Stellar Archaeology as a Time Machine to the First Stars

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Connecting the first galaxies with ultra faint dwarfs in the Local Group

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From first stars to local dwarfs

First stars (Pop III stars, >100 M\(_\odot\))

- at z>15, primordial gas in minihaloes (M\(_{\text{vir}}\) = 10\(^{5-6}\) M\(_\odot\))

Second gen. of stars (Pop II stars, \(\sim 1\) M\(_\odot\))

- Pop II stars could contain chemical signatures of Pop III stars.
- Low-mass Pop II stars survive until today – we observe those.

First galaxies

- at z\(\sim\)15, M\(_{\text{vir}}\) < 10\(^{8-9}\) M\(_\odot\) (JWST, GMT)

No or a little additional star formation

Dwarf galaxies could preserve chemical signatures of early stars.

Fossil galaxies?

First stars & Galaxies (t\(_H\) \(\sim\) a few 100 Myr)

Reionization (t\(_H\) \(\sim\) 1 Gyr)

Today z=0
Dwarf galaxies as a time machine
Stellar Archaeology

No/a little star formation for ~ 13 Gyr

Ultra faint dwarf galaxies (UFDs) from > 70% of stars at high-z.
- Reionization
- Supernova feedback
- Environmental effect

: see Eline Tolstoy’s talk

Weisz et al. 2017
Key Questions

(1) Which physical processes played an important role in determining star formation histories (SFHs) in UFDs?

(2) Can we reproduce the chemical abundances of observed UFDs from cosmological simulations?

(3) What will be the mass scale of the galaxies that show ‘pure’ signatures of Pop III stars?
Simulated Dwarfs

Characteristics of the simulated UFD analogs at $z = 0$.

<table>
<thead>
<tr>
<th>Halo</th>
<th>$M_{\text{vir}}$ $[10^9 M_{\odot}]$</th>
<th>$r_v$ [kpc]</th>
<th>$M_*$ $[10^4 M_{\odot}]$</th>
<th>$D_h$ [Mpc]</th>
<th>$f_b$ [%]</th>
<th>$r_{1/2}^*$ [pc]</th>
<th>[Fe/H]</th>
<th>[$\alpha$/Fe]</th>
<th>$\sigma_*$ [kms$^{-1}$]</th>
<th>SF$_{\text{trun}}$</th>
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<tr>
<td>halo1</td>
<td>1.53</td>
<td>23.7</td>
<td>4.3</td>
<td>0.6</td>
<td>0.08</td>
<td>345</td>
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<tr>
<td>halo2</td>
<td>1.53</td>
<td>23.5</td>
<td>3.8</td>
<td>2.0</td>
<td>0.07</td>
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<td>6.0</td>
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<tr>
<td>halo3</td>
<td>1.60</td>
<td>23.9</td>
<td>8.2</td>
<td>2.1</td>
<td>0.1</td>
<td>296</td>
<td>-2.28</td>
<td>0.52</td>
<td>6.7</td>
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<tr>
<td>halo4</td>
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<td>26.6</td>
<td>13.0</td>
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<tr>
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<td>20.0</td>
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<td>88.6</td>
<td>3.7</td>
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<td>0.47</td>
<td>11.6</td>
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</tr>
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</table>

(Jeon, Besla & Bromm, 2017)
Simulation detail

- Gadget-3
- Resolution: 500 $M_\odot$ (gas), $\sim$2000 $M_\odot$ (DM)

- Star formation:
  - Schmidt law
  - Density threshold of $n_H = 100$ cm$^{-3}$, critical metallicity $Z_{\text{crit}} = 10^{-5.5}Z_\odot$ (PopII/I)
  - Pop III: top-heavy IMF, [10, 150] $M_\odot$
  - Pop II/I: Chabrier IMF, [0.1, 100] $M_\odot$

- SNe feedback: thermal energy
- Non-equilibrium cooling, UV photoheating (Haardt & Madau 2011),
- reionization ($z=7-6$),
- self-shielding of the dense gas

- SNe yield: C, O, Mg, Ne, Si, Iron (Wiersma et al. 2009)
  PopIII Pair-instability SNe (PISNe): Heger & Woosely (2002)
  PopIII Core-collapse SNe (CCSNe): Heger & Woosely (2010)
  PopII: Marigo (2001), Portinari (1998), Thielemann et al. 2003

- Metal mixing: diffusion method, diffusion coefficient $D \sim \rho \times \text{velocity} \times l$
  (Greif et al. 2009)
Mass resolution (gas): 500

Stellar Mass: $7 \times 10^4$

DM Temp.  

Gas Density  

Density  

Metals
Mass Growth

Total mass

Gas mass

Pop III era

Atomic cooling halo

(Jeon, Besla & Bromm, 2017)
Truncated star formation haloes by reionization

Quenching of SF by reionization and SNe in low-mass galaxies \((M_h < 2 \times 10^9 \, M_\odot)\)
Continuous SF in galaxies \((M_h > 3-4 \times 10^9 \, M_\odot, \, M_{HI} \sim 10^5 \, M_\odot; \, \text{Leo P, Leo T})\)

(Jeon, Besla & Bromm, 2017)
Stellar abundances: signatures of PopIII SNe - external metal enrichment

- CEMP–Pop III SNe - external metal enrichment
- Carbon-normal – self-enrichment via Pop II SNe.

- Alpha-elements are enhanced, meaning that they were mainly enriched by Type II SNe from PopIII and PopII stars.

(Jeon, Besla & Bromm, 2017)
Stellar abundances (Halo5: $M_{\text{star}}=2 \times 10^5 \, M_\odot$)

**Carbon**

**Alpha-elements**

(CEMP: $[\text{C/Fe}] > 0.7$

Type Ia SNe

(Jeon, Besla & Bromm, 2017)
Presence of metal-poor stars

Low metallicity stars were formed in minihalos at high-z via external metal-enrichment.

Metal poor stars, $[\text{Fe/H}<-3]$, were mainly formed via external metal enrichment.

(Jeon, Besla & Bromm, 2017)
Multiple vs. mono enrichment

Pop III signatures is dominated

Pop II signatures is dominated
Do we need smaller galaxies?

$M_{\text{gas}} \sim 63 \, M_{\odot}$, $M_{\text{DM}} \sim 260 \, M_{\odot}$, with/without photoionization heating (RT)

(Preliminary)

(Jeon, Besla & Bromm, 2017, Jeon et al., in prep.)
Abundance from a single Pop III SN

- $M_{\text{halo}} \approx 10^9 \, M_\odot \,(z=0)$, multiple metal enrichment
- $M_{\text{halo}} \approx 10^8 \, M_\odot \,(z=0)$, maybe a mono enrichment is possible.

Jeon et al. (in prep.)

$M_{\text{PopIII}} = 38 \, M_\odot$, $M_{\text{halo}} = 10^8 \, M_\odot$
The other probe of first stars

Metal poor stars

[Fe/H \] < -2
at z=0

Metal poor gas

[Fe/H \] < -2
at z=0 - 4
Damped Lyman alpha system (DLAs)

Gas with neutral hydrogen column density of $N_{\text{HI}} \sim 10^{20.3}\ \text{cm}^{-2}$
Metal-poor DLAs as another probe of first stars

The origin of the DLA.

Q: Can the progenitors of local, gas-rich dwarf galaxies possibly be detected as DLA systems over cosmic time?

Q: Is it the gas at z=3 that could contain the signatures of Pop III?

[Fe/H] ~ -3 at z=3, $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$ (Cooke et al. 2017)

“Gas polluted by metals from 20.5 $M_\odot$ Pop III star?”
Neutral gas in dwarfs

- Gas-rich dwarf
- $M_{\text{HI}} \sim 10^5 \, M_\odot$ (similar to field dwarfs - Leo P, Leo T.)

Jeon, Besla & Bromm, 2018 (submitted)
Can do dwarfs contain Pop III DLAs?

- The progenitors of local dwarfs are expected to be seen for most of their evolution as DLAs that are contaminated by Pop II stars.

- Pop III DLA could exist at high-z ($z > 7$).

- Extremely metal poor DLA ($[\text{Fe/H}] \sim -3$ at $z=3$, $N_{\text{HI}} \sim 10^{21} \text{ cm}^{-2}$) is hard explain in the context of dwarf galaxy assembly.

- Rather metal-poor DLAs are likely to be located at the outskirts of massive galaxies.

Jeon, Besla & Bromm, 2018 (submitted)
It is important to understand the nature of metal-poor stars in the context of the assembly process of dwarf galaxies.

**UFDs**: one of the best places to look for the metal poor stars that hold clues to the nature of the first generating of stars.

- **Our simulations show that**
  - reionization and supernova feedback played an important role in suppressing star formation in UFDs.
  - **pop III stars and the external metal-enrichment** is important in producing low-metallicity stars ([Fe/H]<-4), and for the origin of CEMP\textsc{s}.
Thank you!