Understanding the rapid decline of black hole growth and star formation since $z \sim 1$

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Star-formation and black hole accretion rate densities as a function of redshift

Star formation rate densities:
- Bouwens et al. (2007)

- Correlation between star formation rate density and AGN accretion rate density (build up of black holes)
- Both peak at z≈1-2 and drop rapidly at later times
- What drives these declines and why are they related?
Understanding the decline since $z \sim 1$
- reconciling multiple observational results

(1) The evolution of the X-ray luminosity function of AGN
(Aird et al. 2010)  AEGIS, CDFs

(2) Evolution of the galaxy stellar mass function
(Moustakas et al. 2012, submitted)  PRIMUS

(3) Incidence of AGN as a function of host stellar mass and color
(Aird et al. 2012)  PRIMUS
(1) Evolution of the X-ray luminosity function


• XLF evolves in luminosity and density but retains same shape

• From z=1 to z=0 the XLF is dominated by luminosity evolution

$L^\star$ shifts to lower $L_X$ with time
(2) Evolution of the galaxy stellar mass function


Very little evolution of total galaxy stellar mass function (above \( \sim 10^{10} \, M_\odot \)) from \( z \sim 1 \) to \( z \sim 0 \)
(2) Evolution of the stellar mass function: star-forming vs. quiescent
(2) Evolution of the stellar mass function: star-forming vs. quiescent number densities

<table>
<thead>
<tr>
<th>Redshift Range</th>
<th>Number Density</th>
<th>Low M - increase in number of quiescent galaxies (with time)</th>
<th>High M - decrease in number of star-forming galaxies (with time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>log ((M/M_\odot) = 9.5 - 10)</td>
<td>(-2.5) to (-3.0)</td>
<td>![Graph showing increase in number density]</td>
<td>![Graph showing decrease in number density]</td>
</tr>
<tr>
<td>log ((M/M_\odot) = 10 - 10.5)</td>
<td>(-2.5) to (-3.0)</td>
<td>![Graph showing increase in number density]</td>
<td>![Graph showing decrease in number density]</td>
</tr>
<tr>
<td>log ((M/M_\odot) = 10.5 - 11)</td>
<td>(-2.5) to (-3.0)</td>
<td>![Graph showing increase in number density]</td>
<td>![Graph showing decrease in number density]</td>
</tr>
<tr>
<td>log ((M/M_\odot) = 11 - 11.5)</td>
<td>(-2.5) to (-3.0)</td>
<td>![Graph showing increase in number density]</td>
<td>![Graph showing decrease in number density]</td>
</tr>
</tbody>
</table>

Fig. 12. — Evolution in the number density of all (black squares), quiescent (red diamonds), and star-forming (blue points) galaxies since \(z = 6\). Meanwhile, the number of \(10^9 M_\odot\) and \(10^{11} M_\odot\) galaxies vastly outnumber quiescent galaxies, and their number density varies by \(\pm 15\%\) since \(z = 6\). By contrast, among \(10^{10} M_\odot\) galaxies relatively constant over the range of stellar mass.

To summarize, we have shown that the evolution of massive galaxies—within the global galaxy population—history is driven entirely by the much more significant evolutionary trends exhibited by the population of massive galaxies. It is apparent that these relatively subtle evolutionary trends are in fact a major driver of the downsizing of the massive galaxy population toward low redshift. Between \(10^9 M_\odot\) and \(10^{11} M_\odot\) the number density changes by \(4\%\), while the number density of massive star-forming galaxies decreases precipitously toward lower redshift. Between \(10^{10} M_\odot\) and \(10^{11} M_\odot\) the number density decreases by \(14\%\) and \(35\%\), respectively. Finally, the number density decreases by nearly \(60\%\) for \(10^{11} M_\odot\) galaxies, a factor of \(28\%\) decrease in the number of massive star-forming galaxies since \(z = 6\). Thus, we find evidence for mass assembly downsizing—a continued buildup of the low- and intermediate-mass galaxy population toward low redshift. The distinct evolutionary trends in galaxy properties, such as stellar mass function and star formation, remarkably constant (within \(\pm 15\%\)) space density of star-forming galaxies over the same range of redshift and the decline of the star-forming population at large masses. The number density of quiescent galaxies increases significantly since \(z = 6\) and continues toward lower redshift. At low mass, and the dominance of quiescent galaxies, marks the transition regime between the dominance of star-forming vs. quiescent galaxies. The distinct evolutionary trends exhibited by star-forming and quiescent galaxies conspire to keep quiescent galaxies dominant at all masses and redshifts probed by PRIMUS.
(2) Evolution of the stellar mass function: constraints on rate of quenching

- The rate at which SF galaxies are quenched is relatively low and roughly constant with redshift.

- Quenching of star formation is not responsible for the rapid decline in the overall star formation rate density of the universe since $z \sim 1$.

- Decline of SFR density is due to reduction in specific star formation rates of the SF galaxy population.

Dominated by quenching of intermediate mass galaxies

![Graph showing rate of quenching vs. redshift]
The incidence of AGN... vs. stellar mass

X-ray AGN in PRIMUS
Exclude QSOs (unable to probe host galaxy)
(3) The incidence of AGN... vs. stellar mass

Probability of a galaxy of a given stellar mass, $M_*$, and redshift, $z$, hosting an AGN of luminosity, $L_X$

Increase in probability of finding an AGN with increasing $M_*$ at fixed $L_X$
(3) The incidence of AGN... vs. stellar mass

Specific accretion rate
\[ \frac{L_{\text{bol}}}{M_*} \propto \lambda_{\text{Edd}} ? \]
Eddington ratio
(3) The incidence of AGN... vs. stellar mass
(3) The incidence of AGN... vs. stellar mass

The probability of a galaxy hosting an AGN is independent of stellar mass.

Specific accretion rate

\( p(\lambda_{\text{Edd}} | M_*, z) \) [dex\(^{-1}\)]

\( \log \lambda_{\text{Edd}} \)
(3) The incidence of AGN... vs. redshift

(combining all stellar masses)

Strong evolution with redshift
\( \propto (1+z)^{3.5\pm0.5} \)

\[ p(\lambda_{\text{Edd}} | M_*, z) \text{ [dex}^{-1}\text{]} \]

Specific accretion rate

0.8 < z < 1.0
0.6 < z < 0.8
0.4 < z < 0.6
0.2 < z < 0.4
(3) The incidence of AGN... vs. host optical color


Mild (factor ~2-3) enhancement of incidence of AGN in the green valley and blue cloud.

AGN

Specific accretion rate

$p(\lambda_{\text{Edd}} | M_\ast, z)$ [dex$^{-1}$]

$\log \lambda_{\text{Edd}}$

Magnitude

Color

Blue cloud

Green valley

Red sequence
(3) The incidence of AGN... star-forming vs. quiescent (not in Aird+12)

Star formation rate

\[ \log(\text{SFR} / \text{M}_\odot \text{yr}^{-1}) \]

Quiescent

Star-forming

Using UV-IR SED fits

\[ \log(\text{M}_*/\text{M}_\odot) \]

0.20 < z < 0.60

0.60 < z < 1.00

Contours=galaxies

\[ x = \text{X-ray AGN} \]

Mild (factor ~2-3) enhancement of incidence of AGN in star-forming galaxies, spanning range of specific accretion rates,

\[ \lambda_{\text{Edd}} \]

Specific accretion rate

\[ p(\lambda_{\text{Edd}} | \text{M}_*, z) \text{ [dex}^{-1}] \]

\[ \text{Stellar mass} \]
Putting it all together

Galaxy stellar mass function

\[ \phi(M_*, z) \]

Specific accretion rate distribution

\[ p(\lambda_{Edd} | M_*, z) \]

\[ \longrightarrow \]

X-ray luminosity function

\[ \psi(L_X, z) \]

\[ \log \frac{M_*}{M_\odot} = 8 \quad 9 \quad 10 \quad 11 \quad 12 \]

Cut off at \( \sim \) Eddington limit?
Putting it all together

- Low $L_X$, AGN population dominated by $\sim 10^{11} M_\odot$ galaxies with BHs growing at low accretion rates
- Around $L_\star => 10^{11} M_\odot$ galaxies with BHs growing close to Eddington limit
- High $L_X =>$ massive galaxies with very rapidly growing BHs

X-ray luminosity function

$\psi(L_X, z)$

$\Phi(L_X, z, N) = \int \phi(M_*) \frac{d\phi}{dM_\star} dM_\star$
Putting it all together - star-forming and quiescent

- Star-forming host galaxies dominate number density for low \( L_X \) AGN

Galaxy stellar mass function  
Specific accretion rate distribution \((w/\) bolometric correction) 
X-ray luminosity function \( \psi(L_X, z) \)

\[ \phi(M_*) / \text{Mpc}^{-3} \text{dex}^{-1} \]

\[ p(\Lambda_{\text{Edd}} | M_*) \]

\[ \psi(L_X, z) / \text{Mpc}^{-3} \text{dex}^{-1} \]

\[ \log L_X / \text{erg s}^{-1} \]
Putting it all together - as a function of redshift

Galaxy stellar mass function
\[ \phi(M_*, z) \]

Specific accretion rate distribution
\[ p(\lambda_{Edd} | M_*, z) \]

X-ray luminosity function
\[ \psi(L_X, z) \]

Mild evolution (above \( \sim 10^{10} M_\odot \))

Strong evolution \( (1+z)^{3.5} \)

\[ z = 0.9 \]
Putting it all together - as a function of redshift

Galaxy stellar mass function

\[ \phi(M_*, z) \]

Specific accretion rate distribution

\[ p(\lambda_{Edd} \mid M_*, z) \]

\[ \rightarrow \]

X-ray luminosity function

\[ \psi(L_X, z) \]

Mild evolution

(above \( 10^{10} M_\odot \))

Strong evolution

\( (1+z)^{3.5} \)

\( z = 0.25 \)
Putting it all together - as a function of redshift

Galaxy stellar mass function
\[ \phi(M_\ast, z) \]

Specific accretion rate distribution
\[ p(\lambda_{Edd} | M_\ast, z) \]

\[ \rightarrow \]

X-ray luminosity function
\[ \psi(L_X, z) \]

\( 0.80 < z < 1.00 \)

Mild evolution
(above \( \sim 10^{10} M_\odot \))

Shift in characteristic accretion rate

\( z = 0.9 \)
Putting it together:

- Evolution of AGN driven by a fall in specific accretion rates with time
  (cf. drop in specific star formation rates)

Galaxy stellar mass function

\[ \phi(M_*, z) \]

\[ \mathcal{L}(M_*, z) \]

\[ H(z) \]

\[ \lambda_{\text{Edd}} \]

\[ \psi(L_X, z) \]

\[ \phi(M_*, z) / \text{Mpc}^{-3} \text{dex}^{-1} \]

\[ L_X / \text{erg s}^{-1} \]

Mild evolution (above \( \sim 10^{10} M_\odot \))

Shift in characteristic accretion rate

\[ z = 0.25 \]
Summary of findings

- Strong luminosity evolution of X-ray luminosity function

- Little evolution of total stellar mass function
  - Star-forming and quiescent populations do evolve differently
  - Quenching is not responsible for rapid decline of star formation

- Incidence of AGN is described by power-law distribution of specific accretion rates - independent of stellar mass, evolves strongly with redshift, weak enhancement in star-forming galaxies

- We can reconcile these results with a basic model where the evolution of AGN is driven by a drop in characteristic BH accretion rates with time

  (mirrors drop in specific star formation rates with time)
Open questions

• (Why) is there a cut-off at high accretion rates?

• What causes the drop in the characteristic specific accretion rate for AGN?

• How and why is this related to the drop in specific star formation?

• Why do we find AGN in quiescent galaxies? Is there a shift in their specific accretion rate distribution?

BH feedback?