Could Supermassive Black Holes be Primordial?

black is the new dark

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Cosmic Controversies
Chicago USA
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How did the most massive Supermassive Black Holes ($M_\bullet > 10^{10} M_\odot$) seen at high redshifts (z up to 7) come into being?

**Uncontroversial:**

- matter falling onto Super Massive Black Holes (SMBHs) powers emission of quasars (QSOs) and active galactic nuclei (AGN)
- Event Horizon Telescope recently dramatically confirmed this!
- infalling matter accretes into SMBHs causing black hole mass ($M_\bullet$) to grow!
Uncontroversial SMBH phenomenology

- Lower mass active SMBH numbers increase.
- Higher mass don’t.

Graphs showing the distribution of SMBHs across different mass ranges and redshifts.
mass function grows more steep
uncontroversial statements

- number density \( \sim 10^9 \) M\(_\odot\) SMBHs has increased by orders of magnitude over time
  - w/ timescale \( \geq 100\) Myr
- number density \( > 10^{10} \) M\(_\odot\) has increased by only a small factor
  - w/ timescale \( \geq 400\) Myr
- small SMBHs growth leads to steepening mass function

commentary

  this does not “feel” like a bottom up scenario
  
  the “big ones” have been around “since the beginning”

controversy :

- what / when is the beginning? \( z \sim 6-7, \quad z > 10^3 \)
... this (QSO) is only the latest and most extreme of a growing number of known giant BHs at early times whose rapid growth, within the (somewhat squishy) constraint of the Eddington limit, is difficult to understand. ...

The point worth making is this: Such objects are so rare that any attempt to find a “natural” explanation is probably wrong. If the suggested process that makes these objects is not extremely unusual, it is probably the wrong process. Kormendy 2013
Eddington Limit

for accretion radiative repulsion < gravitational attraction
\[ \frac{\partial t}{M} < \frac{M}{\tau_{\text{salpeter}}} \]

\[ \tau_{\text{salpeter}} \approx 50 \text{Myr} \varepsilon/0.1 \]

\[ \varepsilon \equiv \frac{L_{\text{bol}}}{(\partial t M c^2)} \]

canonically \( \varepsilon \approx 0.1 \)

\[ L < L_{\text{Eddington}} \propto M \]

Inayoshi & Haiman 2017
Uniformitarian Population Dynamics

\[ \tau \partial_t \ln[\Psi] = - (1 + \beta - \partial \ln[M] \ln[\tau]) \]

\[ \langle \partial_t M \rangle = M / \tau[M,z] \quad \Psi \equiv \partial M n[M] \propto M^\beta \quad \text{fixed } \tau[M,z] \propto M^\alpha \]

FIT:
\[ \beta \rightarrow -2.05 \]
\[ \tau = 805 \text{ Myr} \quad M_{10}^{1.6} \]
\[ \Phi \rightarrow 0.76 \text{ Gpc}^{-3} M_{10}^{-1.05} \]

\[ \Phi \equiv \int_{M}^{\infty} dM \Psi \]
Proposed Power Law Initial Mass Function

\[ \Psi_0 \propto M^{\beta_0} \]

and \( \beta_0 \) which introduces **no new dimensional parameters**

**Matter Scaling:** \( \beta_0 = -2 \)

\[ \Psi_0 = f_{BH} \frac{\rho_{m0}}{M^2} \]

\( f_{BH} \sim 10^{-10} \)  no BH dark matter

N.B. scalar perturbation amplitude \( A_s = 21 \times 10^{-10} \sim 3.5 \ f_{BH} \)

**Gravitational scaling:** \( \beta_0 = -5/2 \)

à la Harrison-Zel’dovich

\[ \Psi_0 = 2^{5/4} \phi_{BH} \left( \Omega_{m0}^{5/2} \Omega_{r0}^3 \right) \left( \frac{M_{eq}}{M} \right)^{5/2} \left( \frac{GH_0^4}{c^6} \right) \]

(for \( M < M_{eq} \approx 3 \times 10^{17} \ M_\odot \))

\( \phi_{BH} \sim 10^{-15} \)  cutoff / BH dark matter @ \( 6 \times 10^{-10} \ M_\odot \)
Mostly Unconstrained by usual PBH Arguments

- matter scaling below bottom of this graph
- gravitational scaling must be cutoff

Carr, Kuhnel, Sandstad 2016
IMF Extremely Red

- Nearly all statistical properties of BH distribution dominated by the most massive BH in the volume.
- All mass moments diverge: but can work with medians.

\[
\frac{\max_{\text{Hubble volume}} \left[ R_{\text{Schwarschild}} \right]}{\text{median realization}} \propto \frac{3 \Omega_m [z]}{4 \pi \ln[2]} f_{\text{BH}}
\]
Uniformitarian Model

- most massive SMBHs grow slowly due to sub-Eddington accretion and/or low duty cycle
  - super/hyper Eddington accretion not possible unless radiative efficiency very low, we would have seen this
  - growth by major mergers is not possible because large massive SMBHs are observed to be too far apart, >30Mpc.

Consequence

- SMBHs existed in the early $z>10$ universe
- they would be extremely rare
- extrapolating to lower mass: an IMBH seed in every galaxy

Controversy

- massive SMBHs would not form in $\Lambda$CDM standard model
Uniformitarianism Issues

• primordial $10^{10} \text{M}_\odot$ localized *uncompensated* masses would have accreted halos $>10^{15} \text{M}_\odot$ which surely would not have gone unnoticed.

• compensated perturbations corresponding to local rearrangements of matter will ameliorate this problem.

• the required modification of $\Lambda$CDM is not a different $P[k]$ or $f_{nl}$ but some sort of extreme non-Gaussianity.

• Topological defects such as cosmic textures comes to mind

• what about the CMB?
The Universe is an Excellent Magnifying Glass

M87 would appear larger (in angle) at $z=1000$!
Model Distribution of Black Hole Shadows

black hole shadow flux deficit

\[ \bar{N}[ > \Omega_{\text{eff}}] \approx 413 \frac{f_{\text{BH}}[\infty]}{3 \times 10^{-12}} \frac{1 \mu\text{asec}}{\Omega_{\text{eff}}^{1/2}} \]

\[ 1 - e^{-\bar{N}_{5 \sigma}^{\text{SPT}}} \approx 0.0013 \]

\[ 1 - e^{-\bar{N}_{1 \sigma}^{\text{SPT}}} \approx 0.0028 \]
Most photons absorbed near time of BH formation is at very hi-z (rad. era $z_{\text{form}} \propto M^{-\frac{1}{2}}$)

- extrapolated shadow past SoLS $\Omega_{\text{eff}} \propto M^2 z_{\text{form}}^2 \propto M$

Monte Carlo scattering of “missing photons”

- scattered missing photons form a “gray halo”
- proper Boltzmann analysis more accurate
- polarized scattering yields highly polarized halo
Halos are Much More Easily Seen

black hole halo flux deficit
Summary

• A simple extrapolation of observed QSO/SMBH mass evolution suggest $M > 10^{10} M_\odot$ existed early in the universe.

• While this is not compatible with $\Delta$CDM - I have argued it is compatible with observations.

• This would have observable consequences for future CMB observations

• Extrapolation to lower mass BHs could
  • provide seeds for central SMBHs in most galaxies
  • might be the low mass PBH dark matter

What's this Cheshire Cat smiling about?
Additional Slides
Is WMAP cold spot a SMBH?

Sachs Wolfe ($\frac{1}{3}\Phi$) effect from $10^{14} \, M_\odot$ SMBH $\sim 200$ Mpc (comoving) in front or back of surface of last scattering.

$\sim$ most massive SMBH expected in observable universe
### Detection Using CMB Backlighting

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<tr>
<th>effect</th>
<th>where operative</th>
<th>volume</th>
<th>spectrum</th>
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<tbody>
<tr>
<td>shadow $\propto z^2$</td>
<td>$z&lt;10^3$</td>
<td>$10^4\text{ Gpc}^3$</td>
<td>black</td>
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<tr>
<td>halo scattered shadow</td>
<td>$z\sim10^3$</td>
<td>$200\text{ Gpc}^3$</td>
<td>$\sim$gray</td>
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<td>doppler</td>
<td>$z\sim10^3$</td>
<td>$200\text{ Gpc}^3$</td>
<td>$\Delta T$</td>
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<tr>
<td>Sachs-Wolfe</td>
<td>$z\sim10^3$</td>
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<td>nonlinear ISW</td>
<td>$z&lt;10^3$</td>
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SDSS 7 Quasar Survey: A large survey

Shen et al. 2011

$0 < z < 5 \quad f_{\text{sky}} = 0.194 \quad 410 \text{ Gpc}^3 \quad 104,746 \text{ SMBHs}$
Can supergrowth explain the origin of the most massive SMBHs?

Does supergrowth scenario explain the origin of the any SMBHs?

We only know of formation of stellar mass BHs which may not sink by dynamical friction or accrete much.

The earliest stars may be more massive but are they massive enough?

**Illustration: ULAS J1120+640**

\[ M = 2^{+1.5}_{-0.7} \times 10^8 M_\odot @ z=7.085 \]

assuming canonical Eddington limited accretion \( \epsilon=0.1 \) \( T_{\text{Salpeter}}=45\text{Myr} \).

\[ M = 4.2^{+3.1}_{-1.6} \times 10^6 M_\odot @ z=10 \]

\[ M = 168^{+126}_{-59} M_\odot @ z=100 \]

Is it plausible to produce required seed BHs?

N.B. this only needs to happen rarely.

There is no evidence that BH masses evolve at anything as short as a 45Myr timescale! Most massive QSOs are not Eddington limited!
Worse Problem

At large $M$ and $z$ observations indicate

- Flattening not steepening of mass function.
- Slow not fast growth of $\Psi$ and therefore $M$.

Can super growth or direct formation explain this?

Illustration: ULAS J1120+640

$M = 2^{+1.5}_{-0.7} \times 10^9 M_\odot \ @ \ z=7.085$

assuming canonical $\tau_{\text{Salpeter}}=45 \text{Myr}$ versus empirical $\tau_{\text{growth}}=805 \text{ Myr}$

$M = 4.2^{+3.1}_{-1.5} \times 10^6 M_\odot \ @ \ z=10$

$M = 168^{+120}_{-59} M_\odot \ @ \ z=100$
The observed existence of large mass large redshift SMBHs is difficult to understand.

The flat mass function and slow evolution does not match expectations for baryonic formation.

Simple extrapolation suggests formed very early at nearly the observed mass.

Primordial SMBHs is an option for their origin.

A variety observational tests could validate this hypothesis. QSO outliers and CMB anomalies may be the key for detection.

If confirmed this would change our understanding of the early universe.

Could the same mechanism produce negative density “point defects” resulting in super voids?
Figure 2 | Central stellar light profiles for NGC 1600 and for a sample of other core and coreless elliptical galaxies. Surface brightness profiles (in the V-band) are shown for a sample of galaxies, on the basis of HST observations up to a distance of 100 Mpc from Earth. NGC 4889, at 102 Mpc, is included because its black-hole mass has been measured. $\mu$ is the surface brightness and $r$ is the galactic radius at which the brightness was measured. Lower-luminosity elliptical galaxies typically have rising light profiles towards the galactic centres (steep grey curves), whereas NGC 1600 and other very massive elliptical galaxies often exhibit a marked deficit of stars in the central region (red curves). Highlighted are the brightest galaxies in the Leo Cluster (NGC 3842) and the Coma Cluster (NGC 4889), and the brightest (NGC 4472) and central (NGC 4486 or M87) galaxies of the Virgo Cluster. The stellar core in NGC 1600 (dark red curve) is the faintest known among all galaxies for which dynamical $M_{BH}$ measurements are available.

Thomas Ma McConnell Greene Blakeslee Janish Nature (2016)

NGC 1600 $M_{\bullet} = 1.7 \times 10^{10} \, M_{\odot}$ @ 64 Mpc from Earth