Formation and detection of supermassive black holes at high redshift

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LOCAL RELATION BETWEEN BH MASS & STELLAR BULGE VELOCITY DISPERSION

Reines+ 14; McConnell+ 13; Jiang, Greene & Ho 11; Gultekin+09
Correlations Between $M_{\text{BH}}$-Host Galaxy Properties

+ **Galaxy bulge mass** $[M_{\text{BH}} \sim 10^{-3} M_{\text{bulge}}]$ Dressler 89; Magorrian+ 98

+ **Galaxy bulge luminosity** $[M_{\text{BH}}-L^{1.0 \pm 0.1}]$ Kormendy 93; Kormendy & Richstone 95

+ **Stellar velocity dispersion** $[M_{\text{BH}} \sim \sigma^4]$ Tremaine+ 99; Ferrarese & Merritt 00

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McConnell & Ma+13  
van den Bosch et al.+12
How do BHs and the host galaxy know about each other

Do these scaling relations evolve through cosmic time

When are these correlations set up

Initial conditions? accretion physics? merger dynamics? self-regulated feedback?

How do seed BHs grow? can we see this?

How do seed BHs form? can we constrain this?
MULTI-WAVELENGTH DATA FOR ACTIVE & QUIESCENT BHs

$M_{BH} \sim 10^6 - 9 \, M_{\text{sun}}$
even $10^{10} \, M_{\text{sun}}$
$z \sim 0 - 7$
z=7 660 \, \text{Myr} 
550 \, \text{Myr} \text{ after the Big Bang}$

Urry+; Treister+; Scoville+; Sanders; Faber+; Wu+; Ferguson+; Harrison+; Hasinger+; Comastri+; Gilli+
EVIDENCE FOR IMPACT OF BHs ON THEIR ENVIRONMENT

On the smallest scales
ALMA data of NGC 1433 outflows & molecular disk

On the largest scales
CHANDRA data of the Perseus cluster outflows & shells
BHMF FOR BLQSOs FROM SDSS 1 < z < 4.5

Fig. 3. — BLQSO BHMF (thin solid lines) obtained using our Bayesian approach, compared with the local BHMF for all SMBHs (dashed line), and the BHMF from Vestergaard et al. (2008, solid red line with points); as in Figure 11, each thin solid line denotes a random draw of the BHMF from its probability distribution. The thick green line is the median of the BHMF random draws, and may be considered our "best-fit" estimate. The vertical line marks the mass at which the SDSS DR3 sample becomes 10% complete.
Bright quasars host $10^9 - 10^{10} \, M_{\text{sun}}$ BHs

LATEST PLANCK RESULTS: first stars form even later!

Age of the universe 1 Gyr

Eddington limit growth rate of mass

$$\frac{dM}{dt} = \frac{L_{\text{acc}}}{\eta c^2} < \frac{4\pi G M m_p}{\eta c \sigma_T}$$

$$M \leq M_0 e^{\frac{t}{\tau}}$$

$$\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5 \times 10^7 \, \text{yr}$$

$\eta$ = fraction of gravity dominated, $c$ = speed of light, $\sigma_T$ = Thompson scattering cross-section, $M$ = mass, $M_0$ = initial mass, $t$ = time, $\tau$ = growth time, $L_{\text{acc}}$ = accretion luminosity, $G$ = gravitational constant, $m_p$ = proton mass.

$L_{\text{min}} = 0.001 \, L_*$

Forced Match to WMAP

68% Credibility Interval

Maximum Likelihood SFR History

- ML SFR History Without $\tau$ Constraint
- SFR Density from UV Luminosity Density
- SFR Density from IR Luminosity Density

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MASS GROWTH OF BH SEEDS: TIMING CHALLENGE

AGE OF THE UNIVERSE AT $z = 7$ [771 Myr]; $z = 4$ [1.57 Gyr]; $z = 3$ [2.9 Gyr]

$\langle f_{\text{Edd}} \rangle_t = \frac{t_{\text{Edd}}}{t_{\text{Hubble}}(z)} \frac{\epsilon}{1 - \epsilon} \ln \left( \frac{M_{\text{BH}}}{M_0} \right)$.

$L = \epsilon \dot{M}_i c^2 = f_{\text{Edd}} L_{\text{Edd}} c^2$,
**Light Seeds**

PopIII

\[ \sim 10^{1-2} \, M_{\odot} \]

**Massive Seeds**

Direct collapse

Nuclear star cluster

\[ \sim 10^{3} \, M_{\odot} \]

Supermassive Star

Quasi star

\[ \sim 10^{4-6} \, M_{\odot} \]

Uncertainty in the masses of the first stars

A challenge to grow monster BHs seen by \( t < 2 \) Gyrs

New Planck results push first stars to later even \( \sim 550 \) Myrs after the Big Bang

In protogalaxies: need to avoid fragmentation and star formation, need to centrally concentrate mass

- Metal-free gas
- Prevent molecular H-cooling
First black holes in pre-galactic halos $z = 20-30$

- **Pop III remnants**: Simulations suggest that the first stars have a range of masses (Bromm+ 02; Abel+ 02; Abel+ 00; Alvarez+ 08; Hirano+ 14) Metal free Pop III stars leave remnant BHs

- **Supra-exponential early growth boost**: Super-Eddington growth in nuclear star clusters at high-$z$ (Alexander & PN 14)

- **Direct Collapse**: Efficient viscous transport, H2 cooling suppressed, Lyman-Werner radiation, formation of central concentration (Eisenstein & Loeb 95; Koushiappas+ 04)+ proper dynamical treatment of disk stability (Lodato & PN 06, 07)

- **Supermassive star** (Haehnelt & Rees 93)

- **Quasi-star** - Bar unstable self-gravitating gas + large quasi-star (Begelman 08; 10; 12)

$$M_{BH} \sim 1 - 100 \, M_{\odot}$$ **LIGHT SEEDS**

$$M_{BH} \sim 10^3 - 10^6 \, M_{\odot}$$ **MASSIVE SEEDS**
DO WE NEED MASSIVE BH SEEDS?
Tracking the fate of PopIII seeds in 2.5-3 sigma peaks

BHs simply not growing much down to \( z = 8 \) even when PopIII formation has ceased
BHs spend almost all their time in the wrong place in \( 10^8 \) M_{\odot} DM halos

Abel, Wise, Turk, Alvarez+; Stacy+
WHAT ABOUT Pop III REMNANTS IN $10^9 M_{\text{sun}}$ HALOS AT $z=15$
Tracking the fate of Pop III remnant BHs in 3-sigma peaks

snapshot with 20 BH seeds, 300 Mpc$^3$ box, ENZO AMR 12 level refinements $\sim 19$ comoving pc, DM resolution $\sim 3 \times 10^4 M_{\text{sun}}$

$\sim$ DM halos where Pop III star clusters formed at $z = 15$
HOW MASSIVE ARE POP III STARS?

~ Mass distribution of Pop III stars formed at $z = 30 \rightarrow 10$
Circumventing the Eddington limit
BH seed formation at high $z$

Baryons inside DM halo collapse and form a rotating pre-galactic disc

Disc becomes gravitationally unstable and accretes to the center

Angular mom of DM halo + Gas reservoir + dynamics (disc stability) + cooling

FINAL DCBH MASS

Regan+ 12; 14; Latif+ 15; Hirano+ 14
Massive BH seed formation simulations

Smith, Davis & PN 15; Regan+ 08; 13; Hirano+ 14

Choi, Shlosman & Begelman 13
**STRUCTURE FORMATION IN THE EARLY UNIVERSE**

First Billion Years

**FiBY**
Sadegh Khochfar & Claudio Dalla Vecchia
Max Planck Research Group
Max Planck Institute for Extraterrestrial Physics

**Visualization**
Klaus Reuter & Markus Rampp
Garching Computing Center of the Max Planck Society and the IPP

This movie was rendered using *Splotch*, the SPH particle ray tracer.
http://www.mpa-garching.mpg.de/~kdolag/Splotch
Low spin DM halos; satellite halos; Lyman-Werner radiation from nearby halos with star formation to dissociate mol H and prevent fragmentation
DIRECT COLLAPSE BHs AND THEIR OBESE BH HOST GALAXIES

- No PopIII
- Pop II Cluster
- DCBH
- Pop II Cluster
- DCBH+Pop II Miniquasar
- OBG Miniquasar [z=6]
- local relation
- Pop III-BH
- Pop II Cluster
- Pop III
- Pop III-BH
- Pop II Cluster
- Pop III BH+Pop II Miniquasar
- PopIII BH Miniquasar [z=6]
MODEL GROWTH HISTORIES OF BHs OVER COSMIC TIME

$10^{13} \, M_{\odot}$ halo

MASSIVE

LIGHT

Volonteri & PN 09; 11, 13
HIGH REDSHIFT SIGNATURE OF MASSIVE BH SEEDING MODELS

PREDICT NEW CLASS OF GALAXIES
OBESE BH GALAXIES (OBGs)

Agarwal+ 12; 14
Intermediate $z$ signature: journey to the $M_{\text{BH}} - \sigma$ relation; overmassive BHs outliers

Sequence of BH growth versus stellar assembly scatter in $z = 1$ to $z = 4$ correlations overmassive BHs for their host galaxies

Volonteri & PN 09; PN 13
Exploring growth histories

Outliers encode information on seed formation channels

CDM halo merging, environment
AGE OF THE UNIVERSE AT $z = 7$ [771 Myr]; $z = 4$[1.57 Gyr]; $z = 3$[2.9 Gyr]

$\langle f_{Edd} \rangle \tau = \frac{t_{Edd}}{t_{\text{Hubble}}(z)} \frac{\epsilon}{1 - \epsilon} \ln \left( \frac{M_{\text{BH}}}{M_0} \right)$.

$L = \epsilon \dot{M}_{\text{in}} c^2 = f_{Edd} L_{\text{Edd}} c^2$. 
SYNOPSIS OF CURRENT VIEW ON BH SEEDS TO MAKE THE MOST MASSIVE BHs AT ALL EPOCHS

MASSIVE SEEDS
DCBHs

Pre-galactic disk
Bars within bars

Super-Eddington growth
Quasi-star?

$10^4 - 10^6 \, \text{Msun}$
@ $z \sim 10 - 12$

Supress $H_2$ cooling

Super-Eddington growth

PN+ 15
Detecting the first black holes: Pop III seeds & DCBHs

\[ \langle \lambda_{\text{rad}} \rangle = \langle \dot{M}/M_B \rangle \]

- $10^6 M_\odot$, w/ Rad Feedback
- $10^7 M_\odot$, w/ Rad Feedback
- $10^8 M_\odot$, w/ Rad Feedback

\[ \dot{M}_{\text{Edd}} \]

$\delta_{\text{bulge-bh}} + 1$
What can we do with X-ray Surveyor
Masses of initial BH seeds
Early accretion history of seed BHs
Contribution to Re-ionization
Observational signatures of Super-Eddington flows
Importance of mergers
When do the correlations between BHs and their hosts get set-up