The Impact of Feedback Processes on Population III Star Formation

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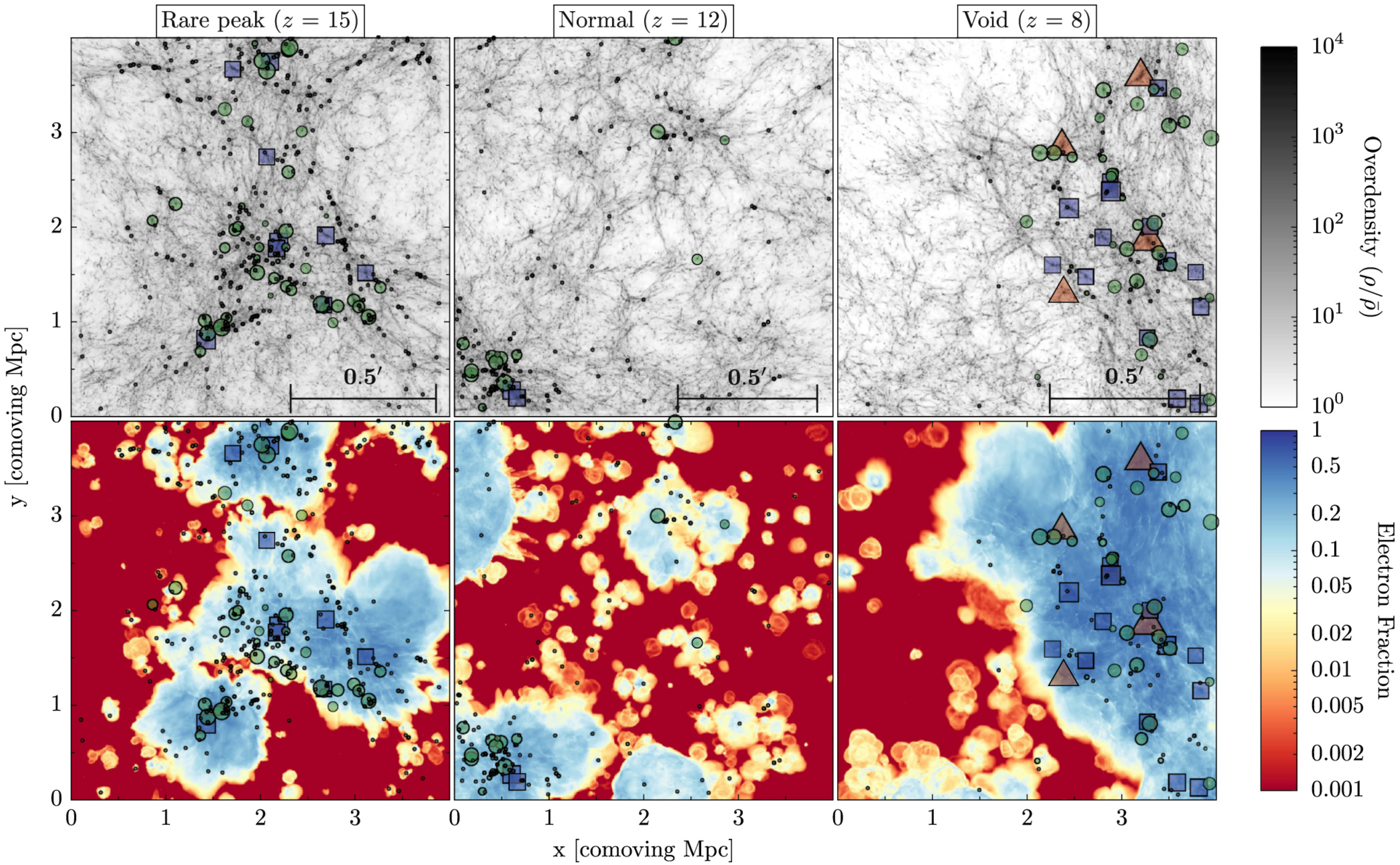
Motivation

- Hydrodynamical cosmological simulations
  - Detailed treatment of physical processes
  - Computationally expensive (millions of CPU-hours)
  - Restricted in volume & redshift range
  - Free parameters
    - Pop III/Pop II IMF
    - Critical metallicity for Pop III
- Alternative, faster approach is complementary



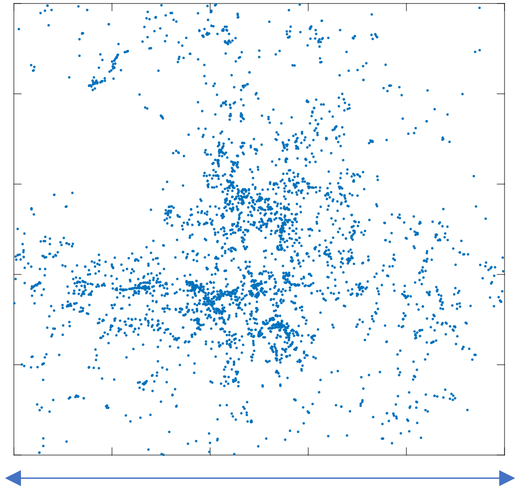
Renaissance Simulations; O'Shea et al (2015)

Semi-analytic Model of First Stars/Galaxies

Visbal et al. (2018, 2020). See also: Trenti et al. (2009), Agarwal et al. (2012), Crosby et al. (2013), Griffen (2016), Magg et al. (2018)

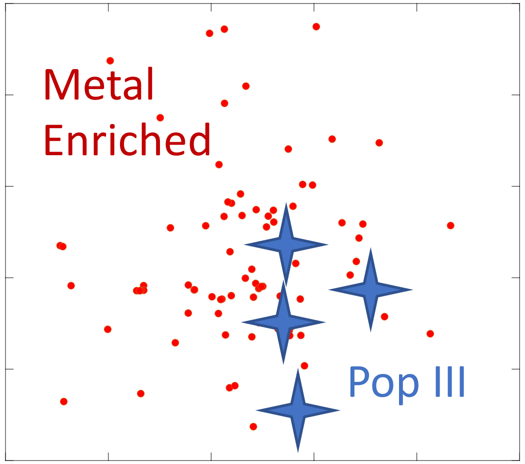
- Based on cosmological N-body simulations (Springel et al. 2001)
- Merger trees and ***3D positions*** (Behroozi et al. 2013)
- Analytic prescriptions for Pop III and metal enriched star formation
- Feedback processes
  - **H_2 photo-dissociation from Lyman-Werner radiation**
  - Metals spread via supernova winds (internal + **external enrichment**)
  - **Ionization of IGM**
  - Baryon-dark matter streaming velocity (Tseliakhovich & Hirata 2010)
- Computationally efficient

Dark Matter Halos at z=20



5 Mpc

First Stars and Galaxies

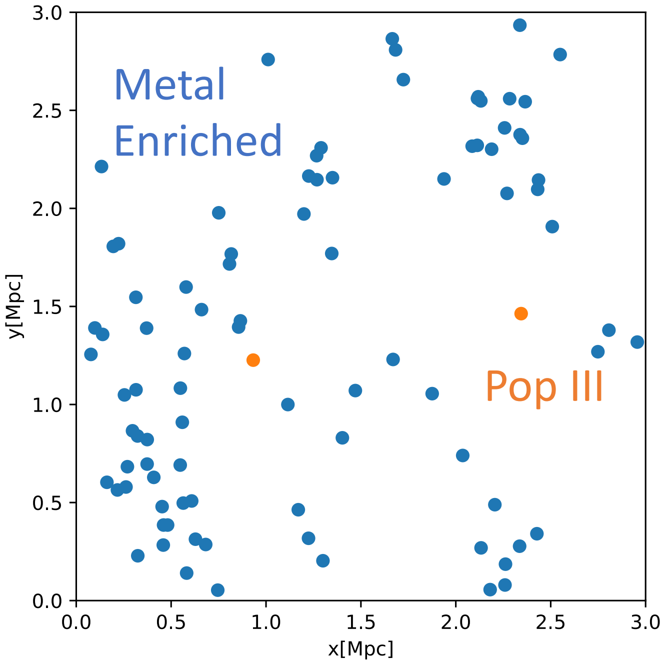


Visbal et al. (2018)

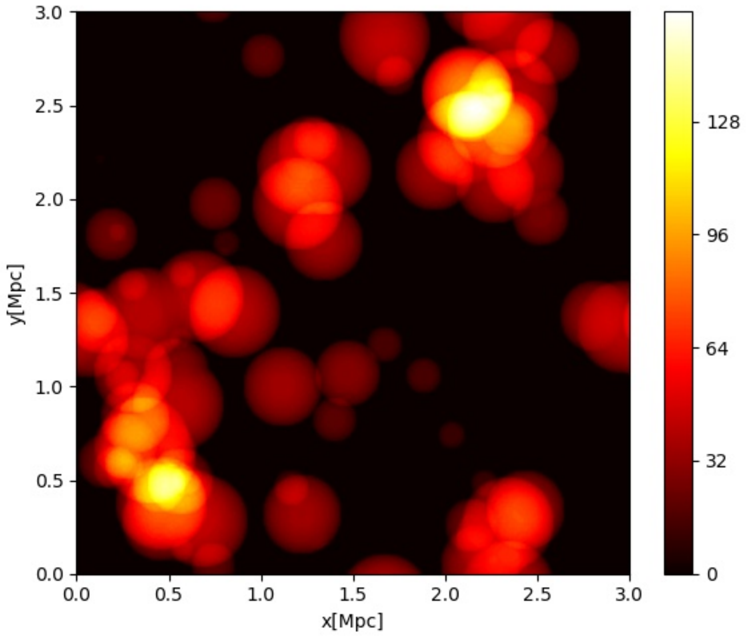
3D Feedback

- New grid-based method
  - Halos distributed on cubic grid
  - Lyman-Werner feedback, external metal-enrichment, reionization computed efficiently with FFTs
  - Impacts which halos produce Pop III/metal enriched stars

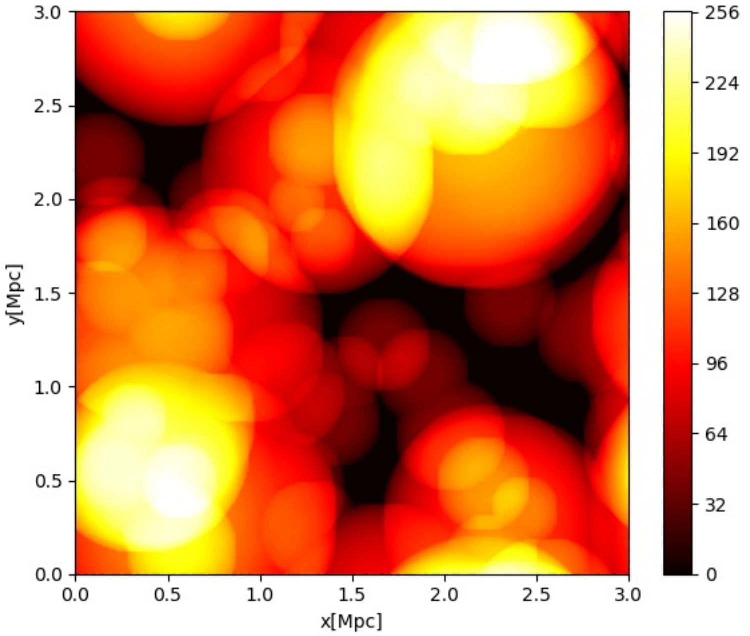
3 Mpc box at z=8.6



Halos Hosting Pop III or metal-enriched star formation



Metal-enriched intergalactic medium

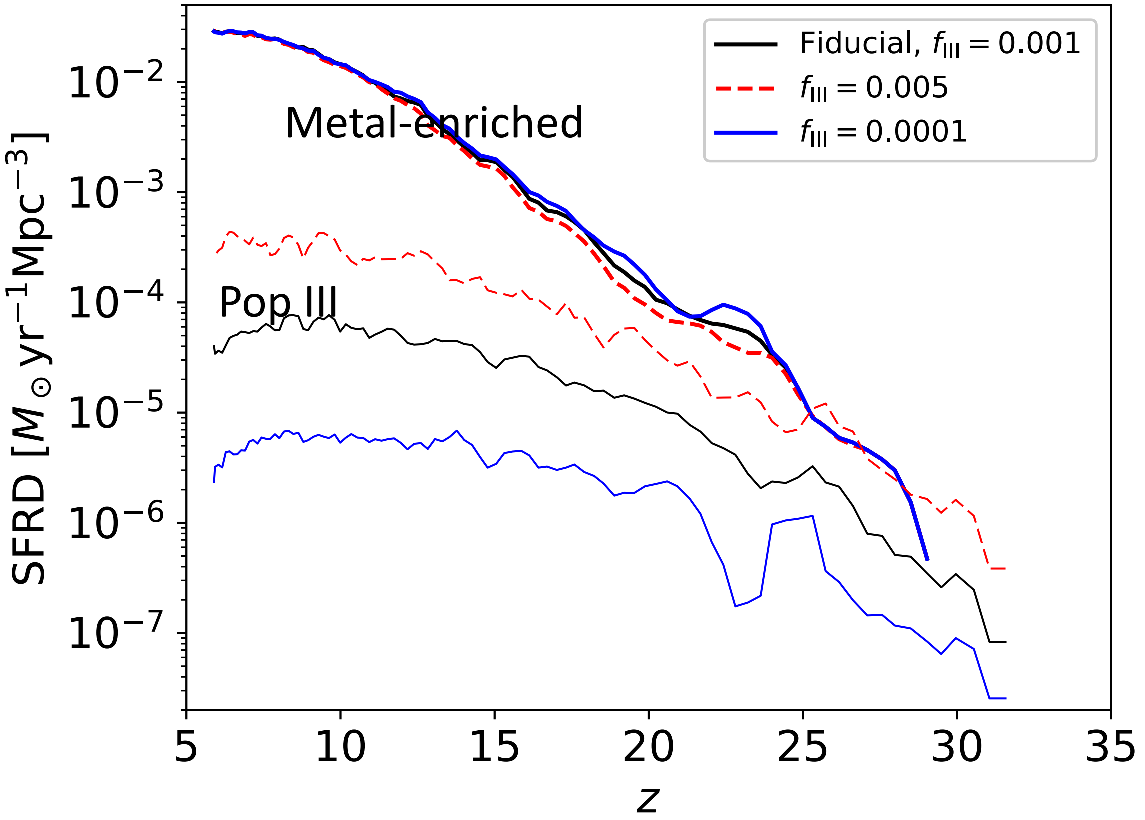


Ionized fraction of intergalactic medium

Pop III/Metal-enriched SFRD

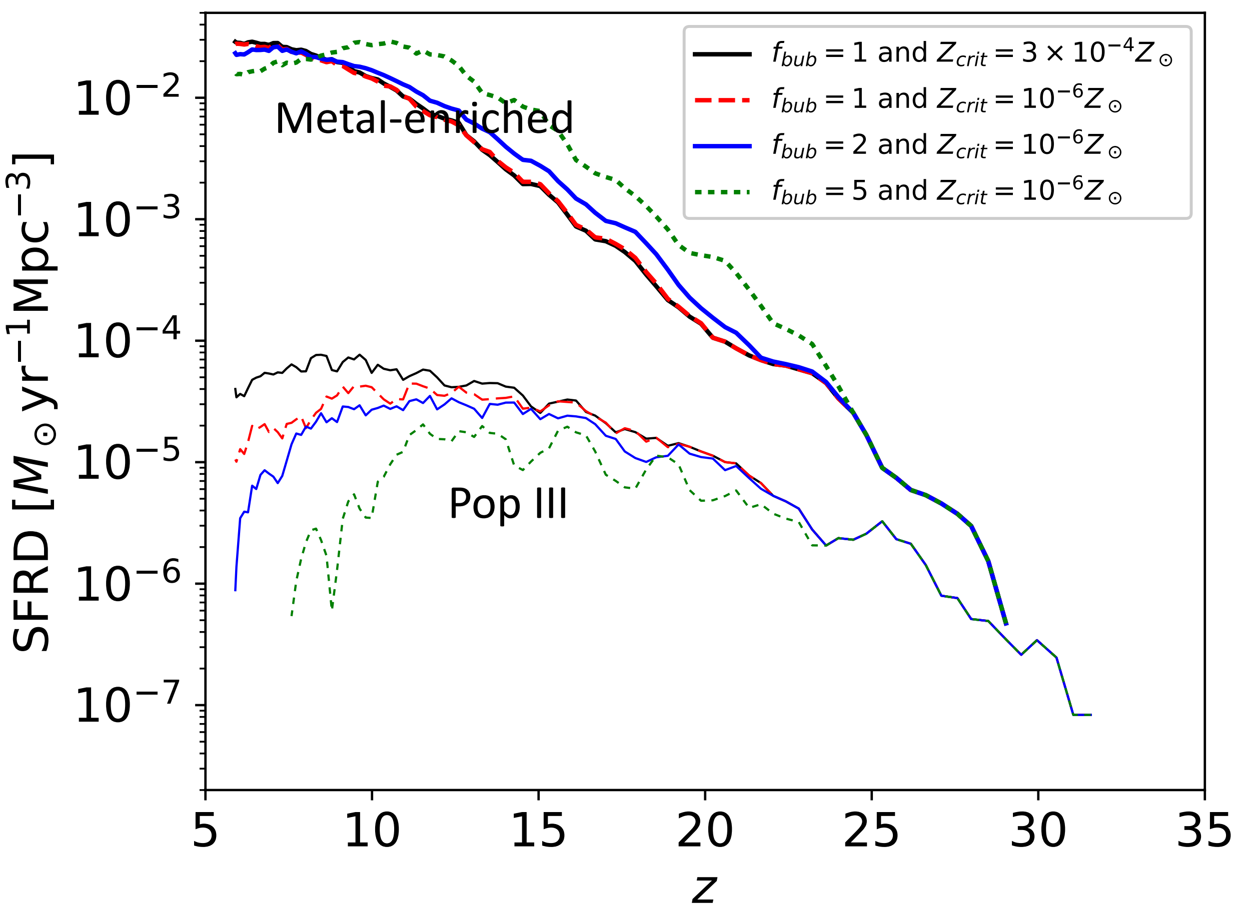
- Explore SFRD through model parameter space
- Rapid transition to metal-enriched SF dominating
- Persistent Pop III SF to lower redshifts
- External metal enrichment/reionization important for Pop III at $z \lesssim 15$

Average of 10 realizations of 3 Mpc box

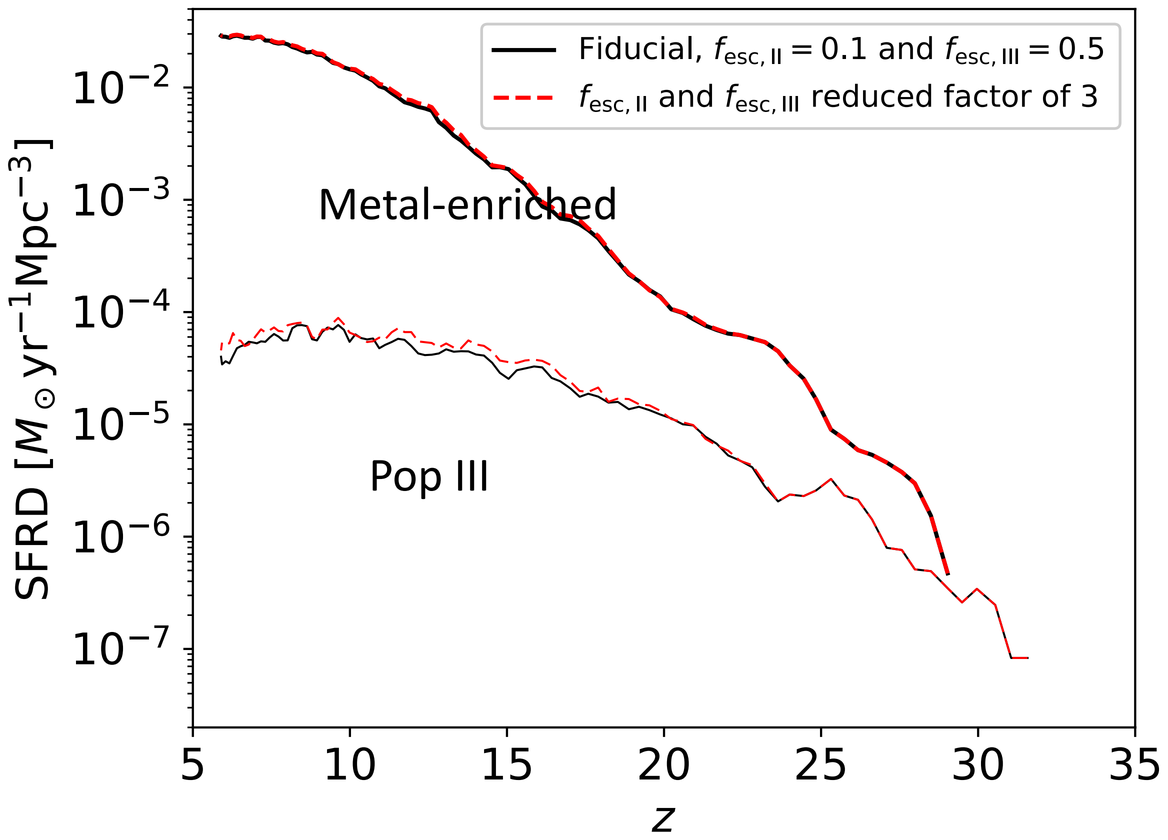


External Metal Enrichment

- Simple model for metal bubbles
  - v = 60 km/s
  - R_{max} = 150 h^{-1} ckpc
  - f_{bub}: parameter to vary size
  - Z_{crit}: Critical metallicity for PopIII → metal-enriched transition
- <u>Pop III SFRD may continue to z<6, depends strongly on metal bubble properties</u>

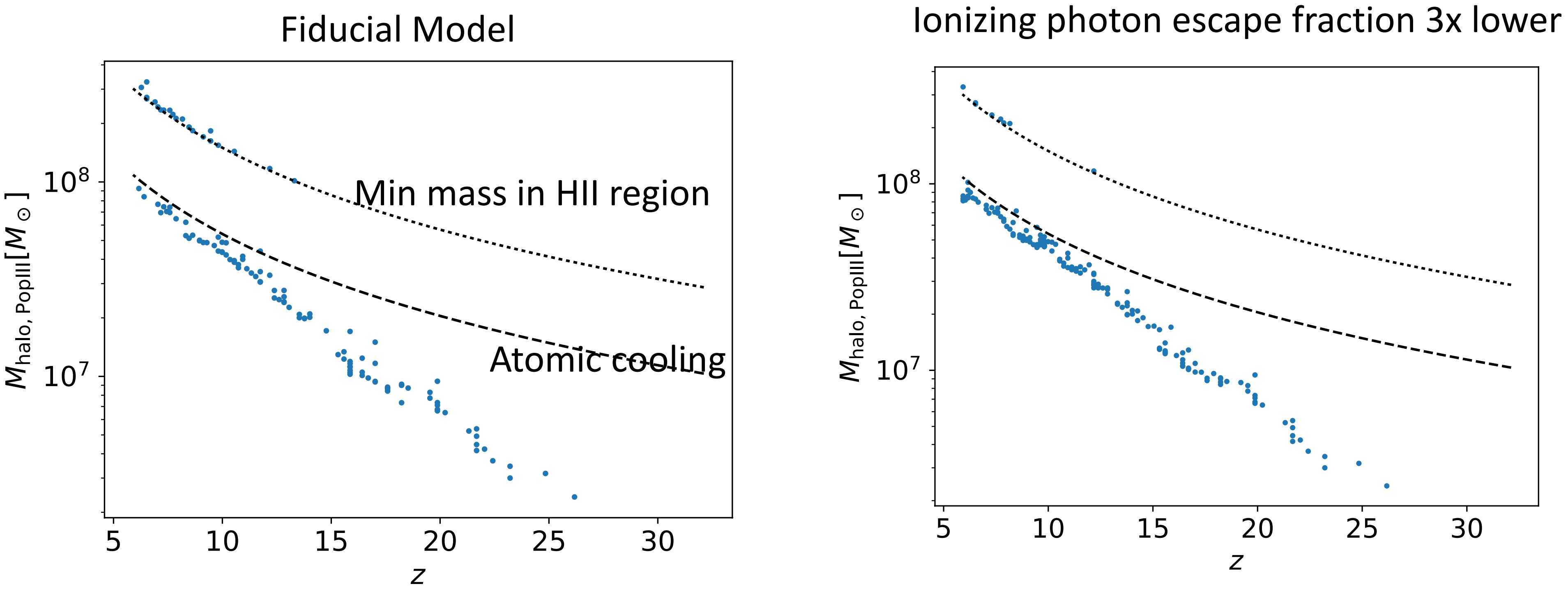


Impact of Reionization



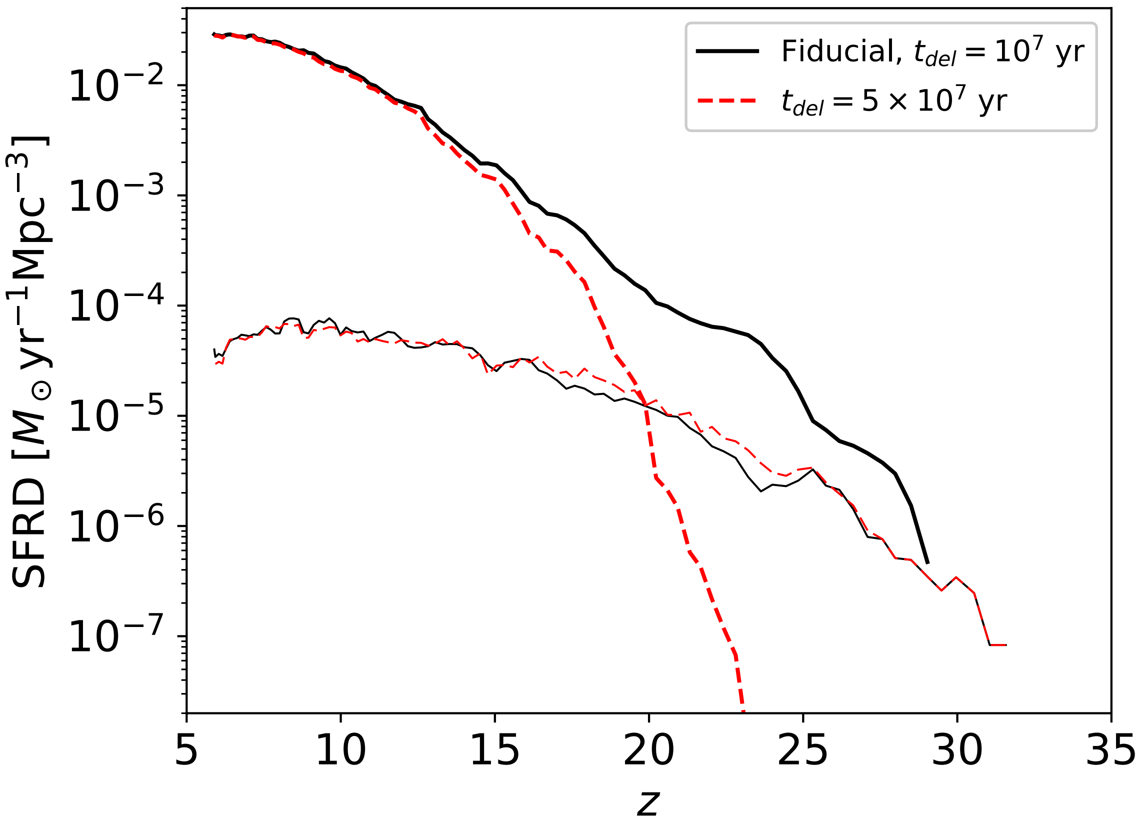
- Ionization → suppression of star formation in low-mass halos (e.g., Shapiro et al. 1994, Dijkstra et al. 2004, Sobacchi & Mesinger 2013)
- Pop III SFRD density relatively unchanged by f_{esc}

Impact of Reionization



- Total Pop III SF the same, but in different halos
- <u>Pop III in more massive halos dominant at lower redshifts</u>

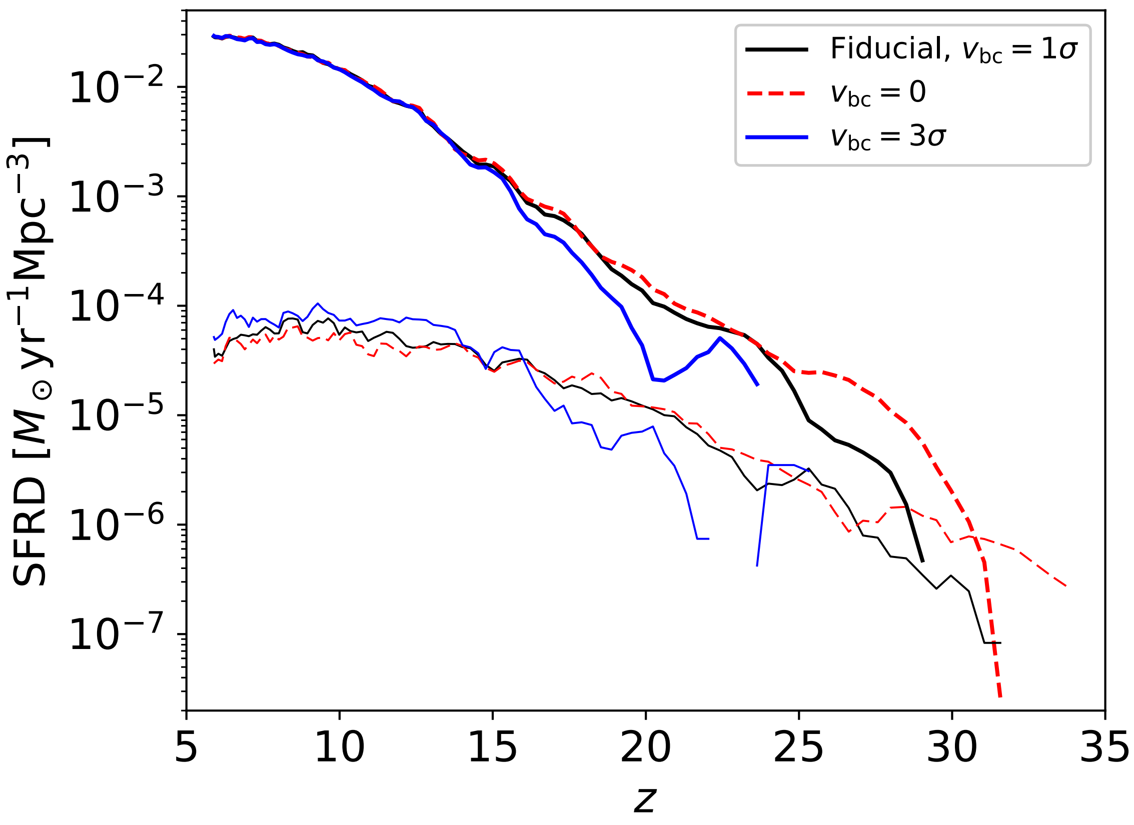
Supernovae Feedback



Summary and Conclusions

- New semi-analytic model of the first stars/galaxies
  - N-body backbone: merger trees and 3D positions
  - Grid-based method for metal bubbles, ionization bubbles, Lyman-Werner feedback
- Results
  - Pop III SF likely to extend to z<6, can be quenched by external metal enrichment
  - Reionization + metal bubbles important at z<15
  - Pop III star formation transitions from minihalos to atomic cooling halos or larger over cosmic time
  - SNae feedback impacts Pop III → metal-enriched transition
- Future applications
  - Stellar archaeology, BH remnants, Pair-instability SNae with *JWST,* 21cm observations
- **Postdoctoral Position at the University of Toledo: high-z universe, first stars, SMBHs, galaxy intensity mapping. Ad will appear on AAS job register next week!**

Streaming Velocity



Star Formation

- Minimum halo mass for Pop III SF set by Lyman-Werner feedback, baryon-DM streaming, ionization state of IGM
- Metal-enriched star formation t_{delay} after Pop III
- Star formation efficiency calibrated with high-z galaxy LFs

$$M_{\rm min} = \min\left(M_{\rm H2}, M_{\rm a}\right),$$

$$M_{\rm H2} = M_{\rm cool}(v_{\rm bc}, z) \times \left(1 + 6.96[4\pi J_{\rm LW,21}]^{0.47}\right)$$

Fialkov et al. (2013)

Model Parameters

Parameter	Description	Fiducial Value	Range
f_{III}	Pop III star formation efficiency	0.001	$0.0001 - 0.005$
f_{II}	Metal-enriched star formation efficiency	0.05	–
η_{II}	LW/Ionizing photons per baryon of metal-enriched stars	4000	–
η_{III}	LW/Ionizing photons per baryon of Pop III stars	65000	–
t_{delay}	Delay in subsequent star formation due to Pop III SNe	10^7 yr	$10^7\mathrm{yr} - 5 \times 10^7\mathrm{yr}$
Z_{crit}	Critical metallicity for externally metal-enriched halos	$3 \times 10^{-4}\ Z_\odot$	$10^{-6}\ Z_\odot - 10^{-2}\ Z_\odot$
$M_{\mathrm{min,met}}$	Critical mass for externally metal-enriched halos	$2 \times 10^5\ M_\odot$	$2 \times 10^5\ M_\odot - 10^6\ M_\odot$
M_{ion}	Ionization feedback mass	$1.5 \times 10^8 \left(\frac{1+z}{11}\right)^{-3/2}\ M_\odot$	Fiducial $-$ $3.3 \times$ Fiducial
$f_{\mathrm{esc,II}}$	Ionizing escape fraction in metal-enriched halos (Section 3.3)	0.1	$0.0 - 0.1$
$f_{\mathrm{esc,III}}$	Ionizing escape fraction in Pop III halos (Section 3.3)	0.5	$0.0 - 0.5$
v_{bc}	Streaming velocity at recombination	30 km s^{-1} (1σ)	$0 - 90$ km s^{-1} $(0 - 3\sigma)$
f_{bub}	Metal bubble size scaling factor (Section 3.4)	1	$0 - 5$
M_{min}	Minimum halo mass for Pop III star formation	see Eqns. 1-3	–