Physical and Observable Predictions for the First Galaxies

John Wise

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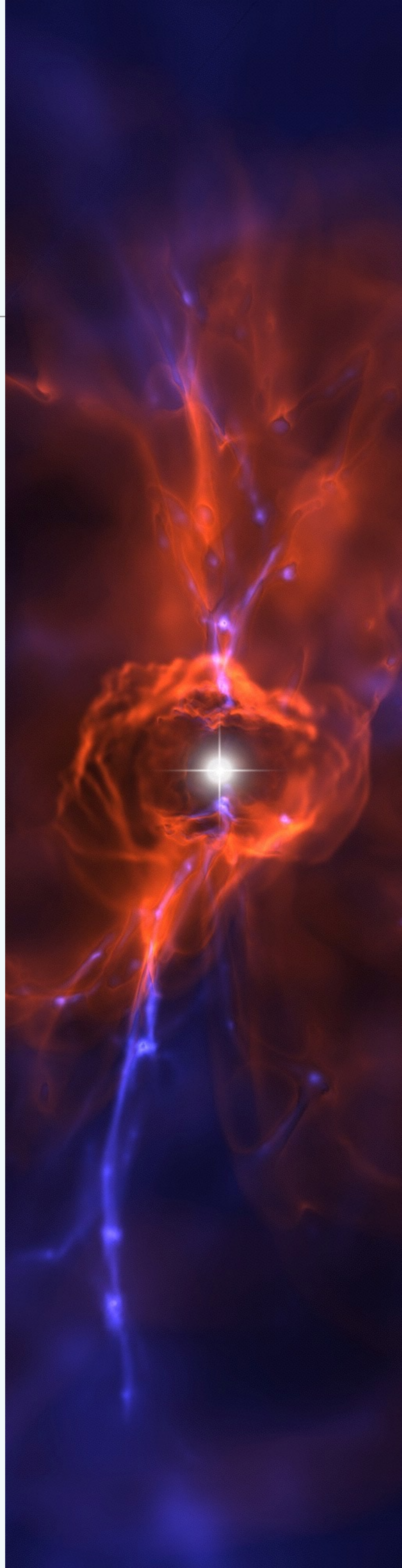
Outline

- **Radiation hydrodynamics simulations of the First Stars and Galaxies ($z \geq 7$)**
  - **“Birth of a Galaxy” simulation (30 galaxies; boxsize = 1 Mpc)**
    - Star formation histories, galaxy properties, reionization, and luminosity functions
    - Wise et al. (2012ab, 2014)
  - **“Renaissance” simulation (3000 galaxies; boxsize = 40 Mpc)**
    - Remnants from the first stars, galaxy properties, luminosity functions – investigated in three zoom-in different environments
    - Xu et al. (2013, 2014); Chen et al. (2014); Ahn et al. (2015); O’Shea et al. (2015), Xu et al. (2016ab)
  - **Synthetic observations of the Renaissance Simulation**
  - **Magnetic field amplification around the first stars**



Birth of a Galaxy

Numerical Approach
Rad-hydro Cosmological Simulations

enzo-project.org

- Requirements:
  - Follows the high-z formation of a galaxy in a ~10^9 $M_\odot$ halo ($M_\star \sim 10^{6-7}$ $M_\odot$)
  - Resolves the smallest (Pop III) star-forming mini-haloes ($M \sim 10^5$ $M_\odot$)
  - Accurate model of star formation and feedback – smaller halos are more susceptible to feedback effects.

- Approaches:
  - Small-scale box (1 comoving Mpc^3); 1840 $M_\odot$ DM resolution
  - Adaptive mesh refinement (AMR) – 1 comoving pc maximal resolution
  - Distinct modes of Population II and III star formation and feedback
  - Coupled radiation transport and supernovae feedback from both populations

Solar Superstorms

visualization excerpt

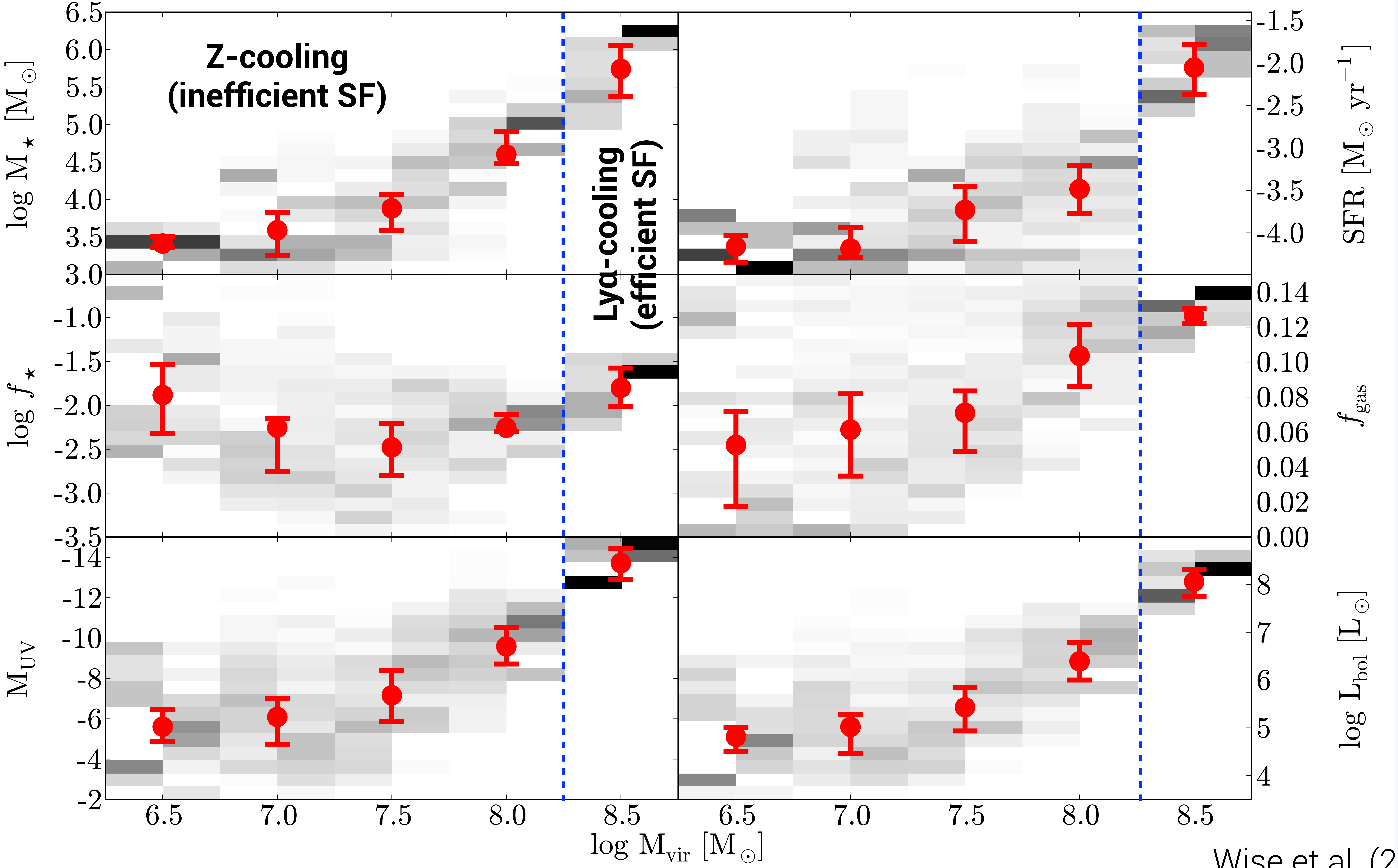
"The Formation of First Stars and Galaxies"

a fulldome production by

NCSA, University of Illinois
Thomas Lucas Productions & Spitz Creative Media

narrated by:
Benedict Cumberbatch

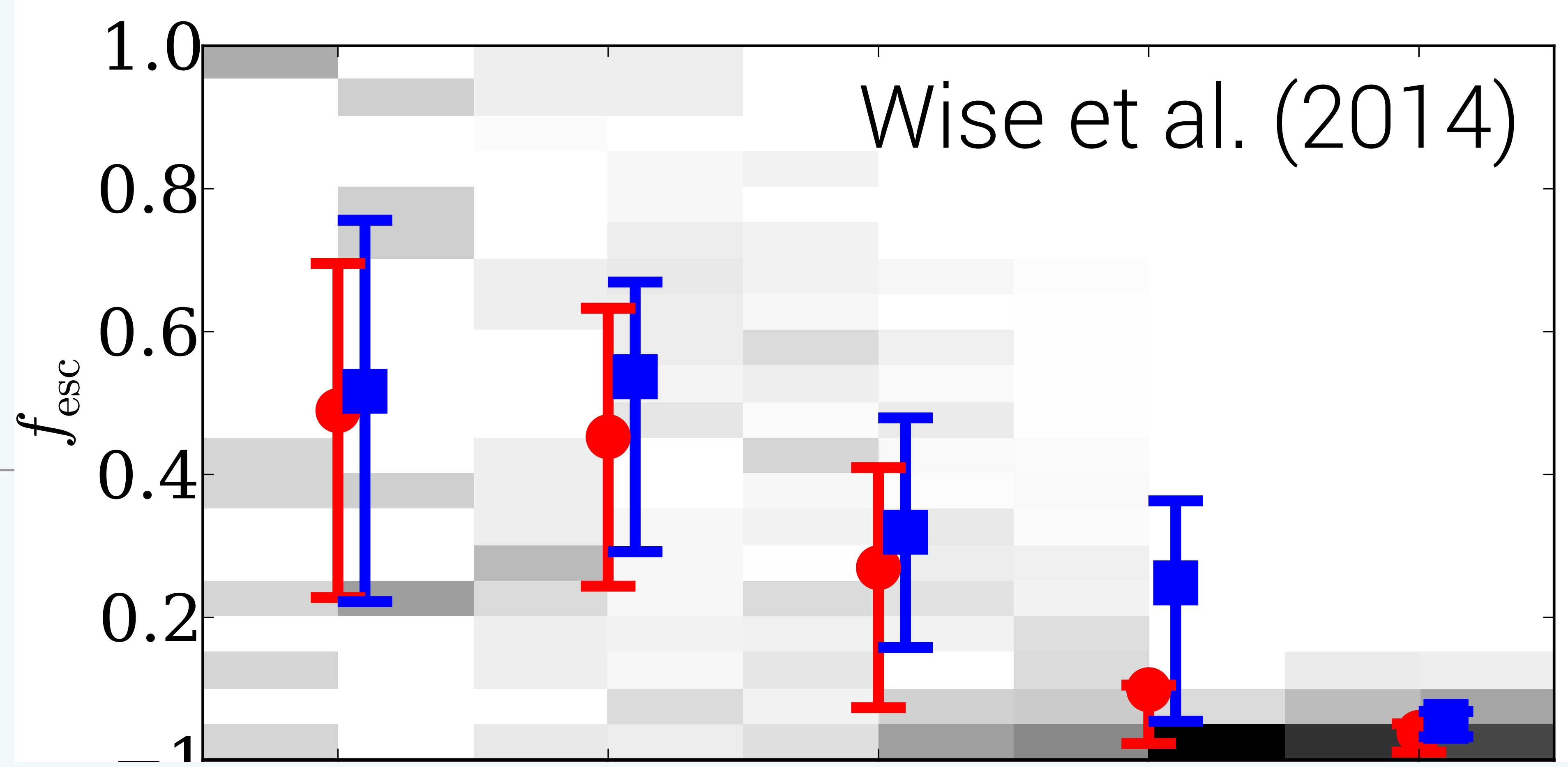
First Galaxy Properties at z>7

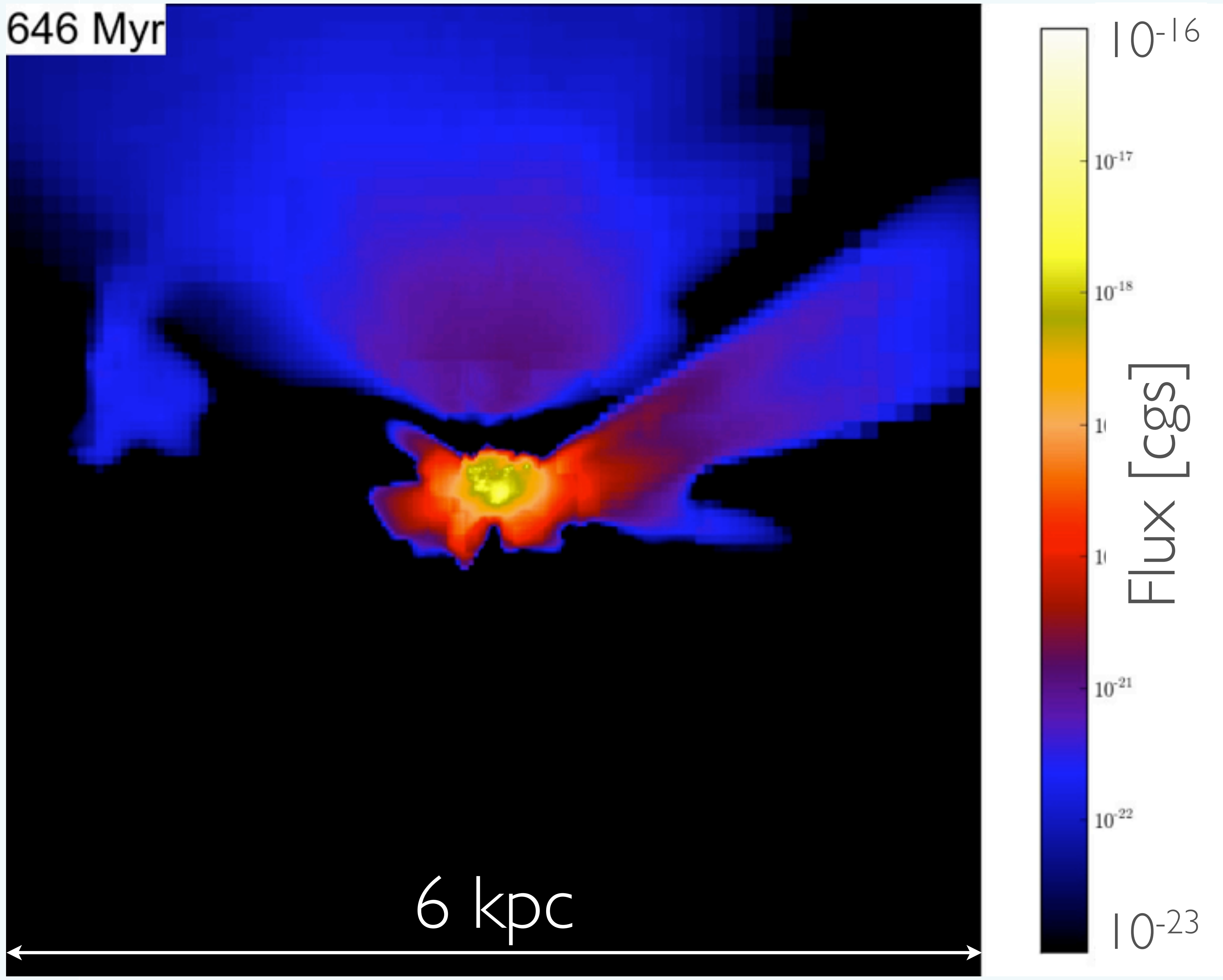


Wise et al. (2014)

UV Escape Fractions

- Red: non-weighted mean
- Blue: luminosity-weighted mean
- Halos with M ≤ 10^8 $M_\odot$ contribute the most to the ionizing photon budget when $x_i < 0.5$.
  - High escape fractions
  - Able to form stars even without atomic cooling, i.e. T < 10^4 K.
- Escape fractions are highly variable.



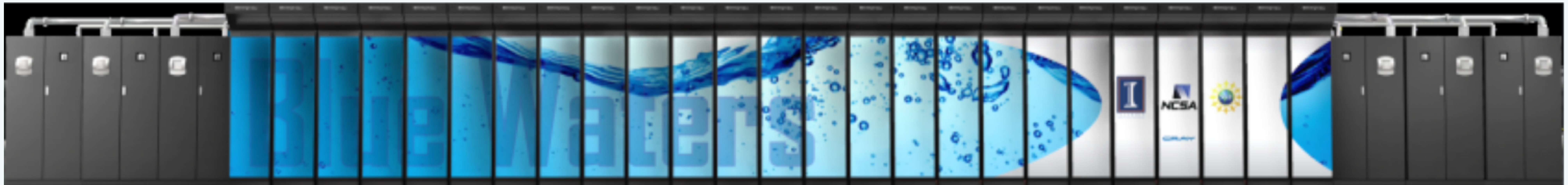


Renaissance Simulations

The First Galaxies
Renaissance Simulations

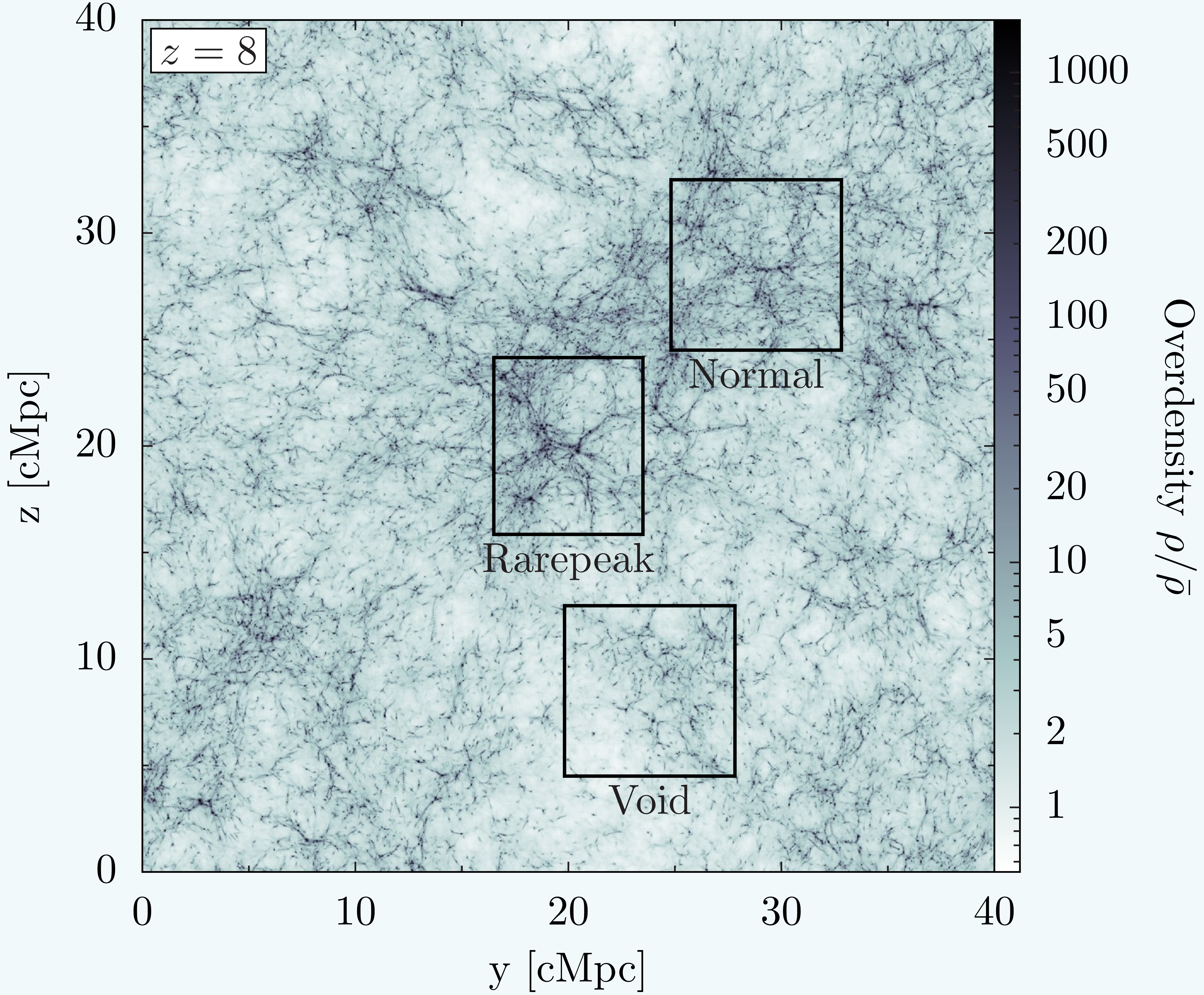
Xu, JW, Norman (2013)
Xu et al. (2014)
Chen, JW, et al. (2014)
Ahn et al. (2015)
O'Shea, JW, et al. (2015)
Xu, JW, et al. (2016ab)

- Follow three regions ("rare peak", mean, void) until z = 15, 12, 8 (respectively).
  - 40 comoving Mpc box, 5 comoving Mpc zoom-in region
  - DM particle mass: 29,000 $M_\odot$
  - Maximal spatial resolution: 19 comoving pc
- At z = 15 in the rare peak region, there are
  - Three >10^9 $M_\odot$ DM halos; >13,000 Pop III stars
  - ~3 x 10^8 $M_\odot$ of Pop II stars in ~1,000 dwarf galaxies



The First Galaxies

Renaissance Simulations



Xu, JW, Norman (2013)
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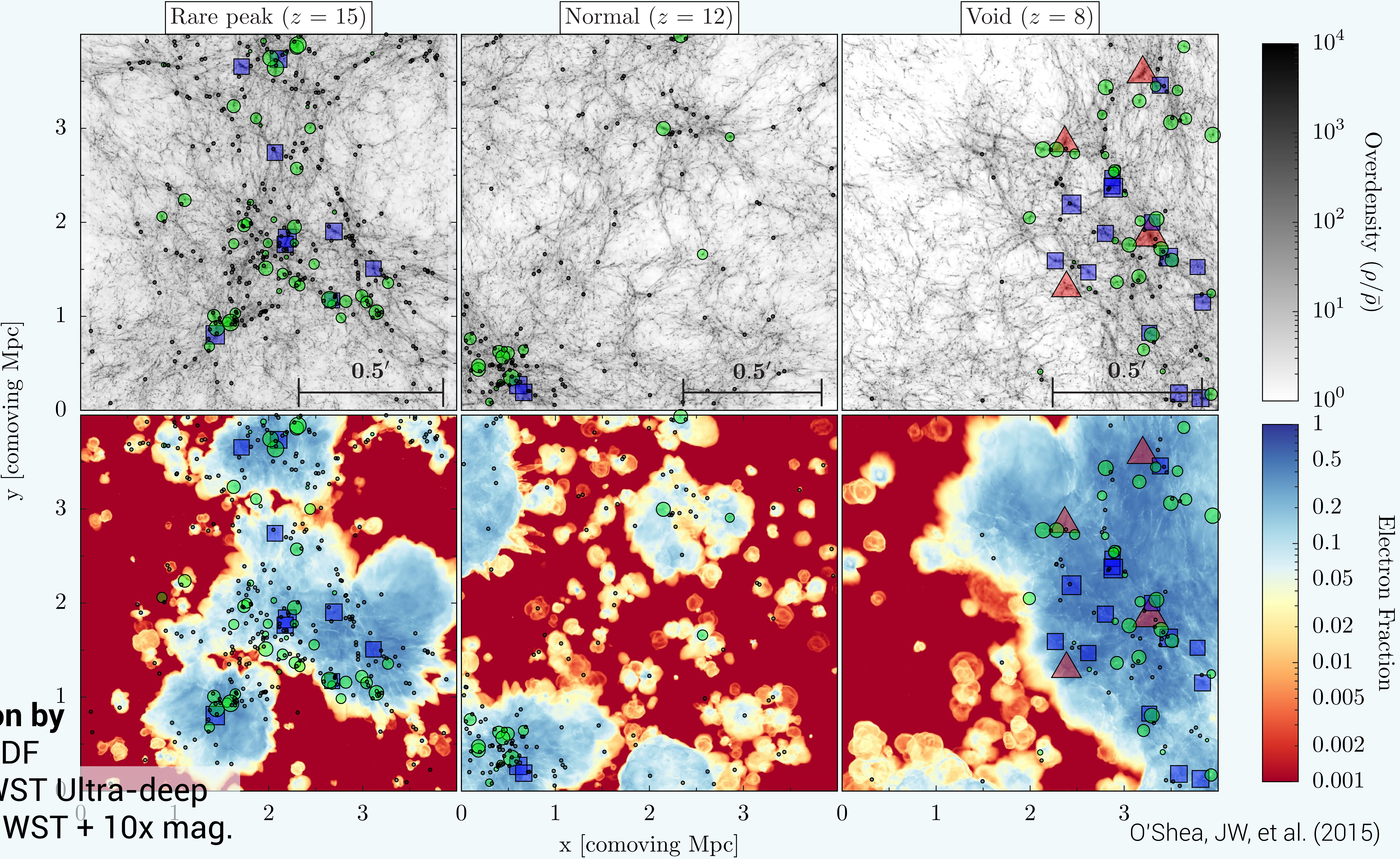
Ahn et al. (2015)
O'Shea, JW, et al. (2015)
Xu, JW, et al. (2016ab)

Flying through the Rare Peak at z = 15

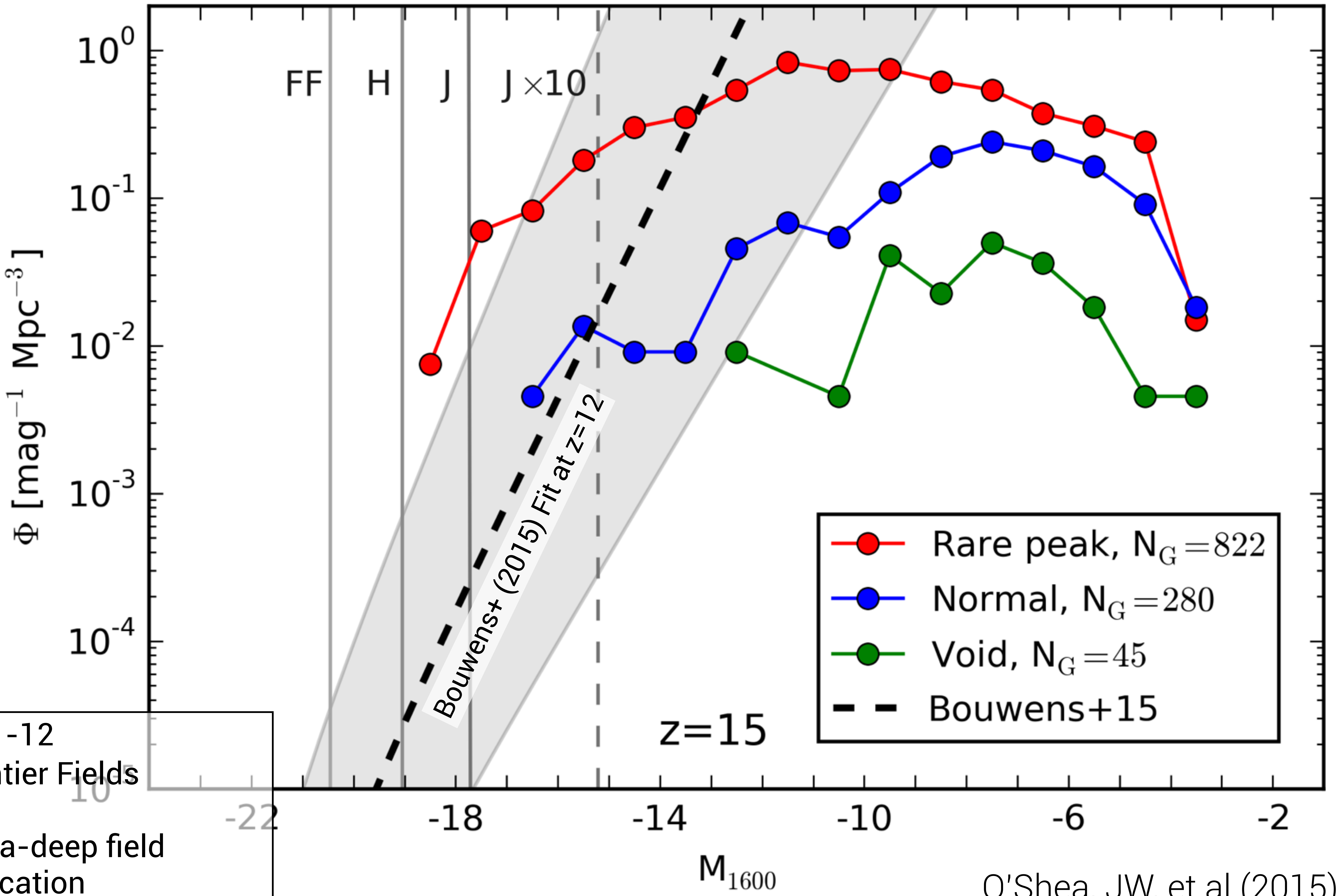
Blue / Red / White → HI / HII / UV Flux



Detection by
Red: HUDF
Blue: JWST Ultra-deep
Green: JWST + 10x mag.

O'Shea, JW, et al. (2015)

Renaissance Simulations
Luminosity Functions

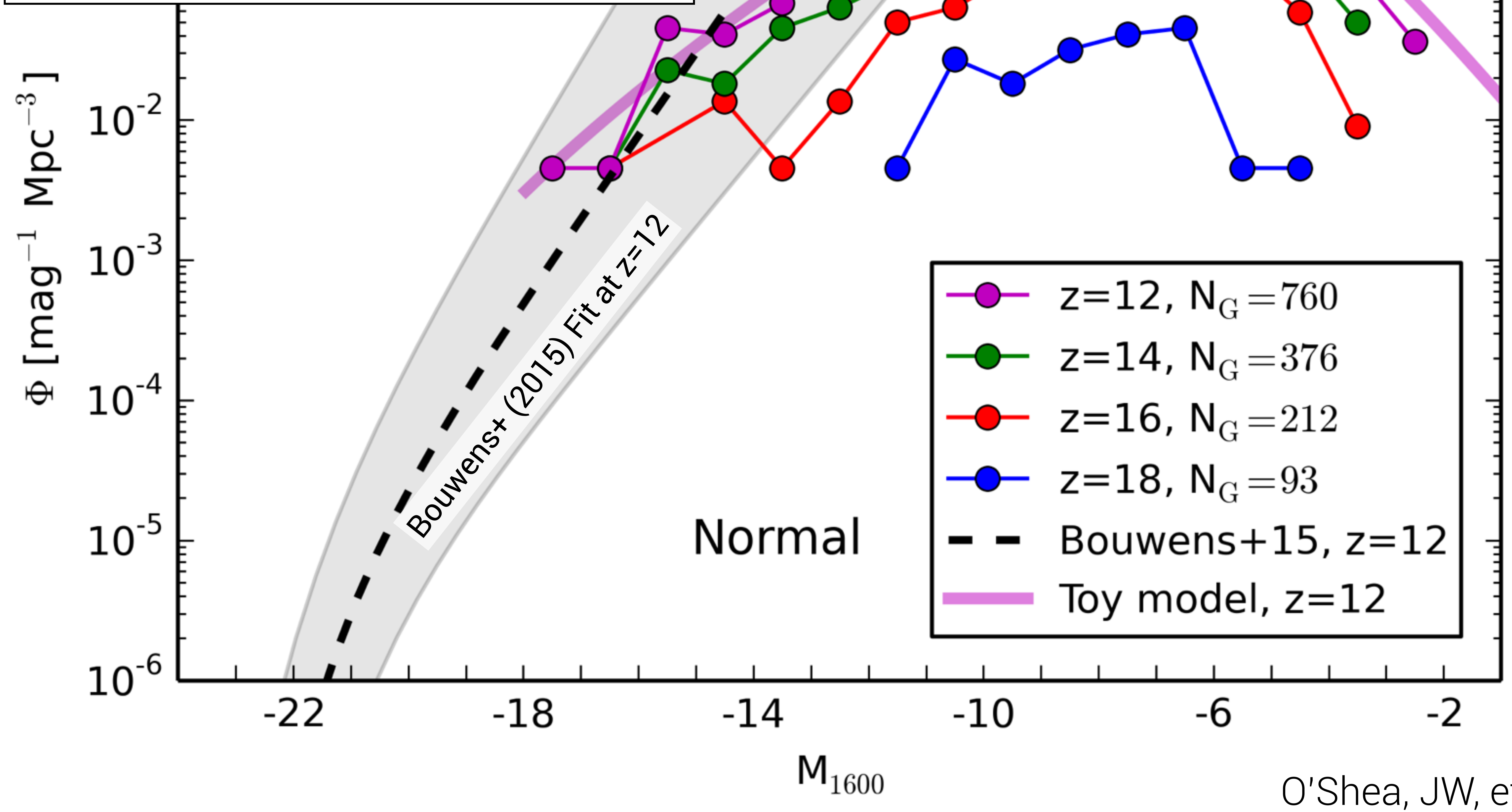


- Flattening at $M_{UV} \gtrsim -12$
- FF = Unlensed Frontier Fields
- H = Hubble XDF
- J = JWST 10^5 s ultra-deep field
- Jx10 = 10x magnification

O'Shea, JW, et al (2015)

Renaissance Simulations
Luminosity Functions

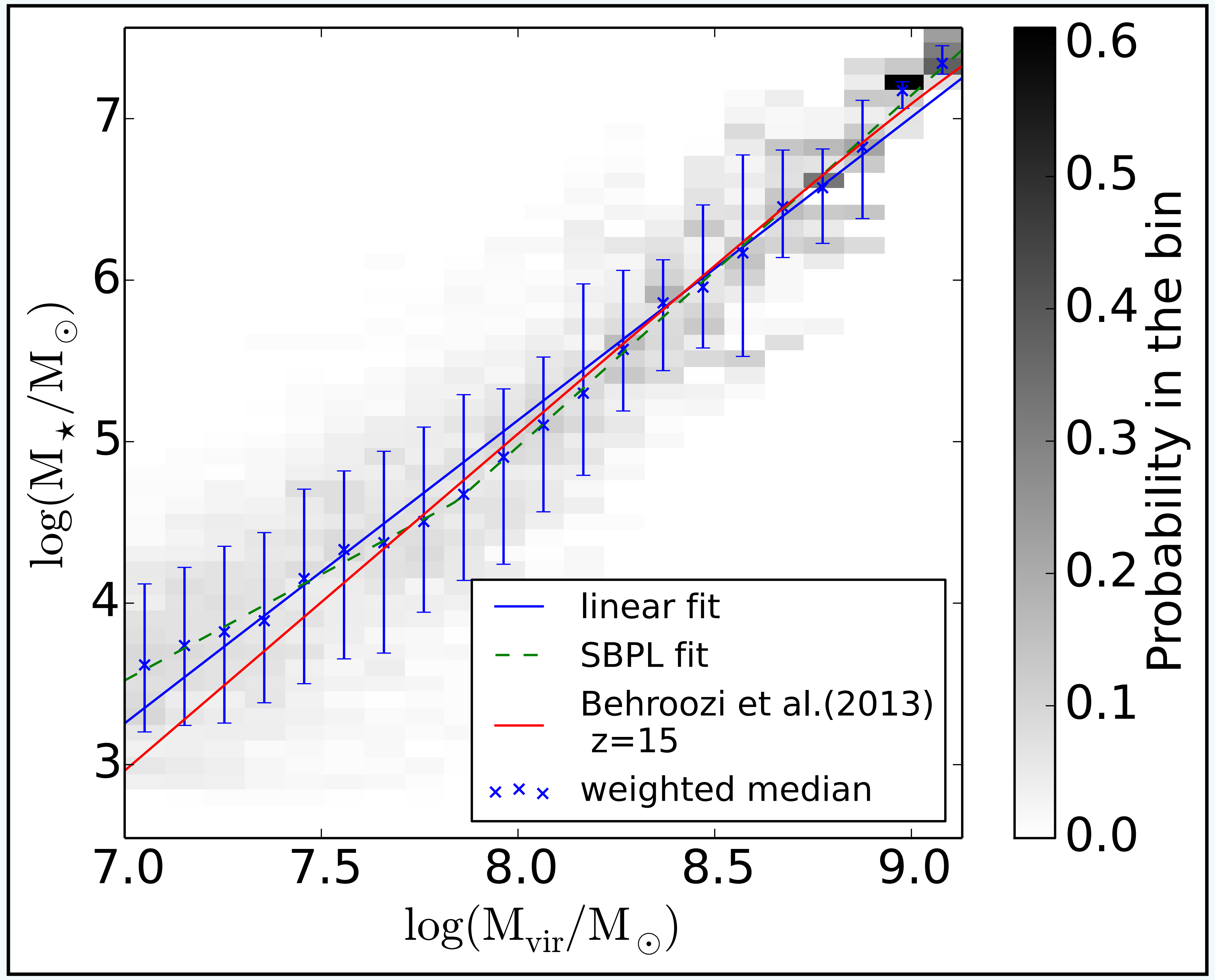
- Flattening at $M_{UV} \gtrsim -12$
- Strong evolution during galaxy assembly
- Toy model uses Behroozi+ (2013) model with a halo-galaxy occupation fraction from the simulation

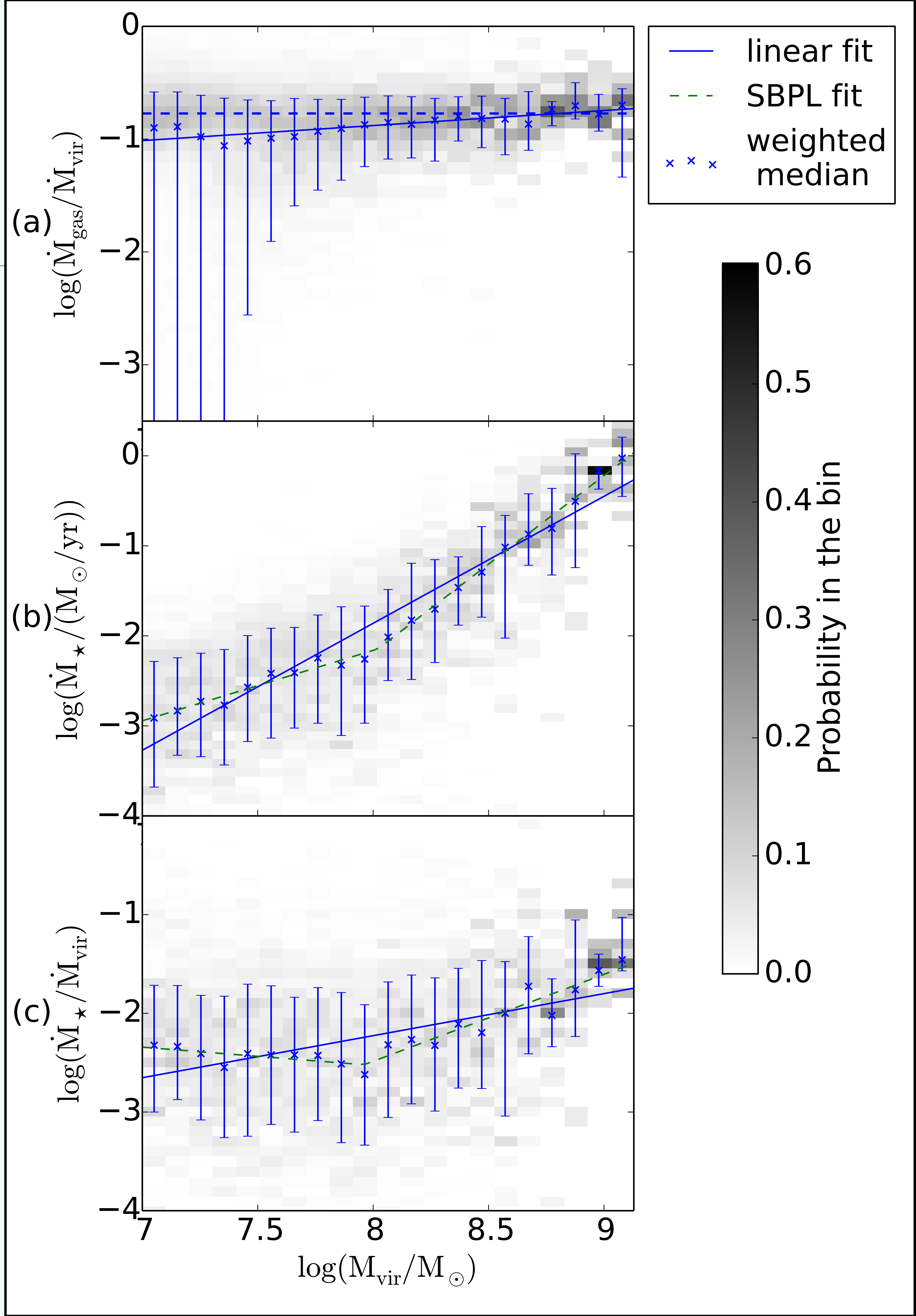


O'Shea, JW, et al (2015)

Renaissance Simulations
High-z Galaxy-Halo Relations

Chen, JW, et al. (2014)
Xu, JW, et al. (2016)



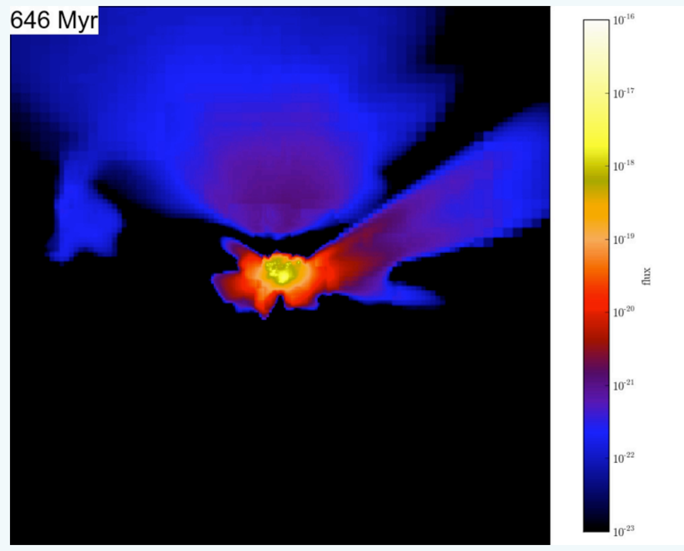


Distinction between metal-cooling halos (uFd progenitors?) and atomic cooling halos.

But how do we relate these models with observables?

But how do we relate these models with observables?

Chen, JW, et al. (2014)
Xu, JW, et al. (2016)



Barrow, JW, et al. (in prep)

The First Galaxies
A Pipeline for Mocking the Simulations

- **Stellar spectra:** Uses FSPS (Conroy+ 2010) from simulated stellar data (star particle resolution = 1000 $M_\odot$)
- **Nebular emission:** Use simulated AMR gas data (density and metallicity) and the FSPS stellar spectrum to generate nebular emission maps with Cloudy (Ferland+ 2013)
- **Dust/Gas Extinction:** Use intrinsic spectra and process them through the Monte Carlo ray-tracing code Hyperion (Robitaille 2011).
  - Trace the rays to the halo's virial radius in 8000 frequencies from 500 Å to 5 μm.
  - Use the Draine (2003) dust model that is scaled with metallicity.

See Kirk Barrow's Poster (#9)

What about magnetic fields?

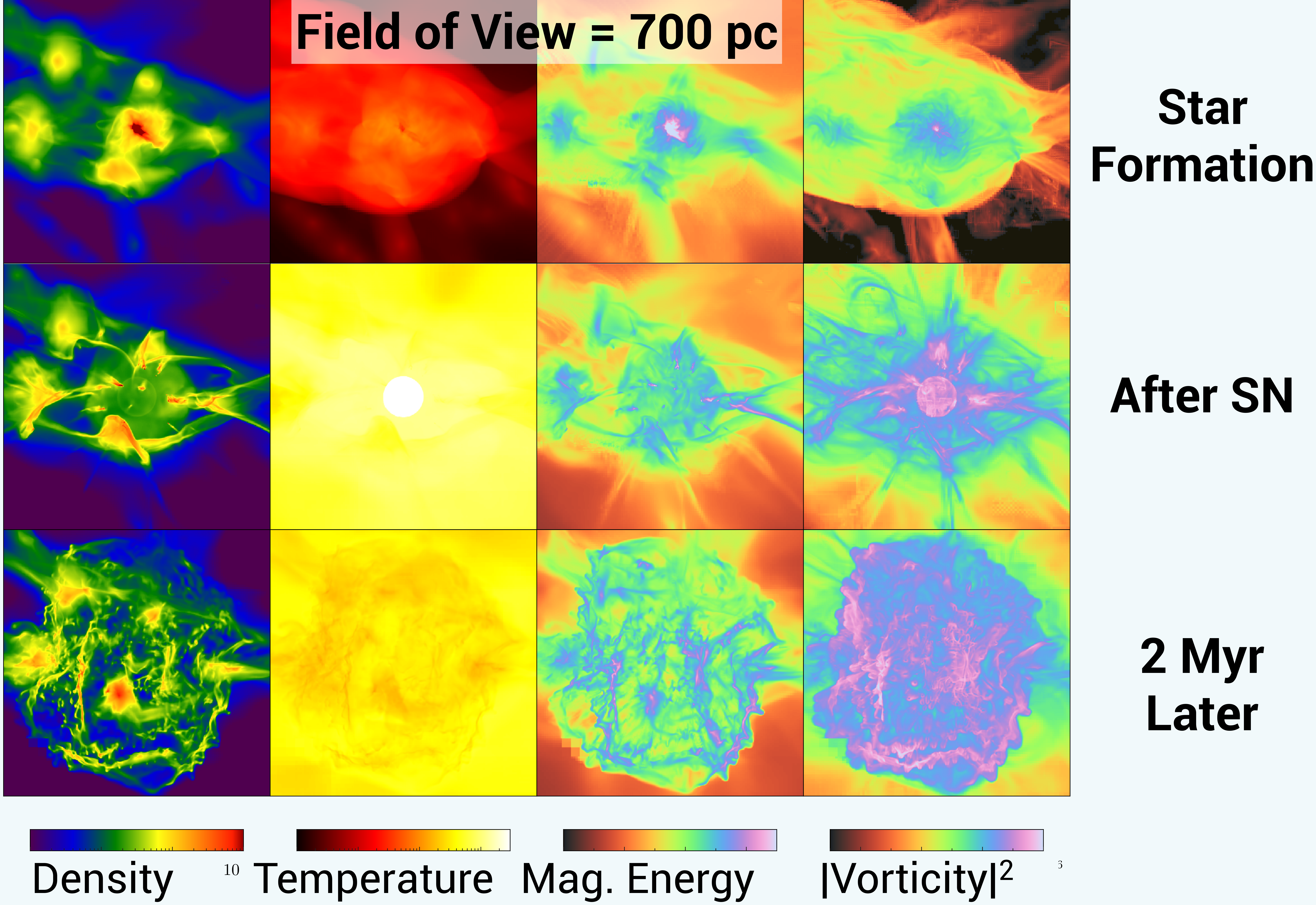
What about magnetic fields?
Amplification from the first stars and their SNe

- Rad-MHD simulation of a Pop III star
- 500 comoving kpc/h box
- DM particle mass: 14 $M_\odot$
- Maximal spatial resolution: 30 AU @ z=15
- Resolve the Jeans mass by ≥64 cells
- Amplification through dynamo processes
- Follow one 40 $M_\odot$ Pop III star and its CCSN (10^{51} erg)
- Three cases: $\mathbf{B}_{0,\mathrm{comoving}}$ = 0, 10^{-14}, 10^{-10} G

Motivation

How is the IGM magnetized?

What are the magnetic field strengths in the first galaxies?



Koh & JW (submitted)

Summary

- Halos below the atomic cooling limit ($T_{vir} < 10^4$ K) can cool through metal-line transitions and form stars inefficiently.
- These low-mass halos can have high UV escape fractions up to 50%.
- Galaxy UV luminosity function flattens at $M_{1600} \geq -12$

- Mocking these simulation results into various observable predictions and diagnostics (Grad student: Barrow).
- Turbulence in SN remnants amplify early magnetic fields (Grad student: Koh).
- Data (~100 TB) will become fully public in the near future through the National Data Service (NDSLabs, led by Matthew Turk at NCSA).