The Interplay Between Galaxies and Black Holes
A Theoretical Overview

Massimo Ricotti (U of Maryland)
..a tale of many sleepless nights

Maya and Noemi Ricotti
Outline

• **Cosmological Context**

• **Formation of “Seed Black Holes”**
  1. Primordial Black Holes
  2. Pop III Stars Remnants
  3. Direct Collapse
  4. Stellar Dynamics

• **Black Hole Growth**
  1. Gas Accretion vs BH-BH Mergers
  2. Feeding Black Holes
    » M-sigma relation
    » Feedback and duty cycles
  3. Feedback on Environment
    » Cosmic ionization and thermal history
Black Hole Jargon

Formation at $z<30-50$ in galaxies

- Stellar mass Black Hole (BH): roughly $\sim 1-10 \, M_{\text{sun}}$
- Intermediate mass BH (IMBH): $\sim 100-1000 \, M_{\text{sun}}$
- Massive BH (MBH): $>1000 \, M_{\text{sun}}$
- Supermassive BH (SMBH): $> 10^6 M_{\text{sun}}$

Formation at $z > 5000$ from collapse of “radiation”

- Primordial BH (PBH): $10^{-5} \, \text{g}$ to $10^5 \, M_{\text{sun}}$
How and when BH form?

• Solid evidences of BH and SMBH existence
• Debatable evidences of IMBH existence
  – Ultraluminous X ray sources (ULX) in nearby galaxies (eg, Miller & Colbert 2004)
  – In GCs M15 and G1 (vanderMarel et al. 2002; Gerssen et al. 2002; Gebhardt et al. 2005, but see Baumgardt et al 2003)
• No direct evidence of PBH existence. Upper limits.

• Formation of stellar BHs is more or less understood. We do not know how all other BHs formed ...
Evidence for SMBH at the center of our Galaxy
SMBHS form early! High-z Quasars

Fan 2006
How fast can a black hole grow? (by gas accretion)

1. Quasars shine by converting potential energy to radiative energy when accreting gas: radiative efficiency of ~10%

2. Quasar maximum accretion rate is limited by radiation pressure (Eddington limit). The growth is exponential with maximum accretion e-folding timescale 40 million years.

3. The age of the universe at z~6 is ~800 million years: maximum growth is 500 million times (about 20 e-folding timescale)

4. Earliest quasars have a mass of several billions solar masses: “seed” black holes must be massive (> 10-100 Msun)

5. Feedback effects likely to prevent non-stop accretion at maximum rate
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Start here!

Rees 1984
General remarks to grow SMBHs

- Bondi accretion rate proportional to BH mass square: need massive seeds

- Golden rules for BH formation from gas cloud
  1. Avoid gravitational fragmentation
  2. Accrete gas with low angular momentum or dissipate angular momentum

High redshift Universe is ideal. Why?
  1. Low metallicty and low cooling rate helps with fragmentation problem
  2. Smaller amplitude of cosmological perturbations helps with angular momentum problem

However, there are no direct observations to guide us
Brief history of the Universe

CMB (observed)

z ~ 1000: Last Scattering Surface

z ~ 7-30: first stars and quasars, reionization begins

Not observed

H Reionization complete

He Reionization complete

Observed Universe

PBHs?

IMBHs from Pop III?

Direct collapse of MBHs?

Quasars (accreting SMBHs)
Cosmological structure formation

- Gaussian perturbations from inflation + CDM
- Bottom-up galaxy formation

Phase transitions: Non Gaussian perturbations?
1. PBHs modify recombination history and produce spectral distortions and anisotropies
2. New upper limits on $f_{\text{pbh}}$ with WMAP3
3. PBHs promote formation of primordial H$_2$ and first stars

Constraints on $f_{pbh}$ from CMB

Ricotti, Ostriker & Mack 2008
Discussion

• Only upper limits on their existence. Do not know if they can form
• However, may provide plenty of IMBH to explain ULXs and the seeds to form SMBHs

• **Note:** Ultra-compact minihalos much more likely than PBHs. Can be probed as MACHOs and gamma-ray from DM self-annihilation (Ricotti & Gould 2009)
• First stars and BHs may form in ultra-compact minihalos at z>>30 (see also Loeb 1993)
2 – First stars

- Form in $10^5$-$10^6 \, M_{\text{sun}}$ minihalos
- Zero metallicity gas
- One star per halo
- Mass 20-300 $M_{\text{sun}}$?

Discussion

• Of course the first stars formed but we do not know their mass and number:
  – IMF depends on environment. In relic HII regions smaller mass due to HD cooling, metallicity contamination, etc..
  – Binary Pop III

• Remnants may be too small IMBHs
3 – Direct collapse of gas cloud


• General considerations:
  – Form later in more massive halos > $10^7-10^8 \, M_{\text{sun}}$
  – Need to suppress star formation in cloud because SNe increase kinetic energy
  – Need to cool via atomic H and not molecular H, due to the temperature of these clouds
  – Perhaps possible if stars have already formed! (in other places, not the cloud). Then UV light dissociates $H_2$
Discussion

• Physical processes to prevent fragmentation:
  – Suppression of metal and H$_2$ cooling (Bromm & Loeb 2003)
  – Steepening of equation of state due to Lya trapping (Spaans & Silk 2006)

• Angular momentum dissipation:
  – Viscosity (Lodato & Natarajan 2006)
  – Bar-unstable self gravitating gas (Begelman, Volonteri & Rees 2006)
  – Compton Drag (Loeb 1993, Umemura et al 1993)
4 – MBHs from dense star clusters


Stellar BH mergers

Gultekin, Miller & Hamilton 2004

1. Run out of BH before growth to 300 $M_{\odot}$.
2. Starting from small $10 \, M_{\odot}$ seed lead to high probability of ejection.
Cluster must collapse before its massive stars do.

Rasio et al. 2003
Discussion

• BH mergers:
  – Relatively slow growth per BH ejected from cluster
  – Favors clusters with larger escape velocity

• Runaway stellar collisions:
  – Star cluster must have quite small initial mass and size
  – Need to understand when and where such clusters may form (in cosmological volume)
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The black hole-galaxy connection

- Black hole mass is related to host galaxy properties
- Many models to explain this. In general feedback require feedback regulation

Tremaine et al 2002
Evidence for gas accretion and AGN downsizing

Ueda et al. 2003; Fiore et al. 2003; Barger et al. 2005; Hasinger et al. 2005
Gas Accretion vs BH-BH Mergers

Soltan’s argument: Yu & Tremain 2002, Merloni et al 2004, etc

Merger rate: Volonteri et al

\[ \eta = 0.08 \]
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Feeding BHs through galaxy mergers

$T = 0 \text{ Myr}$
Duty cycles: 1D simulations

Ciotti, Ostriker & Proga 2009

Radiative feedback:
0.2 efficiency (left), 0.1 (right)

Mechanical feedback:
0.5% efficiency (left), 0.03% (right)
Discussion

• Types of feedback: Compton heating, photoionization, winds (radiation driven), relativistic jets (do not work well: see Vernaleo & Reynolds 2006)

• Gas feeding: galaxy mergers or recycled gas from stellar evolution

• Reproduce M-sigma relation or properties of giant elliptical. Do not reproduce both.
Early accretion onto IMBHs?

Before reionization?
Bondi accretion with radiation feedback

$100 \, M_{\text{solar}}$ IMBH

Gas density

Ionization fraction
Accretion rate

Park & Ricotti, in preparation

See also Milosavljevic et al 2008
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Reionization of the Universe

From Haiman & Loeb

- **Pre-overlap**
  - $Z \sim 30$
    - First stars and mini-quasars form via $H_2$ cooling.
    - $H_2$ destroyed by photons with energies of 11.2-13.6eV.

- **Overlap**
  - $Z \sim 15$
    - Massive objects cool and form stars via atomic line emission at $T_{\text{vir}} \gtrsim 10^4 \text{ K}$.

  - $Z \sim 8$
    - Expanding HII regions overlap; UV background rises sharply.
    - Free electrons damp CMB anisotropies.

- **Post-overlap**
  - $T_{\text{vir}} < 10^4 \text{ K}$
  - $T_{\text{vir}} > 10^4 \text{ K}$
Effects of early X-ray sources

Outside -> in reionization

Ionization

Molecular hydrogen

Gas density

Temperature

Red-shifted X-rays

- Heli cross section
- Ionized
- Neural
- Voids
- Filaments

- $J_{21}$ [erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$]
- $h_p \nu$ [Kev]
- $z = 10.107$
- $L_{\text{box}} = 4$ Mpc (mass weighted)
Ricotti, Ostriker & Gnedin 2005
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