INTRO: The black hole - galaxy connection
e.g.: The M -σ relation and the evolution of QSOs

Self-consistent treatment of BHs in
SPH Simulations of Galaxy Formation (Gadget)

1. BHs in Isolated Galaxies & Mergers - BHs -> galaxy formation
   implications for QSO lifetime/ LFs
2. BHs in Cosmological Simulations
   - evolution of black hole mass density and M-sigma relation
   - accretion history
   - the quasar hosts from high to low z
The $M - \sigma$ relation for supermassive black holes

Black hole mass related to large scale properties of galaxies

Fundamental link between assembly of black holes and galaxy formation

(Many) Theoretical models: BH growth regulated by Feedback

$M_{BH} = 10^8 M_\odot \left(\frac{\sigma}{200 \text{ km/s}}\right)^4$

Gravitational potential of spheroid

Stellar Velocity Dispersion
SPH simulations of galaxy formation
(GADGET2 so far....)

- Radiative cooling of gas within halos (dissipation)
- Star formation and feedback processes
  (Springel & Hernquist 2003)

N-body METHOD: mass discretised in particles modeled as collisionless fluid governed by Boltzmann Eq. - grav potential solved with Poisson Eq.

SPH Method: fluid represented by particles smoothed by local kernel averaging Hydro eqns solved in its Galilean-invariant Lagrangian Formulation.

SUB-RESOLUTION multiphase MODEL for the ISM
BHs in SPH Simulations of Galaxy formation

• **BH:** collisionless “sink” particle in the centre of galaxies

• **ACCRETION:** relate (unresolved) accretion on BH to large scale (resolved) gas distribution

\[
\dot{M}_B = \alpha 4\pi \frac{(GM_{BH})^2}{(c_s^2 + V_{rel}^2)^{3/2}} \rho
\]

\[
\dot{M}_{BH} = \min(\dot{M}_{Edd}, \dot{M}_B)
\]

• **FEEDBACK:** energy extracted from the black hole (accretion) injected in the surrounding gas

\[
\dot{E}_{\text{feed}} = f(\eta \dot{M} c^2) \quad f \approx 0.5\%
\]
BHs in Numerical Simulations

Implementation in SPH simulation code

✓ BH sink particle - only feel gravity - we compute, SPH
  Properties of local environment (T, rho, vel)

✓ BH particles swallow gas stochastically from their local
  neighbourhoods, in accordance with the estimated BH
  accretion rate.
  \[ p_j = w_j M_{BH} \Delta t / \rho \]

✓ BH has additional internal degree of freedom: Variable
  described BH mass in smooth fashion

✓ Feedback energy is injected kernel-weighted into the thermal
  reservoir of gas in BH environment

✓ BHs are merged if they reach small separations (smoothing
  lengths) and low enough relative speeds

✓ On-the-fly FOF halo finder detects emerging galaxies and
  provides them with a seed black hole
We construct compound disk galaxies that are in dynamical equilibrium

STRUCTURAL PROPERTIES OF MODEL GALAXIES

Components:

- Dark halo (Hernquist profile matched to NFW halo)
- Stellar disk (expontial)
- Stellar bulge
- Gaseous disk (expontial)
- Central supermassive black hole (small seed mass)

We compute the exact gravitational potential for the axisymmetric mass distribution and solve the Jeans equations.
- Gas pressure effects are included.
- The gaseous scale-height is allowed to vary with radius.

Springel, Di Matteo & Hernquist, '05
BH ACCRETION AND FEEDBACK
the central black hole activity blows a wind into the halo
GAS FLOWS INTO THE HALO

Isolated disk galaxy with bulge

\[ T = 0.7 \text{ Gyr} \]

(dynamic range in gas surface density \( \sim 10^6 \))

\[ M_{BH}(t) \sim \frac{M_0}{1 - \chi M_0 t} \]

\[ M_{BH}(t) \sim M_0 \exp \frac{t}{t_S} \]

without feedback

Eddington growth

With feedback

Bondi growth
BH GROWTH and Fuelling of AGN:

NGC 6240 FINAL STAGES GALAXY MERGER: contains 2 AGN

S. Komossa et al. 03 (MPE)
89.0% turned into stars
0.05% expelled from halo
1.2% cold, star forming gas
9.8% diffuse gas in halo

51.9% turned into stars
35.3% expelled from halo
0% cold, star forming gas
11.1% diffuse gas in halo
1.6% swallowed by BH(s)
QuickTime™ and a decompressor are needed to see this picture.
Di Matteo, Springel & Hernquist 05

- Star formation rate
- BH supply rate
- BH Mass

DISC + BULGE Merger

no BH with BH

Di Matteo, Springel & Hernquist 05
BLACK HOLE MASS AND GALAXY PROPERTIES:

EXPERIMENTAL MEASUREMENTS

$$E_{fb} = \varepsilon f M_{BH} c^2$$

$$E_{bind} \sim M \sigma^2$$

$$E_{fb}/E_{bind} \sim 10 \left( \frac{\varepsilon f}{0.005} \right) \left( \frac{\sigma}{300} \right)^{-2}$$

RESULTS FROM SIMULATIONS

- 80% gas
- 40% gas
- 20% gas
BLACK HOLES: IMPACT ON GALAXY COLOURS:
FORMATION OF RED ELLIPTICALS

Springel, Di Matteo & Hernquist 2005

**w/o BH**

- E forms can sustain SF over extended period
- remains relatively BLUE

**with BH**

- AGN feedback quenches SF over short timescale
- marked difference in color evolution of galaxies
  - red, “dead” E forms

N feedback quenches over short timescale. 

For evolution of galaxies, “dead” E forms
Di Matteo, Springel & Hernquist 05

Star formation rate

BH supply rate

BH Mass

Quasar phase

with BH

no BH
PREDICTIONS FOR THE QUASAR PHASE:
large fraction of the QUASAR phase is obscured

QSO obscured: time of the starburst
 " " of BH growth

DO WE SEE THESE AGN?
Recent follow up of 20
SCUBA sources in CDFs:
High SFR, obscured, MERGERS

Hopkins et al. 2005

Alexander et al.’05, Nature
BLACK HOLES GROWTH ALONG THE HISTORY OF THE UNIVERSE

COSMOLOGICAL SIMULATIONS WITH BLACK HOLES

D4 BOX \( L = 33.75 \, h^{-1} \, \text{Mpc} \)

\[
M_{DM} = 2.75 \times 10^7 \\
M_{gas} = 4.24 \times 10^7
\]

\( N = 2 \times 216^3 \)
The evolution the black hole mass function
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Conclusions:

- Self-Consistent treatment of BLACK HOLES IN NUMERICAL SIMULATIONS OF GALAXY FORMATION

- Self-Regulated Black hole growth and activity

  **GALAXY MERGERS:**
  - Black hole growth saturates in response to feedback
    - $M-\sigma$ relation
    - IMPACT on galaxy COLOURS
    - OBSCURED QSOs phase, QUASAR lifetime, luminosity functions
    - …. Heating in clusters, ISM enrichment etc.....

  **COSMOLOGICAL RUNS**
  - Track the cosmic history of BH accretion and BH growth
    - follow growth black hole mass function
    - Constraints on $t_Q$ duty cycle, and specific properties of BH hosts
    - Impact on reinization etc...