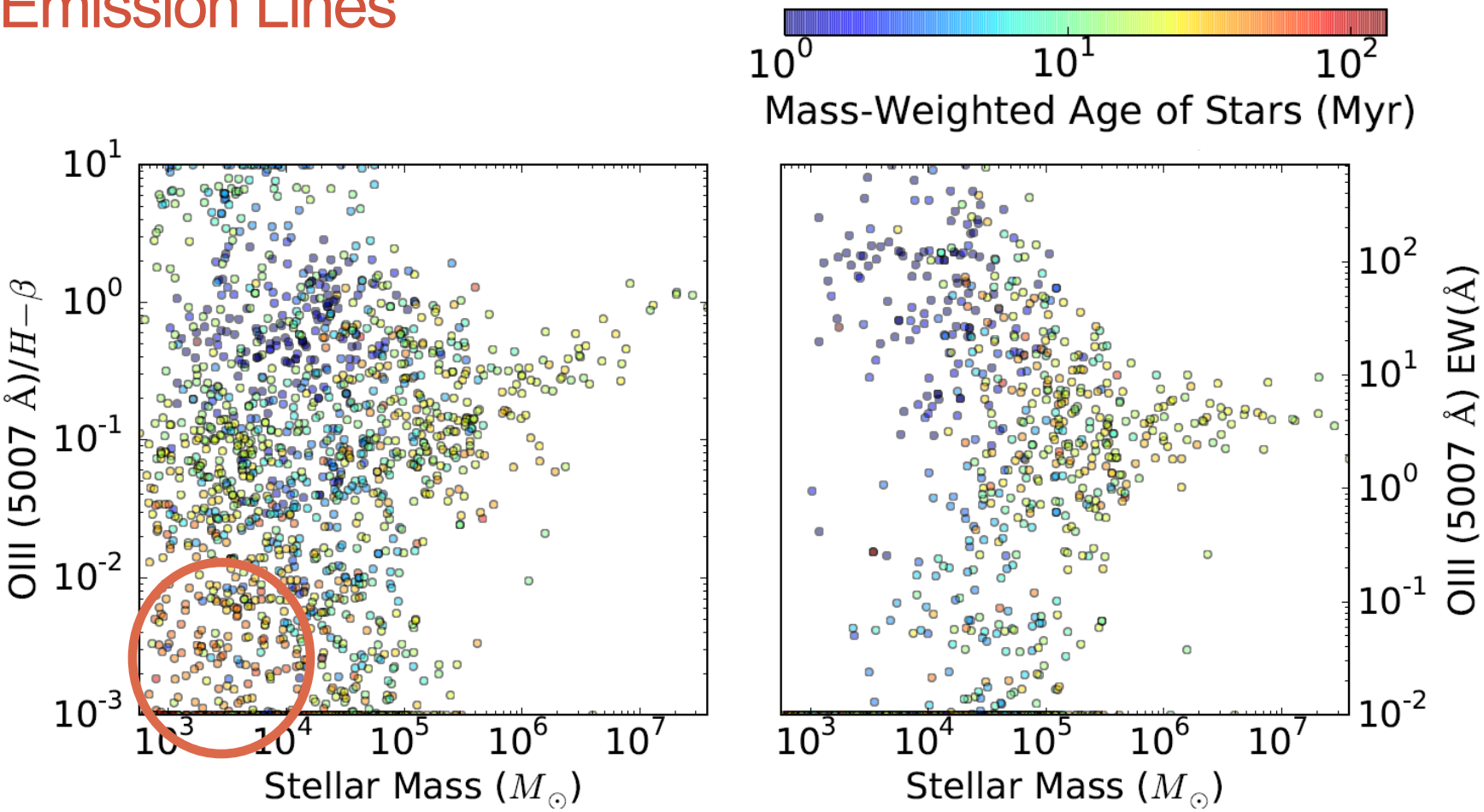
Emission Lines



Emission Lines

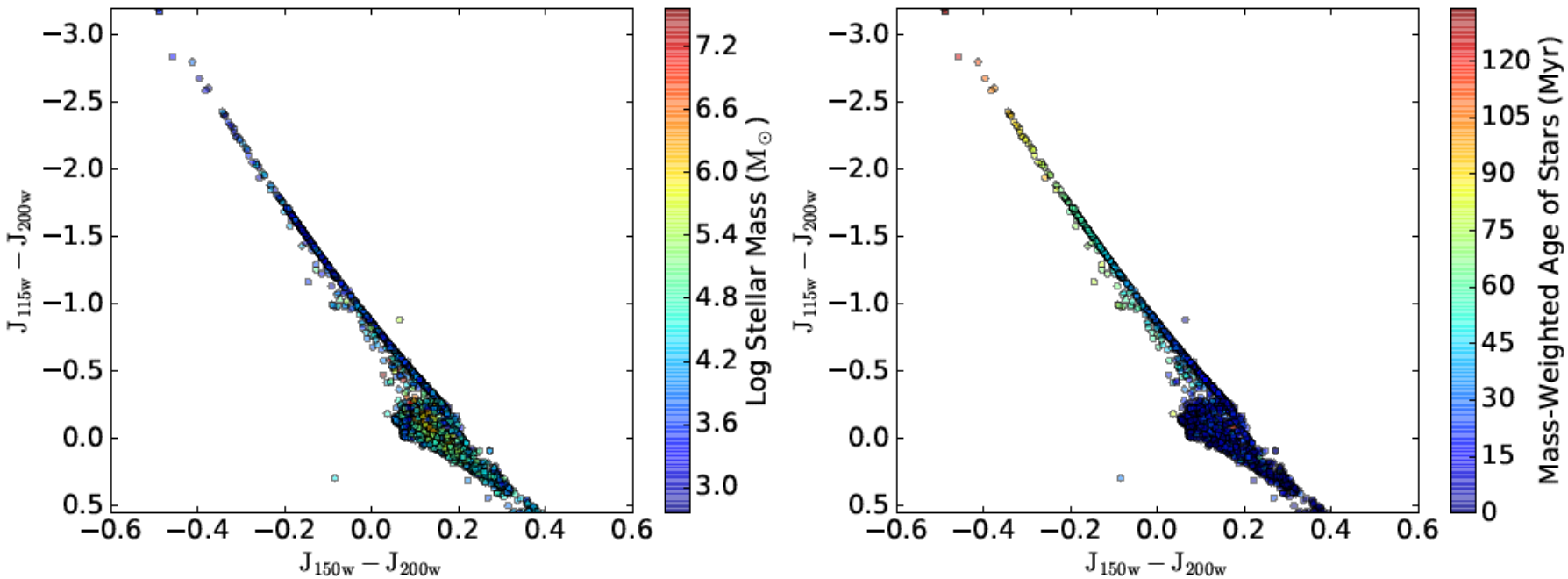


Emission Lines



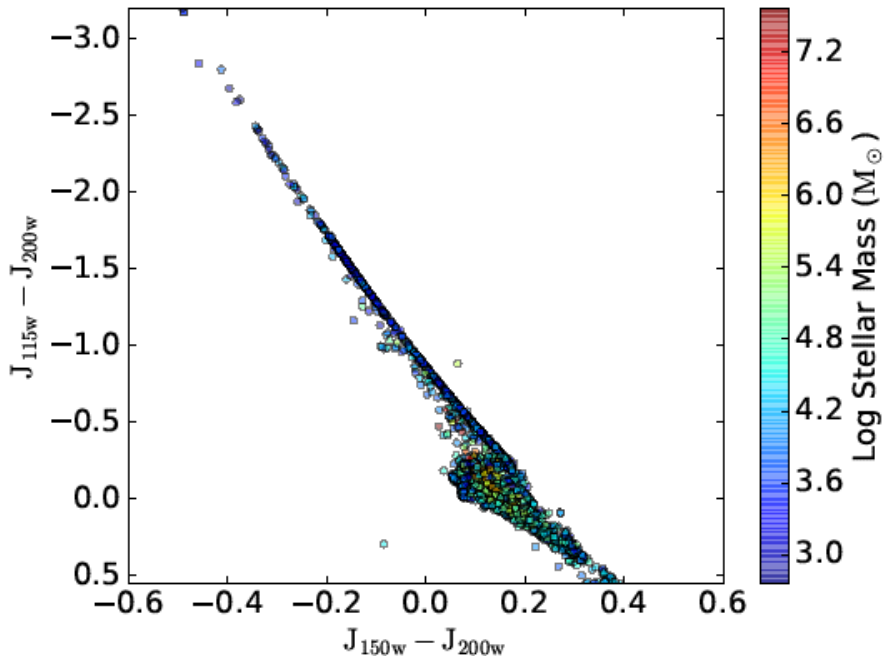
Halos with long intervals between periods of star formation

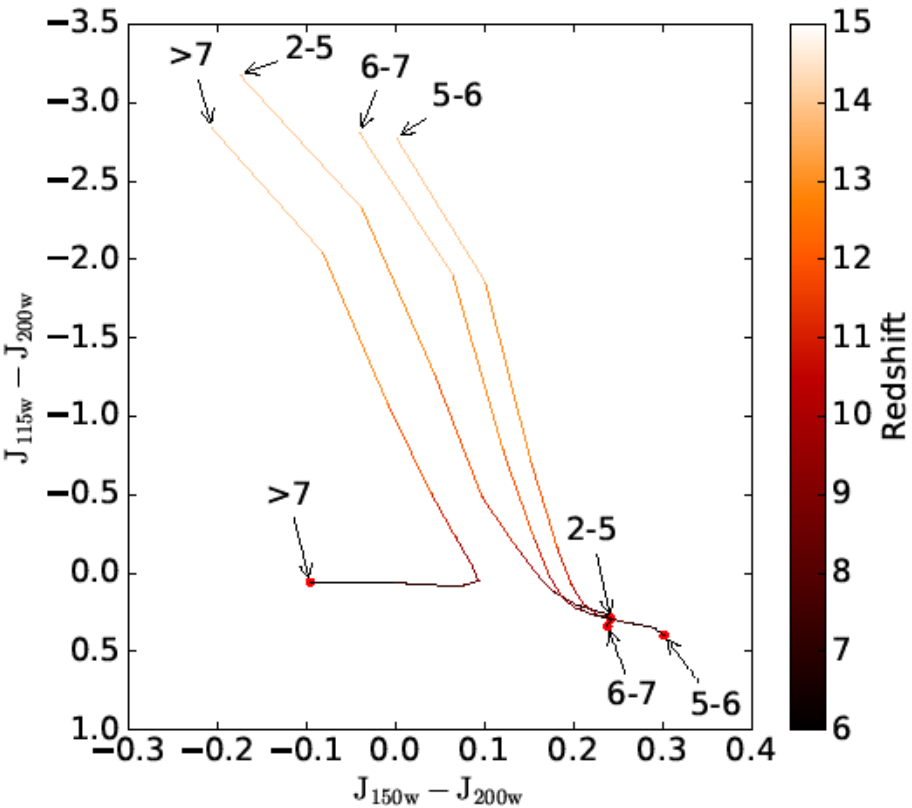
JWST Color-Color



Trends in color-color plots
of all halos using JWST

JWST Color-Color

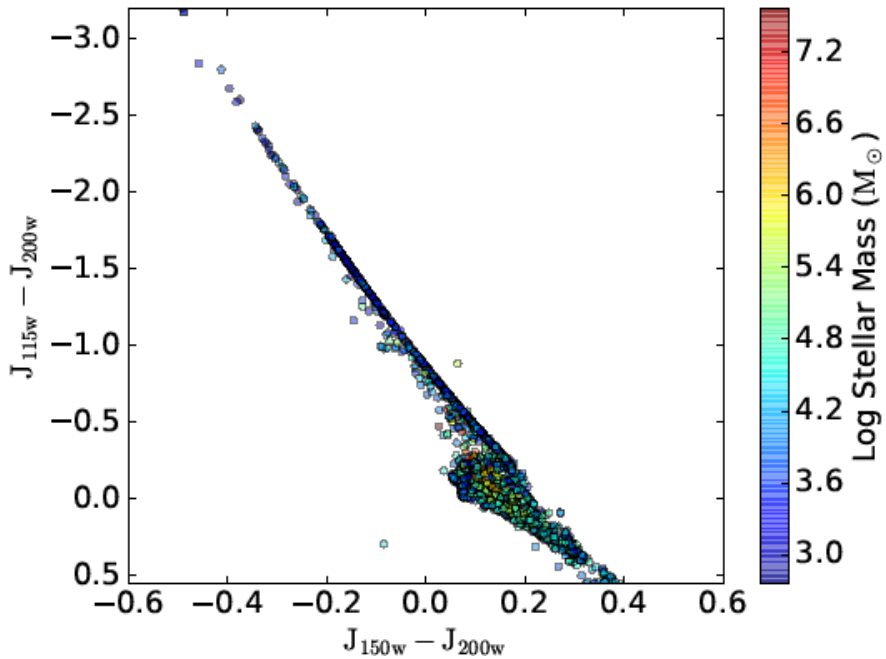


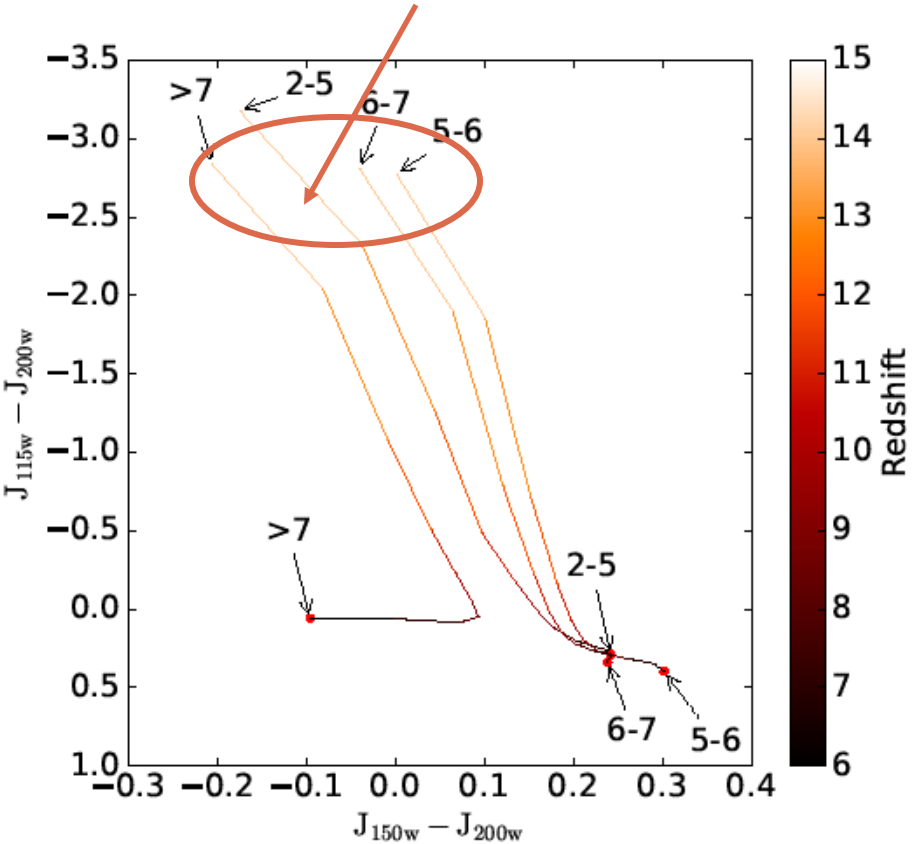


Colored with respect to log stellar mass

JWST Color-Color

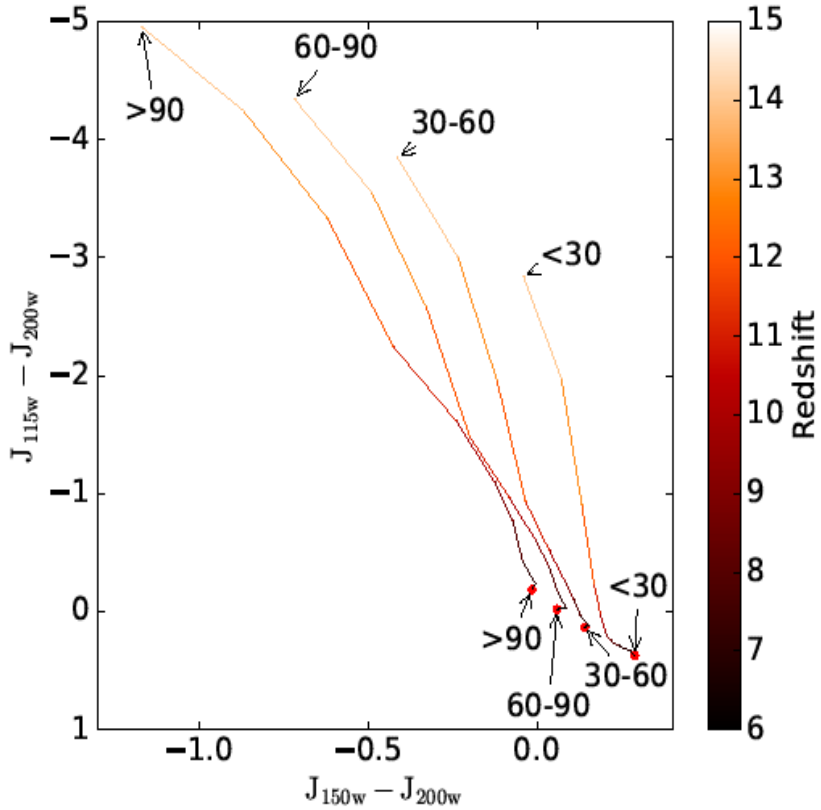
Small difference in mean color with respect to stellar mass bins

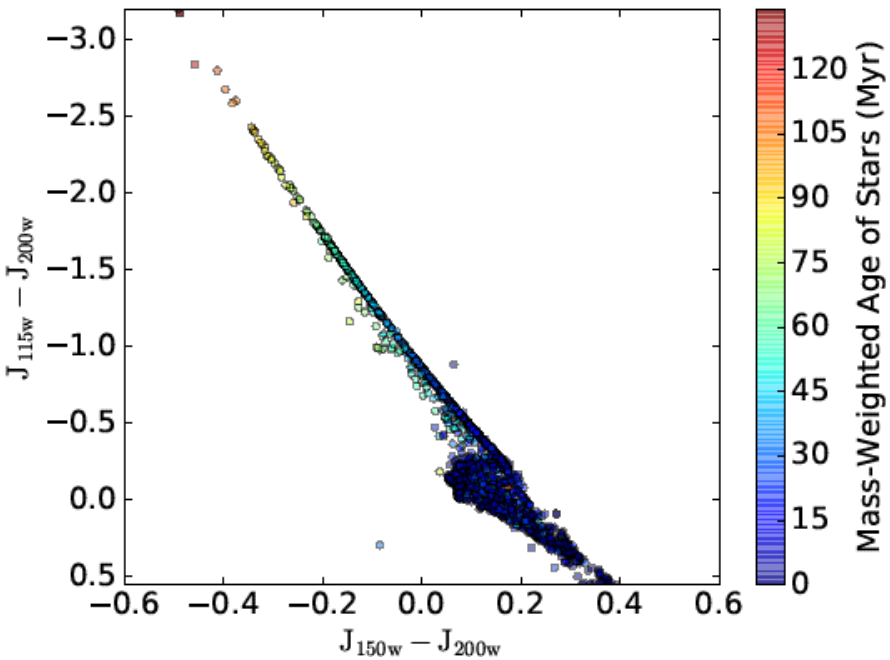




Colored with respect to log stellar mass

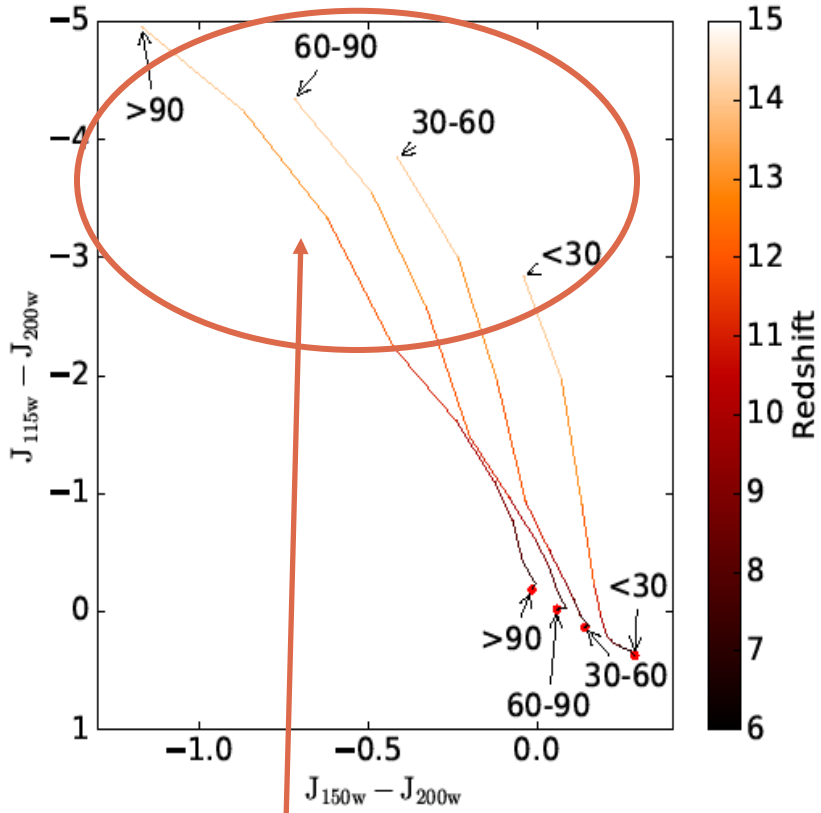
JWST Color-Color

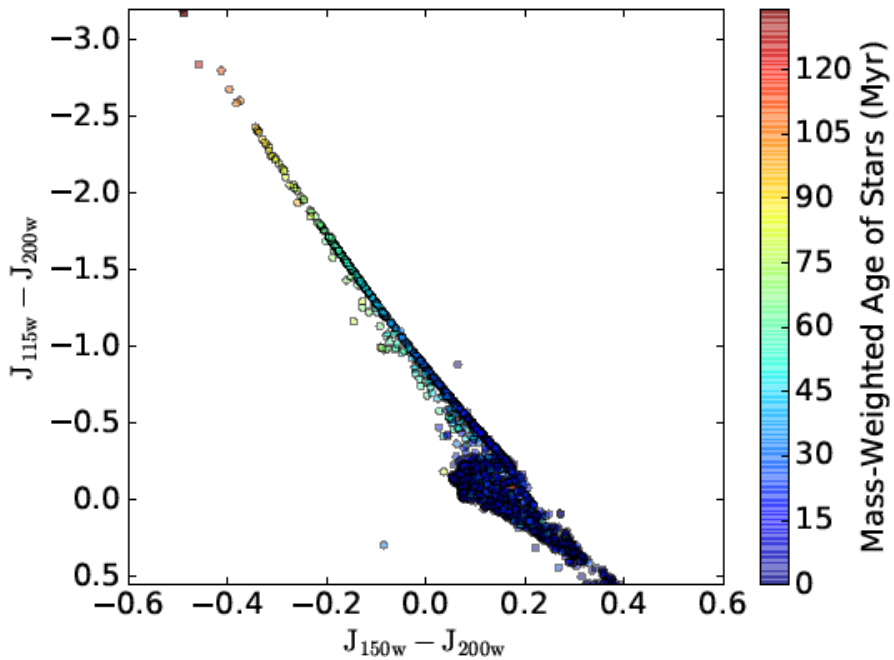




Colored with respect to mass-weighted stellar age

JWST Color-Color

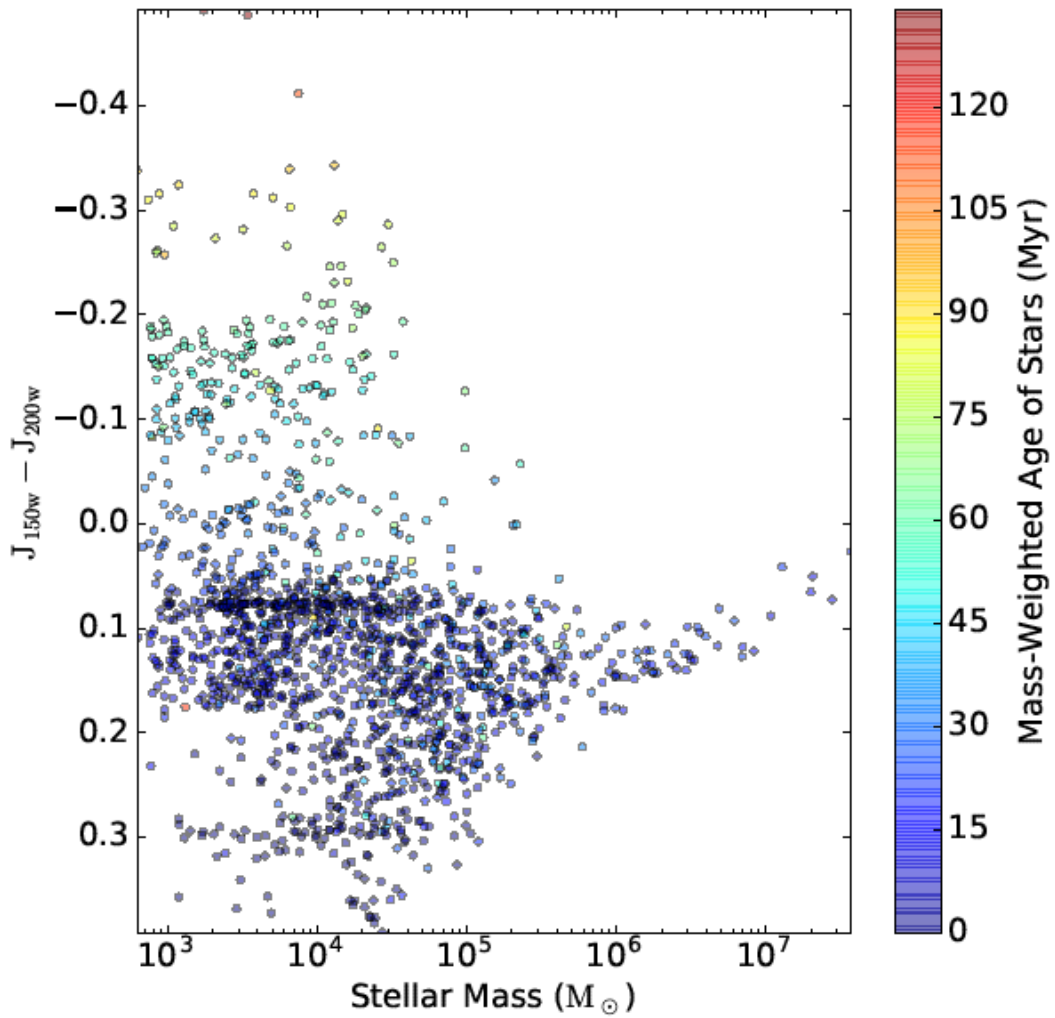




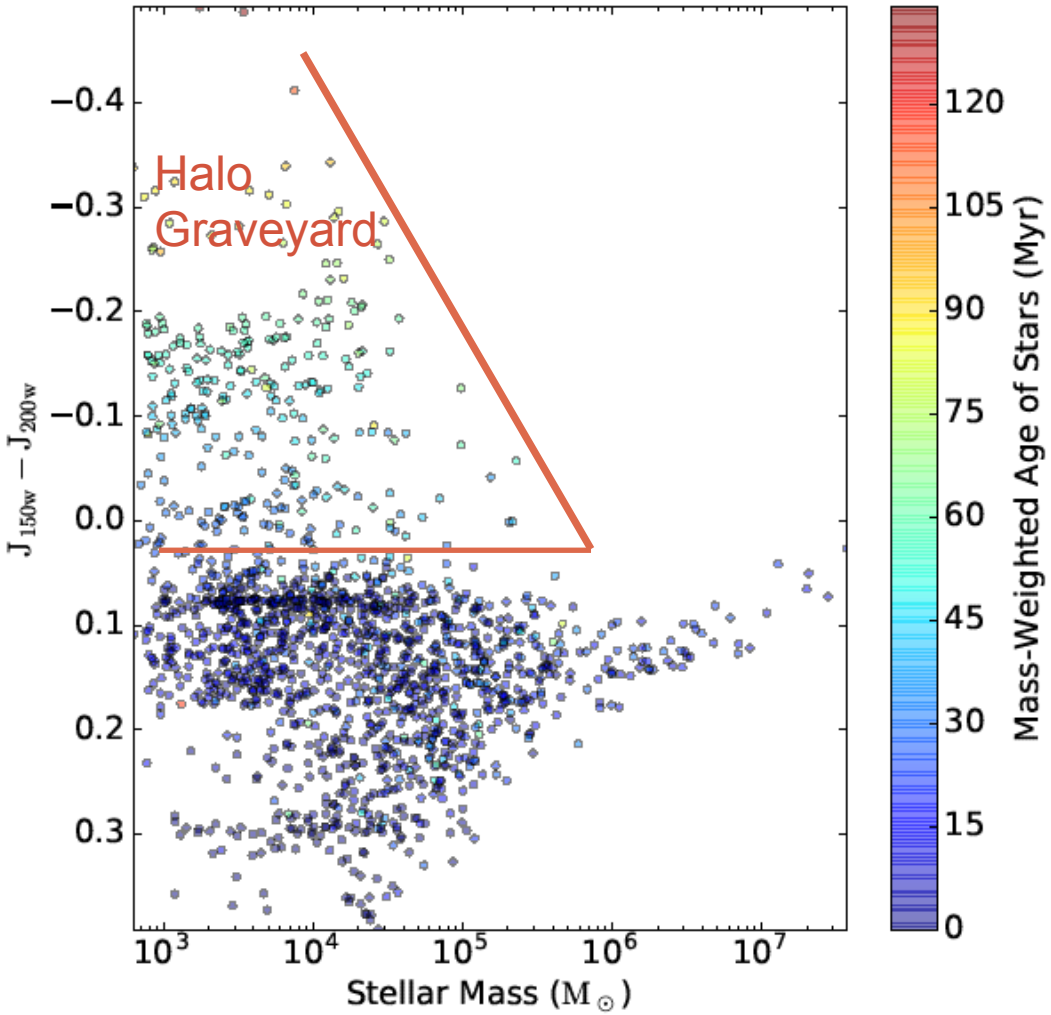
Large difference in color with respect to mean stellar age allowing color-color plots to act as tracers of both redshift and age.

Colored with respect to mass-weighted stellar age

JWST Color


−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
$J_{150w} - J_{200w}$
10^3
10^4
10^5
10^6
10^7
Stellar Mass ($M_\odot$)
120
105
90
75
60
45
30
15
0
Mass-Weighted Age of Stars (Myr)

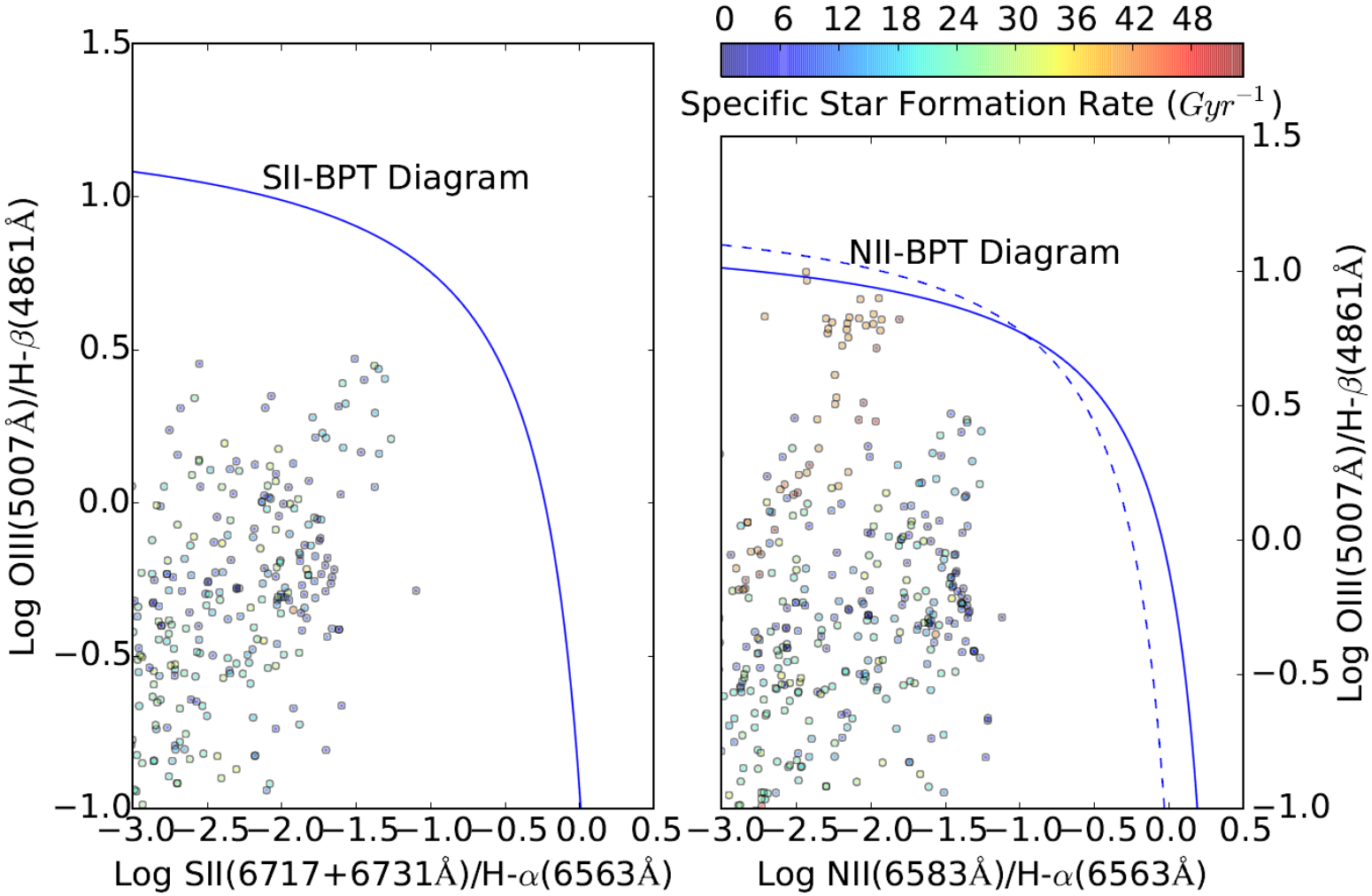
JWST Color


Halo
Graveyard
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
$J_{150w} - J_{200w}$
10^3
10^4
10^5
10^6
10^7
Stellar Mass ($M_\odot$)
120
105
90
75
60
45
30
15
0
Mass-Weighted Age of Stars (Myr)

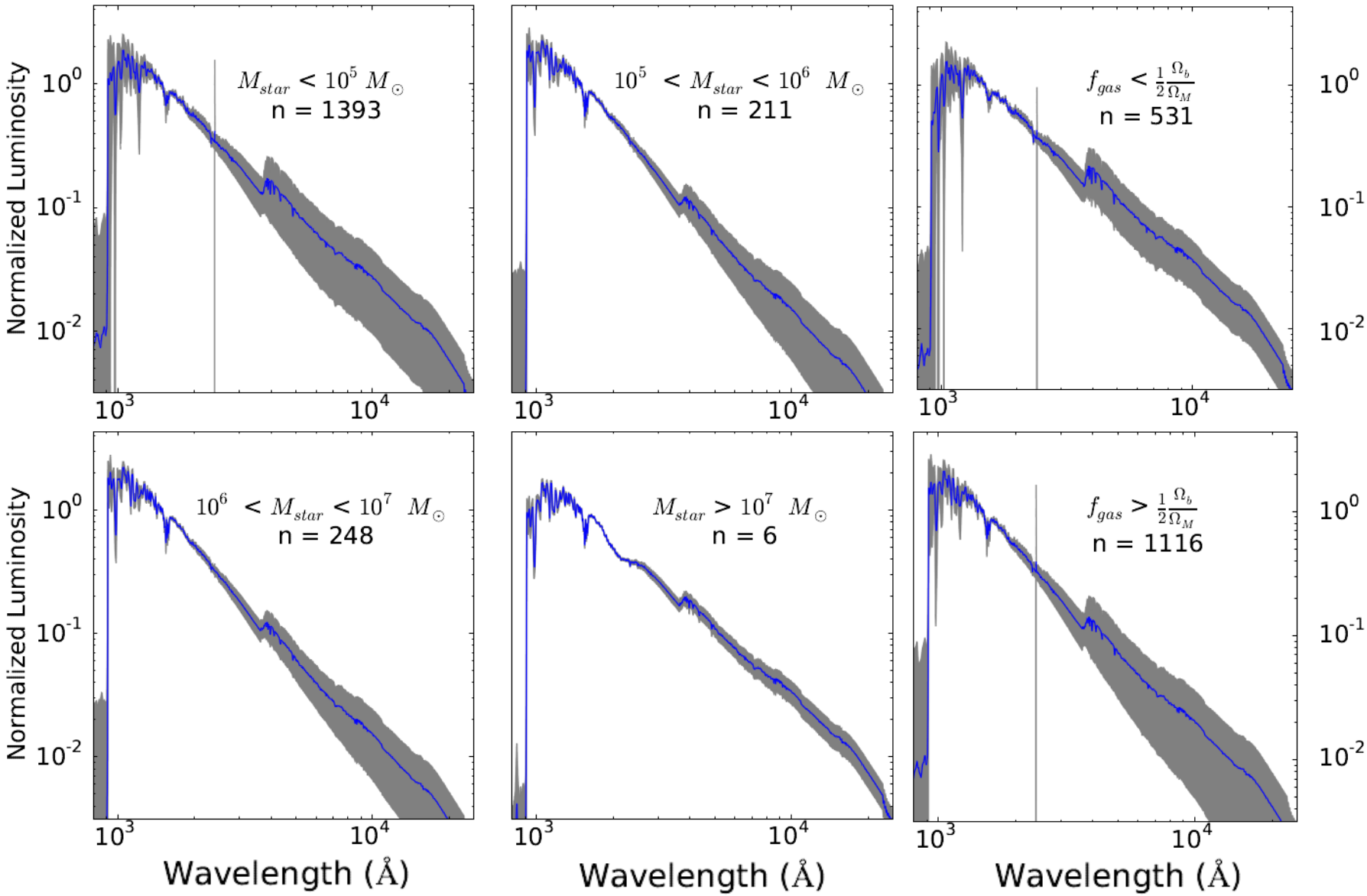
Summary

- Our method allows the creation of synthetic spectra and photometry from cosmological simulations
- Galaxies in our simulation that would be visible through JWST have as much as a half order of magnitude variation in total flux depending on orientation with respect to the telescope
- Plots of OIII show a “zig-zag” pattern for smaller halos as young stars heat up the gas and squelch new star formation periodically
- Color-color plots indicate a relationship between redshift, color, stellar mass, and mean stellar age

Emission Lines



Spectra


$M_{star} < 10^5\ M_\odot$
n = 1393
$10^5 < M_{star} < 10^6\ M_\odot$
n = 211
$f_{gas} < \frac{1}{2}\frac{\Omega_b}{\Omega_M}$
n = 531
$10^6 < M_{star} < 10^7\ M_\odot$
n = 248
$M_{star} > 10^7\ M_\odot$
n = 6
$f_{gas} > \frac{1}{2}\frac{\Omega_b}{\Omega_M}$
n = 1116
Normalized Luminosity
Wavelength (Å)
10^0
10^{-1}
10^{-2}
10^3
10^4