Evolution of Supermassive Black Holes: Cosmological Simulations

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Observational evidences

Sagittarius A* - galactic centre

DMO in M87, M84 and NGC4261

Ghez et al. 1998
**Black holes and galaxies**

Strong correlations are observed between the black hole mass and:

- **Stellar velocity dispersion**: $M_\bullet \propto \sigma^{3.5-4.5}$
  - Tremaine et al. 2002; Gebhardt et al. 2000

- **Stellar bulge mass**: $M_\bullet \propto M_{bulge}^{1.12}$
  - Haring and Rix, 2004

- **Stellar bulge luminosity**: $M_\bullet \propto L_B^{1.26}$
  - Marconi and Hunt, 2003

- **Dark halo mass**: $M_\bullet \propto M_{halo}^{1.27}$
  - Baes et al. 2003

**Co-evolution of SMBH and galaxies**
Coeval growth of galaxies and their central black holes

- **galaxy-galaxy interactions**
  - Gas flow into galaxies
  - SMBH accretion & coalescences
  - Star formation
  - SMBH growth
  - Supernovae
  - AGN's

- **Feedback**
Cosmological simulations

**Advantages**
- follow up of seeds
- gas dynamics & merger tree
- follow up of the star formation history

**Difficulties**
- Two extreme scales:
  - Galaxies interactions: several kpc
  - Black hole physics: several pc

| Number of Particles | Mass resolution (gas) $V=(50 \text{ Mpc})^3$ | CPU/hours/run (128 processors) |
|---------------------|---------------------------------|--------------------------------|
| $2 \times 160^3$    | $5.35 \times 10^8 \text{ M.}$  | 4 000                          |
| $2 \times 192^3$    | $3.09 \times 10^8 \text{ M.}$  | 12 000                         |
| $2 \times 256^3$    | $1.30 \times 10^8 \text{ M.}$  | 60 000                         |

$\Omega_v=0.7 \quad \Omega_m=0.3 \quad \Omega_b \, h^2= 0.0224 \quad h=0.70 \quad \sigma_8=0.9$
The Code

GADGET-II
Springel 2005

Gravitation (tree code)
Hydrodynamics (SPH)

DARK MATTER
GAS

Introduction of BH seeds at potential minima (z=15)

SMBH

SMBH coalescences during galaxy mergers

BH Growth (« disk » and HLB mode)

AGN activity (feedback)

Ionisation, heating and radiative cooling

Star formation (conversion of gas into tars)

Supernovae (type Ia and II)

Galactic winds

Metallic enrichment
Energy injected by supernovae $\Rightarrow E_{SN} = \frac{\alpha_{Ia,II}}{10^{51} \text{erg}} \Rightarrow 0.03 - 0.2$

Weight for the blast $\Rightarrow w \propto \frac{1}{r^n}$ energy per particle $\Rightarrow \varepsilon_i = \frac{w_i}{\sum_i w_i} \left( \frac{E_{SN}}{N} \right)$

"turbulent" diffusion efficiency $\Rightarrow \eta = \frac{D_t \Delta t}{L^2} \Rightarrow 0.1 - 0.2$

Accretion mode $\Rightarrow$ spherical (Bondi – Hoyle) $\Rightarrow$ "disk" $\Rightarrow \frac{dM}{dt} = \frac{6\pi c_s V^2_{\varphi}}{9 \mathcal{R} QG}$

AGN feedback
- gravitational energy $\Rightarrow L_J = \alpha_{AGN} L_{bol} \Rightarrow \alpha_{AGN} = 0.1$
- rotational energy $\Rightarrow L_J = \frac{\pi}{2} \left( \frac{c}{V_A} \right) \left( \frac{S}{S_{\text{max}}} \right)^2 H^2 c r^2_{\text{hor}}$

Jet angle $\Rightarrow \theta = 20^\circ, 45^\circ, 180^\circ$

Jet length $\Rightarrow 100 - 400 \text{ kpc}$
Evolution of gas and stars

$z = 5 \quad \rightarrow \quad t = 2.8 \text{ Milliards d’années}$
$z = 3 \quad \rightarrow \quad t = 4.1$ milliards d’années
$z = 2 \quad \rightarrow \quad t = 5.4 \text{ Milliards d’années}$
$z = 1 \quad \rightarrow \quad t = 7.8$ Milliards d’années
$z = 0 \rightarrow t = 13.5$ Milliards d’années
Detection of Structures

Structure determination

FoF

SubFind

Davis et al, 1985; Huchra and Geller, 1982

Springel et al, 2001
Dynamical Properties of Simulated Galaxies

"Red" galaxies \( (U-V) > 1.1 \) and \( (B-V) > 0.8 \)

"Blue" galaxies otherwise

Faber-Jackson & Tully-Fisher relations

Angular momenta of blue & red galaxies
Properties of Simulated Galaxies

Grey zone – SDSS data from Gallazzi et al. 2005
Properties of Simulated Black Holes: the mass function at $z=0$

All simulations give similar results, with BHMF slightly overestimated for $M_\bullet > 10^7 M_\odot$

BH seeds of $100 M_\odot$: evolution of massive pop III stars

192/160: resolution
disk/kerr: AGN feedback from accretion /rotation
S: with higher SNIa efficiency
Evolution of the Black hole mass density

Black hole mass density at $z=0$

Estimates: $\rho_\bullet = 2 - 9 \times 10^5 \text{M}_\odot \text{Mpc}^{-3}$

- Chokshi and Turner 1992
- Salucci et al., 1999
- Aller and Richstone, 2002
- Marconi et al, 2004, ...

| Simulation | $\rho_\bullet (z=0)$ [M$_\odot$.Mpc$^{-3}$] | $M_{\text{BH, min}}$ [M$_\odot$] |
|------------|--------------------------------|-------------------------------|
| 160kerr    | $5.0 \times 10^5$               | $2.4 \times 10^4$             |
| 160disk    | $9.6 \times 10^5$               | $1.8 \times 10^4$             |
| 160diskS   | $7.4 \times 10^5$               | $3.7 \times 10^3$             |
| 192disk    | $8.2 \times 10^5$               | $1.2 \times 10^3$             |

Assuming bolometric luminosity proportional to the accretion rate

$192/160$: resolution
$\text{disk/kerr}$: AGN feedback from accretion /rotation
$S$: with higher SNIa efficiency
The $M_* - \sigma$ relation

Good agreement, except for the four galaxies having black holes apparently too massive.

192disk simulation

Cygnus A, NGC 5252, NGC 3115 and NGC 4594
The $M_\bullet - M_{\text{halo}}$ relation

- $M_{\text{halo}}$ is directly extracted from simulations.
- Good agreement with Baes et al, 2003.
Effect of jets – creation of gaseous cavities

- Formation of hot gas – X-ray emission
- Generation of magnetic fields -

Graphs showing:
- \( L_{\text{\(2-10\text{keV}\)}} \) in units of \( 10^{34} \text{ erg s}^{-1} \)
- \( M_{\text{BH}} \) in units of \( 10^{7} \text{ M}_{\odot} \)
Formation of jets and lobes
Formation of jets and lobes
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Formation of jets and lobes
Feedback Effects

Effects of the jet geometry on the mass distribution of black holes (panel below) and on the colour-magnitude diagram of galaxies (right panel).
Coalescence Rate of supermassive black holes
Some problems: no SMBH at $z \sim 6$!

- No supermassive black holes at $z=6$ → hierarchical growth

- No super-Eddington accretion rates are observed (resolution effect?)

- Absence of QSOs at $z=6$ → star formation in massive early type galaxies is not quenched (excess of massive red objects)
Conclusions

• Cosmological simulations are the best tool to study the coeval evolution of galaxies and their central black holes

• Properties of galaxies and their growth of supermassive black holes depend strongly on feedback mechanisms

• Most of the relations (at \(z=0\)) involving the black hole mass and properties of the bulge component can be explained by the growth of \(100 \, M_\odot\) seeds

• An early growth of SMBH requires an improved disk accretion model (non-stationarity, slim-disks, …)

• The coalescence history of SMBH can be tracked by the resulting gravitational wave emission