The Formation of SMBH in Cosmological Simulation

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Motivation: Super Massive Black Hole at high-z

- SMBH with $10^9 M_\odot$ is observed at the high-z universe. ($z \sim 7 \equiv 0.8\text{Gyr}$)

- Eddington accretion onto the BH...

$$\dot{M} \propto M \implies M = M_{\text{ini}} \exp(t/t_E)$$

where $t_E \sim 40\text{Myr}$

\[
\begin{cases}
\text{PopII} \implies M_{\text{ini}} = 1M_\odot \implies \text{not enough time} \\
\text{PopIII} \implies M_{\text{ini}} = 100M_\odot \implies M = 10^9 M_\odot \text{ at } t=0.6\text{Gyr}
\end{cases}
\]

However, the assumption of Eddington accretion is not realistic. (due to many feedback processes)

⇒ How about more massive BH seed?
Direct Collapse (DC)

- Massive star formation ($\sim 10^5 M_\odot$) path at high-z
- strong UV radiation from nearby galaxies
  $\Rightarrow$ dissociation of H$_2$ molecules $\Rightarrow$ atomic cooling path (Red line)

- higher accretion rate
  $\Rightarrow$ $\dot{M} \sim M_J / t_{ff} \sim c_s^3 / G \propto T^{3/2}$
  $\Rightarrow$ accretion rate: $0.1 \sim 1 M_\odot / \text{yr}$
  mass: $\sim 10^5 M_\odot$

Typical PopIII: $T \sim 200K$

Direct Collapse: $T \sim 8000K$

no UV case

strong UV case

higher density

(Omukai.2001)
Condition for the Direct Collapse

1. Irradiated by Strong UV field
   ⇒ H2 cooling ✗

2. Prestine Environment (stars are yet formed)
   ⇒ dust and metal line cooling ✗

3. Massive Halo \((T_{\text{vir}} \geq 8000K, M_{\text{halo}} \sim 10^7 M_\odot)\)
   ⇒ atomic H cooling
   (only valid T > 8000K)
Direct Collapse Scenario (DC scenario)

Cosmological Initial Condition → mini halo ($\sim 10^7 M_\odot$)

Super Massive Star ($\sim 10^5 M_\odot$) → gravitational collapse

Black Hole ($\sim 10^5 M_\odot$) → mass accretion

SMBH ($\sim 10^9 M_\odot$)
Direct Collapse Scenario (DC scenario)

This work

Cosmological Initial Condition

Super Massive Star \( \sim 10^5 M_\odot \)

gravitational collapse

Black Hole \( \sim 10^5 M_\odot \)

mass accretion

SMBH \( \sim 10^9 M_\odot \)

minihalo \( \sim 10^7 M_\odot \)

(DC halo)

(Agarwal et al. 2012)
(Johnson et al. 2013)
Purpose of this work

1. Does Direct Collapse halo really exist?
   ⇒ Cosmological N-body simulation
   ⇒ distribution of DC candidate halos

2. Evolution from gas cloud to star
   ⇒ Hydro dynamical simulation
   ⇒ Does Direct Collapse really occur?

Previous works only focuses on 1.
In this work, we calculate the evolution of gas cloud.
Direct Collapse candidate halo

• N-body calculation -> find the DC candidate halo.
• UV field is modeled by the DM distribution.

N-body simulation (DM only)

Zoom-In calculation (Gadget-2)

Zoom-In region: 1.2Mpc in radius
Npart : 2048^3
Particle mass : \( \sim 1.2 \times 10^3 M_\odot \)
resolution : \( \sim 1.2 \times 10^5 M_\odot \)
\( (> 100 \text{ particle } / \text{ halo}) \)
Calculation of UV field

• DM halos are luminous $\epsilon_{\text{duty}}$
  
  $\epsilon_{\text{duty}} : (\text{time scale of star formation}) / (\text{Hubble time})$
  
  $\sim 0.2$

• Intensity of radiation $\Rightarrow$ constant mass-to-light ratio
  
  (Iliev et al. 2006)

Compare 2 snapshots
(time interval = $t_S$)

Give luminosities on the halo with the most rapidly growing halo.
(in terms of mass of halo)
Find DC candidate halo

• DC candidate halo ⇒ close to the light source

Light source

Star formation is suppressed by strong UV field.

UV radiation

Direct Collapse

\[ T_{\text{vir}} < 3000K \]

\[ 3000K < T_{\text{vir}} < 8000K \]

\[ T_{\text{vir}} > 8000K \]

ordinary PopIII star
Find DC candidate halo

Light source

UV radiation

Star formation is suppressed by strong UV field.

• Identify DC halo with rapid growth and strong UV field ⇒ the virial temperature of halo

3000K  ➔  8000K in \( t_s \)

\[ T_{\text{vir}} < 3000K \]
\[ 3000K < T_{\text{vir}} < 8000K \]
\[ T_{\text{vir}} > 8000K \]

( \( t_s \): time scale of star formation \( \sim \) a few 10 Myr)
Evolution of gas cloud in DC halo

- Number of DC halo $\Rightarrow 11$ ($t_s = 80\text{Myr}$)
- the evolutions of 2 samples are calculated.

**Setup:**
- Gadget3 (sph + N-body)
- Primordial gas chemistry (Yoshida et al. 2006)
- radiative and chemical cooling

$\Rightarrow$ Direct Collapse didn’t occur in both cases
$\Rightarrow$ DC candidate halos are too close to the massive luminous halo.
(same order of $R_{\text{vir}}$)
Evolution of DC halo (1 example)

$z = 16.7$

$t = 5\text{ Myr}$

$t = 15\text{ Myr}$

$t = 20\text{ Myr}$

$20kpc$ (comoving)
Why Direct Collapse didn’t occur?

1. DC candidate halo experiences frequently mergers.
   ⇒ the gas in the halo is still not virialized.

2. Strong UV field delays the collapse of gas cloud.
   • Evolution of gas density under the various UV radiation
     ⇒ the collapse is delayed for \( \sim 10 \) Myr.

\[ 1, 2 \Rightarrow \text{DC didn’t occur.} \]
Merger Tree

• Improve the “DC halo” identification in bigger box

1. From N-body simulation
   – construct merger-tree
   – model the star formation in galaxies (SA model)

⇒ 1. identify the light source halo.
2. model the UV field and find DC halos.

2. Gas dynamics of the DC halo is calculated and see whether DC occurs or not in DC halo.

(Lacey & Cole, 1997)
The Condition for DC

1. Metal Enrichment

$\Rightarrow$ PopIII stars form at halo with $M_{\text{halo}} > 10^5 M_\odot$

2. Formation of the UV source

$\Rightarrow$ model the gas cooling, star formation and feedback process

![Diagram showing the relationship between hot gas, cold gas, and stars with cooling, SN feedback, and star formation processes.]
UV field

- calculated clustering region of \((1 \text{Mpc/h})^3\) in the \((20 \text{ Mpc/h})^3\) box

- distribution of \(J_{21}\) at halo center

- spatial variation of \(J_{21}\)

\[ J_{21} = 10^{-21} \text{erg/s/cm}^2/\text{Hz/str} \]

- \(J_{21} > 100\) is required for DC (Shang et al. 2010)
Result

• 3 DC candidate halos are found.
• 1 example
Summary

1. UV field is modeled from the DM distribution and search the DC candidate halo.
   ⇒ number density of DC halo < 11/(5Mpc/h)^3
   ⇒ consistent with previous work

2. The evolution of gas in DC halos are calculated.
   ⇒ in 2 DC halo
   ⇒ Direct Collapse didn’t occur, but DC halo merges with luminous source halo before the formation of Super Massive Star.
Some problems

• The difficulty of maintaining Eddington accretion
  1. many feedback processes
     Photo-ionization: (Yoshida. 2006),
       (Alvarez et al. 2009)
  2. BH merger
     asymmetric BH merger $\Rightarrow$ BH ejection (Blecha & Loeb. 2008)

$\Rightarrow$ One possible solution
If massive BH seed had first formed in high-z universe, •••? (head start scenario)
Discussion

2. Strong UV field delays the collapse of gas cloud.

⇒ the collapse is delayed for \( \sim 10 \text{ Myr} \).
Direct Collapse

- Massive star formation ($\sim 10^5 M_\odot$) path at high-z
- strong UV radiation from nearby galaxies
  $\Rightarrow$ dissociation of H$_2$ molecules $\Rightarrow$ atomic cooling path

(Red line)

1. isothermal evolution
   $\Rightarrow$ no fragmentation

2. high accretion rate
   \[ \dot{M} \sim \frac{M_J}{t_{ff}} \sim \frac{c_s^3}{G} \propto T^{3/2} \]
   $\Rightarrow$ accretion rate: $0.1 \sim 1 M_\odot/\text{yr}$
   mass: $\sim 10^5 M_\odot$

Typical PopIII: $T \sim 200K$

Direct Collapse: $T \sim 8000K$

higher density

(Omukai.2001)
The diagram on the left shows a histogram with the x-axis labeled as $J_{21}$ and the y-axis labeled as fraction. The histogram is plotted on a logarithmic scale, with bars ranging from $10^{-7}$ to $10^6$. The diagram on the right is a graph with the x-axis labeled as redshift and the y-axis labeled as $J_{21}$. The graph is also plotted on a logarithmic scale, with redshift values ranging from 0 to 20 and $J_{21}$ values ranging from $10^{-2}$ to $10^4$. There are noticeable peaks and trends in the data.
Evolution of gas cloud in DC halo

- Number of DC halo $\Rightarrow 11$ ($t_s = 80$ Myr)
- the evolutions of 2 samples are calculated.
  $\Rightarrow$ Direct Collapse didn’t occur in each case
  $\Rightarrow$ DC candidate halos are too close to the massive luminous halo.
  (same order of $R_{\text{vir}}$)