Feedback, AGN and galaxy formation

Debora Sijacki
Formation of black hole seeds: the big picture

Planck data, 2013 (new results 2015)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>68% limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.022242</td>
<td>0.02217 ± 0.00033</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.11805</td>
<td>0.1186 ± 0.0031</td>
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<tr>
<td>$\Omega_k$</td>
<td>0.6964</td>
<td>0.693 ± 0.019</td>
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<tr>
<td>$\sigma_8$</td>
<td>0.8285</td>
<td>0.823 ± 0.018</td>
</tr>
<tr>
<td>$H_0$</td>
<td>68.14</td>
<td>67.9 ± 1.5</td>
</tr>
<tr>
<td>Age/Gyr</td>
<td>13.784</td>
<td>13.796 ± 0.058</td>
</tr>
</tbody>
</table>

Before Planck

- Dark Matter: 22.7%
- Ordinary Matter: 4.5%
- Dark Energy: 72.8%

After Planck

- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%
Formation of black hole seeds: the big picture

CMB black body spectrum

$T = 2.728$ K

CMB dipol: motion of Earth
$v \sim 370$ km/s

$\Delta T = 3.353$ mK

CMB temperature fluctuations:
$\sim 2 \times 10^{-5}$

$\Delta T = 18$ $\mu$K
Formation of black hole seeds: the big picture

Planck 2013

Temperature fluctuations [$\mu K^2$] vs. Angular scale

Multipole moment, $\ell$
Formation of black hole seeds: the big picture

\[ \ddot{\delta}_m + 2 \frac{\dot{R}}{R} \dot{\delta}_m - 4\pi G \bar{\rho}_m \delta_m = 0 \]

Structure formation

Density fluctuations generated by quantum fluctuations during inflation (not known from the first principles)
Gravitational collapse of small density perturbations in a quasi homogeneous Universe dominated by CDM and their subsequent growth within the hierarchical scenario

If density perturbations are very small ($\delta\rho/\rho \ll 1$) they are called linear and their evolution can be studied with a perturbative theory to the first order, e.g. with ideal fluid approximation within the Newtonian limit
Once, due to the gravitational collapse, density perturbations become large and non-linear ($\delta\rho/\rho \sim 1$) numerical integration is needed to follow accurately their evolution in time
Formation of black hole seeds: the big picture

The initial conditions are directly observable

Millennium simulation
Springel et al. 2005

The initial conditions are directly observable
Formation of black hole seeds: the big picture

Simulated and observed large-scale structure in the galaxy distribution

MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2

Springel et al. (2006)
Boylan-Kolchin et al. (2009)
Formation of black hole seeds: baryons

Each initial density perturbation contains baryonic gas and collisionless dark matter in roughly their universal proportions. When an object collapses, the dark matter relaxes violently to form a dark matter halo, while gas shocks to the virial temperature. If gas is dense enough, gas cooling can become effective – gas loses pressure support and flows towards the centre → a protogalaxy forms.

Further collapse increases the density and temperature of the gas, which can reduce the cooling time ($t_{\text{cool}} < t_{\text{collapse}}$). During such runaway collapse the gas becomes self-gravitating and may fragment into small, high-density cores that may form stars.
Formation of black hole seeds: baryons

Each initial density perturbation contains baryonic gas and collisionless dark matter in roughly their universal proportions. But what happens then?

Baryonic mass function versus dark matter mass function at $z = 0$

$\alpha = -1.21$
$\phi_\star = 2.5 \times 10^{-14}$
$M_\star = 1.31 \times 10^{11}$
Formation of black hole seeds: baryons

cosmological initial and boundary conditions

gravitational instability

dark halo (dark matter + gas)

yes cooling effective? no

no large angular momentum? yes no further merger and accretion?

no

dissipative collapse; starburst

gaseous disk

star formation disk galaxy

no major merger? yes

no gas rich? yes

tidal tail starburst, AGN, tidal tail

spheroidal system

no gas accretion? yes

ecliptical bulge/disk system central bulge

disk
Simulations of merging/interacting galaxies

Frank Summers, 2008

Fig. 2.—A flat direct ($i = 0^\circ$) parabolic passage of a companion of equal mass

Toomre & Toomre, 1972

Frank Summers, 2008
Formation of black hole seeds: baryons

Each initial density perturbation contains baryonic gas and collisionless dark matter in roughly their universal proportions. But what happens then?

Baryonic mass function versus dark matter mass function at $z = 0$
Formation of black hole seeds: seed formation pathways

Martin Rees, ARA&A 1984

massive black hole
Formation of black hole seeds: Population III remnants

- Population III stars represent the first generation of stars formed out of zero metallicity gas
- They are expected to form in halos with virial mass $\sim 10^6 M_\odot$ collapsing at $z \sim 20-50$ where gas cools via molecular hydrogen (no dust, no metals, no B fields)
- Numerical simulations suggest that the first generation of stars was very massive e.g $\sim 100 \odot$ (Bromm et al. 1999, 2002, Abel et al. 2000, Yoshida et al. 2006) but a few newer studies suggest some fragmentation and multiple lower mass star forming (Glover et al. 2008, Stacey et al. 2009, Turk et al. 2009)

Matt Turk
Formation of black hole seeds: Population III remnants

The final fate of Population III stars depends on their mass:
1. Between 25-140 $M_{\odot}$ black hole formation (mass ~ half of the stellar mass)
2. Between 140-260 $M_{\odot}$ pair instability supernovae → no remnant
3. Over 260 $M_{\odot}$ black hole forms (mass ~ half of the stellar mass)

Heger et al. 2003
Formation of black hole seeds: Direct collapse of gas

- Efficient gas collapse in halos with \( T_{\text{vir}} > 10^4 \text{K} \) (essentially metal free and no \( \text{H}_2 \) cooling) to avoid gas fragmentation and star formation (e.g. Haehnelt & Rees 1993, Loeb & Rasio 1994, Eisenstein & Loeb 1995, Begelman et al. 2006)
- Gas cools via atomic H to ~ 4000K, thereafter collapse proceeds adiabatically
- High local UV background is needed to prevent formation of \( \text{H}_2 \) (alternatively highly turbulent medium i.e. Begelman & Shlosman 2009)
- Collapsing gas will likely settle into a rotationally supported disk, e.g. for a halo with:

\[
T_{\text{vir}} \gtrsim 10^4 \text{K} \quad \quad M_h \approx 10^8 \, M_\odot \quad \quad r_{\text{vir}} \approx 500 \text{pc} \\
\bar{\lambda}_{\text{spin}} = 0.04 \quad \quad \lambda_{\text{spin}} \equiv \frac{J|E|^{1/2}}{GM_h^{5/2}} \\
M = f_d \, f_{\text{gas}} \, M_h \quad \quad f_{\text{gas}} \sim \text{universal baryon fraction (0.18)} \quad f_d \quad \text{fraction of gas that can cool (0-1)} \\
\text{scale radius} \approx \lambda_{\text{spin}} r_{\text{vir}}
\]

=> typical gas scale radius of a disk with mass \( M \) is \approx 20\text{pc}
Formation of black hole seeds: Direct collapse of gas

Regan & Haehnelt, 2009: “about 0.1-1% of the baryons collapse into a self-gravitating, fat, ellipsoidal, centrifugally supported disk with scale length of 0.075-0.27pc...”
Formation of black hole seeds: Direct collapse of gas

Regan & Haehnelt, 2009: “about 0.1-1% of the baryons collapse into a self-gravitating, fat, ellipsoidal, centrifugally supported disk with scale length of 0.075-0.27pc...”

LATE TIME EVOLUTION
Formation of black hole seeds: Direct collapse of gas

-Mechanism for solving the angular momentum transport problem (below 20pc):
  a. dark matter halos with extremely low spin values (\(\lambda << 0.04\))
  b. low angular momentum tail of material
  c. global dynamical instabilities i.e. “bars-within-bars” mechanism
    (e.g. Shlosman et al. 1989, Begelman et al. 2006)

Self-gravitating gas clouds become bar unstable when the level of rotational support surpasses certain threshold. A bar can transport angular momentum outwards on a dynamical timescale via gravitational and hydrodynamical torques, allowing the radius to shrink.

Hopkins et al. 2010
Formation of black hole seeds: Direct collapse of gas

- Provided that gas angular momentum transfer is efficient, typical gas masses within the central few parsecs can reach $10^4$-$10^6 \text{M}_\odot$

- A supermassive star might form with a mass of a few $10^4 \text{M}_\odot$

- Evolution of isolated supermassive stars has been investigated numerically in full GR even in the presence of significant rotation indicating that the majority of stellar mass would collapse into a Kerr-like black hole

- If there is a fast accumulation of material onto the supermassive star, only the core of the star might collapse into a black hole with a mass of a few $\text{M}_\odot$ and thereafter black hole may growth in mass rapidly from the surrounding envelope → QUASI-STAR (Begelman et al. 2006) thus reaching $10^5$-$10^6 \text{M}_\odot$
Formation of black hole seeds: Stellar cluster

- If star formation proceeds in small mini-halos with $T < 10^4$ K triggered by H2 cooling as more massive halos build up they will be metal enriched

- Fragmentation and formation of low mass stars starts as soon as gas is polluted by metals produced by the first Pop III stars

- Efficient star formation can occur in very compact nuclear star clusters

- The central core of the cluster initially contracts as the system tries to reach a state of thermal equilibrium: energy conservation leads to a decrease in the core radius as evaporation of the less bound stars proceeds → thus central density increases and the central relaxation time decreases → core collapses

- In a multi-mass system, massive stars segregate towards the centre due to the dynamical friction

- If segregation happens before the more massive stars evolve out of the main sequence (~3 Myrs), star-star runaway collision can take place leading to very massive star formation and ultimately a black hole remnant with a mass of $\sim 1000M_\odot$ → IMBH (e.g. Begelman & Rees, 1978, Portegies Zwart & McMillan, 2002, Freitag et al. 2006, Katz, Sijacki, Haehnelt, 2015)
Low mass versus massive seeds scenarios

- Black hole seed mass function (Volonteri 2010)

**Direct collapse** | **Stellar cluster** | **Pop III remnants**

\[
N_{\text{tot}} (\text{Mpc}^{-3})
\]

\[
\log(M_{\text{BH}}/M_\odot)
\]
Growth of the black holes in the early Universe

Several different channels:

1. Gas accretion processes
2. Mergers with other black holes
3. Tidal capture of stars (e.g. in compact stellar clusters)

Efficiency of these channels depends on:
1. black hole seed masses and cosmic time (e.g. retention in the centre, gas accretion dependence on mass)
2. occurrence of gravitational slingshot and recoil events
3. properties of the central region and of the host galaxy (e.g. gas content and thermodynamical state)
4. larger scale environment of the host dark matter halo (e.g. merger history, gas supply)
5. stellar and black hole feedback processes
...

Growth of the black holes in the early Universe

While black hole seeds may form in different ways and grow in mass via different channels, observations of high redshift quasars imply very stringent time constraints on the black hole mass assembly

De Rossa et al. 2011 SDSS, Willott et al. 2010 CFHQS
Mortlock et al. 2011 QSO at $z = 7.085$ mass $\sim 2 \times 10^9 M_\odot$

Costa, Sijacki, Haehnelt, 2013
Growth of the black holes in the early Universe

Light seeds might not be able to grow sufficiently in mass to power high redshift QSOs, or some more exotic processes need to be invoked (e.g. super Eddington accretion)

- In a spherically symmetric case, balance of the force imparted by the radiation of the central object with a luminosity $L$, and of the gravitational force exerted on the accreting material leads to the concept of Eddington limit

Assume:
steady, spherically symmetric accretion
accreting material: fully ionized hydrogen

Radiation exerts a force on free electrons through Thomson scattering (scattering cross section for protons $(\frac{me}{mp})^2$ smaller)

outward radial force on each electron = momentum absorbed

\[
\frac{L \sigma_T}{4\pi r^2 c}
\]

luminosity = energy flux $\times \frac{4\pi r^2}{4\pi r^2 c}$

Thomson cross-section
Growth of the black holes in the early Universe

Electrons and protons are coupled due to Coulomb force => radiation pushes electron-proton pairs against gravity (here $m_e$ neglected)

\[
\frac{GMm_p}{r^2} = \frac{L\sigma_T}{4\pi r^2 c}, \quad \Rightarrow \quad L_{\text{Edd}} = \frac{4\pi cGMm_p}{\sigma_T}
\]

Radiative efficiency: measures how efficiently the rest mass energy (grav. potential energy) is converted into radiation

\[
e \equiv \frac{L}{Mc^2} \quad \Rightarrow \quad \dot{M}_{\text{Edd}} = \frac{4\pi GM_{\text{BH}}m_p}{\epsilon_r \sigma_T c} \quad \Rightarrow \quad t_s = \frac{\sigma_T c}{4\pi Gm_p} \approx 4.5 \times 10^7 \text{yr}
\]

\[
t_{\text{age}} \approx 8 \times 10^8 \left(\frac{\Omega_{m,0}}{0.27}\right)^{-1/2} \left(\frac{h}{0.70}\right)^{-1} \text{yr} \quad \text{(age of universe)}
\]

\[
t_{\text{e-fold}} \approx 4.5 \times 10^7 \left(0.1\right)\left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}}\right)^{-1} \text{yr} \quad \text{(e-folding time)}
\]

\~16 e-foldings to grow a $10^9 M_\odot$ black hole by $z = 7$ from a $100 M_\odot$ seed black hole at constant rate.

\[
16t_{\text{e-fold}} \approx t_{\text{age}}
\]
Powering of high redshift quasars

- Space density of luminous $z \sim 6$ is extremely low!

- If duty cycle is high, then quasars should inhabit halos of mass:
  
  \[ 5 \times 10^{12} - 10^{13} \, M_\odot \]

- If duty cycle is low, quasars will reside in lower mass halos.
Powering of high redshift quasars

- If z~ 6 QSO are residing in very massive dark matter halos, they are living in very rare, overdense and gas-rich environments – ideal for rapid black hole growth

Sijacki et al. 2009
Powering of high redshift quasars
AVERAGE REGIONS OF UNIVERSE AT z ~ 6
Costa, Sijacki et al. 2013
Powering of high redshift quasars

OVERDENSE REGIONS OF UNIVERSE AT z ~ 6

Costa, Sijacki et al. 2013
Powering of high redshift quasars  

Costa, Sijacki et al. 2013

- Growth of the bright QSOs

Strong selection effect:  
Quasars only detected during high accretion episodes.
Powering of high redshift quasars

- Powerful AGN feedback at $z \sim 6$

Costa, Sijacki et al. 2013
- Powerful AGN feedback at $z \sim 6$

AGN drives an outflow that fills outer regions with hot gas and metals.
Powering of high redshift quasars

- Powerful AGN feedback at $z \sim 6$

Costa, Sijacki et al. 2013