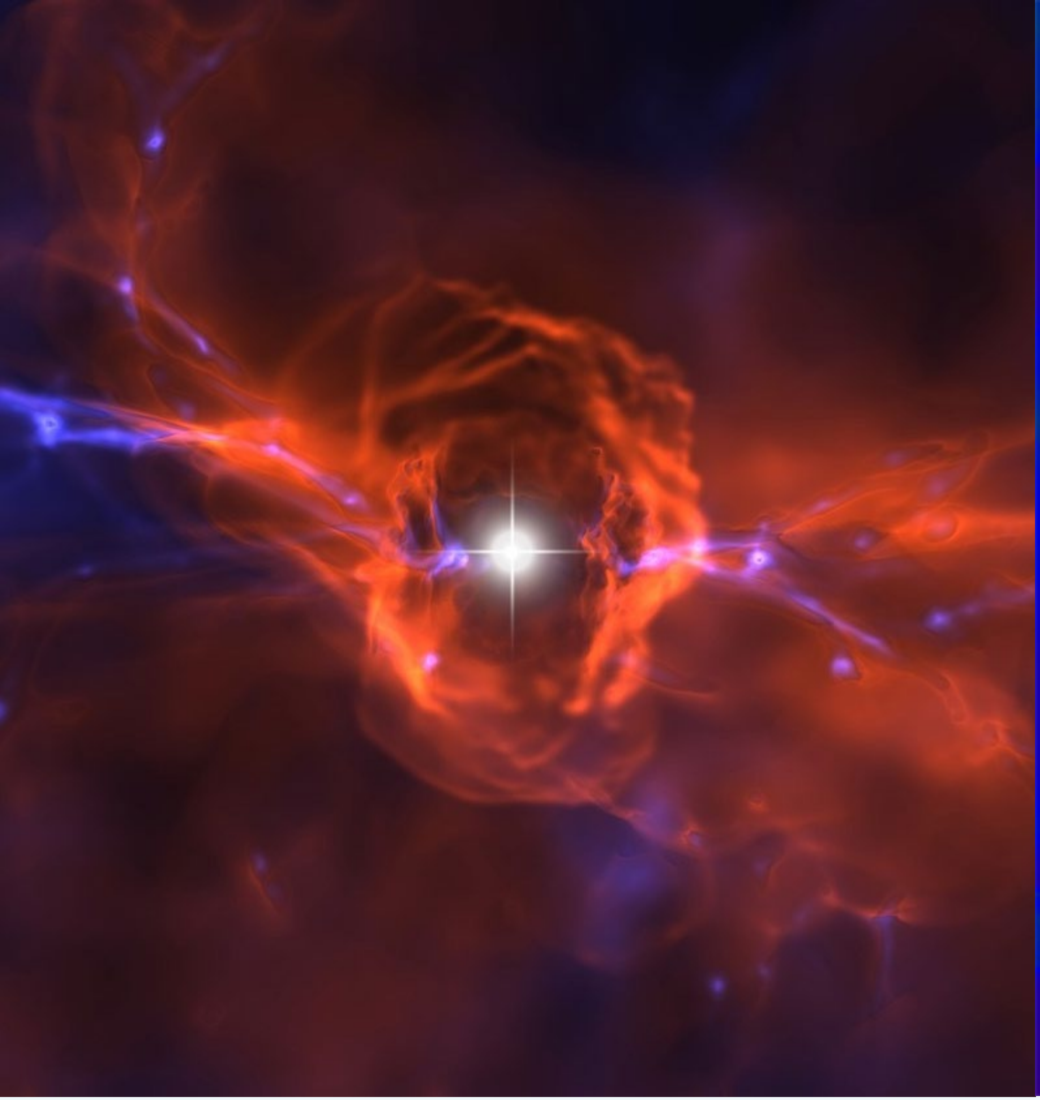
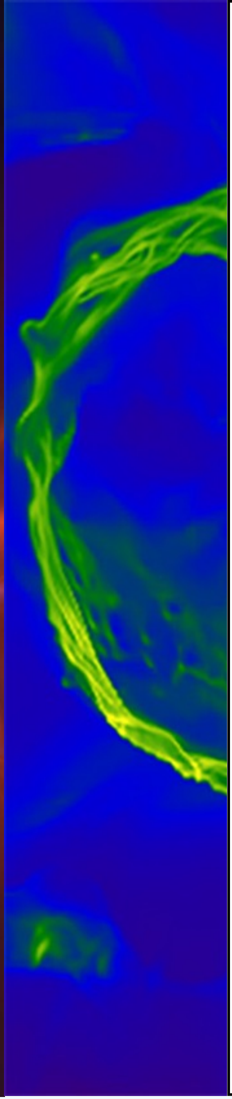




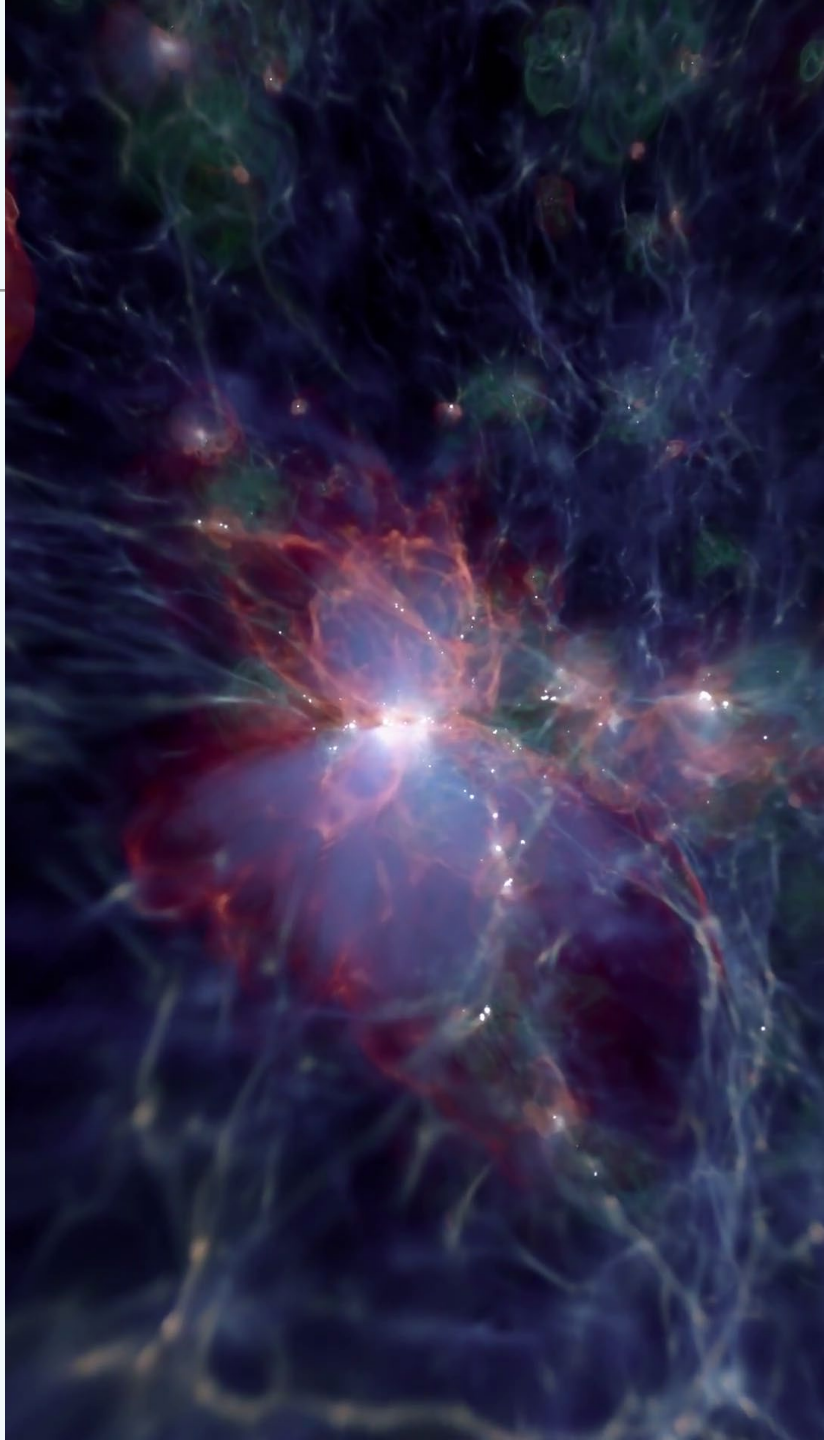
Galaxy Formation during the Epoch of Reionization

John Wise
@AstroAhura

Danielle Skinner, Corey Brummel-Smith (GT), John Regan (DCU), Michael Norman, Britton Smith (UCSD), Brian O'Shea (MSU)

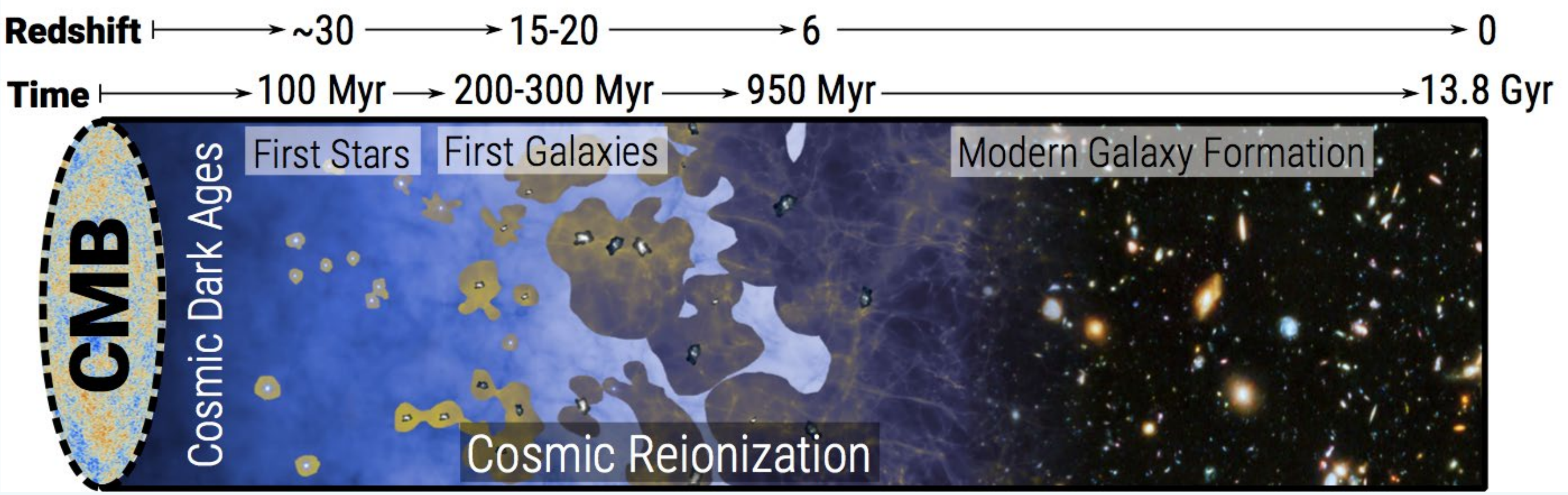
Outline

- **First stars: Population III**
- **Transition to metal-enriched star formation**
- **First generations of galaxies**
  - *How are they affected by feedback from their Pop III progenitors and ensuing reionization?*
  - *Are they different than nearby low-luminosity galaxies?*
  - *Does forming in a neutral medium affect their properties?*
- **Massive BH seeding in pre-galactic halos**



Overview

First (Pop III) stars	$\mathbf{M_{halo} \gtrsim 10^{5.5}\ M_\odot}$	Metal-free; reliant on H_2 cooling only → Massive SF (top-heavy IMF)	H_2 easily dissociated from a soft UVB; high resolution requirements
First galaxies	$\mathbf{M_{halo} \gtrsim 10^{7.5}\ M_\odot}$	Bursty; metals from Pop III SNe can trigger galaxy formation	Low-mass end susceptible to rad/SNe feedback



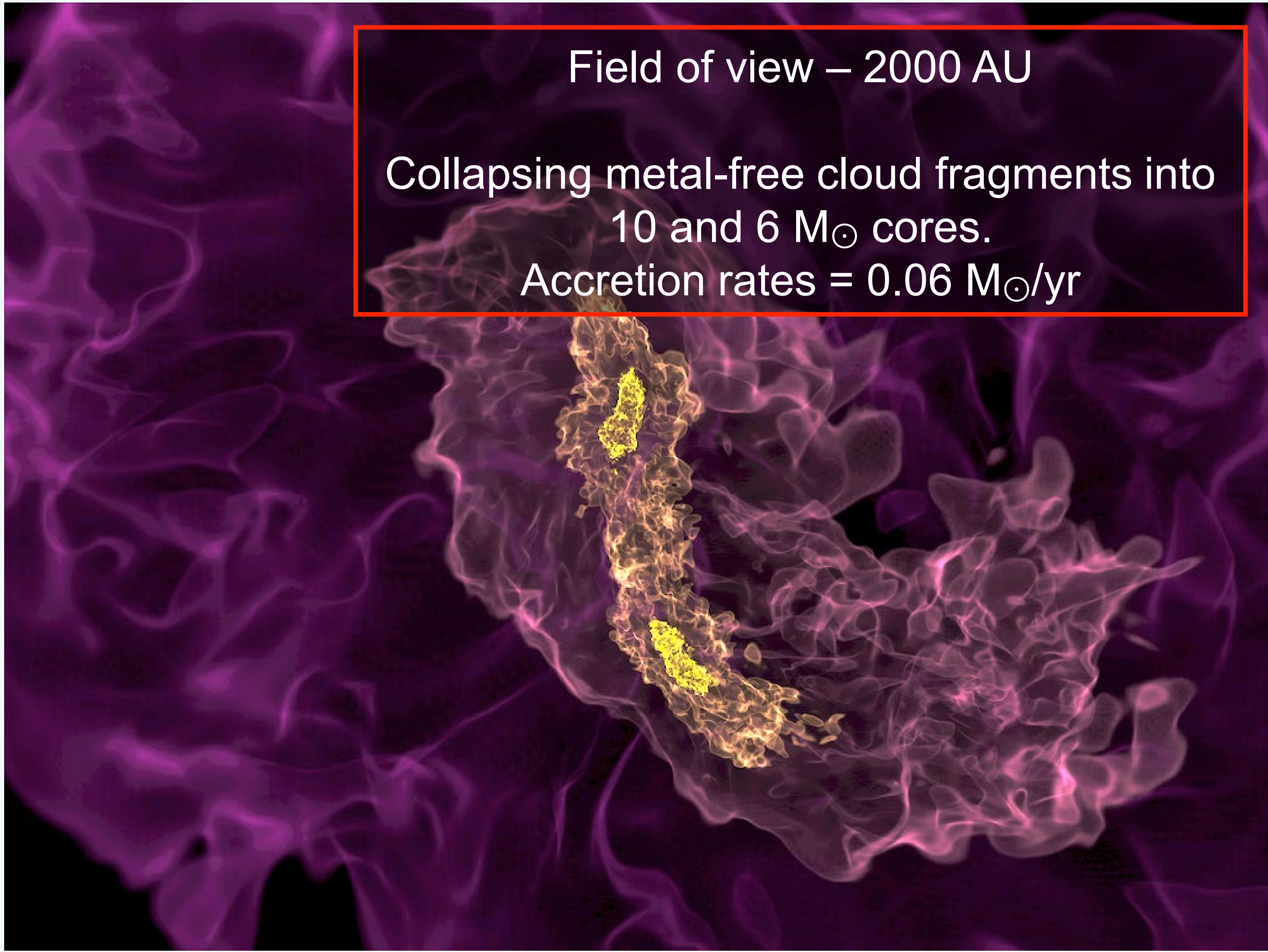
The First Stars

Population III Stars

Properties and environment

Abel+ (2002); Bromm+ (2002)
Turk+ (2009)
Greif+ (2012)
Hirano+ (2015)

- Metal-free stars
- Thought to be generally massive (~tens of $M_\odot$)
- Form in clusters up to ~15 massive stars
- Binaries possible → High mass X-ray binaries
- Form in minihalos with $M < 10^7 M_\odot$
- IMF unclear but top-heavy

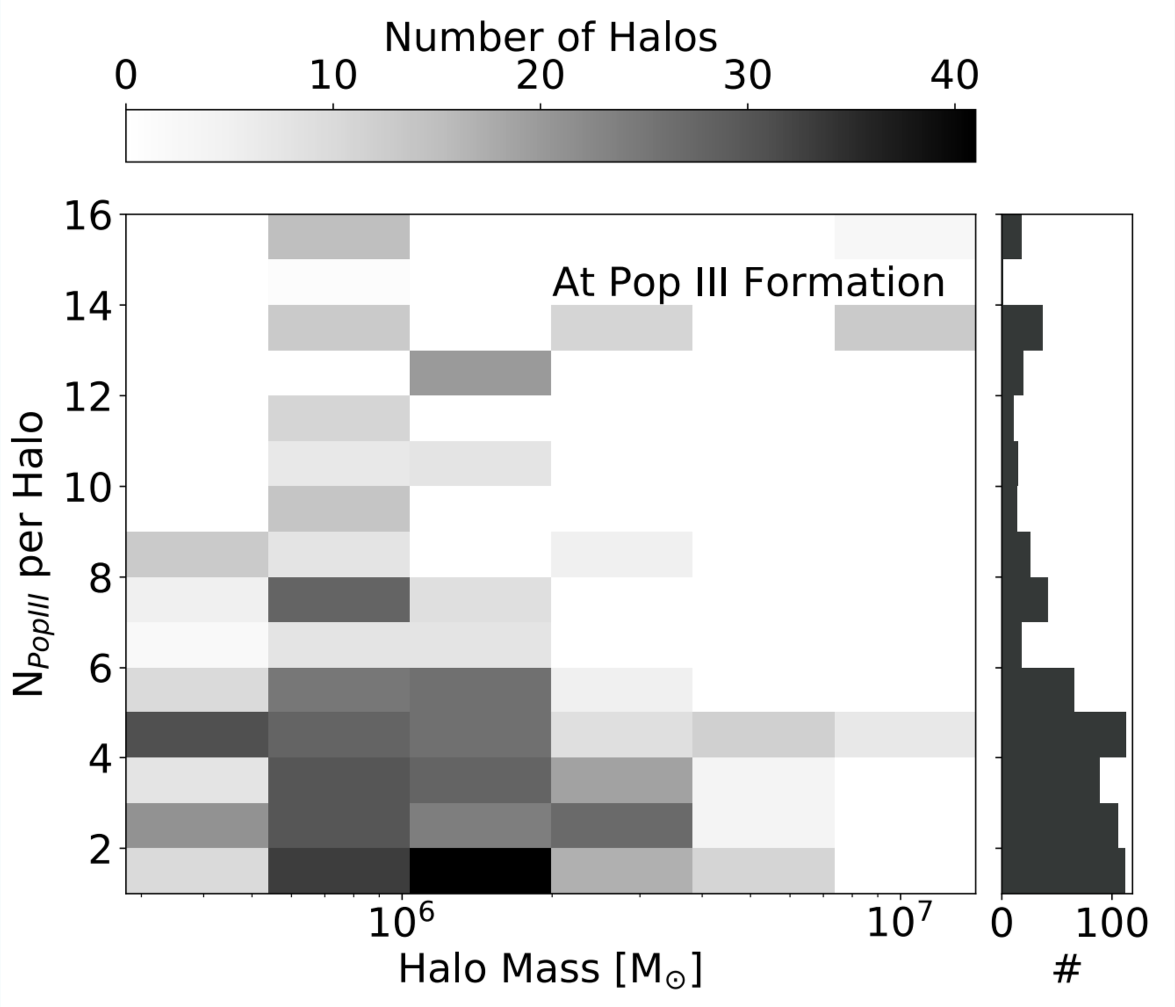


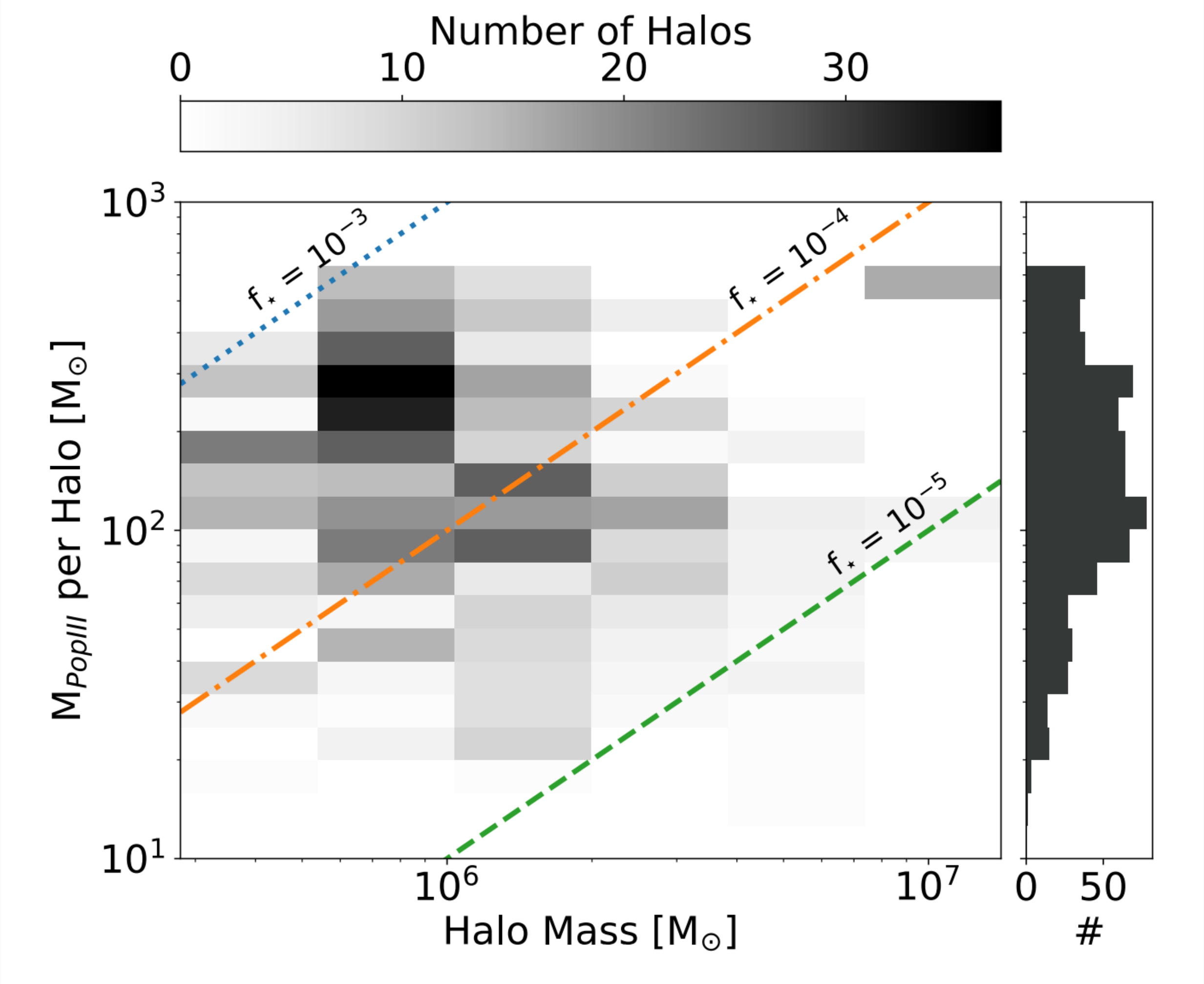
Population III Stars

Multiplicity and SF efficiency

Danielle Skinner & JW (submitted)

- Most form with # < 5
- SFE = $M_\star/M_{gas}$ = 10^{-3} - 10^{-5}
- $M_\star$ up to 700 $M_\odot$



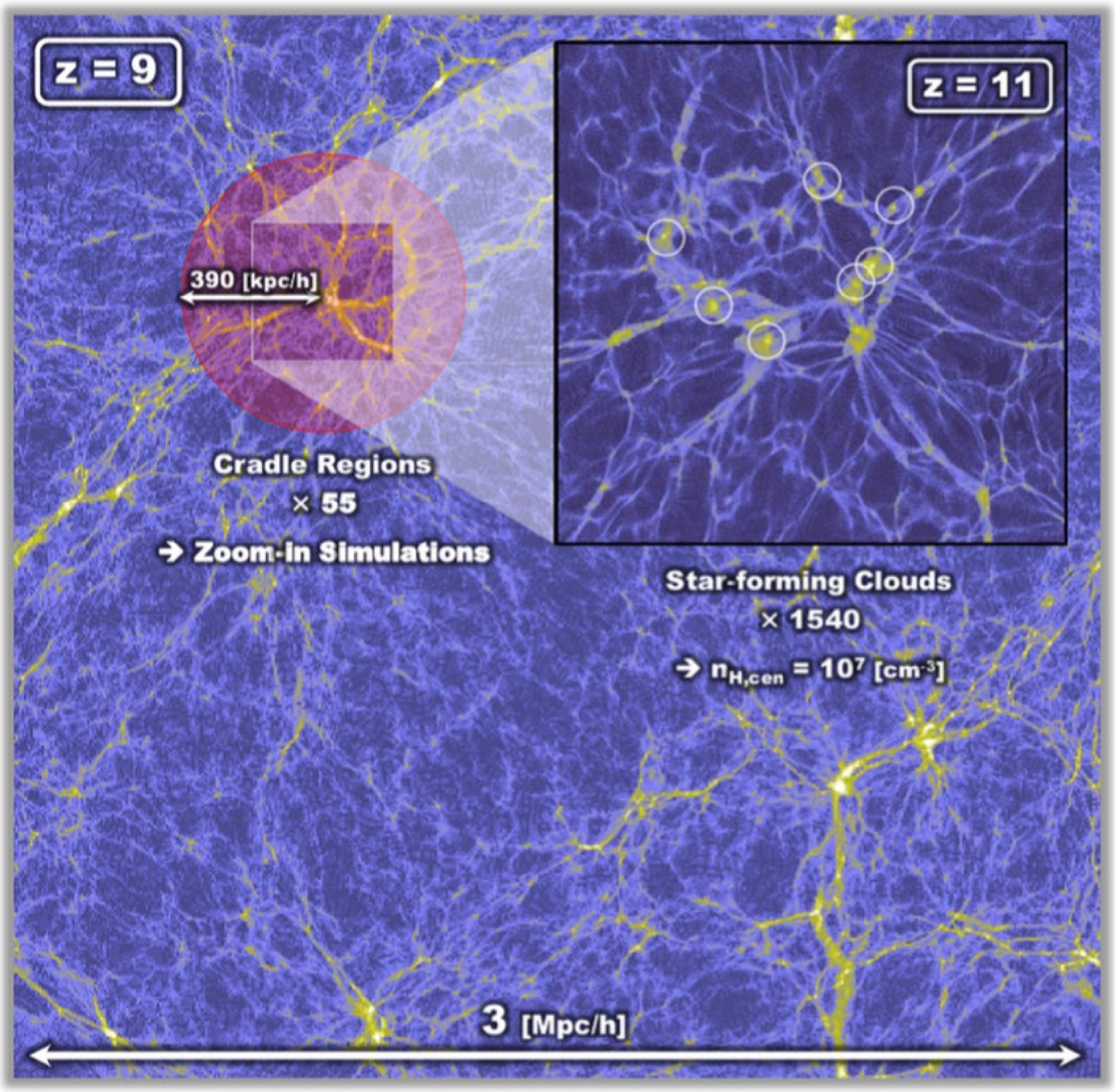


Population III Stars

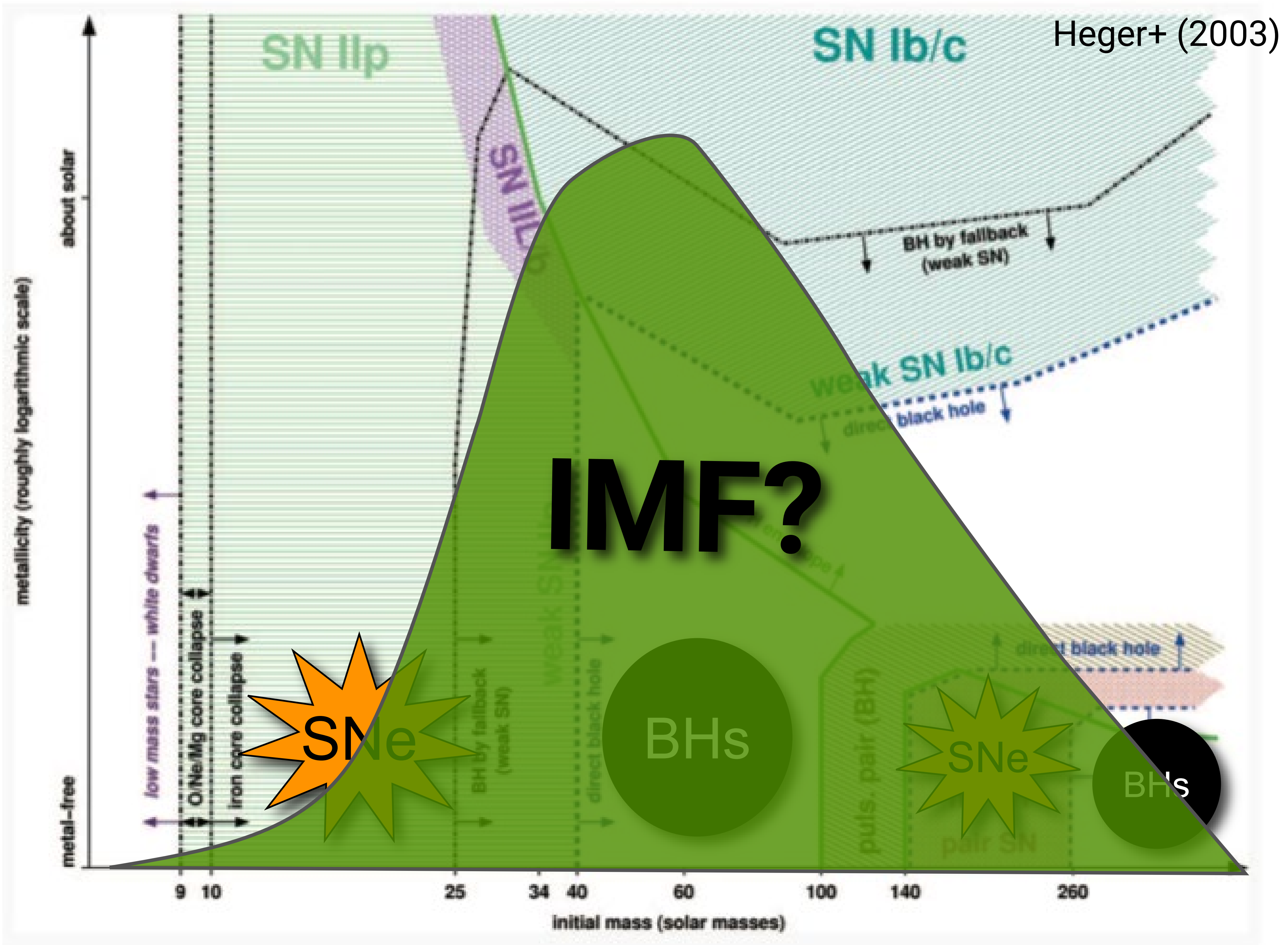
Working toward an IMF

- When do Pop III stars stop accreting?
- Radiative feedback key to determine final masses (general massive SF problem)
- 1540 2.5D protostellar radiation-hydro calculations, taken from a cosmological sample
- Cannot follow fragmentation, though

Abel+ (2002); Bromm+ (2002)
Turk+ (2009)
Greif+ (2012)
Hirano+ (2015)



Population III Stellar Endpoints



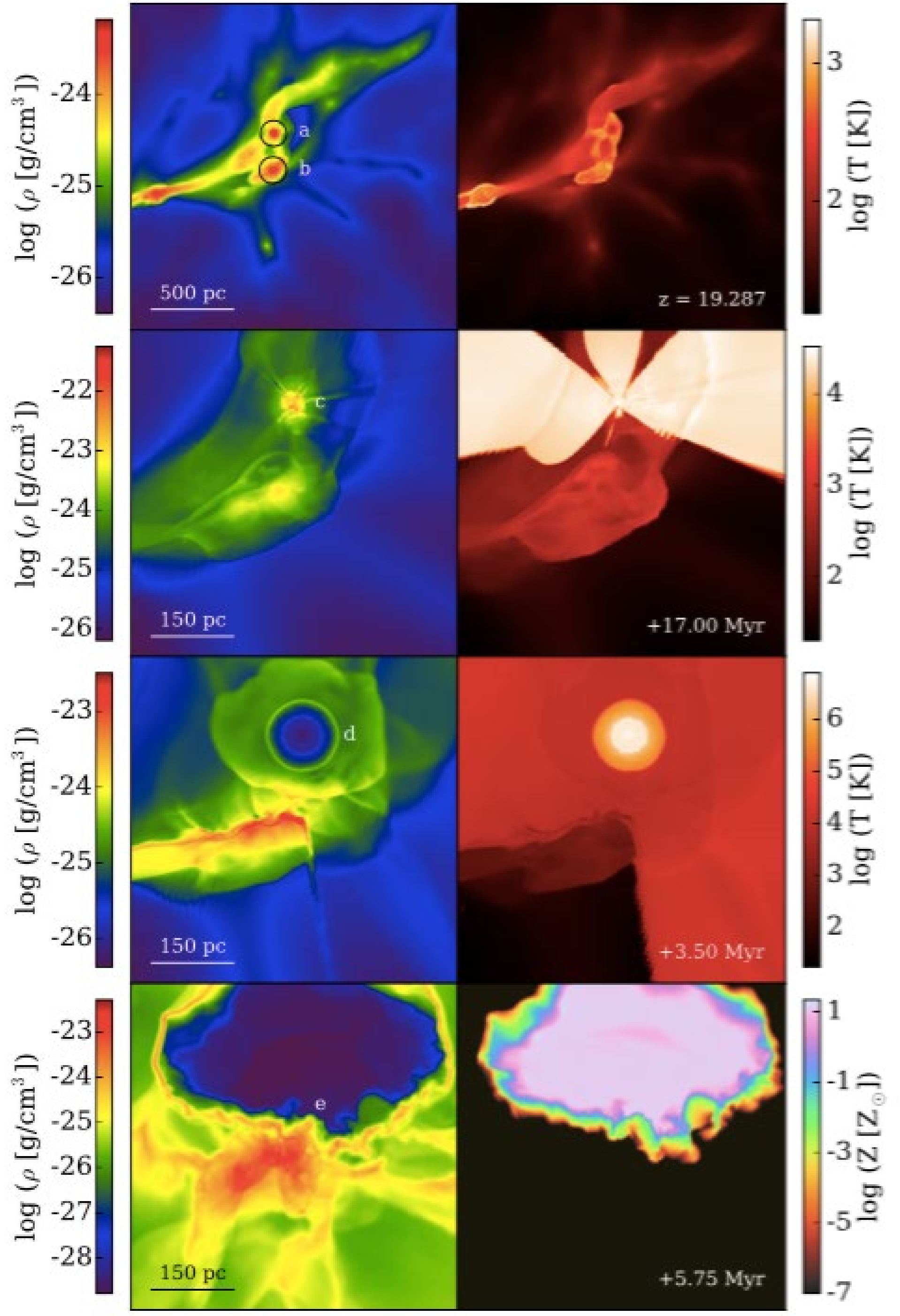
Heger+ (2003)

Metal Enrichment

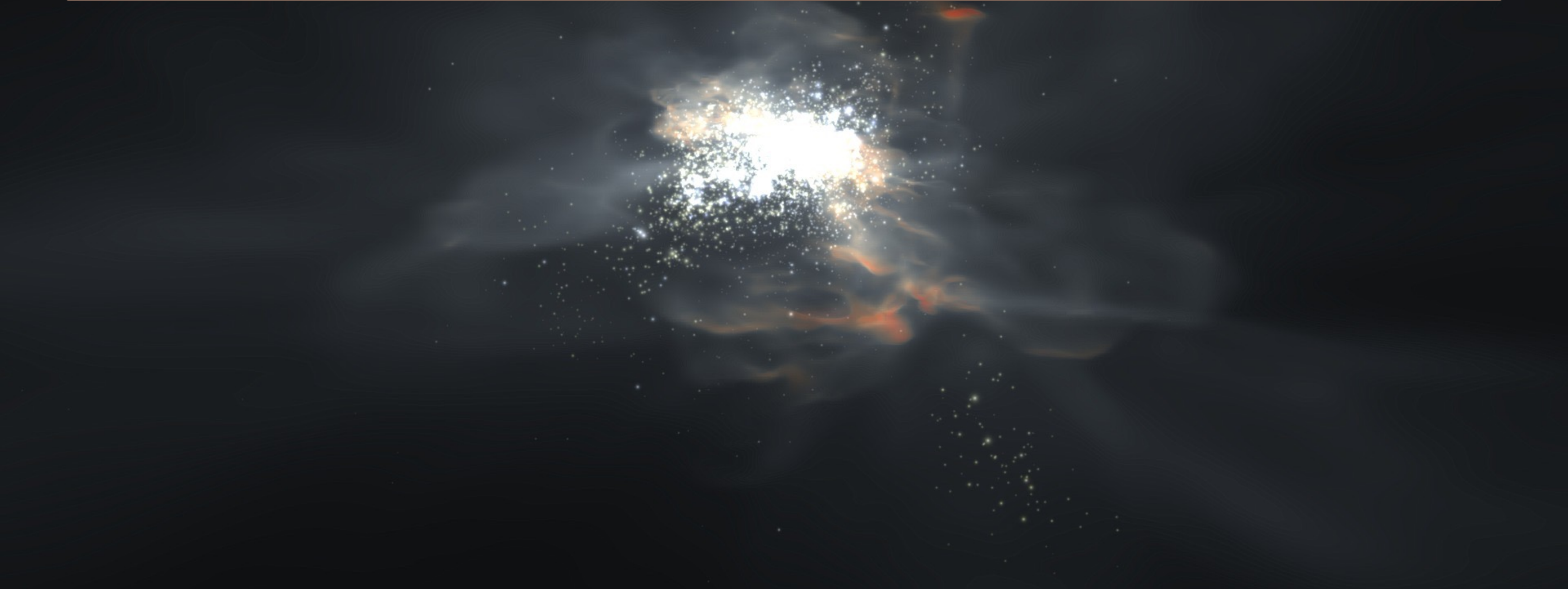
Transition to metal-enriched stars

External enrichment (Smith, JW+ 2015)

- Cosmo sim: 1.3 $M_\odot$ DM resolution, 0.1 AU(!) maximum spatial resolution in a 0.5 Mpc/h box
- Pop III star formation at z = (23.7, 18.2)
- Photo-evaporates most nearby halos
- If it survives, can metals mix into the halo without destroying it?
- First metal-enriched collapse occurs at z = 16.6
- In a DM halo with M = 3 x 10^5 $M_\odot$
- 300 pc away from the blastwave site



Renaissance Simulations

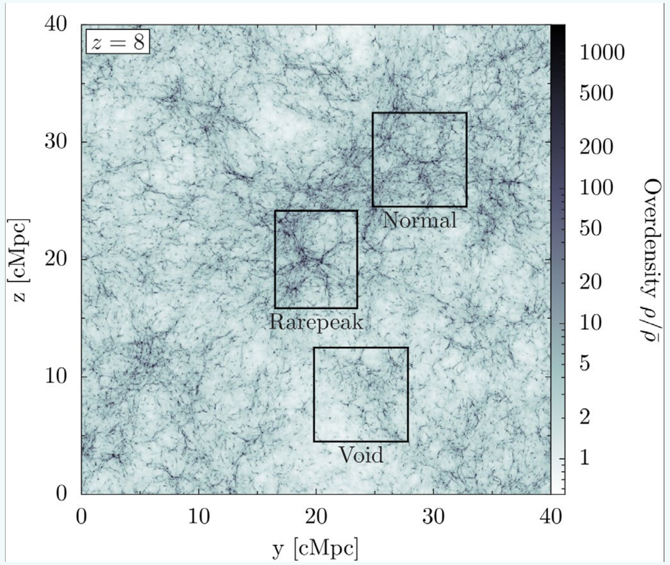


The First Galaxies

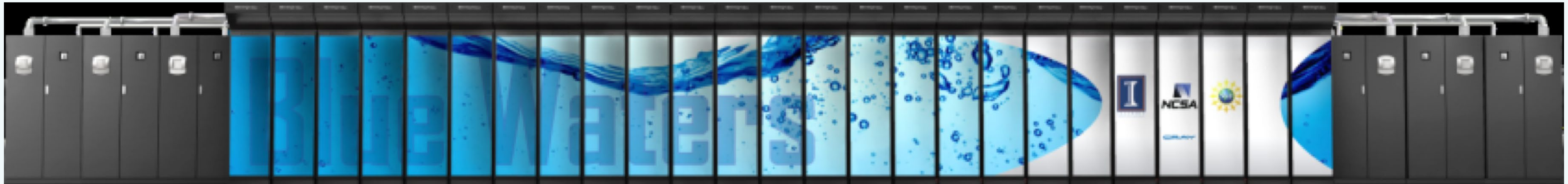
The Renaissance Simulations

Xu, JW, Norman (2013)
Xu et al. (2014)
Chen, JW, et al. (2014)
Ahn et al. (2015)
O'Shea, JW et al. (2015)
Xu et al. (2016abc)
Barrow, JW et al. (2017, 2018)
Smith et al. (2018)
Wise et al. (Nature, 2019)

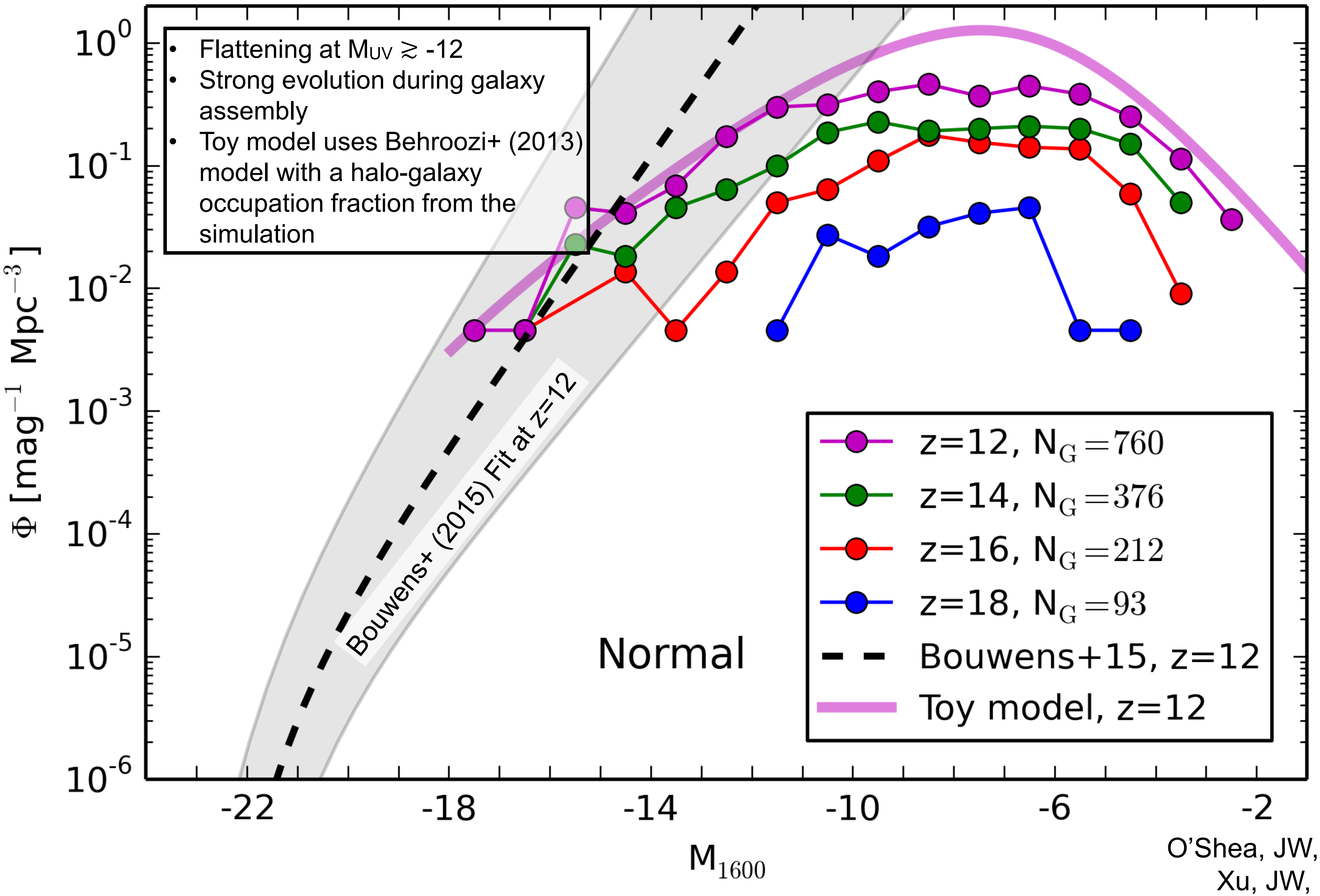
- Follow three regions ("rare peak", mean, void) until z = 15, 12, 8 (respectively).
- 40 comoving Mpc box, 5 comoving Mpc zoom-in region
- DM particle mass: 29,000 $M_\odot$ → Resolve 10^6 $M_\odot$ halos
- Maximal spatial resolution: 19 comoving pc
- Population II & III star formation and feedback, $M_{PopII,min}$ = 1000 $M_\odot$
- H/He ionizing coupled radiative transfer (adaptive ray tracing)
- Follow about 10,000 Pop III stars and 1,000 stars in each region



<u>Per run</u>
10M core-hours
9 months real-time
30TB

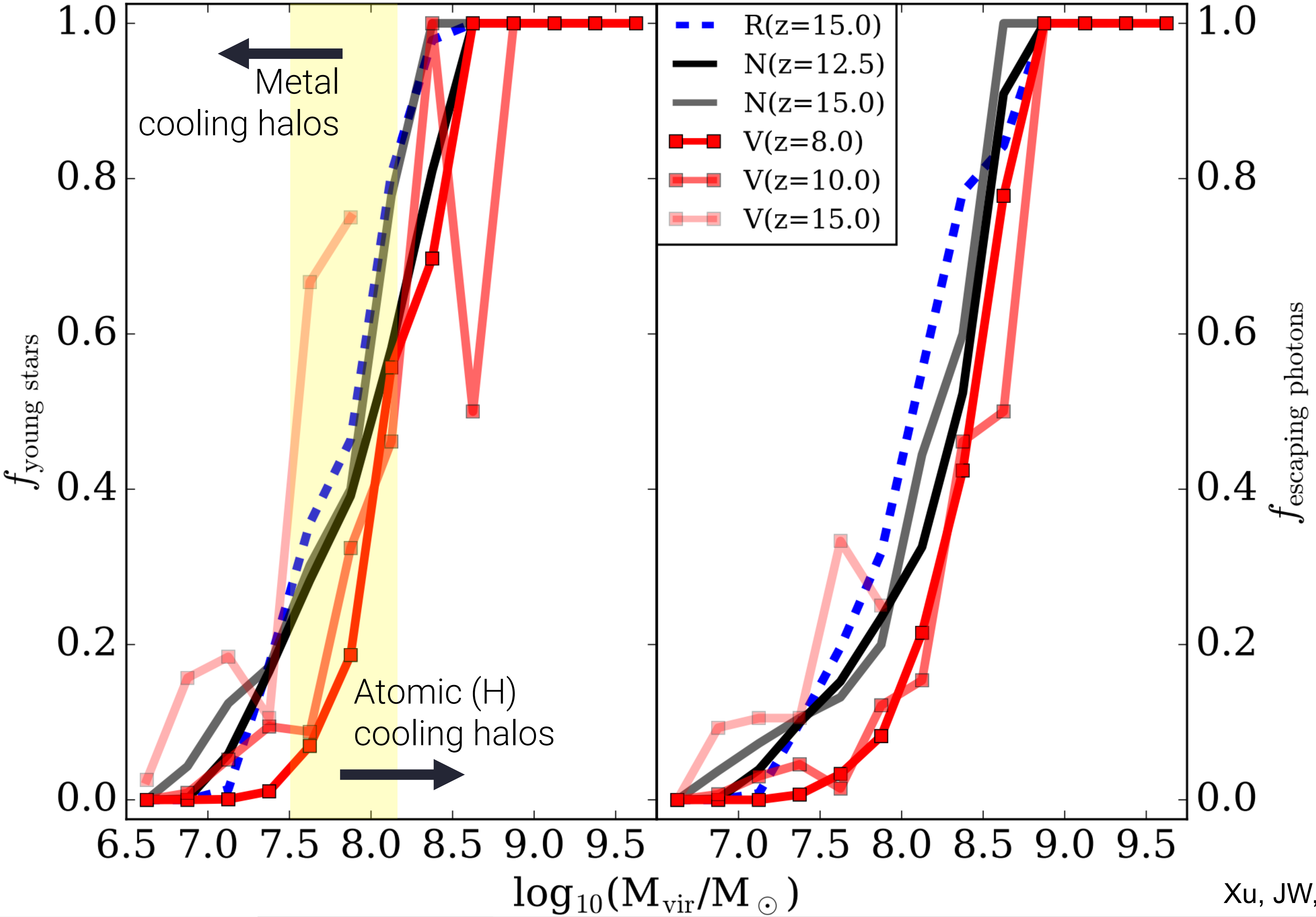


Renaissance Simulations
Luminosity Functions



O'Shea, JW, et al (2015)
Xu, JW, et al. (2016)

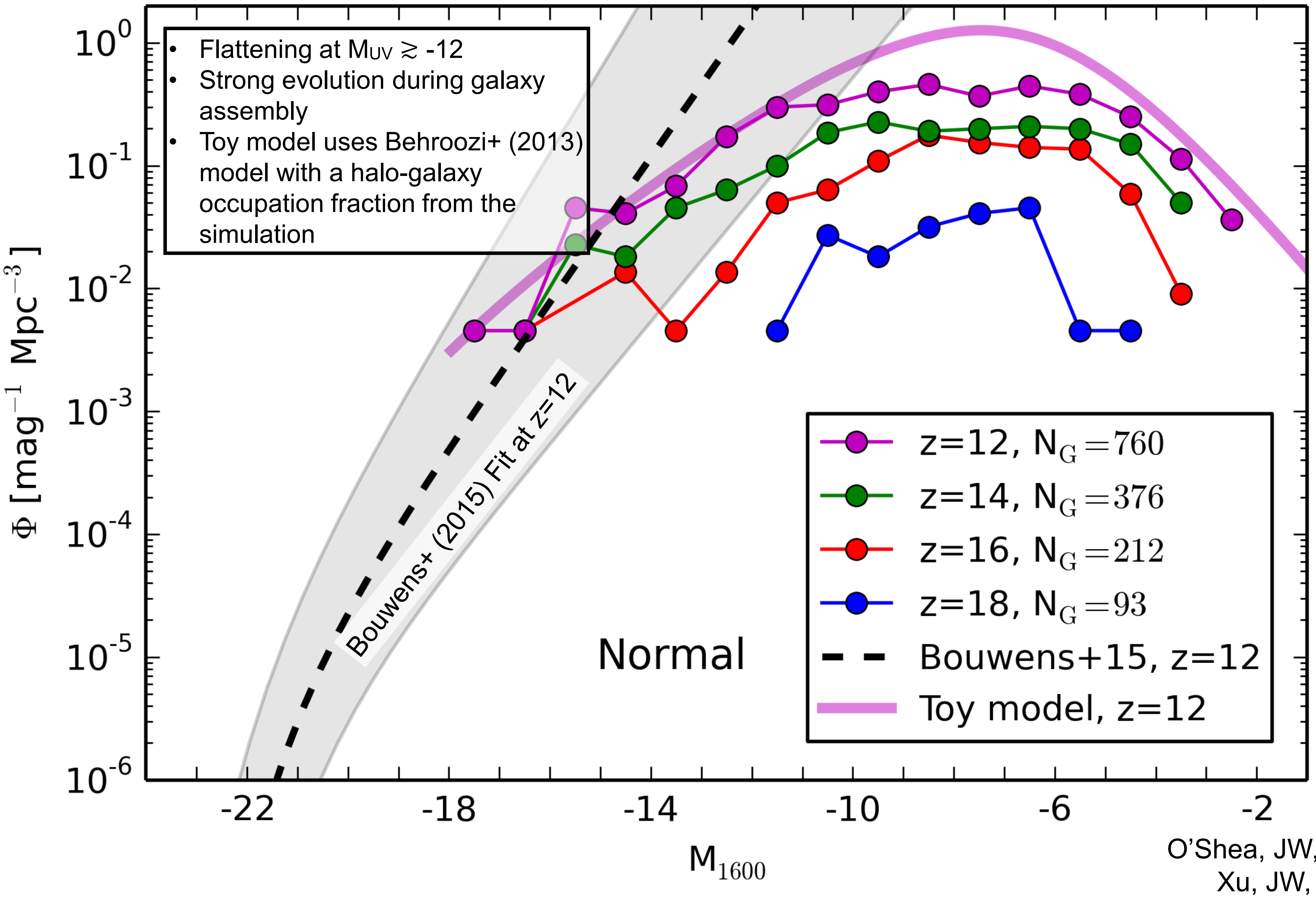
Fraction of halos with young (<20 Myr) stars



Fraction of halos with non-zero (>1%) escape fractions

Xu, JW, et al. (2016)

Renaissance Simulations
Luminosity Functions

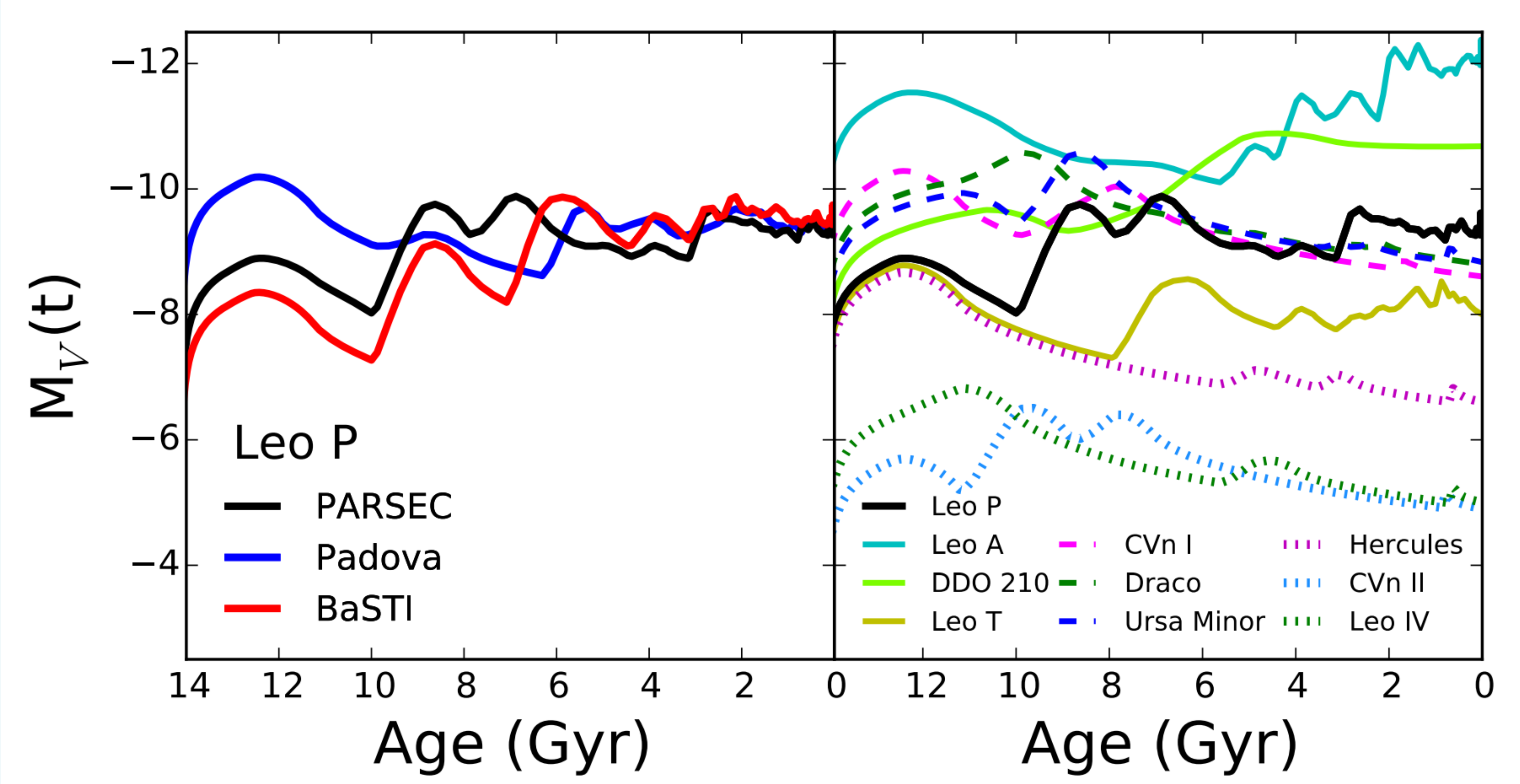


O'Shea, JW, et al (2015)
Xu, JW, et al. (2016)

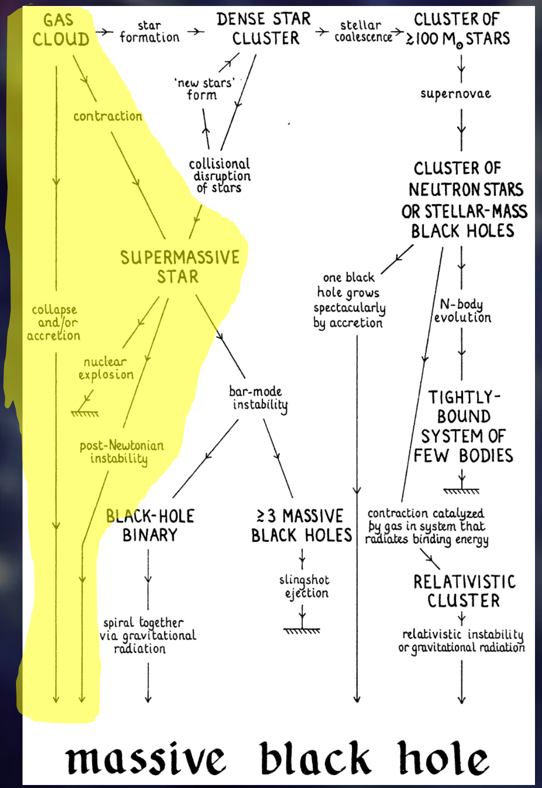
Luminosity History of Local Group Dwarfs

Convert star formation history to magnitudes (McQuinn+ 2015)

~constant over 13 Gyr!

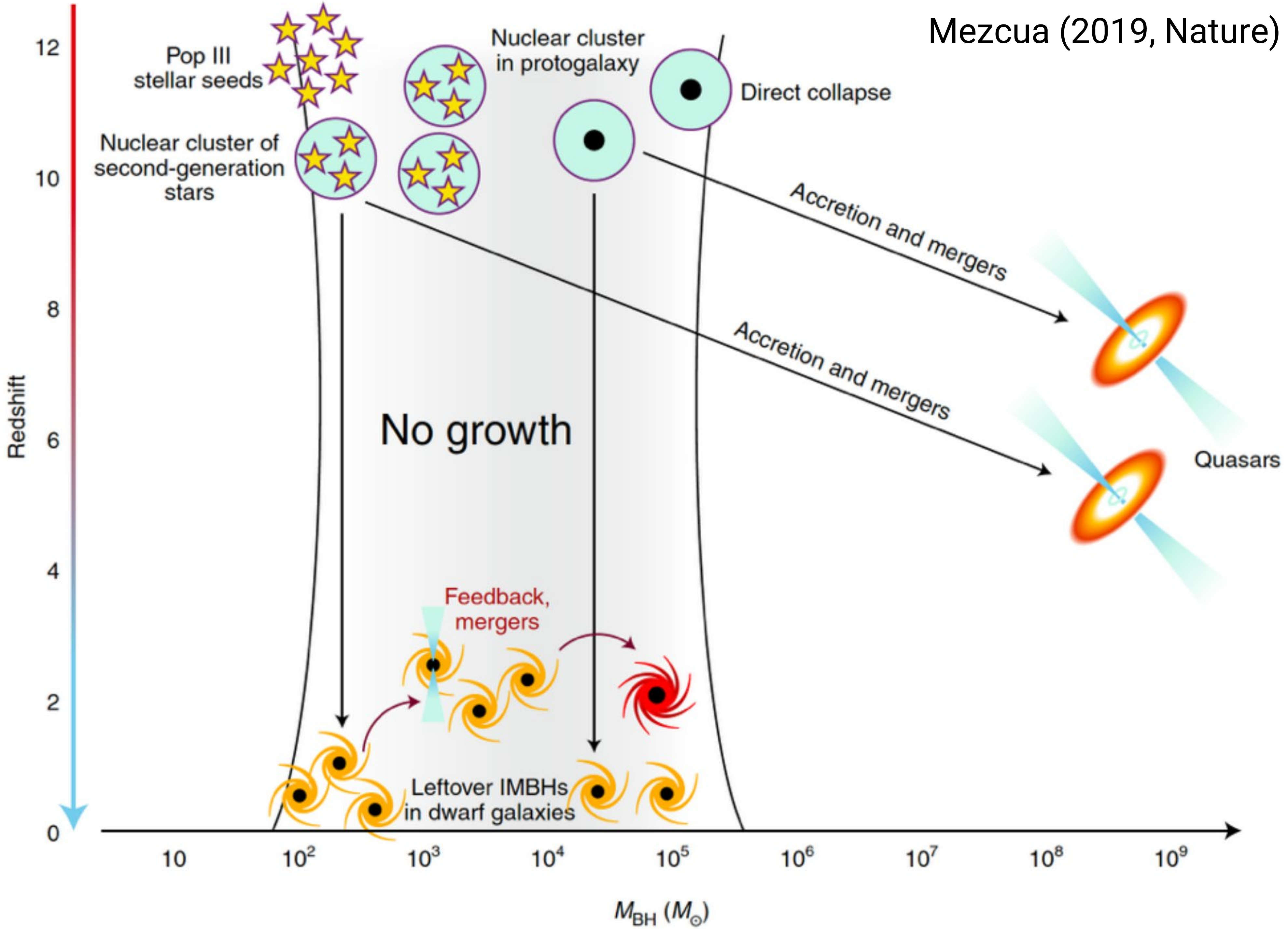


Massive Black Hole Seeds



Seeding Mechanisms

Mezcua (2019, Nature)



Massive Black Hole Seeds

Supermassive stars & Direct Collapse Black Holes (DCBHs)

- The most massive seeds can form through a monolithic collapse in a primordial halo
- Forms either a supermassive star ($10^3 - 10^5\ M_\odot$) or a dense stellar cluster that could form a **massive BH seed**
- Very special conditions required for its formation
- Hypothetical. Need JWST to verify/falsify (Haiman+ 2019)

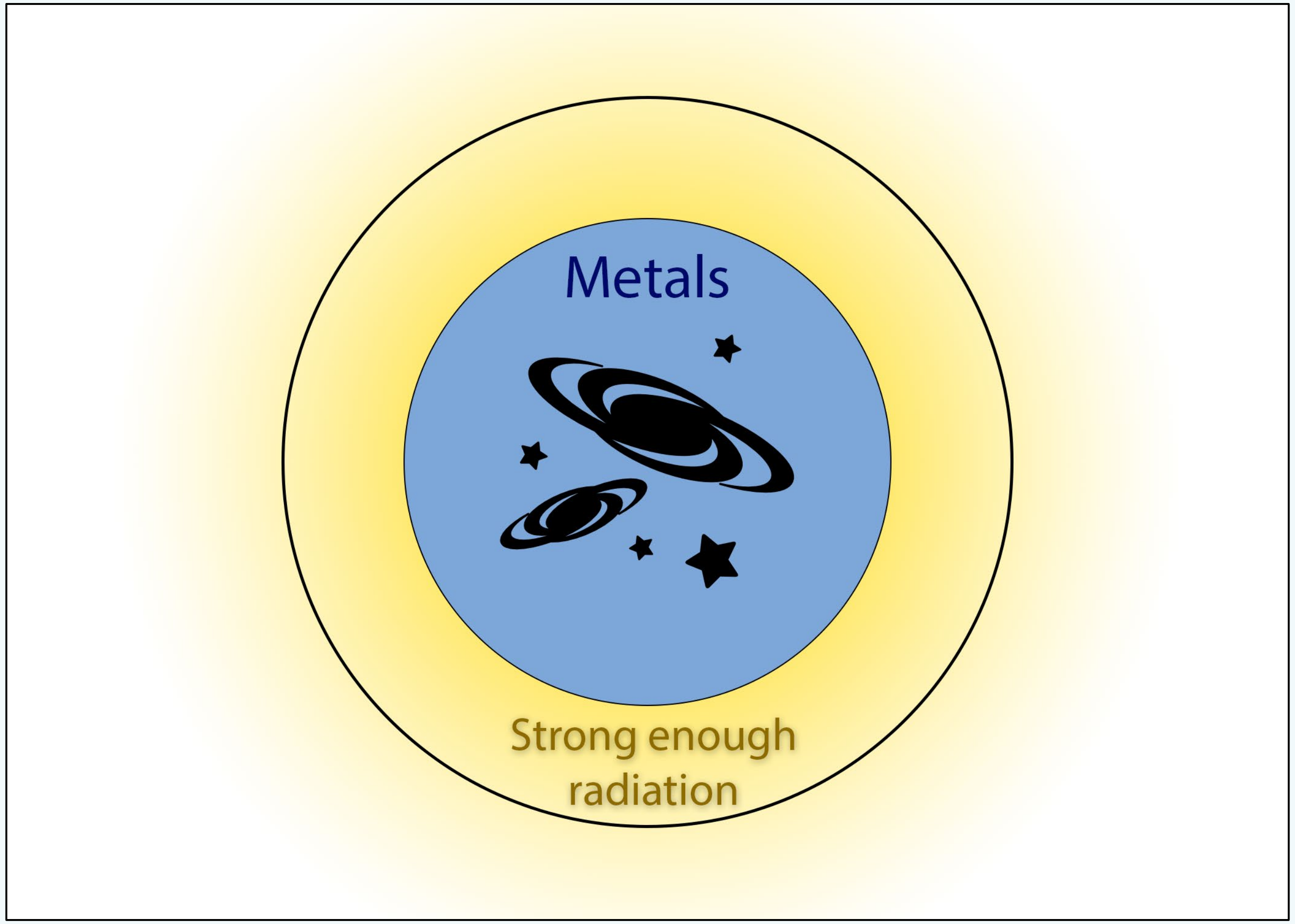
20 pc → 1 AU

(Density isosurfaces; Wise+ 2008)

Massive Black Hole Seeds

Suppressing cooling: metal-free & molecule-free

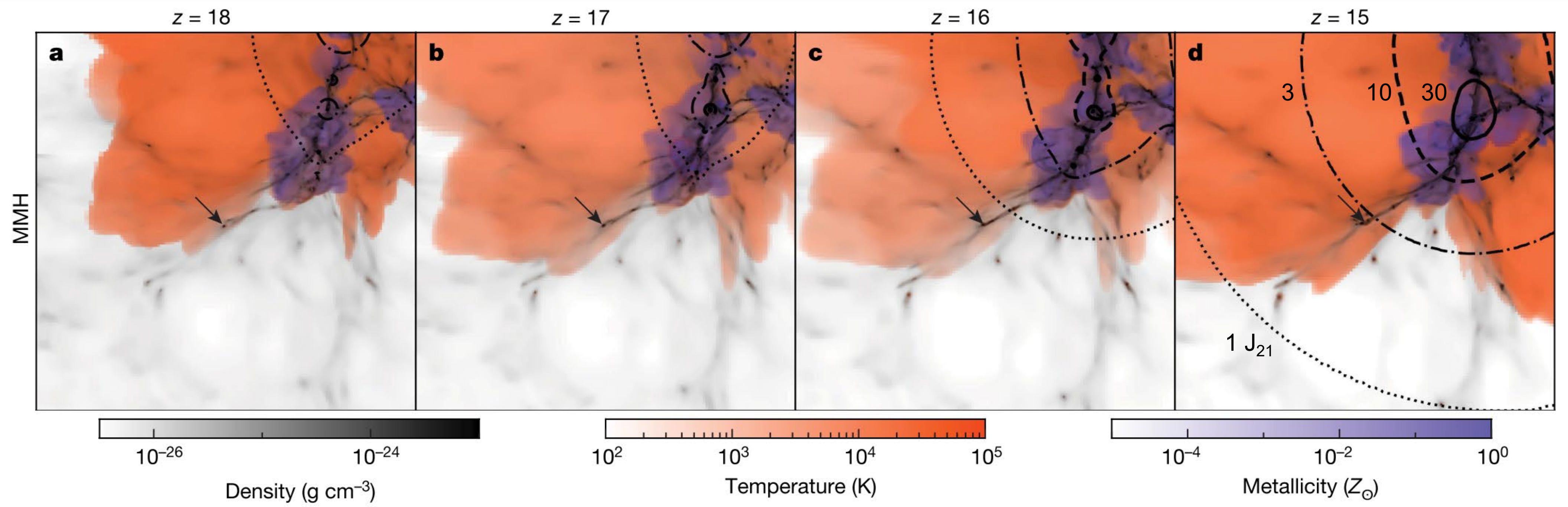
- **#1 condition: Avoid fragmentation**
- **#2 condition: High accretion rates (>0.04 $M_\odot$/yr)** → Atomic cooling halo
- Metal-free → Far from massive stars
- Molecule-free → Strong radiation intensity (>100 J_{21}) → Close to sources
- Previously proposed scenario: “close pair” galaxy formation
- *Just the right distance* away from a young massive galaxy



Massive Black Hole Seeds

Wise+ (2019, Nature)

New scenario: rapid halo growth & "dynamical heating"



40 kpc

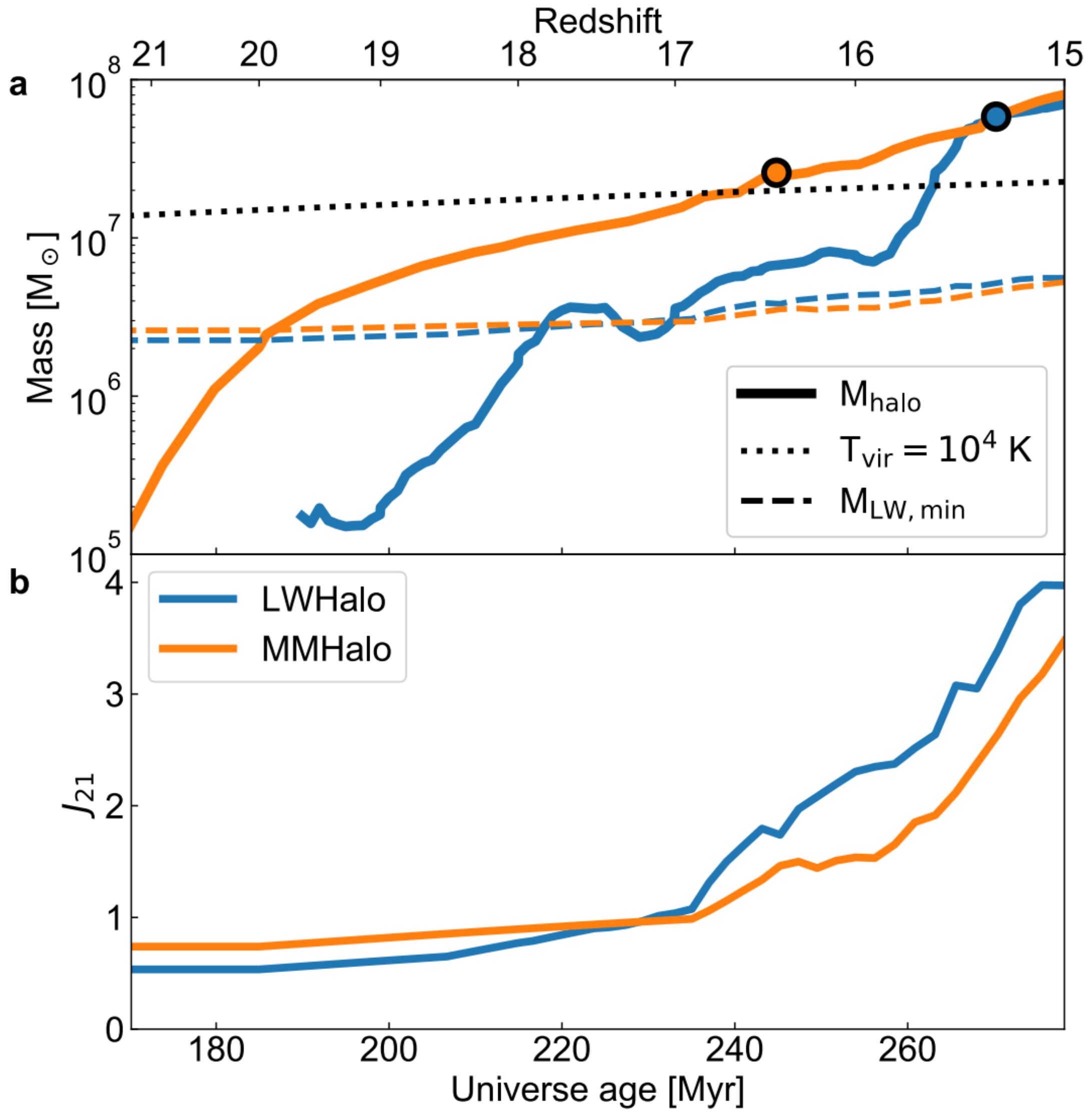
- Moderate (~3 J_{21}) radiation background required
- Forms 10-25 kpc away from young galaxies
- No "close pair" scenario needed
- Halo undergoes rapid growth that suppresses H_2 cooling
- Naturally occurring in CDM

Massive Black Hole Seeds

Wise+ (2019, Nature)

New scenario: rapid halo growth & "dynamical heating"

- Found 10 metal-free and star-less halos above the atomic cooling limit (T_{vir} = 10^4 K) out of 670. Re-simulated two halos at high resolution
- Can "jump" from Pop III star forming to DCBH forming mass range
- Forms $10^3 - 10^4\ M_\odot$ supermassive stars and subsequent DCBHs
- Most likely not the seeds of $z \gtrsim 6$ SMBHs because they exist far from massive galaxies. Faint high-z QSOs?



Massive Black Hole Seeds

Wise+ (2019, Nature)

New scenario: rapid halo growth & “dynamical heating”

Summary

- **Population III Stars**
  - Simulations suggest a top-heavy mass function
  - Provides pre-enrichment for the first galaxies; reduces initial gas fraction
- **Transition to metal-enriched star formation**
  - Internal enrichment: fallback of SN ejecta. [Z/H] ~ -3
  - External enrichment: rare. Incomplete mixing. [Z/H] $\lesssim -3$
- **First generations of galaxies**
  - Luminosity function flattening at $M_{UV} \gtrsim -14$ (efficient $\rightarrow$ inefficient SF)
  - Metal-enriched stars form in ~10% of halos below the atomic cooling limit
- **Massive black hole seeds (10^3 - 10^5 $M_\odot$)**
  - Product of structure formation (rapid growth or streaming velocities)
  - Most likely SMBH seeds. May or may not grow, creating a diversity in $M_{BH} - M_{star}$ relation