The Collapse of First Objects driven by Dark Matter Cusps

Masayuki Umemura
University of Tsukuba, Center for Computational Sciences

Collaborators
Tamon Suwa
Hajime Susa
Minimum Mass of First Objects


SPH & Galli-Palla cooling function

SPH & Galli-Palla cooling function

\( M_{\text{min}} \approx 5 \times 10^4 M_\odot \) (z=100)

\[ - 5 \times 10^7 M_\odot \) (z=10)

FIG. 12.—Minimum mass threshold required for self-gravitation \((M_{\text{sec}})\) vs. redshift. The dash-dotted line shows the result of Tegmark et al. (1997), and the dashed line shows our semianalytic result. The dotted line shows the Jeans mass. The symbols show results of N-body simulations using \( 2 \times 32^3 \) particles. Objects less massive than \( M_{\text{sec}} \) at a given redshift will remain pressure-supported (circles); more massive objects cool efficiently, and the baryonic material in the central region becomes self-gravitating (stars). The solid line shows an approximate fit to the simulation results.
Cosmological Simulations

- CDM context
  (Yoshida et al. 2003; O’Shea & Norman 2007)

\[ M < M_J \quad \rightarrow \quad M \approx M_J \quad \rightarrow \quad M > M_J \]

\[ M_{b,\text{min}} \approx 10^5 M_{\odot} \quad (z \approx 15-20) \]

\[ m_b \geq 30 M_{\odot} \]


mass resolution
Number of First Stars in a Halo

Bromm, Coppi & Larson 1999
multiple fragments
with the mass of order $\approx 10^3 M_\odot$

Yoshida et al. 2003
“one-star-per-halo”
3D AMR Simulations in CDM Cosmology

T. Abel, G. L. Bryan, & M. L. Norman

Runaway core collapse contraction ⇒ disk formation ⇒
no indication for further fragmentation
⇒ ≈100M_{\odot} first stars
Earth-mass dark-matter haloes as the first structures in the early Universe

Diemand, Moore & Stadel, 2005
Nature, 433, 389

Figure 2: Radial density profiles of three typical mini-haloes at redshift $z = 26$. The radial distance is plotted in physical units and we show low-concentration $\alpha r^2$-profiles for comparison. We use the mean dark-matter profile inferred from the highest-resolution galaxy-cluster simulations, that is, $(\alpha r^2) = (1.3, 1.2)$. The vertical dotted line indicates our force resolution and the arrows indicate the radii where the halo density is of 200 times the background density. Across the entire range of halo masses from $10^{-10} M_\odot$ to $10^9 M_\odot$, we find small concentration parameters, $c < 3$. We do not observe a trend of concentration with mass, possibly because the haloes all form at a similar epoch, as expected when the power spectrum is so steep.
Q.

How is the dark matter cusps important for the formation of Pop III objects?
Grants-in-Aid for Specially Promoted Research, MEXT in Japan since 2004
Total budget is 428 million yen (US$4.3 million)

Core Members

Division of Computational Astrophysics
M. Umemura
K. Yoshikawa (2007-)
H. Hirashita
Y. Kato (2005-)
T. Suwa (2005-)
T. Akahori (2007-)
T. Nakamoto (Tokyo I.Tech)
H. Susa (U Kounan)
M. Mori (U Senshu)

Division of High Performance Computing Systems
T. Boku
D. Takahashi
O. Tatebe (2006-)
Blade-GRAPE

Embedded Special Purpose Processor for Gravity

(Newly-developed)

- 2 PCI-X bass full slots for 2U server
- 10 layers in a board
- 4 GRAPE6 chips = 136.8 GFLOPS
- Electric power of 54W
  (from power supply for disk drive)
- Memory of 16MB (260 thousand particles)

Cooperation
Hamamatsu Metrics Co.
“FIRST” Simulator

Completed in March, 2007

256 (16 x 16) nodes
496 CPU +
16 Blade-GRAPE
224 Blade-GRAPE X64

Total Performance = 36.1 Tflops
Host 3.1 Tflops
Blade-GRAPE 33 Tflops

Total Memory = 1.6TB

Total storage = 22TB (Gfarm)
Collapse of First Objects

P³M-GRAPE-SPH Simulations
Suwa, Umemura, Susa, 2008, in prep

Maximum mass resolution:
0.07M⊙ in DM
0.014M⊙ in baryon
No change of mass resolution throughout the simulation

WMAP $\Lambda$CDM cosmology

$z_{\text{in}}=1200$, 60kpc [comoving]$^3$

Baryon mass: $2 \times 10^6 M_\odot$
Dark matter mass: $1 \times 10^7 M_\odot$

3 x $10^8$ particles for baryon + dark matter

$z = 30$

$z = 20$

$z = 16$
Dependence on Mass resolution

\[ \begin{align*}
N &= 5 \times 10^5 \\
m_{\text{DM}} &= 24 M_{\odot} \\
m_b &= 5.1 M_{\odot}
\end{align*} \]

\[ \begin{align*}
N &= 4 \times 10^6 \\
m_{\text{DM}} &= 3.0 M_{\odot} \\
m_b &= 0.64 M_{\odot}
\end{align*} \]

\[ \begin{align*}
N &= 3 \times 10^7 \\
m_{\text{DM}} &= 0.4 M_{\odot} \\
m_b &= 0.08 M_{\odot}
\end{align*} \]

low resolution  intermediate resolution  high resolution
Dependence on Mass resolution

Low

\[ N = 5 \times 10^5 \]
\[ m_{DM} = 38 M_\odot \]
\[ m_b = 7.6 M_\odot \]

Runaway after peak merging

\[ N = 4 \times 10^6 \]
\[ m_{DM} = 4.8 M_\odot \]
\[ m_b = 0.95 M_\odot \]

Runaway before peak merging

\[ N = 3 \times 10^7 \]
\[ m_{DM} = 0.6 M_\odot \]
\[ m_b = 0.12 M_\odot \]

multiple peaks can collapse independently in <100 pc scales
Growth of Dark Matter Cusps

\begin{align*}
N &= 5 \times 10^5 \\
M_{\text{DM}} &= 38 M_\odot \\
z &= 16 \\
N &= 4 \times 10^6 \\
M_{\text{DM}} &= 4.8 M_\odot \\
N &= 3 \times 10^7 \\
M_{\text{DM}} &= 0.6 M_\odot
\end{align*}
Shallowing of Cusps


Pure N-body simulations

\[
\rho = \frac{\rho_0}{(r/r_0)^{1.5}[1 + (r/r_0)^{1.5}]}. 
\]

![Diagram showing the relation between density and radius with 0.01r_{\text{vir}} indicated.]

**TABLE 1**

<table>
<thead>
<tr>
<th>Model</th>
<th>Run</th>
<th>(M_{\odot}) ((M_\odot))</th>
<th>(r_s) (Mpc)</th>
<th>(N_p) ((\times 10^3))</th>
<th>(N) ((\times 10^6))</th>
<th>(m) ((10^7 \times M_\odot))</th>
<th>(1 + z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCDM</td>
<td>S1</td>
<td>(1.58 \times 10^{11})</td>
<td>3.08</td>
<td>29.2</td>
<td>60.3</td>
<td>5.39</td>
<td>44.2</td>
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<tr>
<td></td>
<td>S2</td>
<td>(1.21 \times 10^{11})</td>
<td>2.84</td>
<td>31.2</td>
<td>60.7</td>
<td>3.86</td>
<td>45.5</td>
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<tr>
<td></td>
<td>S3</td>
<td>(1.21 \times 10^{11})</td>
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<td>4.5</td>
<td>10.0</td>
<td>26.5</td>
<td>37.9</td>
</tr>
<tr>
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<td>S4</td>
<td>(4.47 \times 10^{11})</td>
<td>2.03</td>
<td>6.9</td>
<td>13.9</td>
<td>6.46</td>
<td>43.4</td>
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<tr>
<td>LCDM</td>
<td>L1</td>
<td>(9.61 \times 10^{11})</td>
<td>2.43</td>
<td>25.2</td>
<td>62.8</td>
<td>3.80</td>
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<tr>
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<td>L2</td>
<td>(6.06 \times 10^{11})</td>
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<td>26.0</td>
<td>59.9</td>
<td>2.67</td>
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<tr>
<td></td>
<td>L3</td>
<td>(6.49 \times 10^{11})</td>
<td>2.15</td>
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<td>9.01</td>
<td>47.5</td>
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<tr>
<td></td>
<td>L4</td>
<td>(4.45 \times 10^{11})</td>
<td>1.88</td>
<td>7.8</td>
<td>13.5</td>
<td>5.67</td>
<td>49.4</td>
</tr>
</tbody>
</table>
Growth of Dark Matter Cusps

$N=5 \times 10^5$
$m_{DM}=38M_\odot$

$N=4 \times 10^6$
$m_{DM}=4.8M_\odot$

$N=3 \times 10^7$
$m_{DM}=0.6M_\odot$

$z=16$

$\rho \propto r^{-1.5}$

Collapse driven by dark matter cusps.
Minimum Mass of First Objects

$N = 5 \times 10^5$
$m_{DM} = 38 M_\odot$

$N = 4 \times 10^6$
$m_{DM} = 4.8 M_\odot$

$N = 3 \times 10^7$
$m_{DM} = 0.6 M_\odot$

$z = 12$

Jeans Mass

$M_J \equiv \rho_b \left( \frac{c_s^2}{G \rho_{tot}} \right)^{3/2} = \rho_b \left( \frac{4\pi r^3 c_s^2}{3G \left( M_{DM}(r) + M_b(r) \right)} \right)^{3/2}$

Minimm mass $M_{b, \text{min}} \approx 10^3 M_\odot$
$N = 3 \times 10^7$

$m_{DM} = 0.6 M_\odot$

$m_b = 0.12 M_\odot$
Two Fragmentation Modes


1) Fragmentation at the critical density of $\text{H}_2$

$$n_{\text{crit}} \approx 10^4 \text{ cm}^{-3}$$

$$M_{\text{frag}} = l\lambda_m = 2.8 \times 10^3 M_\odot \left( \frac{T}{300 \text{ K}} \right)^{3/2} \left( \frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1/2}$$

2) Opacity limited fragmentation at $n \approx 10^{12} \text{ cm}^{-3}$

$$m_{\text{min}} = 1 \sim 2M_\odot$$

Rees mass  $$m_{\text{min}} = \alpha_c^{-1/2} \mu^{9/4} \left( m_{\text{Planck}}^3 / m_p^2 \right)$$
Conversion of Simulations

High resolution

\[ N = 3 \times 10^7 \]
\[ m_{DM} = 0.6M_\odot, \ m_b = 0.12M_\odot \]
\[ z = 15.6 \]

Ultra-high resolution

\[ N = 3 \times 10^8 \]
\[ m_{DM} = 0.07M_\odot, \ m_b = 0.014M_\odot \]

peak separation \(\approx 60-80\) pc
Summary

The collapse of first objects has been revisited with uniformly high-resolution cosmological simulations.

- It is found that the dark matter cusps can reduce the minimum mass of firsts objects down to $M_{b,\text{min}} \approx 10^3 M_\odot$.
  (Direct collapse to first stars)

- If we define the first mini-halo by the physical size of 100 pc, then multiple stars form in a halo.

- If we redefine the first mini-halo by the new minimum mass $M_{b,\text{min}} \approx 10^3 M_\odot$, then a single star forms in a halo.

- The number of first stars could be larger by more than a order of magnitude.