The Formation of Massive Black Holes: a Review

Francesco Haardt
University of Insubria@Lake Como
INFN, Milano-Bicocca
Understanding the formation and growth of MBHs along the Cosmic history.

1. How fast can MBHs grow to $10^9$-$10^{10} \, M_\odot$?

2. How many of them along the Cosmic history?

We need to understand the physics of black hole and galaxy mergers.
LOCAL SCALING RELATIONS

Marconi & Hunt 2004

Tremaine 2002

Ferrarese 2004
1. There seems to be little or no correlation between mass and velocity dispersion (Wang et al. 2010).

2. Typically black holes are ‘over massive’ at fixed mass/velocity dispersion compared to z=0 counterparts (e.g. Walter et al. 2004; Decarli et al. 2010; Merloni 2010).

3. Studies suggest that either many massive galaxies do not have MBHs or these BH are less massive than expected (Willott et al. 2010).
from M. Volonteri
When do you make the first SMBHs?

The QSO ULASJ1 12010641 at $z=7.1$ has an estimated SMBH mass $M_{\text{BH}} \approx 2 \times 10^9 M_\odot$ (Mortlock et al. 2011)

As massive as the largest SMBHs today, but when the Universe was only 0.75 Gyrs old

Gultekin et al. 2009
Accretion time needed by a BH to reach a given final mass:

\[ M(t) = M_0 e^{f_{\text{Edd}} \frac{t}{\tau} \frac{1-\epsilon}{\epsilon}} \]

\[ t_{\text{acc}} = 0.45 \text{ Gyr} \frac{\epsilon}{1-\epsilon} f_{\text{Edd}}^{-1} \ln(M_{\text{fin}}/M_{\text{in}}) \]
Accretion time needed by a BH to reach a given final mass:

\[ M(t) = M_0 e^{f_{\text{Edd}} \frac{t}{\tau} \frac{1-\epsilon}{\epsilon}} \]

\[ t_{\text{acc}} = 0.45 \text{ Gyr} \frac{\epsilon}{1-\epsilon} f_{\text{Edd}}^{-1} \ln(M_{\text{fin}}/M_{\text{in}}) \]

\[ M_{\text{fin}} = 10^9 \, M_\odot \]
\[ M_{\text{in}} = 10^2 \, M_\odot \quad (10^5 \, M_\odot) \]
\[ f_{\text{Edd}} = 1 \]
\[ \epsilon = 0.1 \]
\[ \Rightarrow t_{\text{acc}} = 0.8 \text{ Gyrs (0.45 Gyrs)} \]

\[ t_H(z=7) = 0.75 \text{ Gyrs} \]
\[ t_H(z=6) = 0.9 \text{ Gyrs} \]
How do we make SMBH seeds?
DARK AGES

The fate of DM:

CDM: Small scales collapse first

BOTTOM-UP HIERARCHY

DM-HALOS COLLAPSE AS:

\[ M = 10^{15} / (1 + z)^6 \, M_\odot \]
DARK AGES

The fate of DM:

CDM: Small scales collapse first
BOTTOM-UP HIERARCHY

DM-HALOS COLLAPSE AS:
\[ M = 10^{15} / (1 + z)^6 \, M_\odot \]

The fate of baryons:

At \( z \approx 130 \) baryons are free to fall into DM halos

COOLING TIME >> HUBBLE TIME \( \rightarrow \) ADIABATIC COLLAPSE
Baryons virialize as DM particles

COOLING TIME << HUBBLE TIME \( \rightarrow \) ISOTHERMAL COLLAPSE
Baryons fall into DM potential wells \( \rightarrow \) Self-gravitating baryonic objects (POPIII)
\( \rightarrow \) END OF THE DARK AGES (\( z \approx 25 \))
The Fate of POIII Stars
The Nature of BH seeds

Dark Matter Halo

mini-halo
Pop III star

- $T_{\text{vir}} < 10^4$ K
- $Z < Z_{\text{crit}}$

$40 \, M_\odot < M_* < 140 \, M_\odot$

$M_* > 260 \, M_\odot$

$\Rightarrow$ MBH

$z \approx 20-30$

$M_{\text{BH}} \approx 100-600 \, M_\odot$

thanks to Raffaella Schneider
POPIII Stars

Protostar $M \sim 0.01M_\odot$ surrounded by $1M_\odot$ molecular envelope.

Accretion of envelope. Further out molecular disk ($\sim 400$ AU)

Accretion through the disk at $\sim 10^{-3} M_\odot/yr$

Ionizing bipolar flux (disk self-shielded)

HII region breaks the accreting envelope

Bipolar outflows of gas

Shocks propagates into the envelope

Accretion rate falls down

Disk exposed to UV. Photoevaporation.

Accretion stops. $M \sim 45M_\odot$ Limit set by self-regulating radiation feed-back
The Fate of POPIII Stars: Feedback Effects

Hosokawa et al. 2011
The Fate of POIII Stars: Feedback Effects

Hosokawa et al. 2011

Alvarez et al. 2009
The Fate of POPIII Stars: Feedback Effects

POPIII: massive but not very massive (~45 $M_\odot$).
Accretion rate onto the remnant: very sub-Eddington.

Hosokawa et al. 2011
Alvarez et al. 2009
The Nature of BH seeds

Dark Matter Halo

mini-halo

Pop III star

$T_{\text{vir}} < 10^4 \text{ K}$

$z < z_{\text{crit}}$

40 $M_\odot < M_\star < 140 \ M_\odot$

$M_\star > 260 \ M_\odot$

$\rightarrow$ MBH

$z \approx 20-30$

$M_{\text{BH}} \sim 100-600 \ M_\odot$

thanks to Raffaella Schneider
The Nature of BH seeds

Dark Matter Halo

- $T_{\text{vir}} < 10^4 \text{ K}$
- $Z < Z_{\text{crit}}$

mini-halo
Pop III star

- $M_{\text{BH}} < 45 M_\odot$
- accretion $<<$ Eddington

Omukai et al., Alvarez et al.

$z \approx 20-30$
$M_{\text{BH}} < 40 M_\odot$

thanks to Raffaella Schneider
The Nature of BH seeds

Dark Matter Halo

- $T_{\text{vir}} < 10^4 \text{ K}$
- $T_{\text{vir}} > 10^4 \text{ K}$
- $Z < Z_{\text{crit}}$

mini-halo
- Pop III star
- $M_{\text{BH}} < 45 M_\odot$
- accretion $\ll$ Eddington
- Omukai et al., Alvarez et al.
- $z \approx 20-30$
- $M_{\text{BH}} < 40 M_\odot$

proto - galaxy
- dynamical instability
- $Z < Z_{\text{crit}}$

- suppressed star formation
- UV, shocks…

- $z \approx 10$
- $M_{\text{BH}} \sim 10^4 - 10^6 M_\odot$

- direct collapse
- $\Rightarrow$ MBH

thanks to Raffaella Schneider
Direct Gas Collapse

- Deep potential well for gas infall and collapse
- Global dynamical instabilities to trigger inflow and dissipate angular momentum
- Inflow and formation of a super-massive star (quasistar) that collapses into a BH

e.g., Bromm & Loeb 2003, Begelman, Volonteri & Rees 2006
Direct Gas Collapse

- Deep potential well for gas infall and collapse
- *Global dynamical instabilities* to trigger inflow and dissipate angular momentum
- Inflow and formation of a super-massive star (quasistar) that collapses into a BH

Problems

- Angular momentum dissipation
- Star Formation along the long the way down
Direct Gas Collapse

- Efficient gas collapse in halos with $T_{\text{vir}} > 10^4$ K (metal free and no H$_2$ cooling)
- No fragmentation and star formation (Haehnelt & Rees 1993, Begelman et al. 2006)
- Atomic cooling down to 4,000 K (collisionally excited Ly$\alpha$ emission), isothermal collapse, then adiabatic
- Local Lyman-Werner UV to prevent H$_2$ formation (o.w. turbulent medium)
- Collapsing gas settles into a rotationally supported disk.
- Scale radius: $\sim 20$ pc (for $M_{\text{halo}} = 10^8$ M$_{\odot}$)
Direct Gas Collapse

- Efficient gas collapse in halos with $T_{\text{vir}} > 10^4$ K (metal free and no $H_2$ cooling)
- No fragmentation and star formation (Haehnelt & Rees 1993, Begelman et al. 2006)
- Atomic cooling down to 4,000 K (collisionally excited Ly$\alpha$ emission), isothermal collapse, then adiabatic
- Local Lyman-Werner UV to prevent $H_2$ formation (o.w. turbulent medium)
- Collapsing gas settles into a rotationally supported disk.
- Scale radius: $\sim 20$ pc (for $M_{\text{halo}} = 10^8 M_\odot$)

- Angular momentum problem solved if: a) DM halo with very low spin ($\lambda_{\text{spin}} << 0.04$); b) presence of low angular momentum gas; c) onset of global dynamical instabilities, bars-within-bars (Shlosman et al. 1989, Begelman et al. 2006).
- A bar can transport angular momentum outwards on a dynamical timescale via gravitational and hydrodynamical torques, allowing the radius to shrink.
- If gas can cool, this shrinkage leads to even greater instability on shorter timescale, and the process cascades
• If this all works, typical gas masses within the central few pc can reach $10^4$-$10^5 \ M_\odot$

• A Very Massive Star forms with $M_{\text{star}} \approx 10^4 \ M_\odot$. Numerical full-GR calculations predict the core of the VMS collapses into a few $M_\odot$ Kerr BH (via neutrino cooling). A Quasistar is formed: a stellar-size BH embedded into a very massive stellar envelope

• Ultrafast accretion at Eddington rate (where mass is the Quasistar mass)

• The 10 $M_\odot$ BH can swallow 1-10% of the Quasistar envelope: MBH reaches $10^4$-$10^5 \ M_\odot$

Begelman et al. 2006
• If this all works, typical gas masses within the central few pc can reach $10^4$-$10^5 \, M_\odot$

• A Very Massive Star forms with $M_{\text{star}} \sim 10^4 \, M_\odot$. Numerical full-GR calculations predict the core of the VMS collapses into a few $M_\odot$ Kerr BH (via neutrino cooling). A Quasistar is formed: a stellar-size BH embedded into a very massive stellar envelope

• Ultrafast accretion at Eddington rate (where mass is the Quasistar mass)

• The $10 \, M_\odot$ BH can swallow 1-10% of the Quasistar envelope: MBH reaches $10^4$-$10^5 \, M_\odot$

Begelman et al. 2006

Instead of going into BH formation, collapsing gas can fragment and form stars
The Nature of BH seeds

Dark Matter Halo

- $T_{\text{vir}} < 10^4 \text{ K}$
- $Z < Z_{\text{crit}}$

mini-halo

- Pop III star
- $M_{\text{BH}} < 45 \, M_\odot$
- accretion $<<$ Eddington
- Omukai et al., Alvarez et al.

$z \approx 20-30$
- $M_{\text{BH}} < 45M_\odot$

proto - galaxy

- dynamical instability
- $Z < Z_{\text{crit}}$

suppressed star formation
- UV, shocks...

$z \approx 10$
- $M_{\text{BH}} \sim 10^4-10^6 \, M_\odot$

direct collapse $\Rightarrow$ MBH

thanks to Raffaella Schneider
The Nature of BH seeds

Dark Matter Halo

- $T_{\text{vir}} < 10^4 K$
- $Z < Z_{\text{crit}}$
- $T_{\text{vir}} > 10^4 K$
- $Z > Z_{\text{crit}}$

**mini-halo**

- Pop III star
- $M_{\text{BH}} < 45 M_\odot$
- accretion $<<$ Eddington
- Omukai et al., Alvarez et al.

$z \approx 20-30$

$M_{\text{BH}} < 45 M_\odot$

**proto-galaxy**

**dynamical instability**

- suppressed star formation
- UV, shocks...

$z \approx 10$

$M_{\text{BH}} \sim 10^4 - 10^6 M_\odot$

- direct collapse $\rightarrow$ MBH
- run-away collisions $\rightarrow$ MBH

thanks to Raffaella Schneider
Star Formation and Run-Away Collapse

• If gas is metal enriched by first POPIII stars can not avoid fragmentation
• *Local dynamical instabilities* lead to mass infall
• The inflow produces an inner, compact, very dense star cluster
• Mass segregation: more massive stars sink to the centre of the cluster
• Stellar collisions form a VMS
• The VMS accretes gas. BH remnant of $10^3 \, M_\odot$ (Begelman & Rees 1978, Freitag et al. 2006)

e.g., Devecchi & Volonteri 2009
Star Formation and Run-Away Collapse

- If gas is metal enriched by first POIII stars can not avoid fragmentation
- *Local dynamical instabilities* lead to mass infall
- The inflow produces an inner, compact, very dense star cluster
- Mass segregation: more massive stars sink to the centre of the cluster
- Stellar collisions form a VMS
- The VMS accretes gas. BH remnant of $10^3 \, M_\odot$ (Begelman & Rees 1978, Freitag et al. 2006)

- This route happens above a critical metallicity: $Z > 10^{-5} \, Z_\odot$. But $Z$ needs not to be too high to avoid excessive gas consumption by star formation
- Time for mass segregation must be $<<$ main-sequence timescale (3 Myrs) to avoid SN driven mass-loss, and formation of compact objects (small cross section)
The Nature of BH seeds

POP III remnants

Gas-dynamical collapse

Dark matter collapse

Gas

The black hole swallows the envelope growing up to ~one million solar masses

First stars: maybe one star per galaxy, up to several hundred times larger than the Sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

M~100M\(_{\odot}\)
High efficiency

M~10^5M\(_{\odot}\)
Low efficiency

M~10^3M\(_{\odot}\)
Intermediate efficiency

Stars merge into a very massive star that collapses into a black hole \(~1000\) times more massive than the Sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

M~10^5M\(_{\odot}\)
Low efficiency

M~10^3M\(_{\odot}\)
Intermediate efficiency

Gas fragments into stars, and a dense star cluster forms

Gas cools very slowly forming a stable disc

Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms

Locally unstable gas flows toward the galaxy center

Stellar-dynamical collapse

POP III remnants

Gas-dynamical collapse

Dark matter collapse

Gas

The black hole swallows the envelope growing up to ~one million solar masses

First stars: maybe one star per galaxy, up to several hundred times larger than the Sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

M~100M\(_{\odot}\)
High efficiency

M~10^5M\(_{\odot}\)
Low efficiency

M~10^3M\(_{\odot}\)
Intermediate efficiency

Stars merge into a very massive star that collapses into a black hole \(~1000\) times more massive than the Sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

M~10^5M\(_{\odot}\)
Low efficiency

M~10^3M\(_{\odot}\)
Intermediate efficiency

Gas fragments into stars, and a dense star cluster forms

Gas cools very slowly forming a stable disc

Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms

Locally unstable gas flows toward the galaxy center

Stellar-dynamical collapse

POP III remnants

Gas-dynamical collapse

Dark matter collapse

Gas
Low Mass Seeds vs High Mass Seeds

Volonteri & Gnedin 2009

Light Seeds
solid: Eddigton limited
dashed: a la “Merloni Heinz”

Heavy Seeds

The diagram shows the distribution of black hole masses for different redshifts, comparing light and heavy seeds in AGN formation. The plots illustrate how the distribution of black hole masses changes over cosmic time, with distinct features for light and heavy seeds.
Low Mass Seeds vs High Mass Seeds

direct collapse, stellar cluster, Pop III remnants

Volonteri 2010
Madau & Rees 2001
Low Mass Seeds vs High Mass Seeds

Volonteri 2010

Madau & Rees 2001
Low Mass Seeds vs High Mass Seeds

- Massive seeds
- Pop III remnants
- Direct collapse
- Stellar cluster

Volonteri 2010
Madau & Rees 2001

mass density (M⊙Mpc⁻³)

mass density vs redshift

OBSERVATIONS

BHOF

massive seeds
POP III

van Wassenhove et al. 2010

MBH Fraction

massive seeds

Bellovary et al. 2011
Low Mass Seeds vs High Mass Seeds

Occupation fraction of dwarf(ish) galaxies is sensitive to seed mass
Low Mass Seeds vs High Mass Seeds (observations)

POIII seeds (green) and massive seeds (purple) from Volonteri et al. (2008).

Estimates from Desroches et al. (2009, blue) and Gallo et al. (2010, red).
Low Mass Seeds vs High Mass Seeds (observations)

POIII seeds (green) and massive seeds (purple) from Volonteri et al. (2008).

Estimates from Desroches et al. (2009, blue) and Gallo et al. (2010, red).

Direct Collapse favoured
Low Mass Seeds vs High Mass Seeds (observations)

Miller et al. 2014
Low Mass Seeds vs High Mass Seeds (observations)

Direct Collapse favoured?
SMBHs at “Low” Redshifts by Gas Collapse

- Simulation of two well-formed hi-z MW-like galaxies merger
- Self-gravitating turbulent nuclear disk (r~40 pc, M~2x10^9 M\(_\odot\)) forms
- Gravo-turbulent instabilities drive the gas toward the centre at very high rate, 10^4 M\(_\odot\)/yr
- A ~1 pc size spherical structure grows by 13% of the disk mass (>10^8 M\(_\odot\)) in 0.1 Myr. T~10^7K prevents fragmentation.
- The core collapse into a BH + envelope = Quasistar
- The key point:
  \[ \dot{M} \approx \frac{M_J}{t_{ff}} = \frac{\pi^2}{8G} c_s^3 \approx 5 \times 10^3 \left( \frac{T}{10^7 K} \right)^{3/2} \text{ M}\(_\odot\)yr}^{-1} \]

High temperature is *instrumental* in keeping Mdot so high
SMBHs at “Low” Redshifts by Gas Collapse

- Simulation of two well-formed hi-z MW-like galaxies merger
- Self-gravitating turbulent nuclear disk \((r\sim 40 \text{ pc}, M\sim 2\times 10^9 \text{ M}_\odot)\) forms
- Gravo-turbulent instabilities drive the gas toward the centre at very high rate, \(10^4 \text{ M}_\odot/\text{yr}\)
- A \(\sim 1\text{ pc}\) size spherical structure grows by 13% of the disk mass \((>10^8 \text{ M}_\odot)\) in 0.1 Myr. \(T\sim 10^7\text{K}\) prevents fragmentation.
- The core collapse into a BH + envelope = Quasistar
- The key point:
  \[
  \dot{M} \approx M_J / t_{ff} = \frac{\pi^2}{8G} c_s^3 \approx 5 \times 10^3 \left( \frac{T}{10^7 \text{K}} \right)^{3/2} \text{ M}_\odot\text{yr}^{-1}
  \]

High temperature is \text{instrumental} in keeping Mdot so high

- Would \(T\) be so high with a realistic thermodynamics? (the simulation uses a polytropic EoS)
- On which timescale is turbulence (the source of energy) dissipated?
Conclusions

Light Seeds

• POPIII stars form copiously in the high-z Universe (z~20).
• $M_{\text{star}} \sim 45 M_\odot \rightarrow M_{\text{BH}} < 45 M_\odot$
• Accretion rate very low because of UV feedback (but simulations need to be truly cosmological)
Conclusions

Light Seeds

• POPIII stars form copiously in the high-z Universe (z~20).
• $M_{\text{star}} \sim 45 \, M_\odot \rightarrow M_{\text{BH}} < 45 \, M_\odot$
• Accretion rate very low because of UV feedback (but simulations need to be truly cosmological)

Heavy Seeds

• Direct gas collapse at high-z (z~10) needs low angular momentum haloes and high UV-H$_2$ dissociating flux. $J_{\text{crit}}$? (see Latif et al. 2014)
• If metal polluted, (i.e., lower z) runaway collisions (need $Z$ fine tuning?)
Conclusions

Light Seeds

• POPIII stars form copiously in the high-z Universe (z~20).
• \( M_{\text{star}} \sim 45 M_\odot \rightarrow M_{\text{BH}} < 45 M_\odot \)
• Accretion rate very low because of UV feedback (but simulations need to be truly cosmological)

Heavy Seeds

• Direct gas collapse at high-z (z~10) needs low angular momentum haloes and high UV-H\(_2\) dissociating flux. \( J_{\text{crit}} \)\? (see Latif et al. 2014)
• If metal polluted, (i.e., lower z) runaway collisions (need Z fine tuning?)

Observations

• Imprint of seeds on occupation fraction.
• Observations tell nothing so far.
• Future GW observations (eLISA) of the MBH merger rate at very-high redshifts.
SuperEddington accretion (slim disks)

\[ M(t) = M_0 \exp^{f_{\text{Edd}} \frac{t}{\tau} \frac{1-\epsilon}{\epsilon}} \]

\( \tau \approx 0.44 \text{ Gyrs} \)

Madau, FH & Dotti 2014
The diagram illustrates the relationship between the log of the black hole mass and redshift, with age of the universe (Gyr) as a parameter. The equations for this relationship are:

- $M_0 = 100 \, M_\odot$
- $a = 0$
- $f_{\text{EDD}} = 1.3$
SuperEddington accretion at not-so high $z$

Lupi et al., in prep