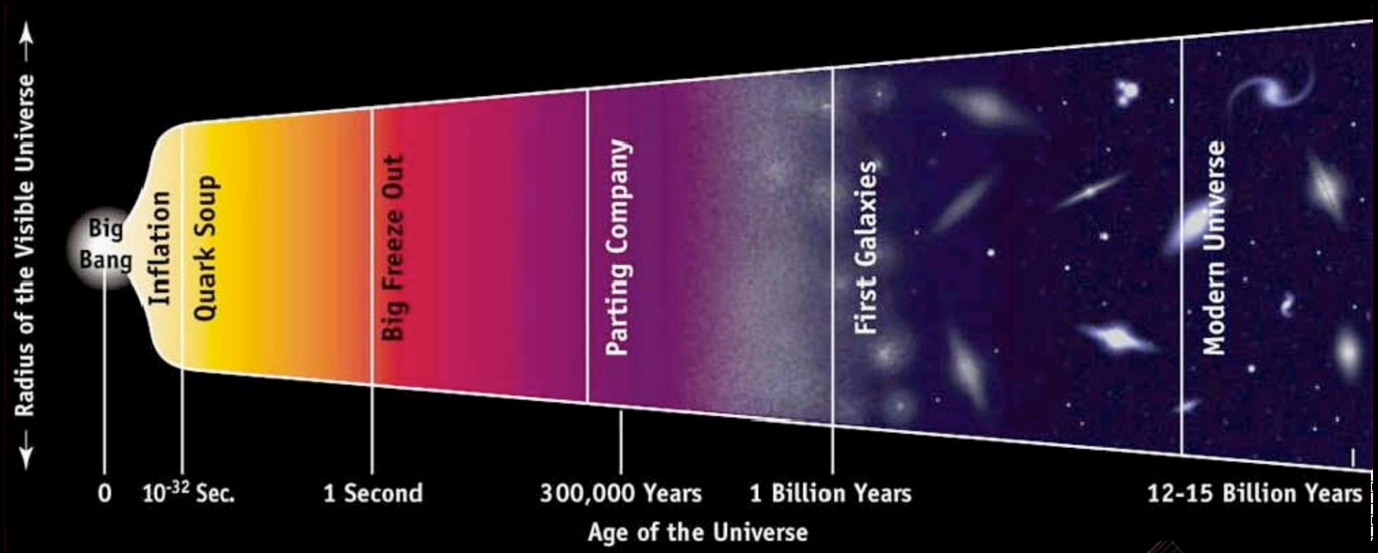
ANDREA CATTANEO

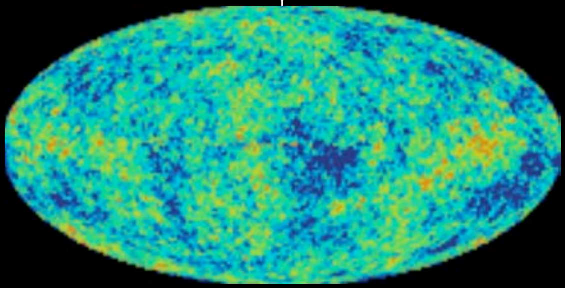
The role of black holes in galaxy formation and evolution

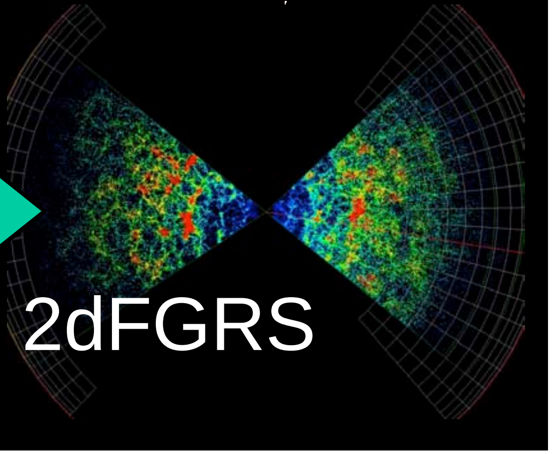
Structure formation in cosmology

Precise determinations of the matter content, expansion and initial conditions of the Universe



WMAP





2dFGRS

Galaxy morphological classification

Hubble 1926

Sa Sb Sc

E0 E4 E5 S0

SBa SBb SBc

Star formation rate and galaxy morphology

Ellipticals/S0s

Red

Early type

Hot gas

Groups, clusters

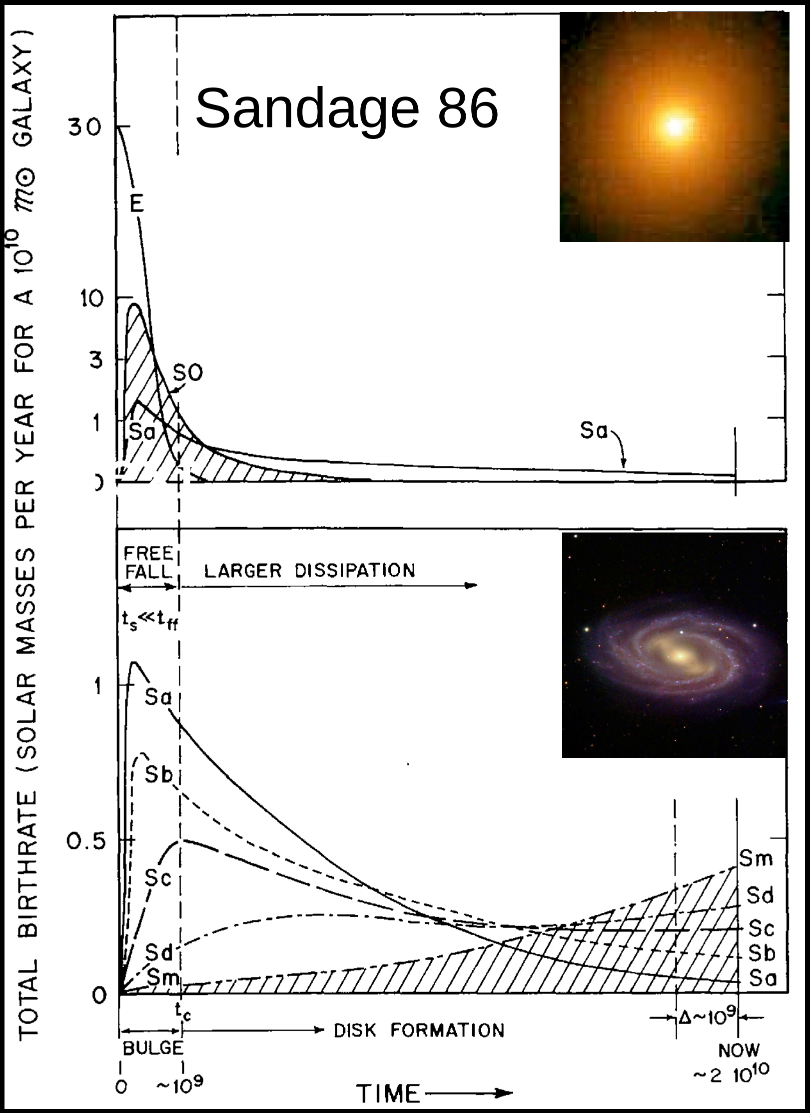
Spirals

Blue

Late type

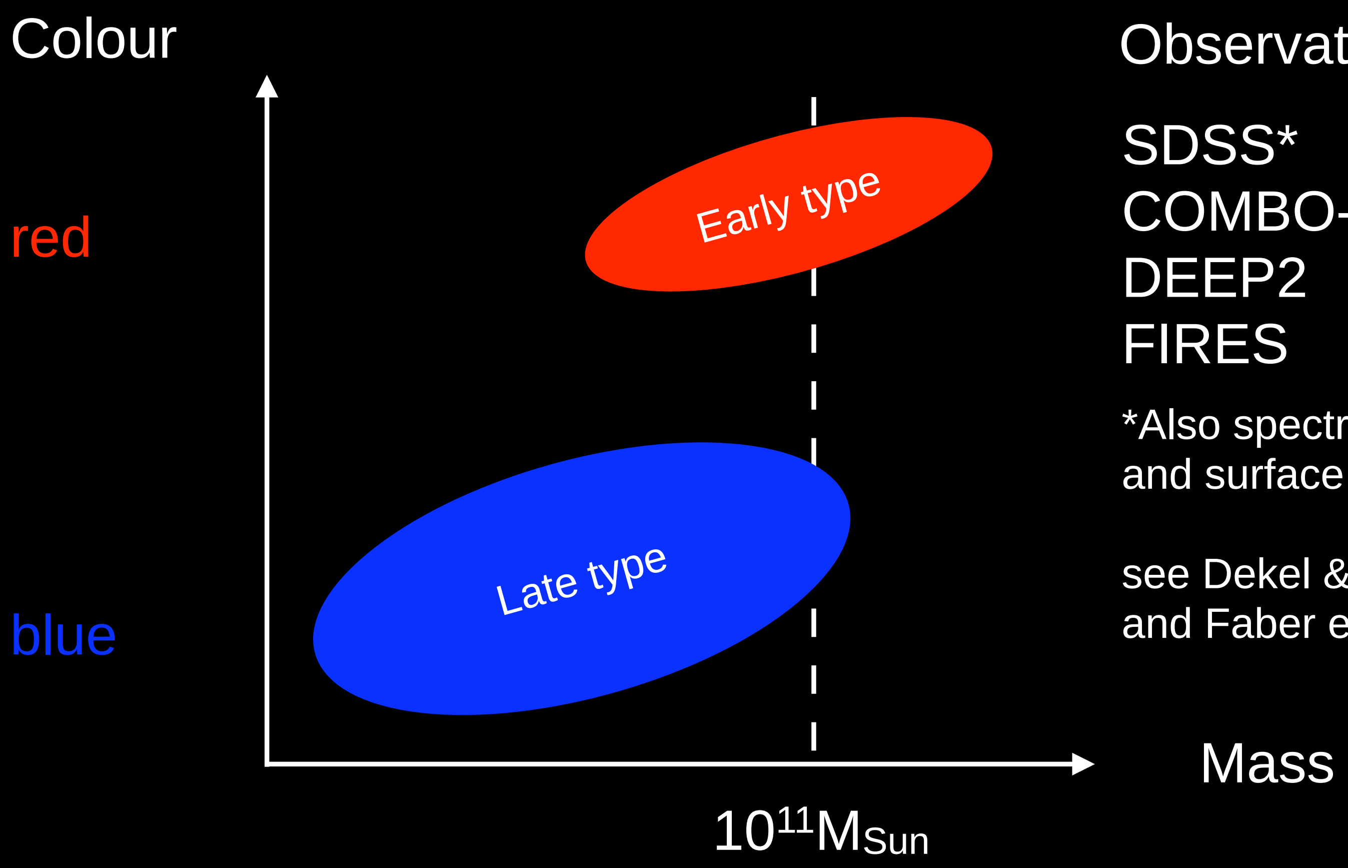
Cold gas

Field



Sandage 86

The galaxy bimodality



Observations

SDSS*
COMBO-17
DEEP2
FIRES

*Also spectral indicators
and surface brightness

see Dekel & Birnboim 06
and Faber et al 07

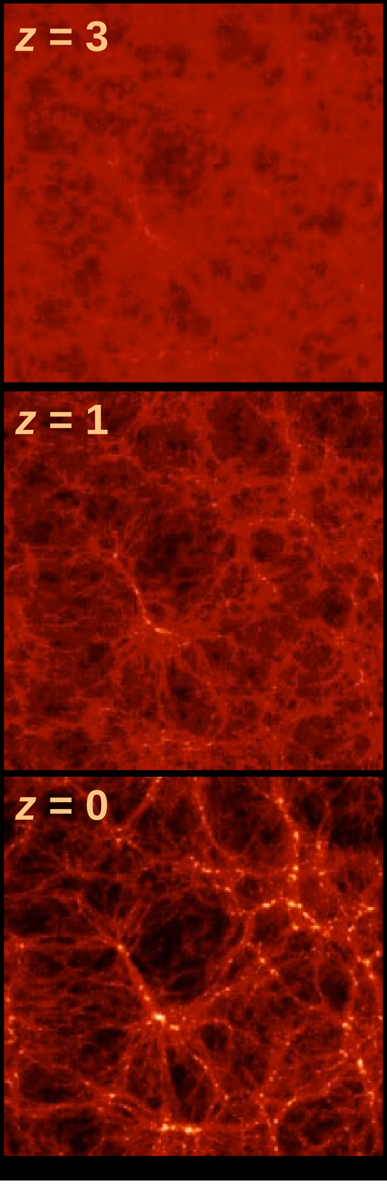
No cold gas in the most massive objects

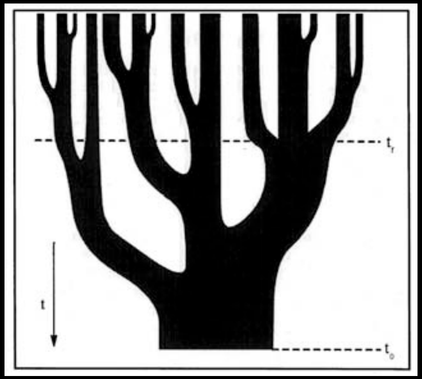
➠ cooling flow problem in galaxy clusters e.g. Peterson & Fabian 06, also Salomé et al 06

➠ challenge for cosmological models of galaxy and galaxy clusters formation

Galaxy formation in cosmology

- Gravitational instability of primordial fluctuations
- Virialised haloes by violent relaxation
- Dissipative baryon infall in dark matter haloes
- Hierarchical merging of dark matter haloes
- Galaxy mergers drive morphology evolution





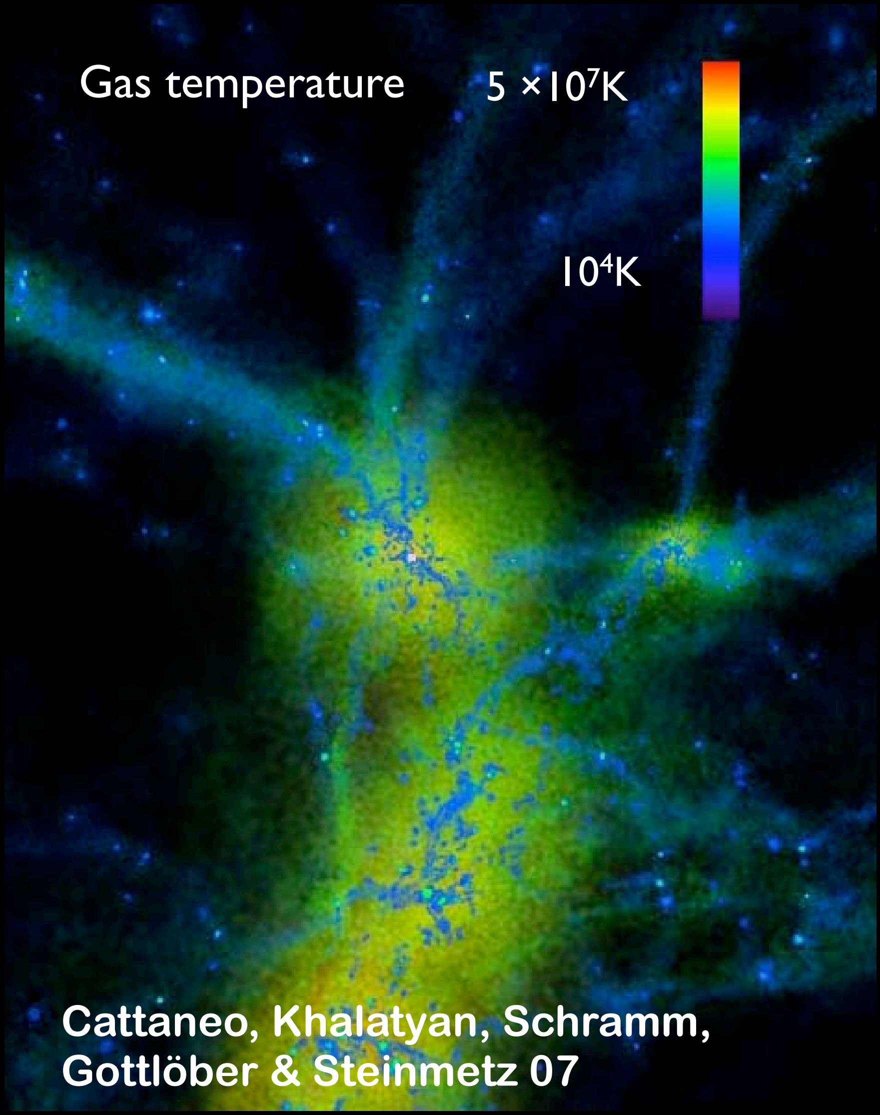
Computer simulations

- **hydrodynamic**
  Lagrangian e.g. **GADGET**
  Eulerian e.g. **RAMSES**
  detailed dynamics of individual objects
- **semianalytic**
  e.g. **GalICS**
  cosmological volume
  statistics

The galaxy scale

- Gravitational heating vs. radiative cooling
  Rees & Ostriker 77
  Silk 77
  White & Rees 78
  Blumenthal et al. 84

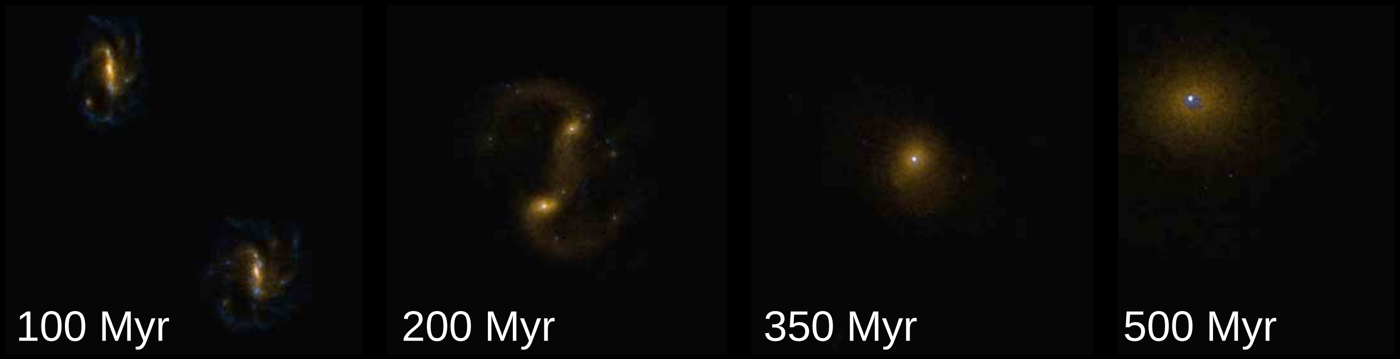
- Cold flows/hot halo transition at the shock heating scale
  $M_{halo} \approx 2 \times 10^{12}\, M_{Sun}$
  Birnboim & Dekel 03
  Keres et al 05
  Dekel & Birnboim 06



Cattaneo, Khalatyan, Schramm, Gottlöber & Steinmetz 07

Morphological evolution

- Cold inflows form galactic discs
  Fall & Efstathiou 80, Mo et al 98
  But also: Navarro & Benz 91, Navarro & Steinmetz 97, Abadi et al 03
- First bulges/elliptical galaxies formed by disc mergers
  Toomre & Toomre 72, Barnes & Hernquist 91,96, Mihos & Hernquist 94,96



Cattaneo,
Combes,
et al.

- E/E mergers important for assembling the most massive ellipticals
  van Dokkum 05, Naab et al 06, Cattaneo et al 07

The colour - morphology relation

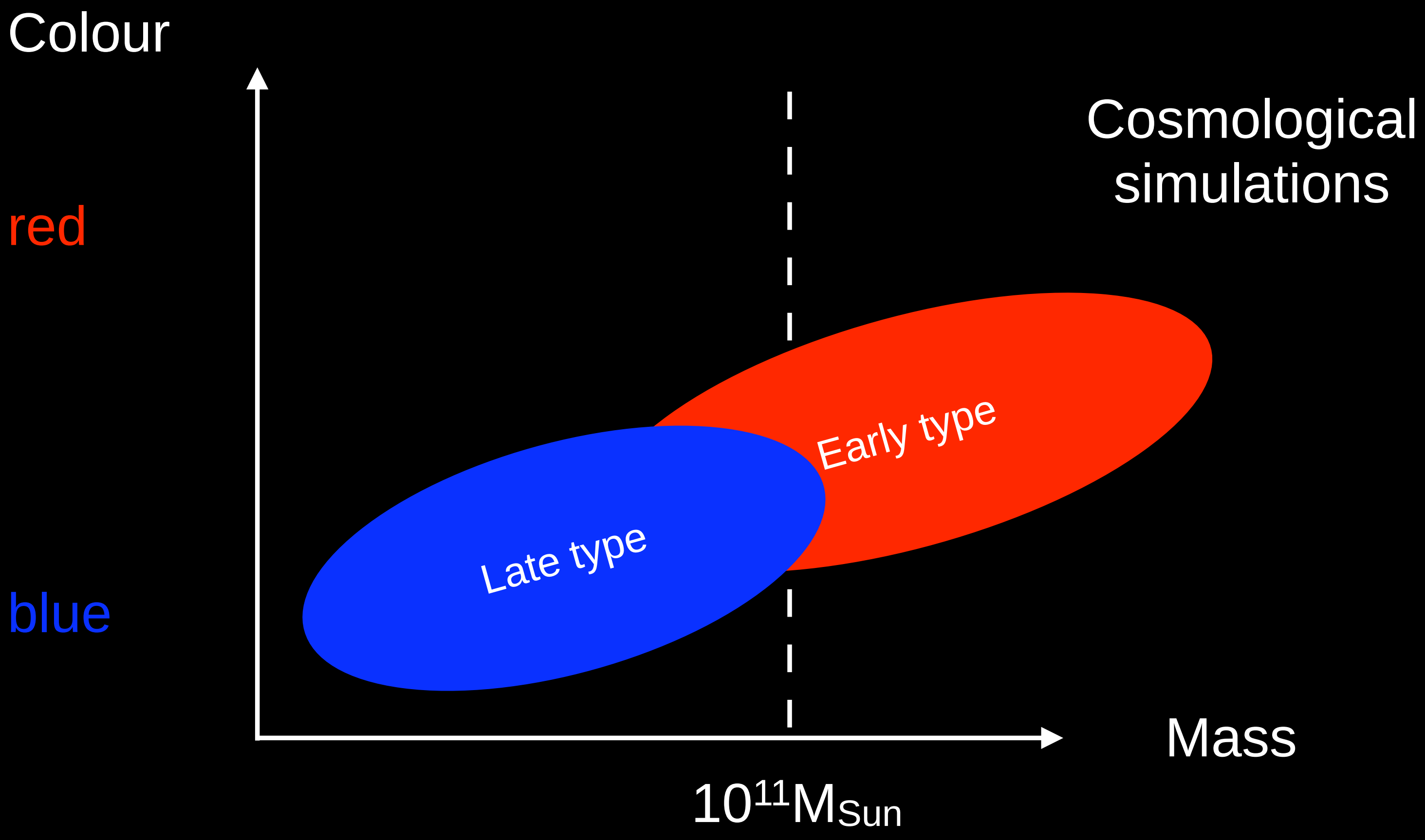
The most massive galaxies tend to be

- elliptical: merging is more frequent in massive haloes
- redder:
  - long cooling time in massive haloes
  - mergers/starbursts have exhausted the disc gas

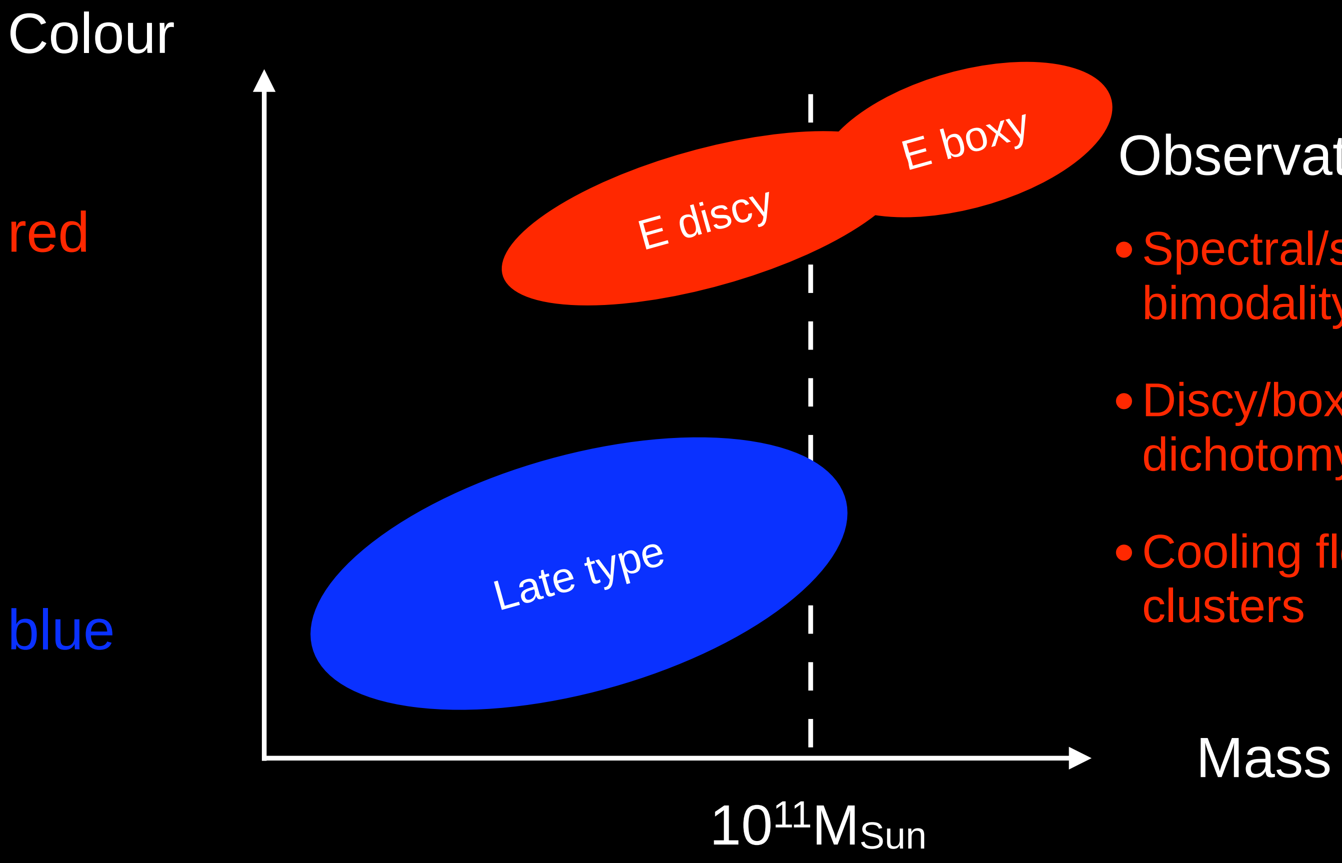
Cattaneo,
Combes,
et al.

But not as red as the observed one Springel et al 05

The galaxy bimodality



The galaxy bimodality

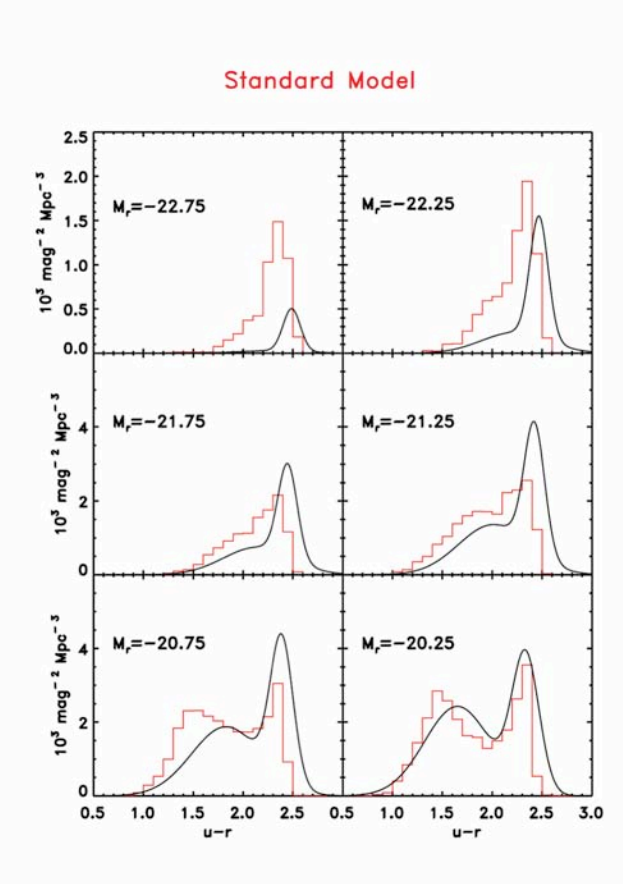


Observations

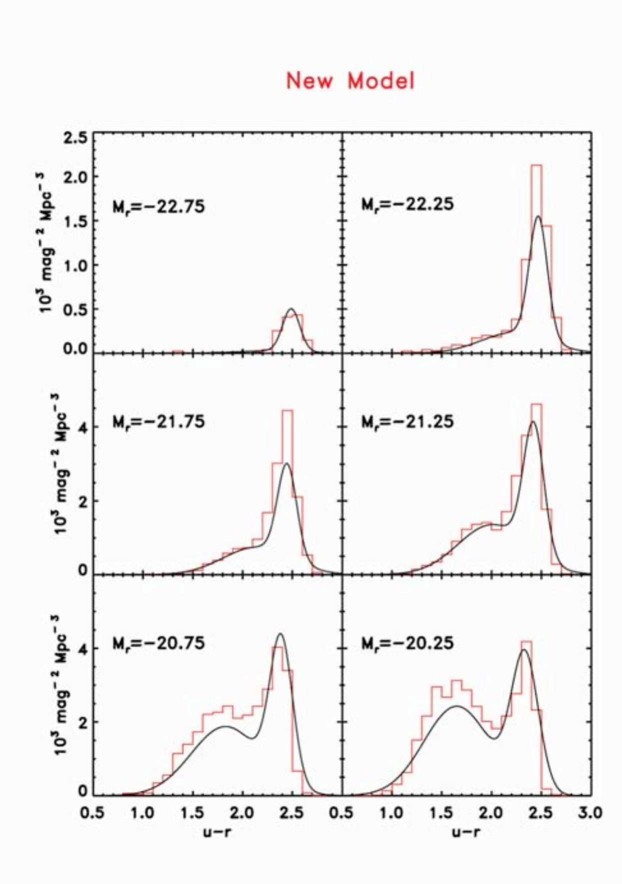
- Spectral/structural bimodality
- Discy/boxy dichotomy
- Cooling flow clusters

The galaxy bimodality

in the distribution of magnitudes and colours



Baldry et al 04
SDSS data
black histograms



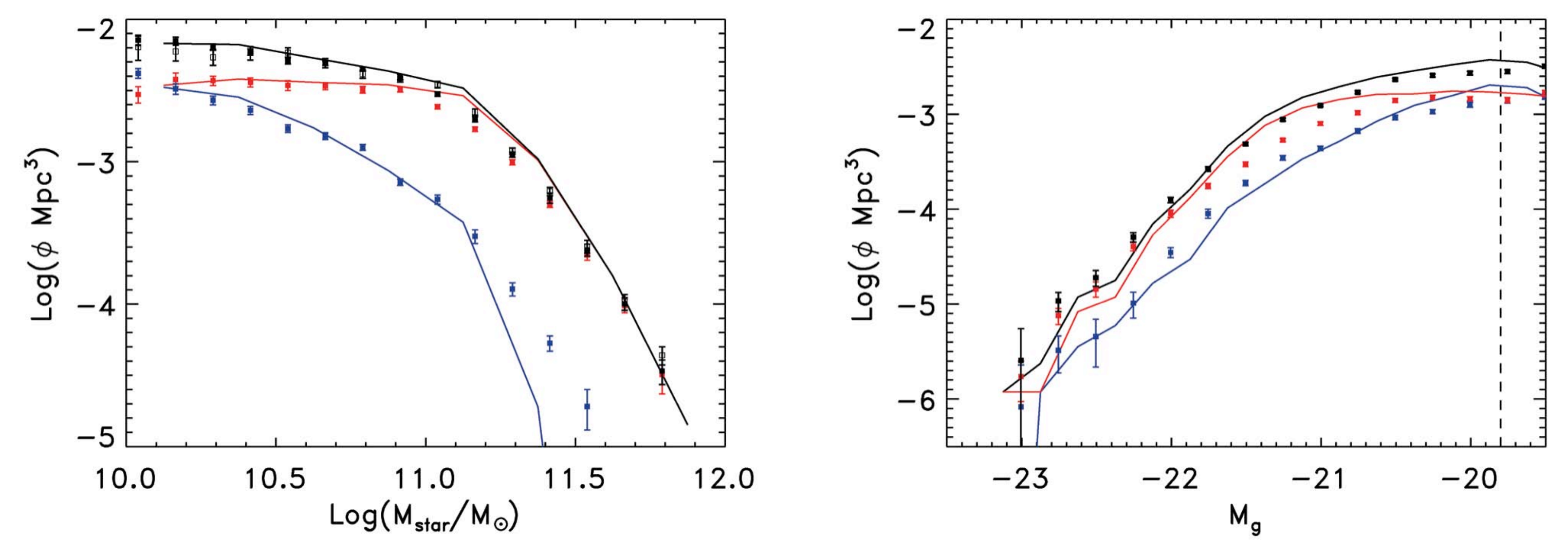
Cattaneo, Dekel, Devriendt,
Guiderdoni & Blaizot 06 GalICS
Bower et al 06, Croton et al 06

Galaxy mass/luminosity function

with cooling shutdown when $M_{halo} \geq 2 \times 10^{12}\ M_{Sun}$

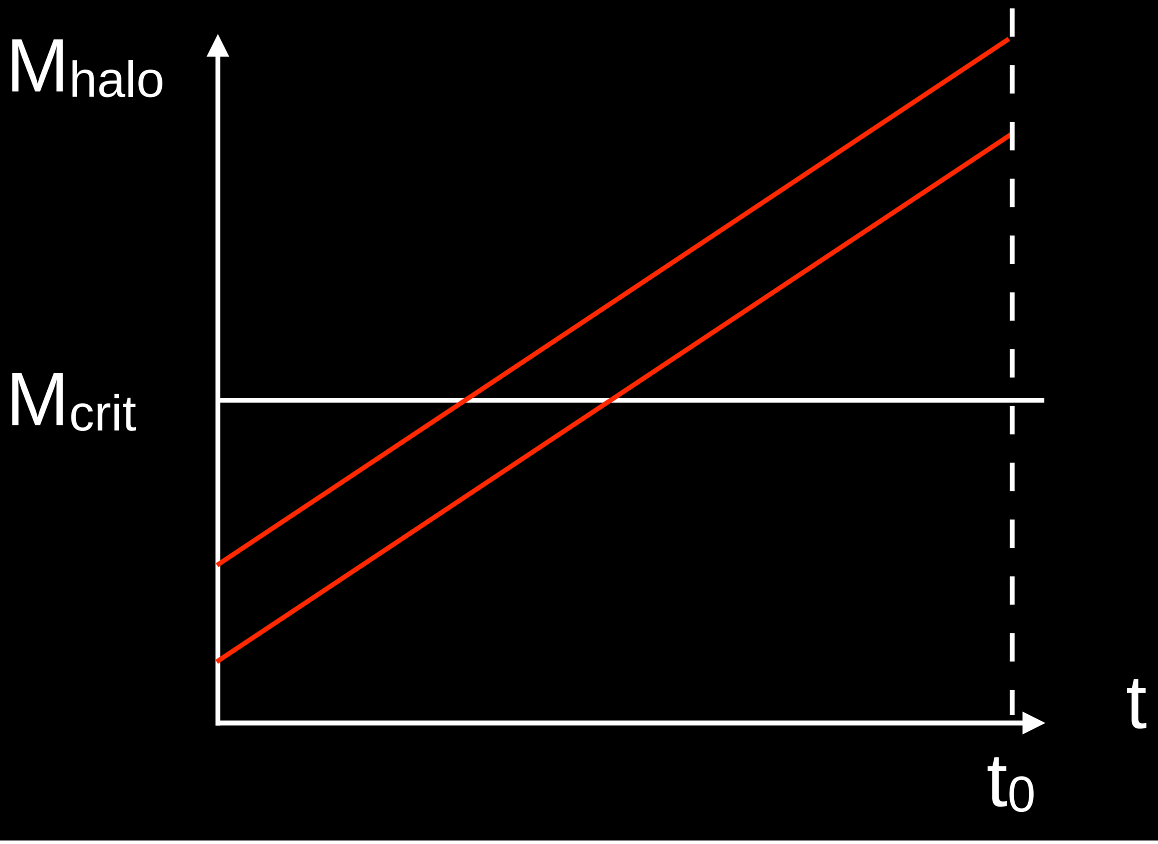
Cattaneo, Dekel, Faber & Guiderdoni 07

Data points from Bell et al 04



Downsizing from shutdown at a critical halo mass $M_{crit} \geq 2 \times 10^{12}\, M_{Sun}$

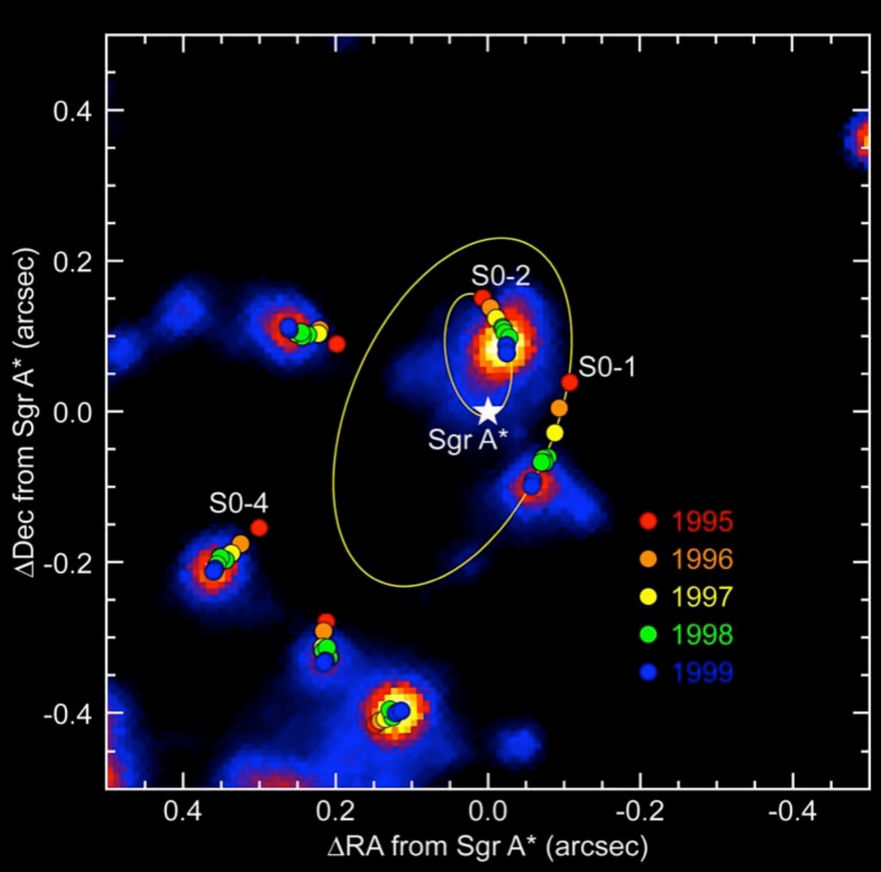
Cattaneo, Dekel, Faber & Guiderdoni 07

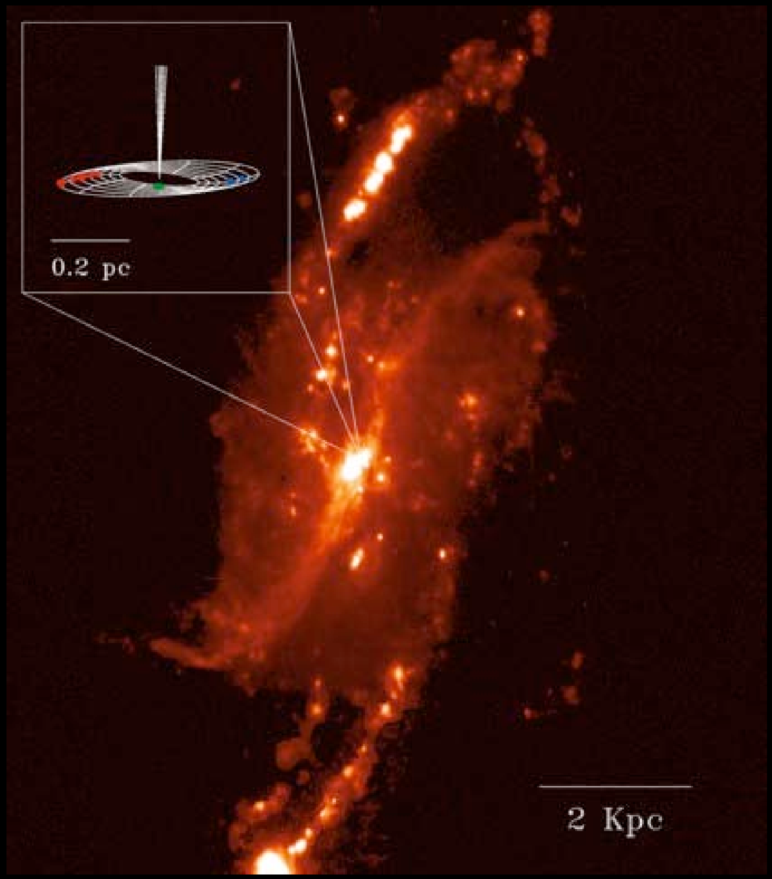


Black holes in galactic nuclei

Milky Way
Stellar kinematics

NGC425
Gas kinematics



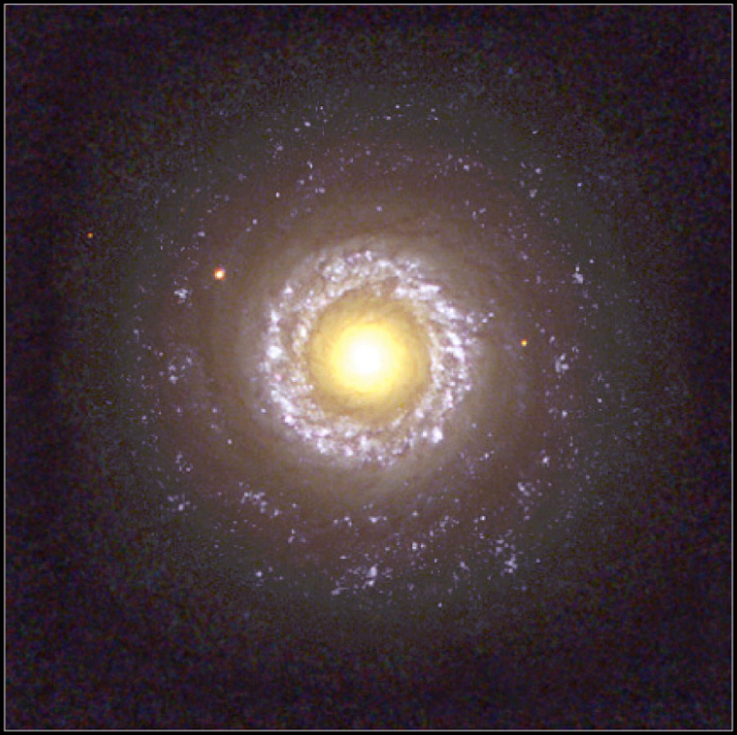


Galactic Nuclei as Collapsed Old Quasars

Lynden-Bell, 1969, Nature, 223, 690

Black holes as the powerhouses of the non-stellar emission in active galactic nuclei

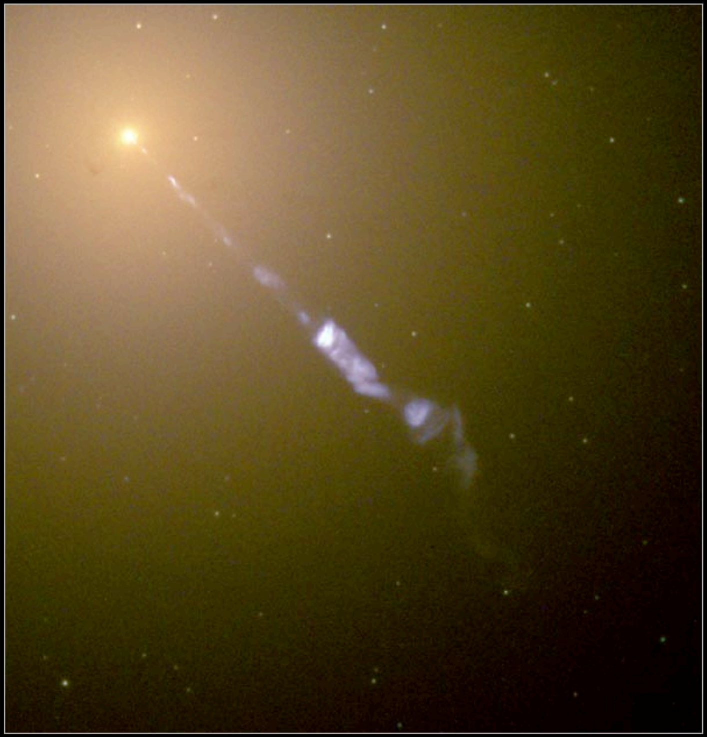
Galaxy NGC 7742



Hubble Heritage

PRC98-28 • Space Telescope Science Institute • Hubble Heritage Team

The M87 Jet



Hubble Heritage

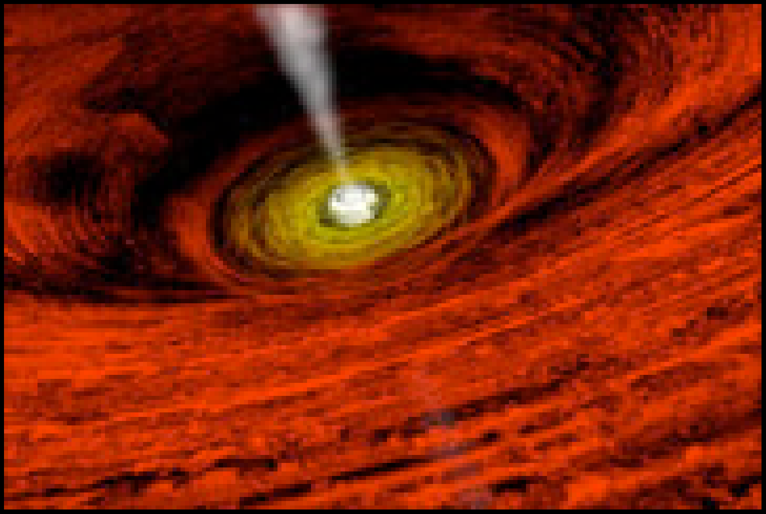
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)

The source of the black hole power

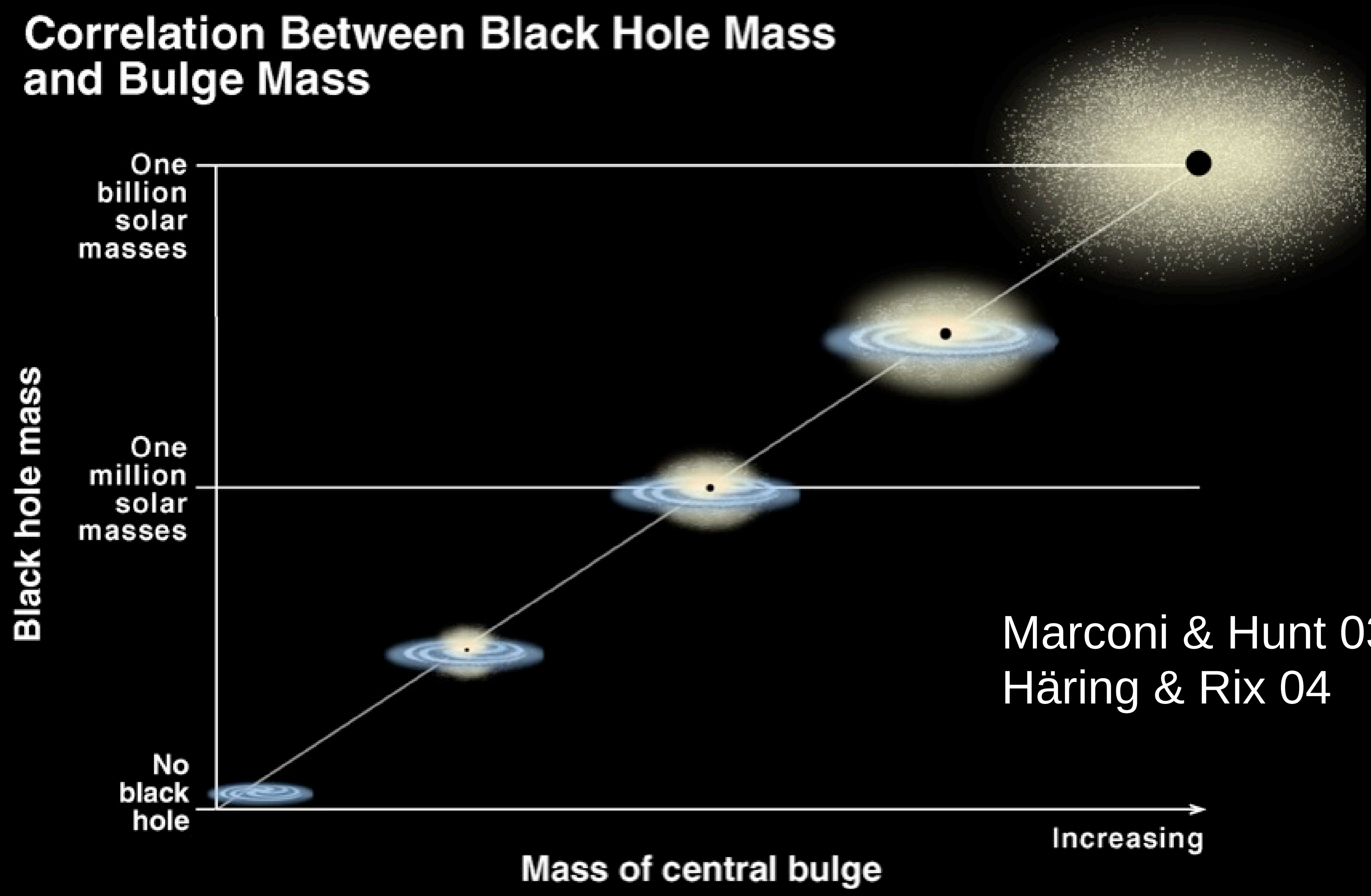
$E \quad = 0.5mv^2 - GM_{bh}m/r$

$r_S \ = 2GM_{bh}/c^2$

$E(\infty) - E(r_S) = 0.25mc^2$



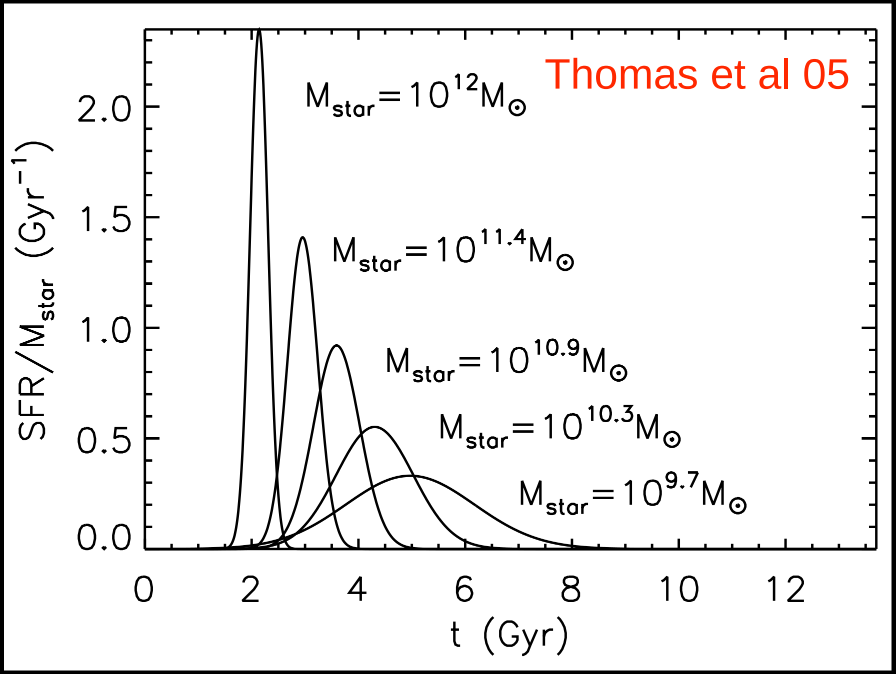
- Viscous dissipation and thermal radiation
- Kinetic outflows favoured at low accretion rates



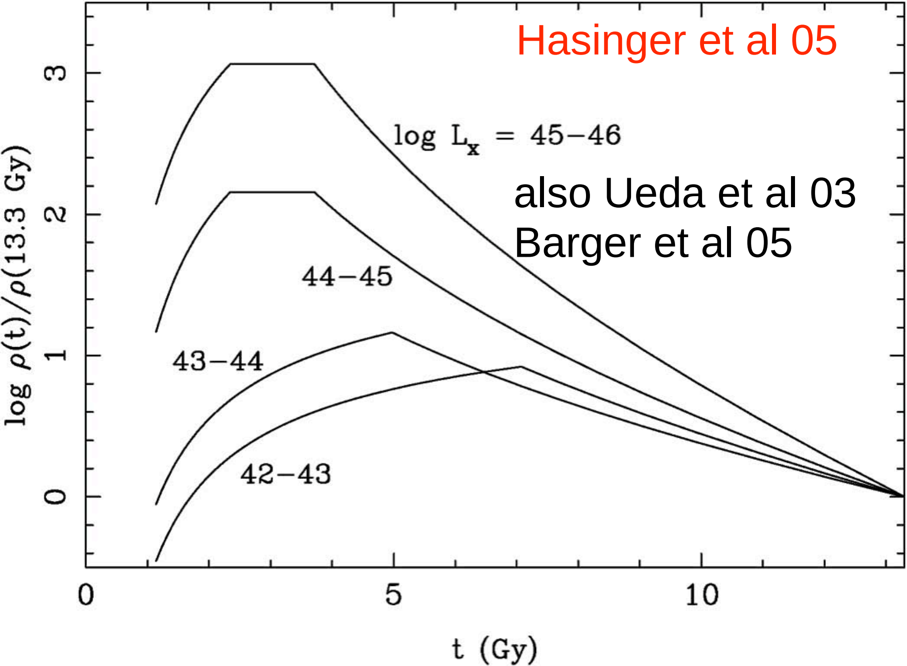
Marconi & Hunt 03
Häring & Rix 04

$0.1 M_{bh} c^2 >> M_{star} \sigma^2$ where $M_{bh} \approx 2 \cdot 10^{-3} M_{star}$ and $\sigma \approx 10^{-3} c$

Star formation rates in early type galaxies and the cosmological evolution of black hole accretion



Thomas et al 05



Hasinger et al 05

also Ueda et al 03
Barger et al 05

Coevolution/downsizing

Cattaneo & Bernardi 03
Hopkins et al 05

Relationship between galaxy formation and black hole growth

Astrophysical scenario

Galaxy evolution

Mergers

Bars

Cattaneo et al
99, 05

Kauffmann &
Haehnelt 00

Black hole growth

Galaxy mass function
Colour bimodality

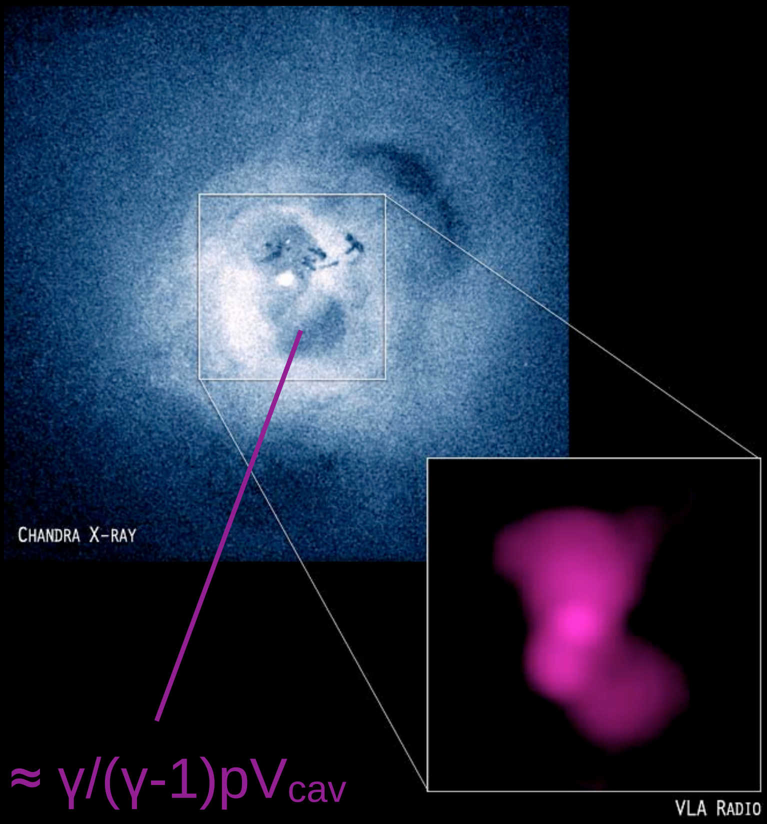
High power
Jets, bubbles

Feedback

Black hole impact on the surrounding gas

- CHANDRA/XMM X-ray observations of high-z quasars reveal massive ($10M_{Sun}$/yr) relativistic (0.4c) winds
  Chartas et al 02,03

- Galaxy clusters contain X-ray holes opened by jet-inflated radio bubbles
  Dunn et al 05, McNamara et al 05, Fabian et al 06



$E_{cav} \approx \gamma/(\gamma-1)pV_{cav}$

Is there a role of black holes in galaxy formation?

Positive evidence

- Black hole and bulge formation go hand in hand
- Black hole formation releases a tremendous amount of energy
- Observations of quasar winds and radio bubbles
- We need a heat source so that the hot gas does not cool

Problems

- How is the black hole energy output converted into heat?
- Black holes accreted most of their mass at high redshift
  We need to prevent cooling now

The long-term impact of black hole heating

Problem

- Black holes accreted most of their mass at high redshift
  We need to prevent cooling now

Proposed solutions

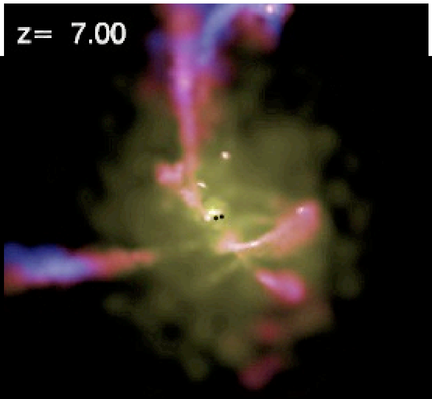
- Black holes are coupled with a reservoir that stores the quasar energy and releases it on cosmological timescales
  ➡ hot gas Babul 02, Oh & Benson 03, McCarthy et al 04

- Black hole heating is decoupled from the quasar phase and occurs in a less sporadic radiatively inefficient accretion mode
  This mode may be more efficient even if it releases less energy because jets are thermalised more easily than photons are
  ➡ Fanaroff-Riley I radio sources Best et al 05, Croton et al 06

Quasars vs. low-power radio sources

Why has the intracluster medium not cooled?

Strongly high z preheating in group-size haloes



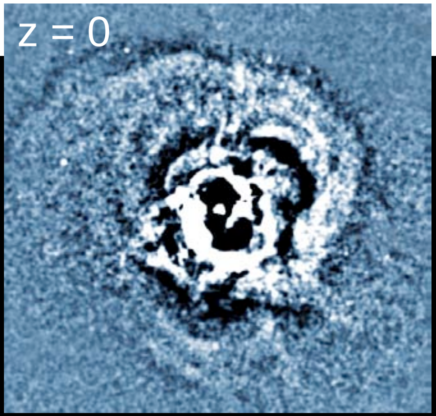
Quasar mode

Short duty cycle

Optical AGNs

Most of M_{bh}

Low z heating in quasi-continuous self-regulated mode



Maintenance mode

Long duty cycle

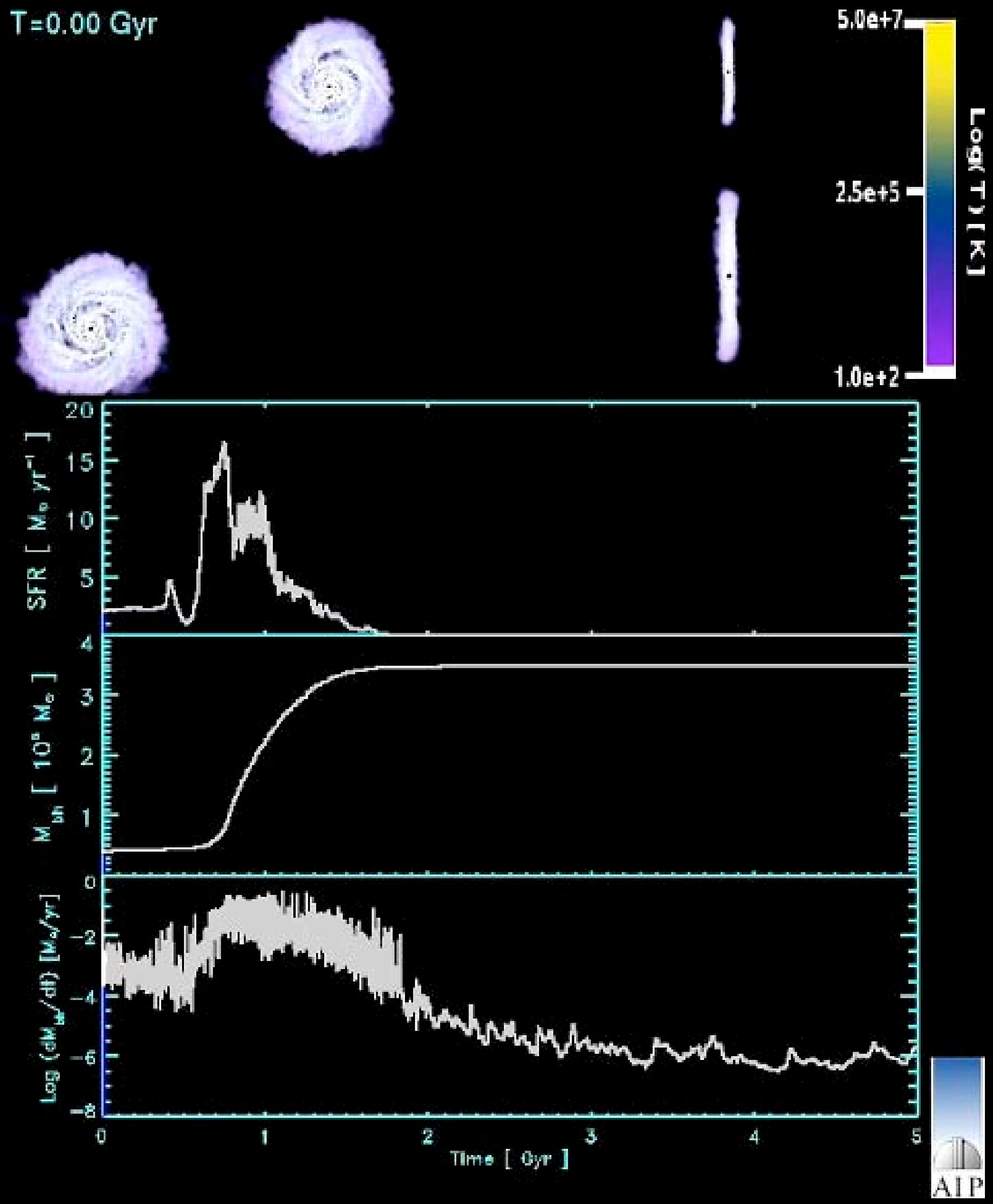
Radio sources

Small accreted mass

Khalatyan, Cattaneo & Steinmetz 07

Also Springel et al 05

Galaxy merger 10% gas
Only gas shown



Star formation

BH mass

Log dM_{bh}/dt

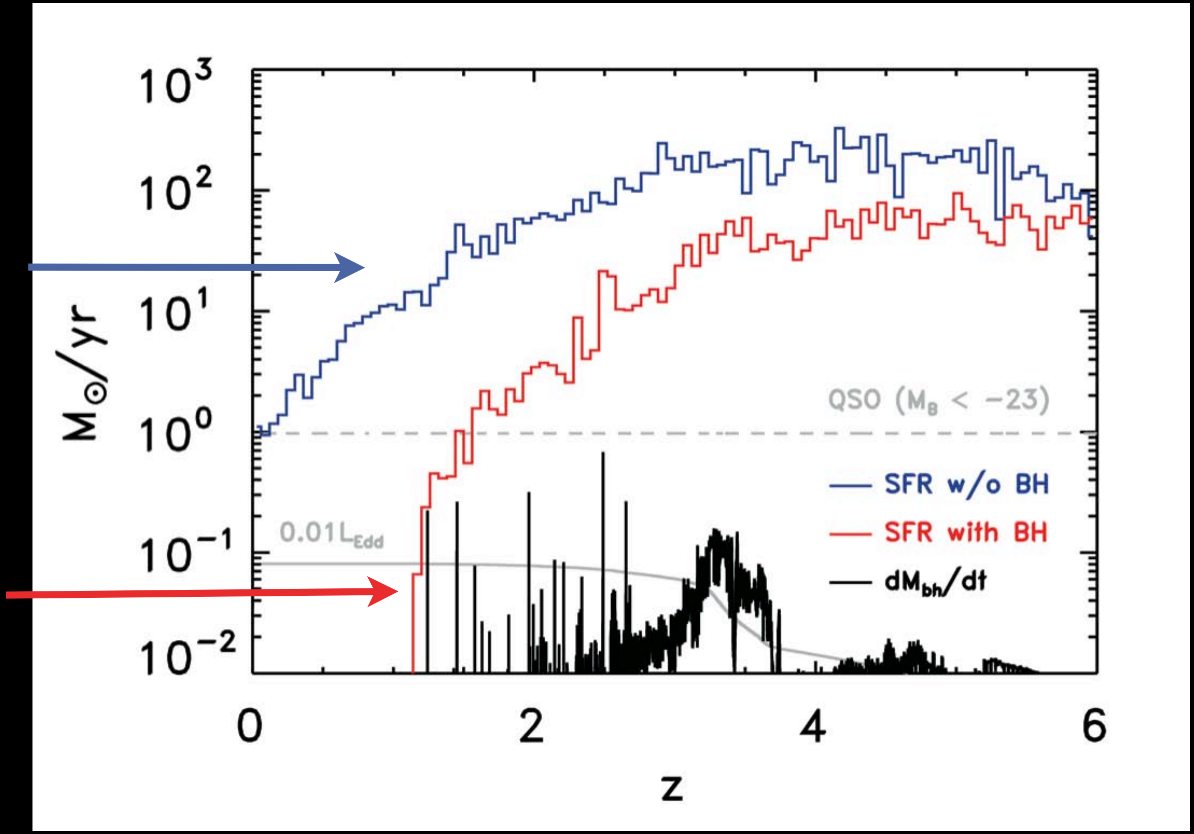
Time (Gyr)

Formation of an elliptical with $M_{halo} \approx 3 \times 10^{12} M_{Sun}$

Mare Nostrum Galaxy Formation Simulation 50/h Mpc

$M_B = -21.8$

$M_B = -19.7$



Cattaneo et al 07 GADGET

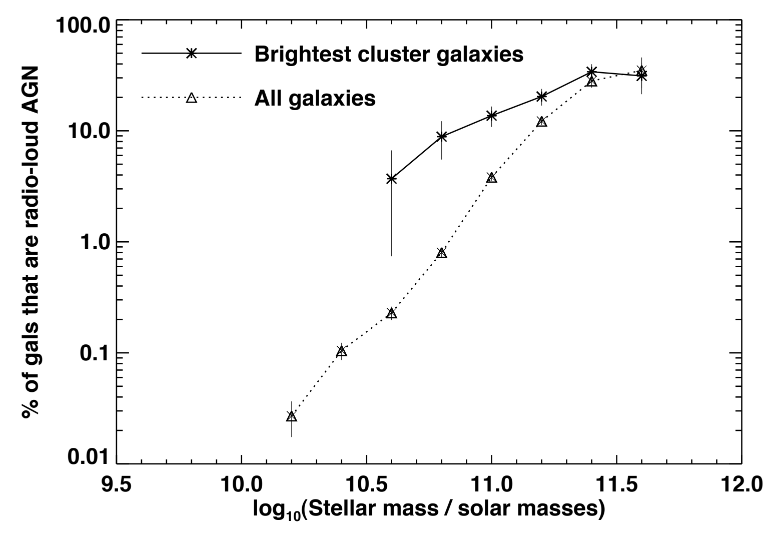
Heating by radio sources

Observational motivations

About 70% of cD galaxies host radio sources Burns 90 Best et al 05

A similar fraction of cooling flow clusters has X-ray holes Dunn et al 05

Based on the radio luminosity function and on a radio luminosity/mechanical power conversion factor based on cavity observations, Best et al 05, 06 conclude that the power output balances the radiative losses in all but the most massive clusters



Energy injection into the central region of M87

$M_{BH} \sim 3 \times 10^9\ M_{Sun}$

$T \sim 0.8$ keV, $c_s \sim 270$ km/s

$=$

$= 4\pi(GM_{BH}/c^s)^2 \rho c_s =$

$= 4\pi(GM_{BH})^2 \rho c_s^{-3} =$

$L_{bondi} = 0.1\ dM_{bondi}/dt\ c^2 =$
$\sim 5 \times 10^{44}$ erg/s

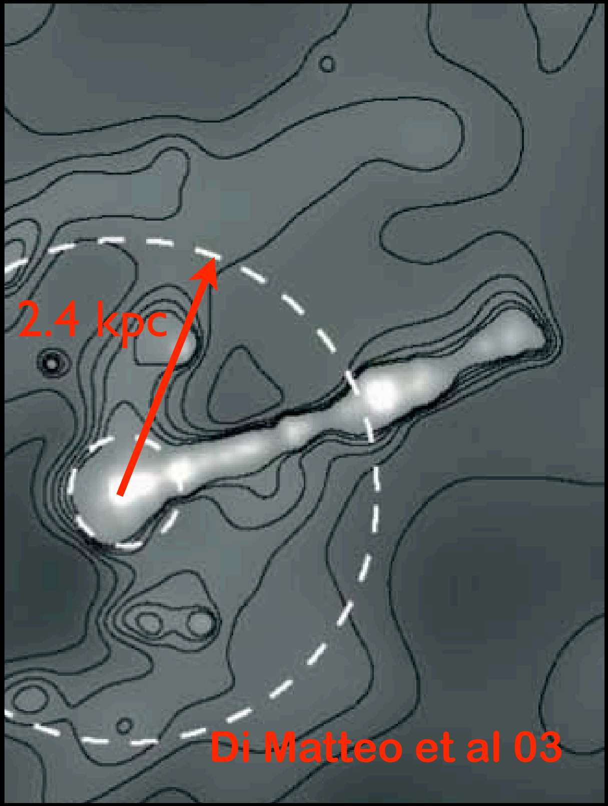
$L_{bol} \sim 10^{42}$ erg/s

$L_{kinetic} \sim 10^{44}$ erg/s
Bicknell & Begelman 99, Owen et al 00

$L_X \sim 10^{44}$ erg/s Boehringer et al 94

Adiabatic Inflow Autflow Solution

ADIOS Blandford & Begelman 99

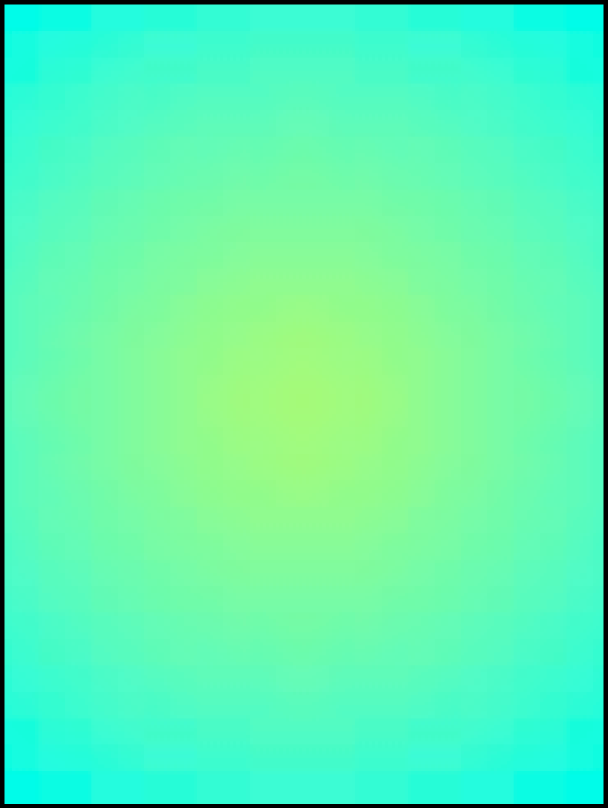


Di Matteo et al 03

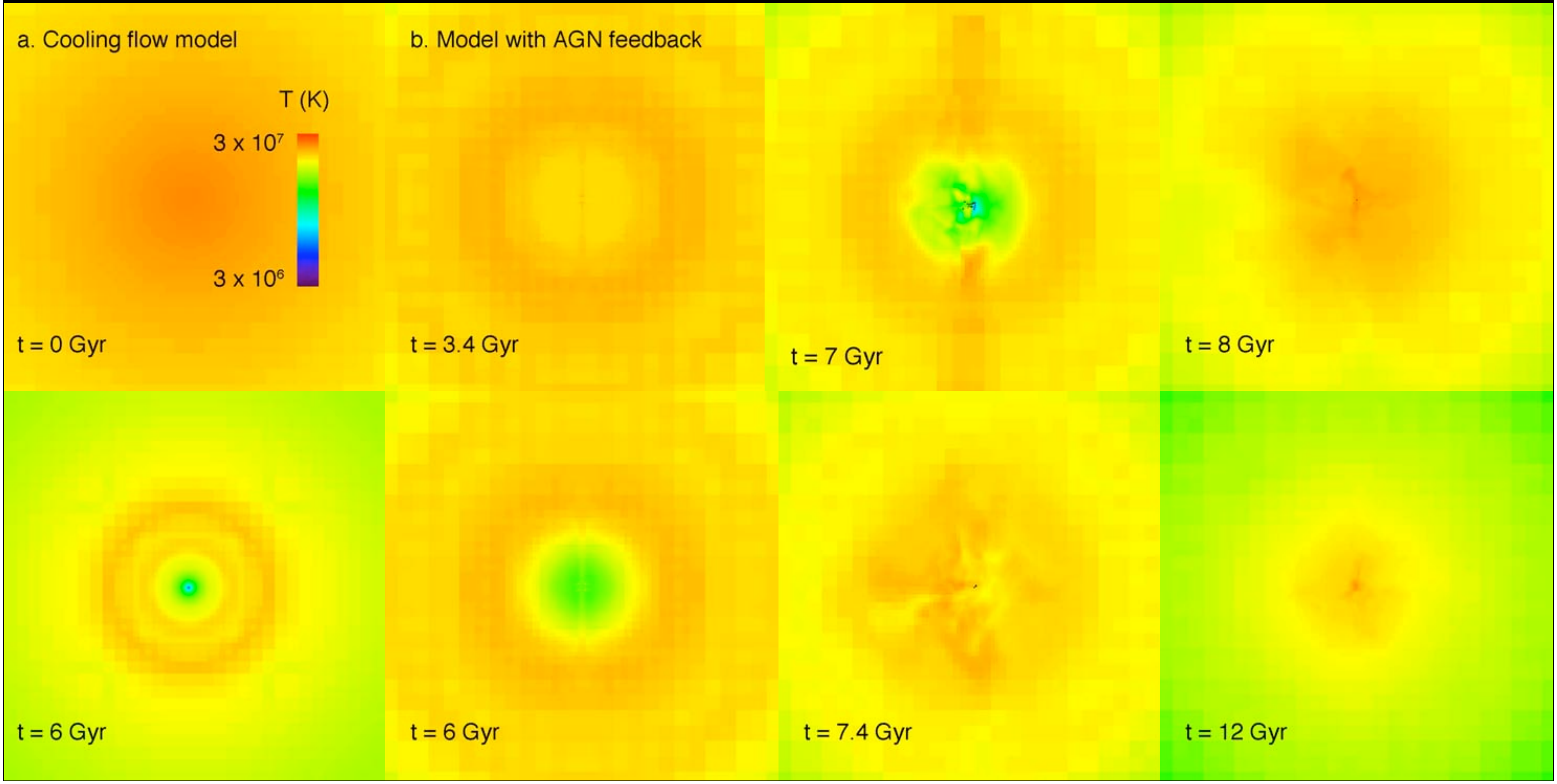
Hydrodynamics of BH - ICM interaction

Cattaneo & Teyssier 07

- NFW halo with mass of Virgo cluster
- Hydrostatic initial conditions for ICM
- $Z_{ICM} = Z_{Sun}/3$
- $M_{BH} = 3\times10^9 M_{Sun}$
- $dM_{BH}/dt = 4\pi(GM_{BH})^2\rho c_s^{-3} \propto (p/\rho^{5/3})^{-3/2}$
- $L_{jet} = 0.1(dM_{BH}/dt)c^2$
- $v_{jet} = 1400$ km/s

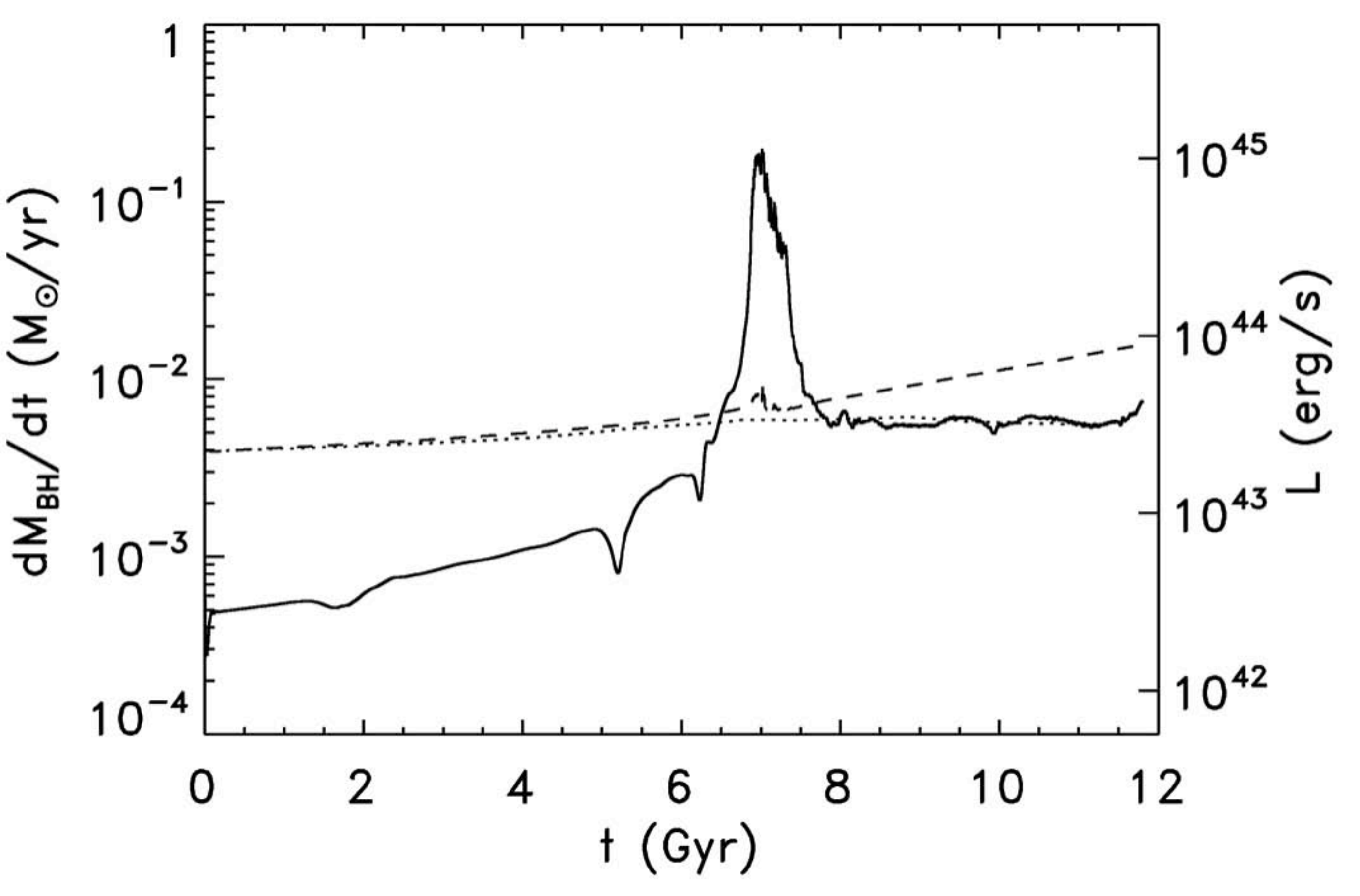


Line-of-sight emission-weighted temperature

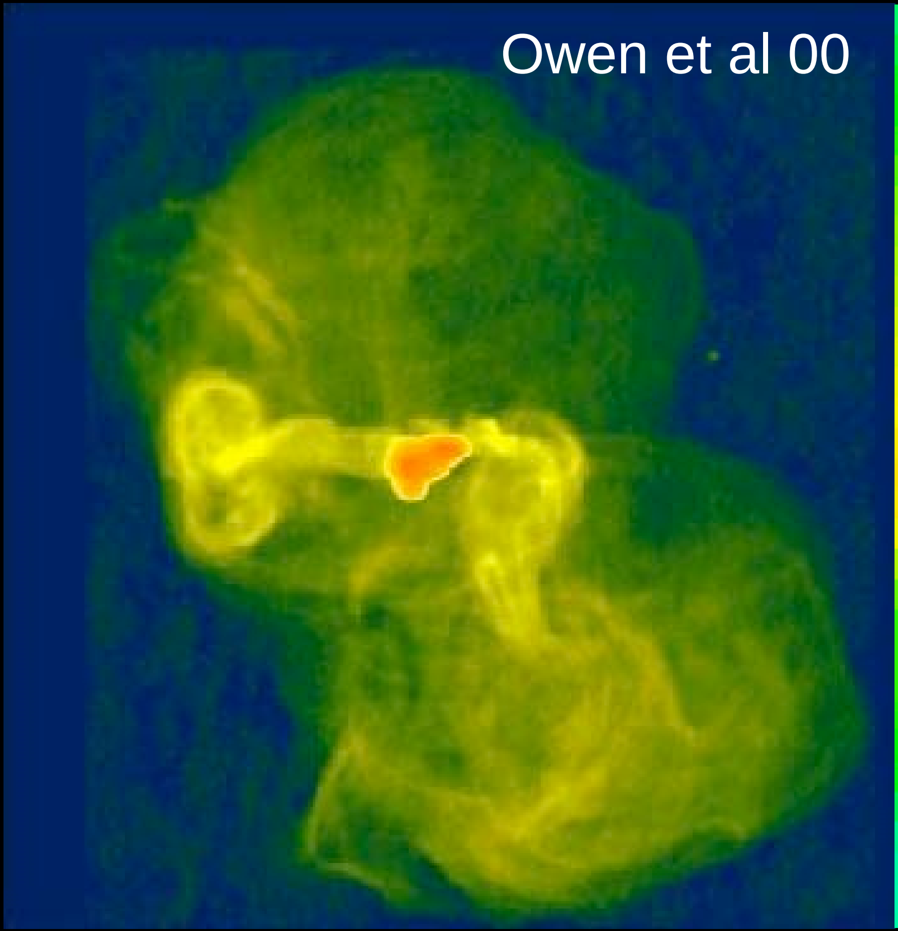


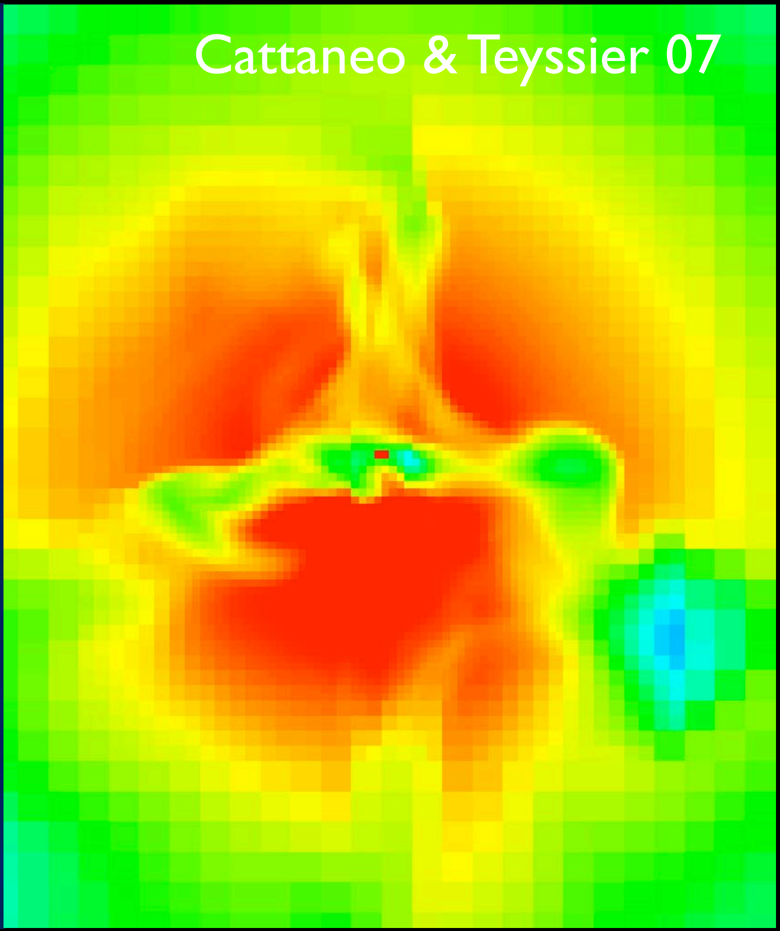
BH self-regulation in cooling flow clusters

Cattaneo & Teyssier 07



Buoyant bubbles in the ICM


Owen et al 00


Cattaneo & Teyssier 07

Turbulent mixing of jet plasma with the ICM may be dumped by viscosity, which creates an alternative heating path, e.g. Ruszkowski et al 04, Fabian et al 06

Conclusion

Bimodal black hole - galaxy coevolution

- Cold/hot mode transition at $M_{halo} \approx 2 \times 10^{12} M_{Sun}$ fundamental scale of galaxy formation
- $M_{halo} \leq 2 \times 10^{12} M_{Sun}$: star formation and luminous black hole growth in galaxy mergers
  In this regime that most of the black hole mass is accreted
  However the energy output is not efficiently coupled with the intergalactic medium
- $M_{halo} \geq 2 \times 10^{12} M_{Sun}$: passive evolution, growth by dry mergers and self-regulated radiatively inefficient black hole accretion
  Most of the accretion power is released mechanically and thermalised through viscous dissipation of sound waves
- This scenario accounts for the galaxy mass function, the spectral bimodality, the boxy/discy dichotomy, downsizing and the cooling flow problem