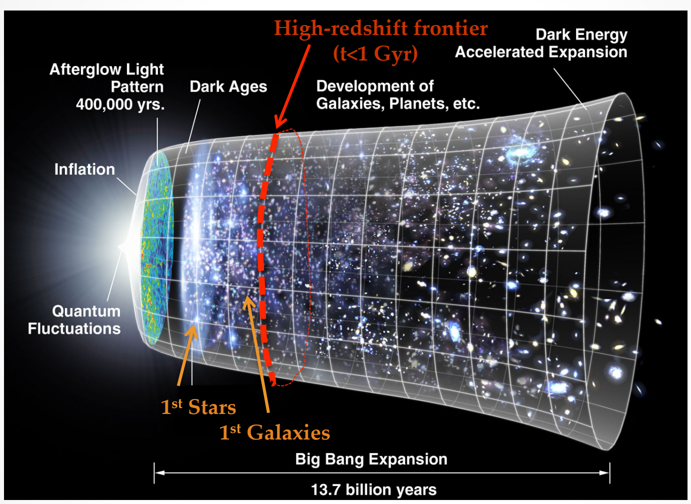
32nd IAP Colloquium
Cosmic Dawn, June 2016

Theory of the First Galaxies: Status and Challenges

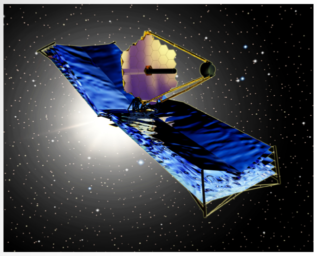
Volker Bromm
Department of Astronomy
University of Texas at Austin

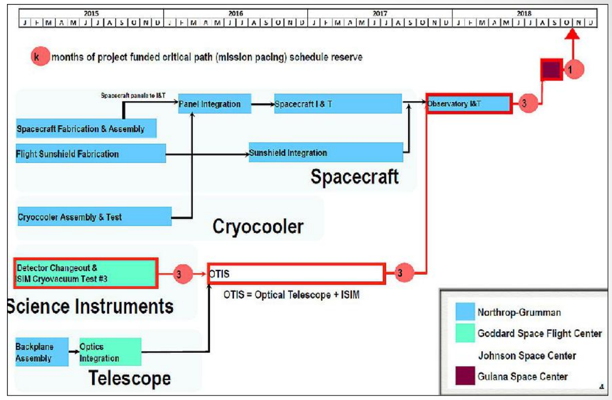
From the Dark Ages to the Cosmic Renaissance



- First Stars (Pop III) → From Simplicity to Complexity

The James Webb Space Telescope





→ **We are getting really close (launch=Oct. 2018)**

Star Formation from Cosmological ICs

→ Properties of First Stellar Systems

- *ab initio* star formation (or: the *Laplace Demon* at work)

Input:

Ω_B, Ω_Λ, Ω_m, σ_8, n_s, H_0, abundances

Laws of nature

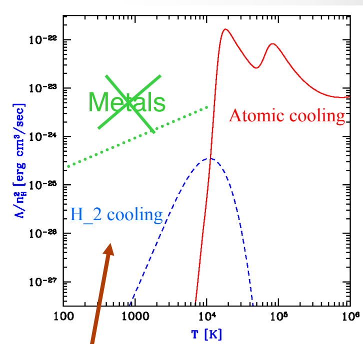
(supercomputer)

Output:

Stellar IMF, SFE, Multiplicity,…

Cooling Channels in the Early Universe:

- First Stars:
  - formed in minihalos (~ $10^6 M_o$)
  - T_{vir} ~ few 1,000 K
  - cooling → molecular hydrogen
- First Galaxies:
  - formed in deeper potential wells (~ $10^8 M_o$)
  - T_{vir} > 10,000 K
  - cooling → atomic hydrogen

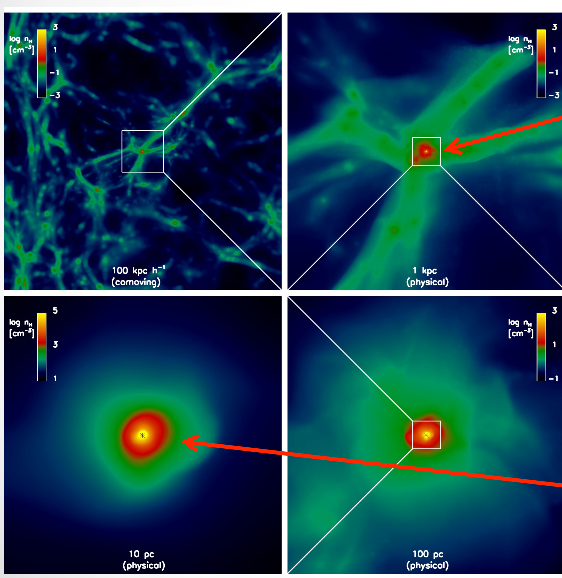


T_{vir} for Pop III

→Thermal evolution may be very different for the two regimes!

Formation of a Population III Star:

(Stacy, Greif & Bromm 2010, MNRAS, 403, 45)



Minihalo:

$M \sim 10^6 M_o$

$R \sim 100$ pc

$z \sim 20$

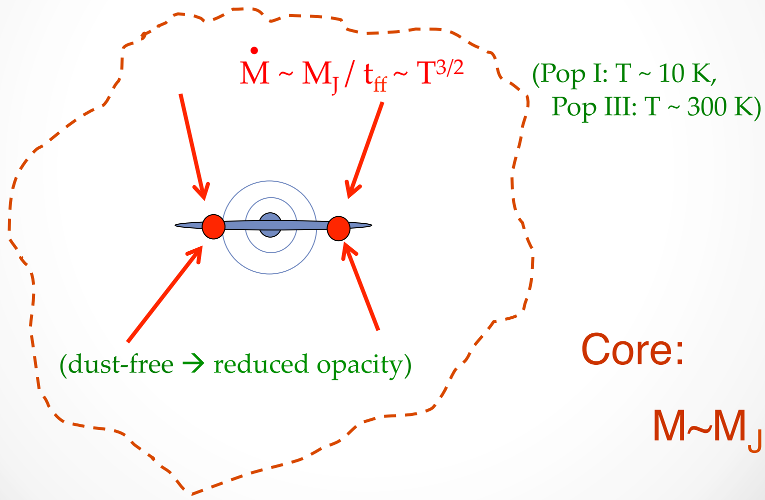
(Pre-stellar) Core:

$M \sim 10^3 M_o$

$R \sim 1$ pc

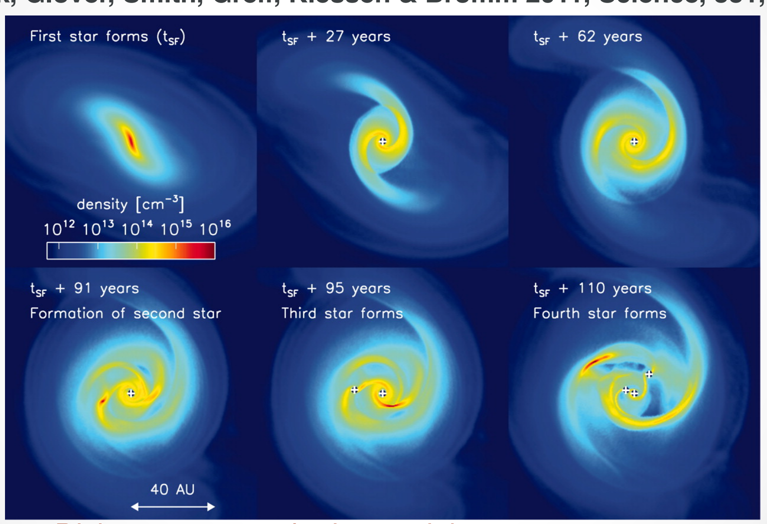
Standard Model for Pop III SF:

- (Ubiquitous) Disk Fragmentation → small multiple



Pop III Star Formation: Disk Fragmentation

(Clark, Glover, Smith, Greif, Klessen & Bromm 2011, Science, 331, 1040)

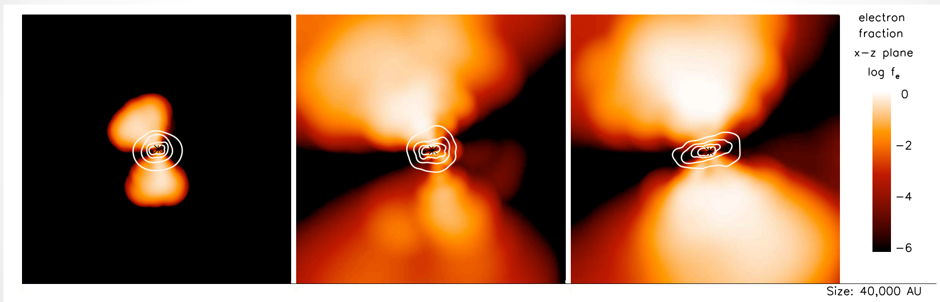


- Disk grows around primary sink
- Disk is gravitationally unstable: small multiple forms

Pop III IMF: Radiative Feedback

(Stacy, Greif & Bromm 2012, MNRAS, 422, 290)

1,500 yr   2,000 yr   3,000 yr



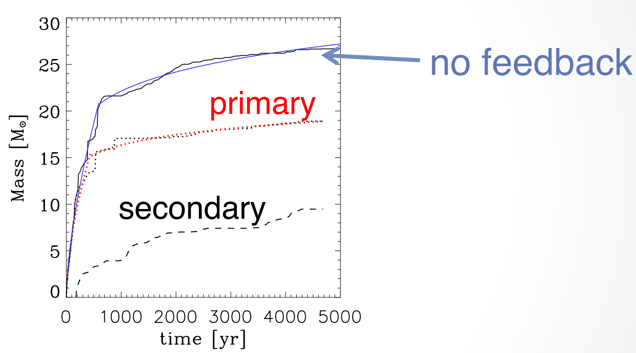
40,000 AU

- after ~5,000 yr: UCHII Region with r~10^4 AU

Pop III Star Formation: Growth by Accretion

(Stacy, Greif & Bromm 2012, MNRAS, 422, 290)

Stellar mass vs. time

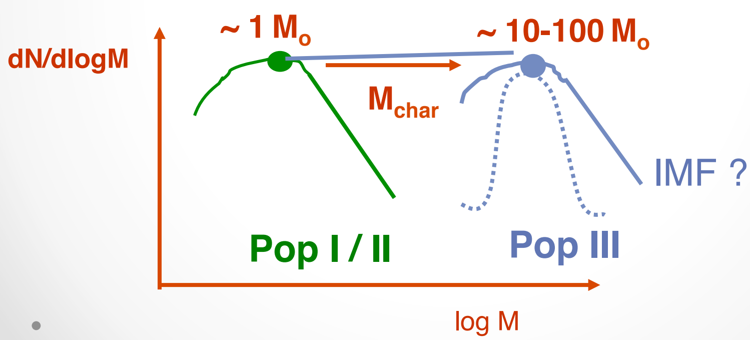


- a dominant binary has formed (~ 20 and ~10 M_O) after ~5,000 yr of accretion

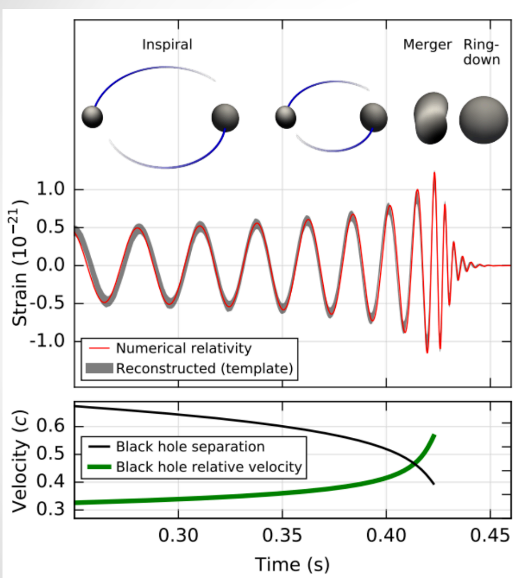
- Similar mass range found in Hosokawa et al. 2011 (Science)

The First Stars: Final IMF

- Numerical simulations
  - Bromm, Coppi, & Larson (1999, 2002)
  - Abel, Bryan, & Norman (2000, 2002)
  - Nakamura & Umemura (2001, 2002)
  - Yoshida et al. (2006, 2008); O' Shea & Norman (2007); Gao et al. (2007)
  - Clark et al. (2011); Greif et al. (2011, 2012); Stacy et al. (2010,12,13,14,16)
  - Hosokawa et al. (2011,16); Latif et al. (2013); Susa (2013); Hirano et al. (2014)
- Likely Outcome: → **Top-heavy initial mass function (IMF)**



Gravitational Wave (GW) Archaeology

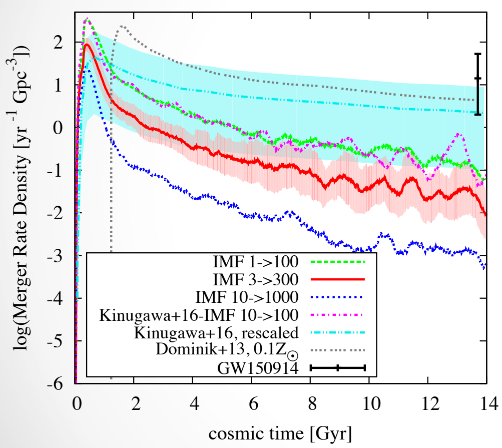


(Abbott et al. 2016, PRL, 116, 061102)

- LIGO: GW150914
  - inspiral and merger of BH-BH binary with
    → M_1=36 $M_\odot$
    → M_2=29 $M_\odot$
  - Big Q: Where did system originate?

GWs from the Remnants of the First Stars

Merger Rate vs. Cosmic time



- LIGO GW150914:

- Pop III BH-BH could possibly provide source

- But: Multiple other scenarios proposed!

- Break degeneracy with better statistics (incidence of very massive BHs)

- Hartwig et al. 2016, MNRAS, 460, L74

The First Galaxies

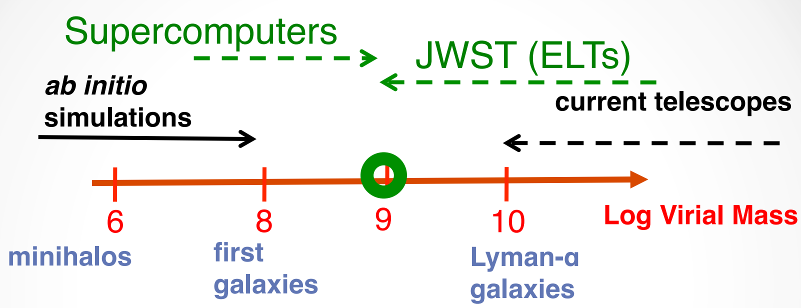
- Definition:
  - Can survive stellar feedback?
  - Self-regulated SF ⟶ establish multi-phase ISM?
  - Formation of low-mass stars?
  - SF does not rely on H2 ⟶ atomic H cooling?

- Tentative definition often used:

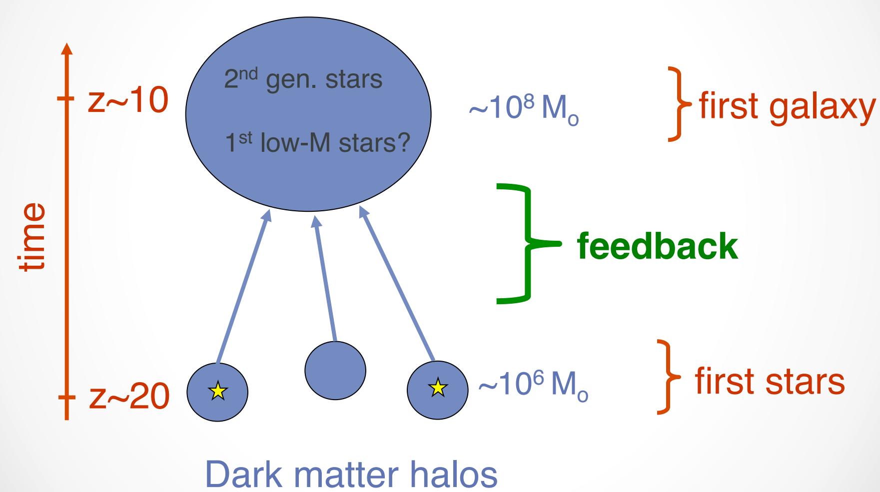
  - First Galaxies = "Atomic cooling halos"

    → M_{vir}~10^8 M_o , z_{vir} ~ 10 -15 (~2σ peaks)
    → T_{vir} ~ 10^4 K ⟶ atomic H cooling enabled!

Theory/Observations: "Mass Gap"



Initial Steps of Hierarchical Structure Formation



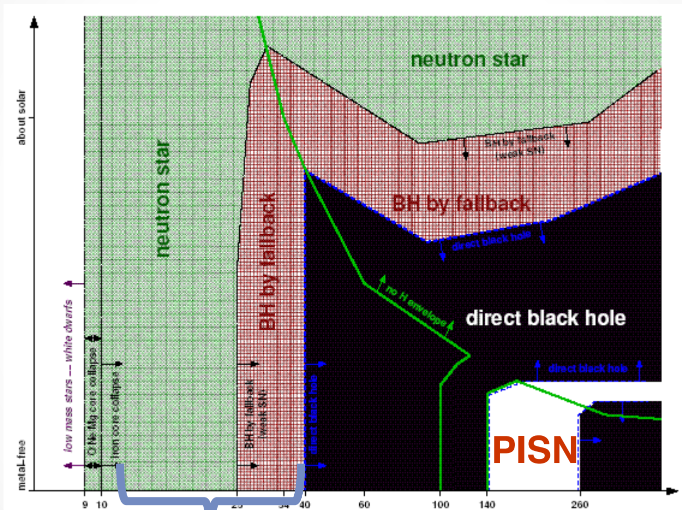
The Death of the First Stars

(Heger et al. 2003; Maeder & Meynet 2012 → include rotation)

Pop I

Z

Pop III



CCSN

Initial Stellar Mass

BH Feedback and Early Galaxy Formation

→ See Marta Volonteri's talk!

Di Matteo et al. 2005

- Input of heat, pervasive (partial) ionization
- Feedback: positive or negative?

-Vigourosly explored, e.g.:
- Ricotti & Ostriker 2004; Kuhlen & Madau 2005; Zaroubi et al. 2007; Alvarez et al. 2009; Mirabel et al. 2011; Park & Ricotti 2011

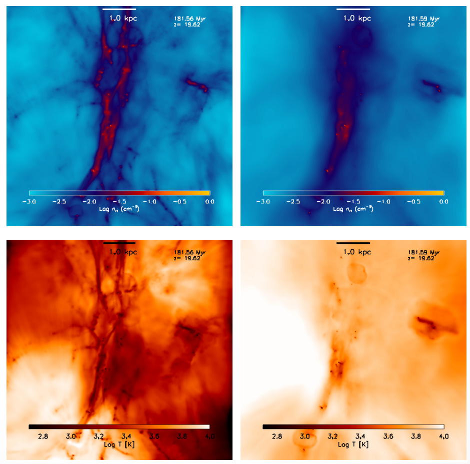
First Galaxies: Assembly with BH Feedback

(Jeon, Pawlik, Bromm, & Milosavljevic 2014, MNRAS, 440, 3778)

no HMXB | with HMXB

Gas density

Gas temperature



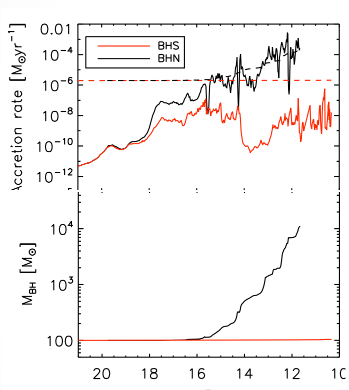
- High-Mass X-ray Binary (HMXB) → Mirabel et al. (2011); Fragos et al. (2013)

BH Feedback: Suppression of Seed Growth

(Jeon, Pawlik, Greif, Glover, Bromm, Milosavljevic & Klessen 2012, ApJ, 754, 34)

Accretion Rate

BH Mass



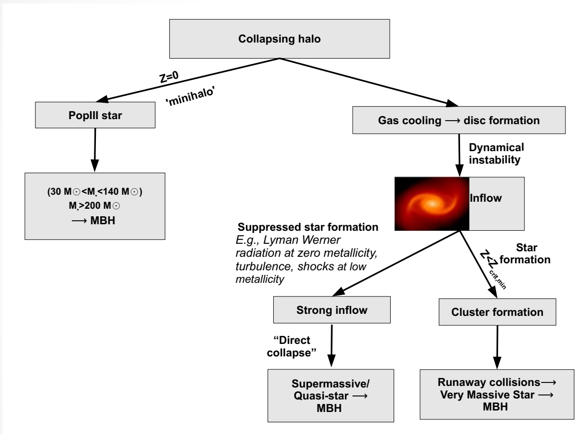
- - - Eddington-limited rate

- Negligible growth of central BH when it is radiatively active
- Significantly sub-Eddington
- Need for more exotic pathway → direct-collapse BH?

(Bromm & Loeb 2003; review of recent developments → Volonteri & Bellovary 2012)

What are seeds for SMBHs at high-z?

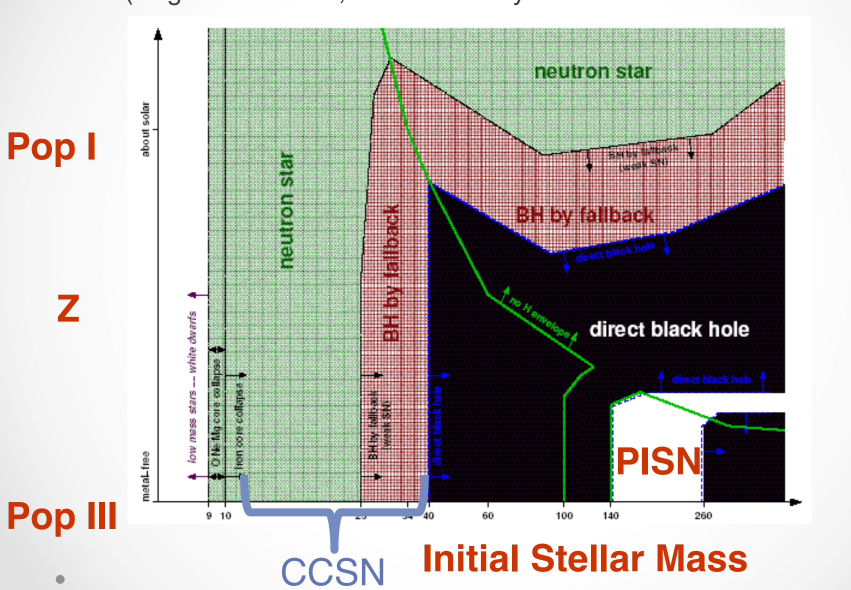
(Volonteri 2012; see also next talk!)



- Promising seed mechanism for early SMBHs:
  → direct collapse BHs (near-isothermal collapse of primordial gas into atomic-cooling halos)

The Death of the First Stars

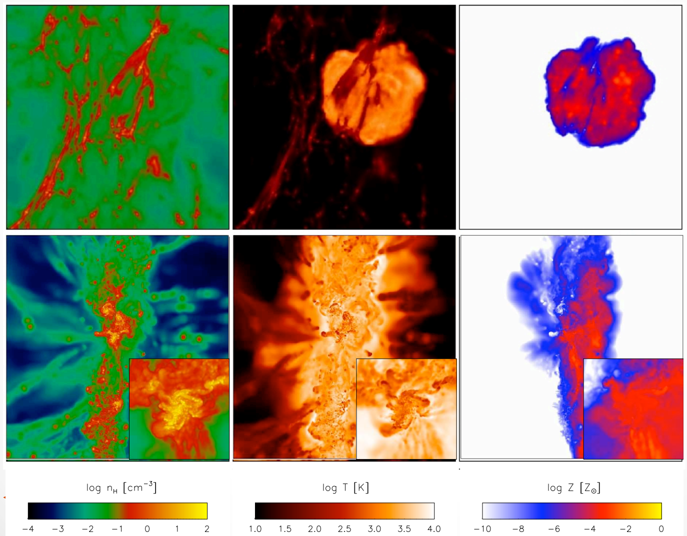
(Heger et al. 2003; Maeder & Meynet 2012 → include rotation)



Pop III SN Feedback: PISN case

(Greif et al. 2010, ApJ, 716, 510)

Gas density Temperature Metallicity



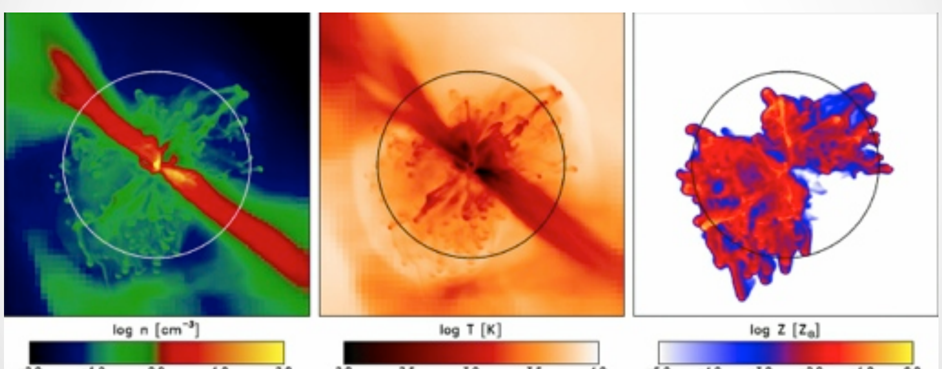
15 Myr

300 Myr

Pop III SN Feedback: Core-collapse

(Ritter, Safranek-Shrader, Gnat, Milosavljevic, Bromm 2012, ApJ, 761, 56)

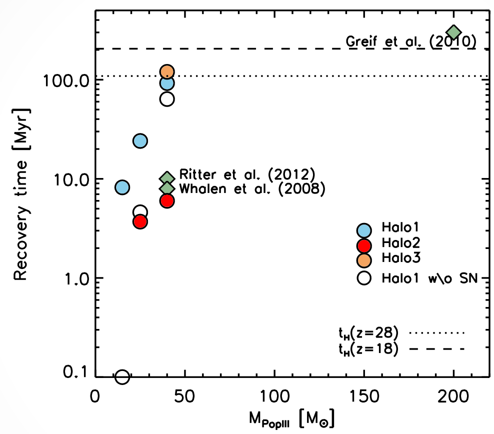
- FLASH/AMR, cosmological ICs
- Less-extreme mass (40 $M_\odot$) → core-collapse SN



• Situation ~ 8.5 Myr after explosion

Cadence of Early Star Formation

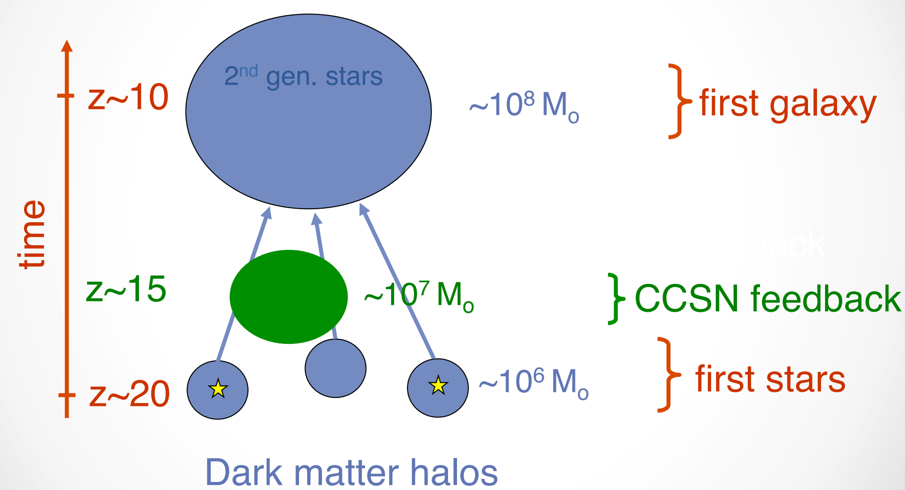
(Jeon et al. 2014, MNRAS, 444, 3288)



- "Recovery time"= time delay between first and second burst (generation) of star formation

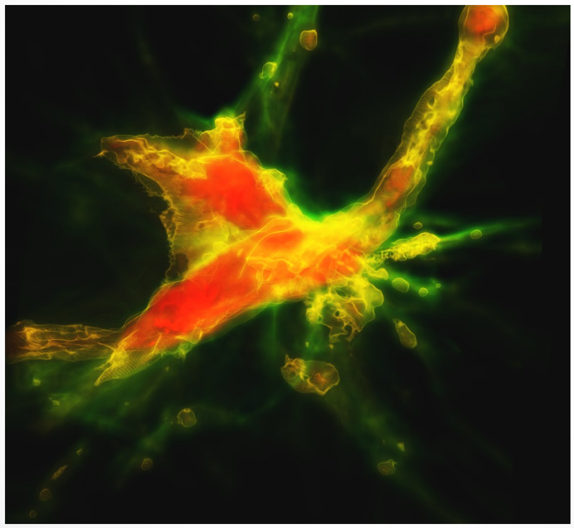
→ strong dependence on Pop III progenitor mass!

Assembly of the First Galaxies



Predicted Properties of the First Galaxies

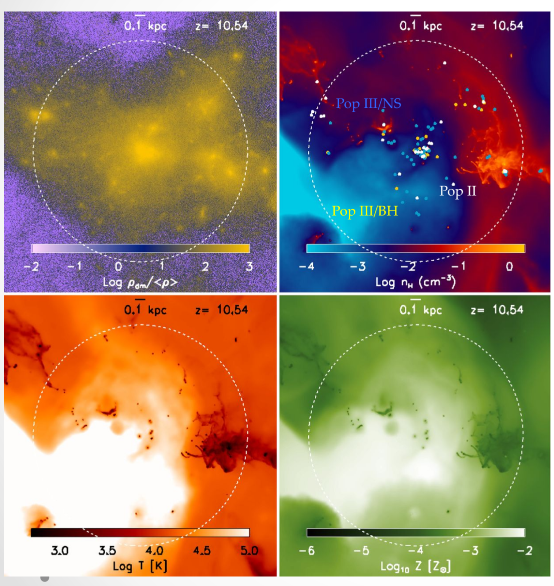
~ 10 kpc



- color indicates temperature (bright red = 10,000 K)

Assembly of the First Galaxies

(Jeon, Bromm, Pawlik & Milosavljevic 2015, MNRAS, 452, 1152)



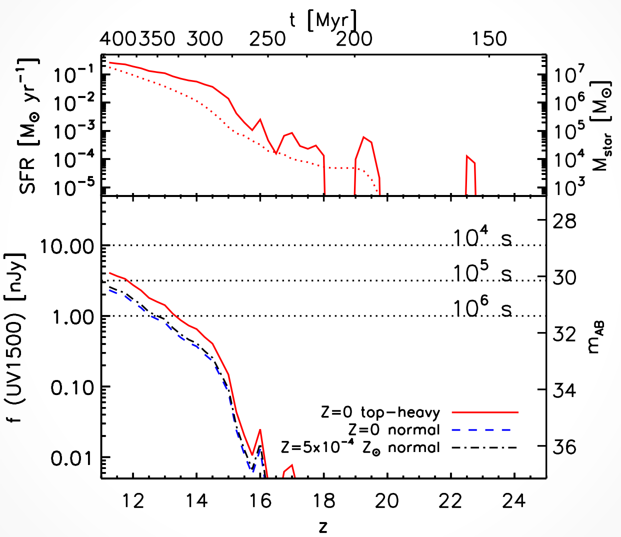
- SPH/TRAPHIC, cosmological ICs
- galaxy collapses at z~10

- Self-consistent feedback
→ One-star-at-a-time

- Ubiquitous metallicity floor
→ First galaxies are pre-dominantly Pop II systems

Observability with the JWST

(Pawlik et al. 2013, ApJ, 767, 59)

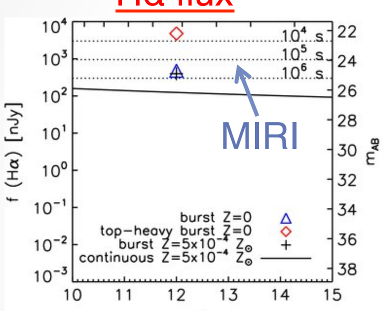


- From episodic to self-regulated SF!

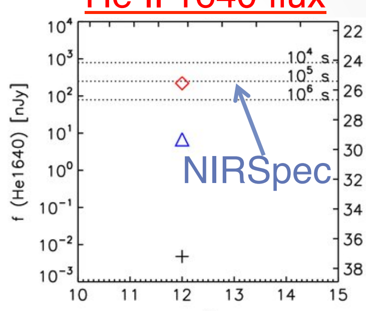
Detecting the First Galaxies with JWST

(Pawlik, Milosavljevic, & Bromm 2011, ApJ, 731, 54)

Hα flux



He II 1640 flux



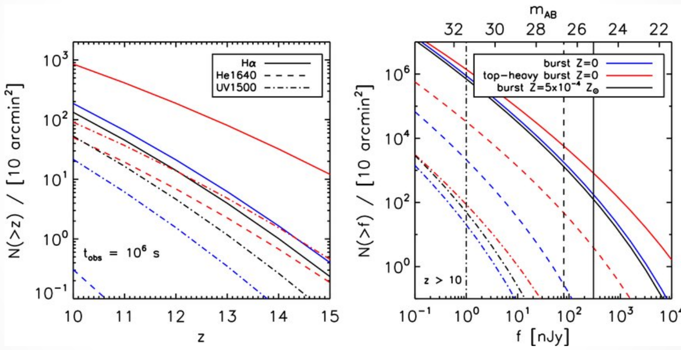
- JWST may diagnose stellar population (Pop III vs. Pop II; top-heavy vs. normal IMF)

Detecting the First Galaxies with JWST

(Pawlik, Milosavljevic, & Bromm 2011, ApJ, 731, 54)

N(>z) vs. z

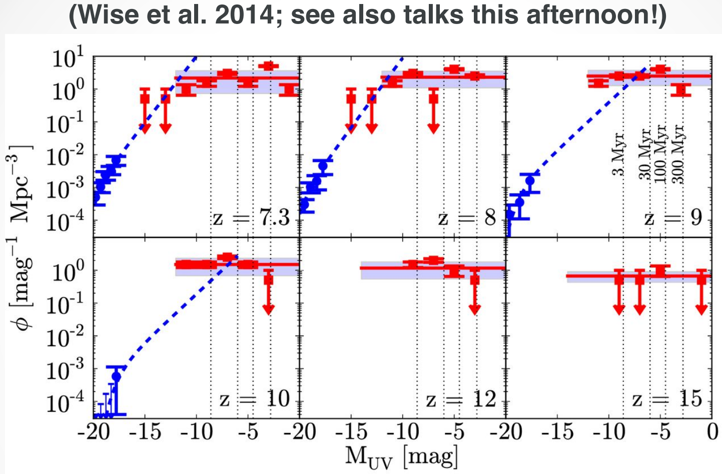
N(>f) vs. f



- JWST may detect ~10-1000 starbursts at z>10

UV Luminosity Function at high z

(Wise et al. 2014; see also talks this afternoon!)

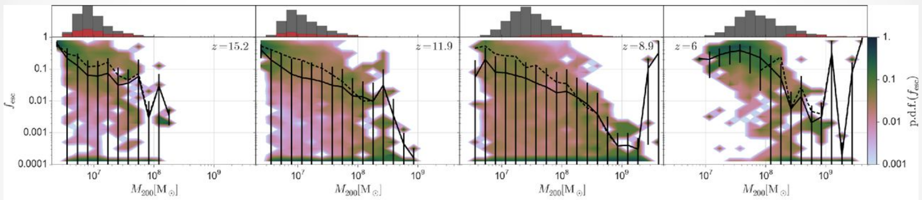


- Turnover at M_{UV}~ -12 ?

Escape Fraction in the First Galaxies

(Paardekooper et al. 2015; see Sadegh Khochfar's talk!)

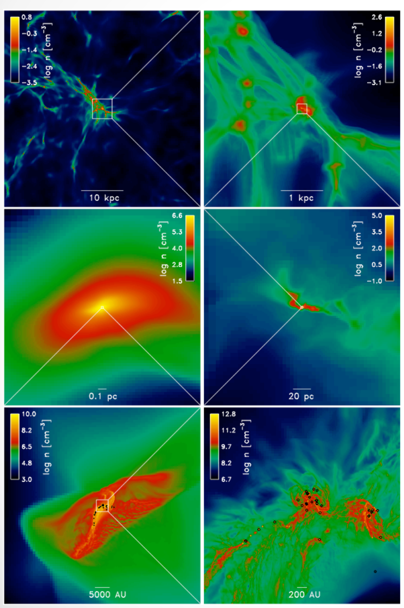
Escape fraction vs. host halo mass



- Physics of the escape fraction is messy! *Not* a single number!

Star Formation in the First Galaxies

(Safranek-Shrader, Milosavljevic & Bromm 2014a, 2014b)



← **(Projected) Gas Density**

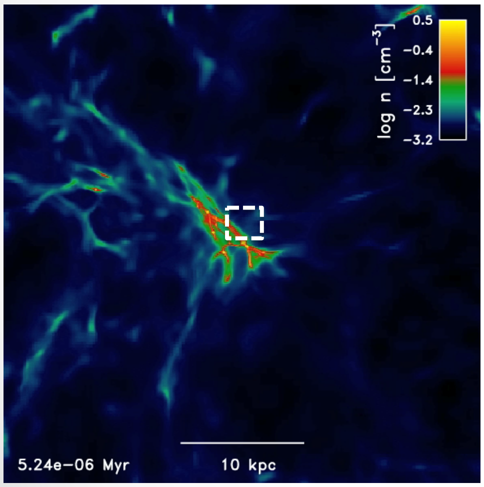
- FLASH/AMR, cosmological ICs
- Atomic Cooling halo at z~15
- pre-enriched to $Z=10^{-2}\ Z_\odot$

→ Pop II (low-mass) SF

Star Formation in the First Galaxies

(Safranek-Shrader, Milosavljevic & Bromm 2014a, 2014b)

(Projected) Gas Density



- FLASH/AMR, cosmological ICs
- Atomic Cooling halo at z~15

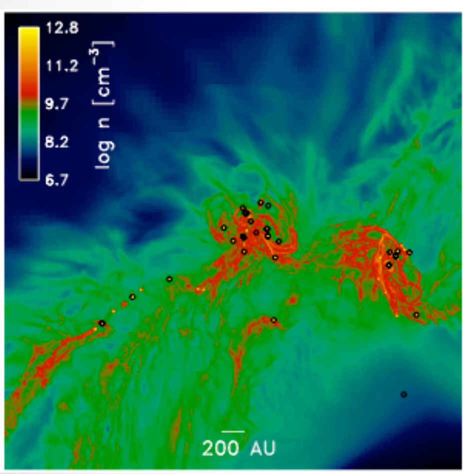
- pre-enriched to $Z=10^{-2}\,Z_{\odot}$

→ Pop II (low-mass) SF

Star Formation in the First Galaxies

(Safranek-Shrader, Milosavljevic & Bromm 2014a, 2014b)

(Projected) Gas Density



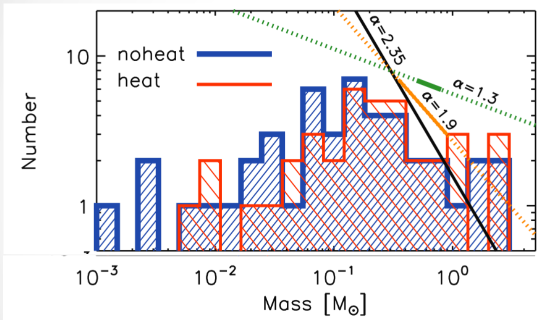
- High-resolution cut-out of pre-stellar clump
- form opacity-limited fragments

→ protostars

- Follow accretion for ~10^4 yr

SF in the First Galaxies: Pop II IMF

(Safranek-Shrader, Milosavljevic & Bromm 2014a, 2014b)

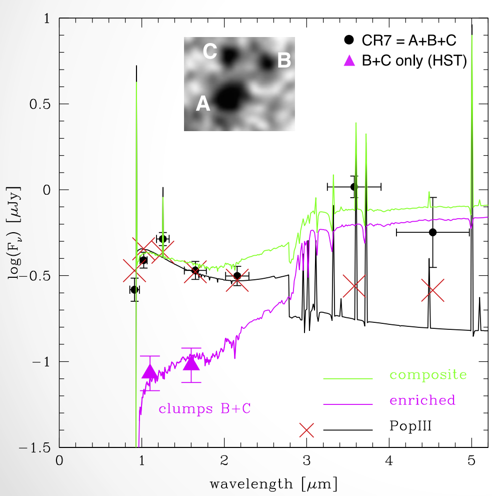


- flattened power-law ($\alpha \approx 1.3$)
- empirical hints in ultra-faint dwarfs (UFDs)
  - - - Leo IV (Geha et al. 2013)
- for comparison:
  - - - SMC (Kalirai et al. 2013)
  - --- Salpeter

Are First Galaxies really all enriched already?

→ The curious case of "COSMOS Redshift 7" (CR7)

(Sobral, Matthee, et al. 2015, ApJ, 808, 139)

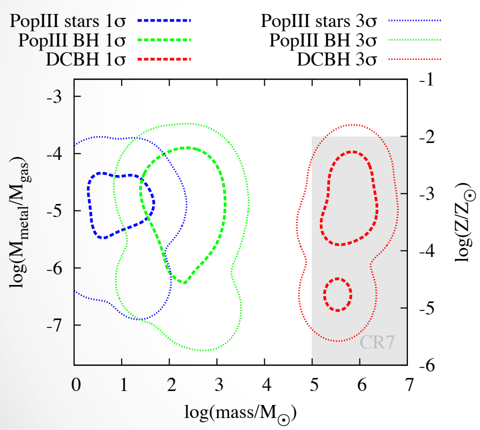


- Luminous Lyα emitter at z=6.6 ($L_{Ly\alpha} \approx 10^{44}$ erg s^{-1})
- Also: strong HeII 1640Å ($L_{1640} \approx 10^{43}$ erg s^{-1})
  => $T_{eff} \sim 10^5$ K
- 3-component system:
  - --- B+C: enriched (Pop II)
  - --- A: only upper limits on Z
  - => Pop III ???

The curious case of CR7

→ Not Pop III Stars but "Direct Collapse BH"!?

(Hartwig et al. 2015; arXiv:1512.01111)

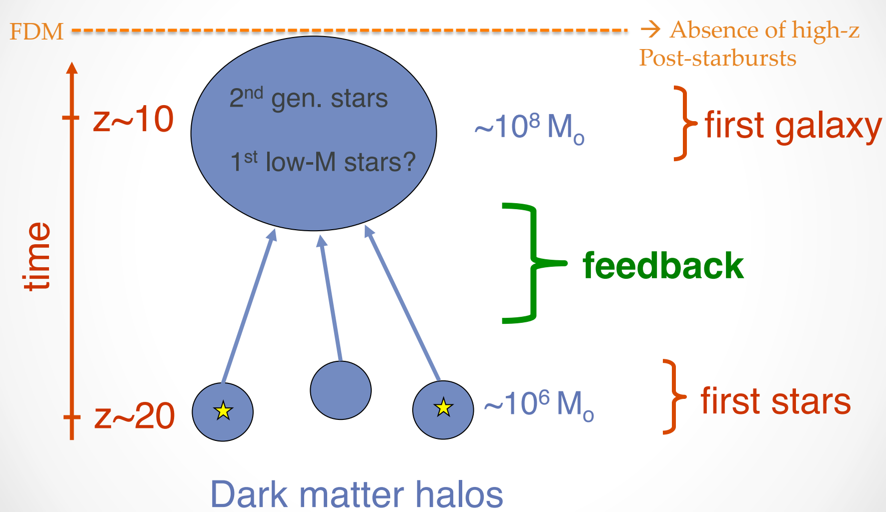


- Need to reconcile high luminosity with "metal tax" (=assembly of massive source will inevitably imply enrichment)
- DCBH plausible candidate for ~metal-free, massive system

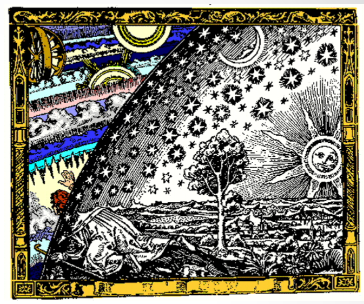
=> Observational agenda:
- deeper NIR spectra
- radio, X-ray

- (see also: Agarwal et al. 2016; Pallottini et al. 2015; Smidt et al. 2016)

Sensitivity to Small-scale Nature of DM



Perspectives:



- Very dynamic, rapidly developing field
- Closing the final gap in our worldview
- Driven by supercomputers and our best telescopes
- The high-redshift frontier: How did it all begin?

Reviews:

- Bromm & Yoshida 2011, ARA&A, **49**, 373
- Karlsson, Bromm, & Bland-Hawthorn 2013, Rev. Mod. Phys., **85**, 809
- Bromm 2013, Rep. Prog. Phys., **76**, 112901

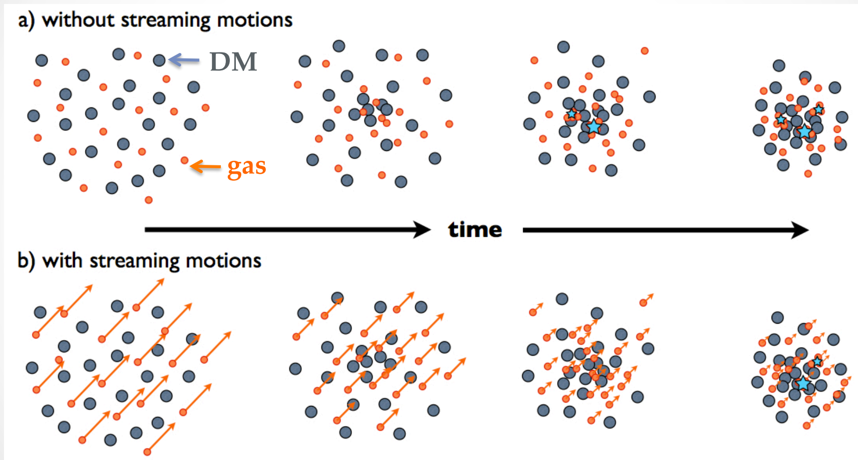
Relative Baryon-DM Streaming

(Tseliakhovich & Hirata 2010; Tseliakhovich et al. 2011)

- Before recombination, baryons tightly coupled to photons → standing acoustic wave pattern
- CDM already decoupled earlier
- Results in v_{stream}~30 km s^{-1}, coherently on scales of few Mpc (comoving)
- After recombination, baryonic c_s~ 6 km s^{-1} → v_{stream} highly supersonic!

Relative Baryon-DM Streaming

(Tseliakhovich & Hirata 2010; Tseliakhovich et al. 2011)

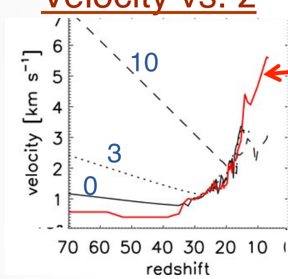


→ **Delayed Onset of (Pop III) Star Formation!**

Pop III SF with Baryon-DM Streaming

(Stacy, Bromm & Loeb 2011, ApJ, 730, L1)

Velocity vs. z



Virial velocity

"Effective velocity":

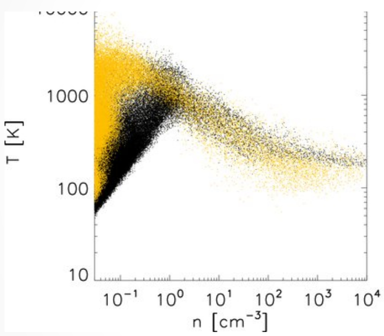
$$v_{\rm eff} = \sqrt{c_s^2 + v_s^2},$$

- Streaming delays collapse (and onset of Pop III SF)
- Similar Studies:
  - Maio et al. 2011, MNRAS, 412, L40
  - Greif et al. 2011, ApJ, 736, 147
  - Naoz et al. 2012, ApJ, 747, 128; 2013, ApJ, 763, 27

Pop III SF with Baryon-DM Streaming

(Stacy, Bromm & Loeb 2011, ApJ, 730, L1)

T vs. n



- no streaming
- with streaming (v_s~10 km s^{-1})

- Thermodynamic evolution quickly converges!