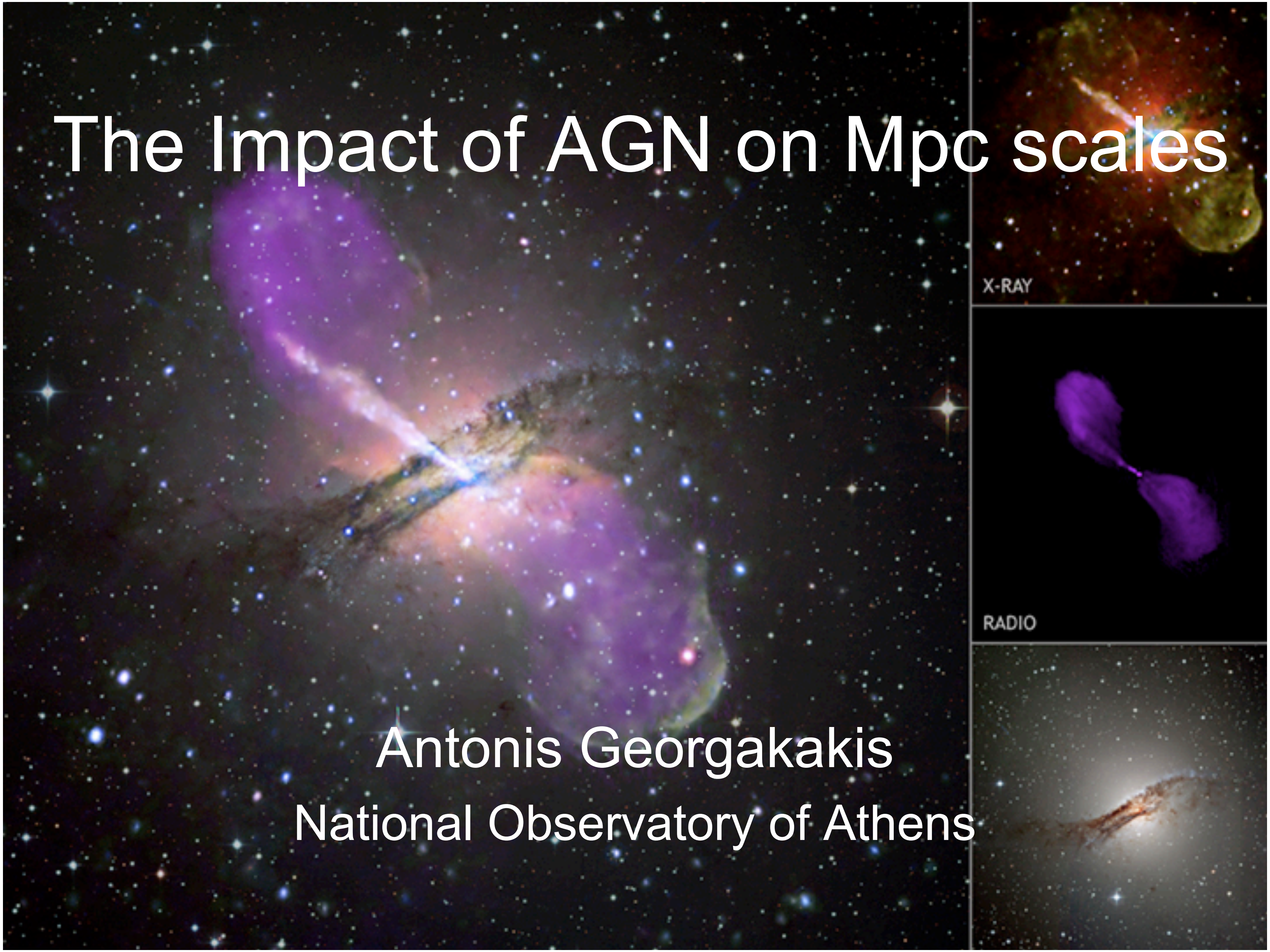
The Impact of AGN on Mpc scales



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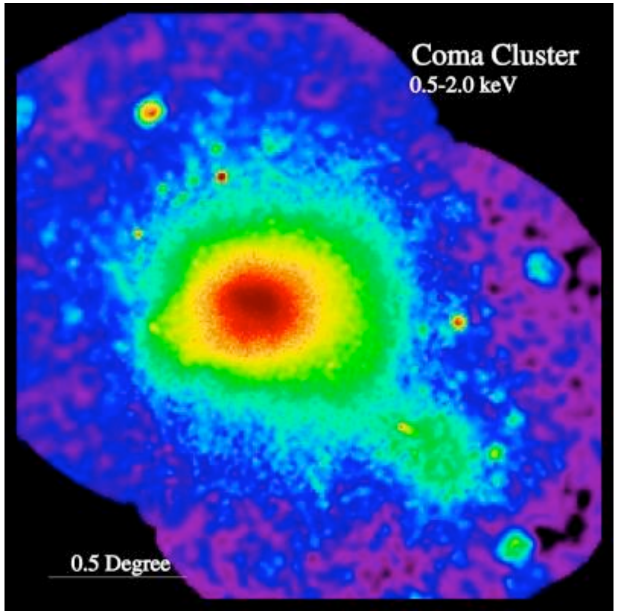
Outline

- Galaxy groups and clusters
  - Hot Inter-Galactic Medium (IGM)
- Problems in our understanding of the IGM
  - Departure from self-similarity
  - Overcooling in cooling flow clusters
- Problems can be resolved if AGN inject energy into IGM
- Observations of AGN/IGM interplay
- Simulations of AGN/IGM interplay
- Cosmological significance

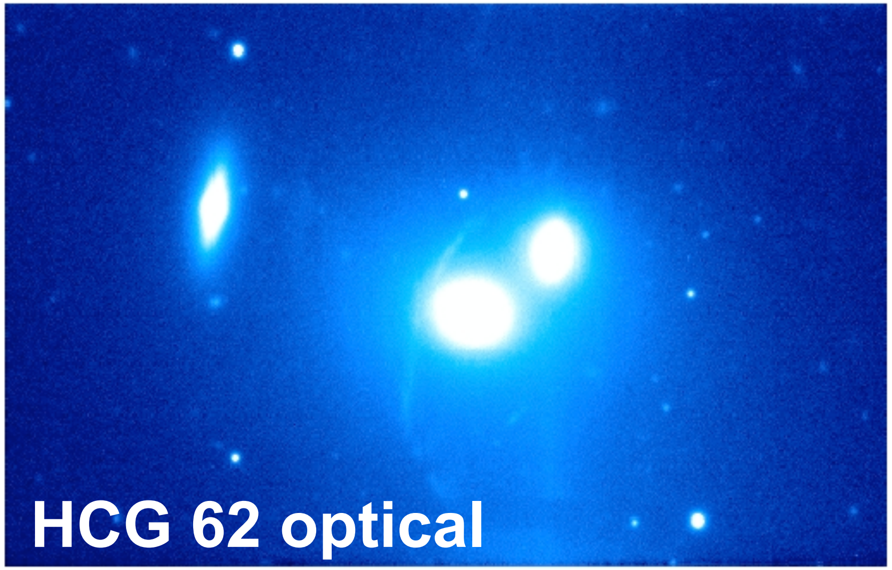
Galaxy groups and clusters

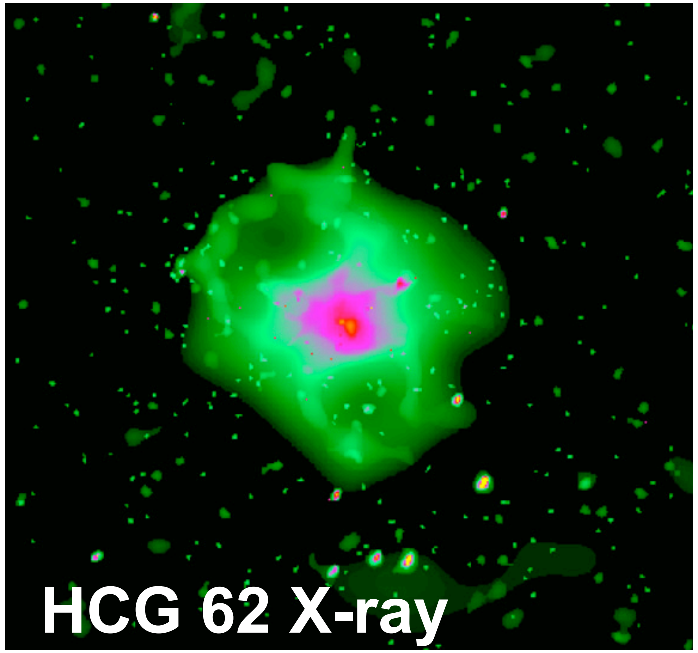


Most massive structures in the Universe

- Total mass 10^{13}–$10^{15}M_{\odot}$
- Only ~14% of mass in baryons
- Stars are a tiny fraction of the baryonic mass, ~1-2%
- Most baryons in the form of hot X-ray emitting gas with temperatures 10^7-10^8keV

Galaxy groups and clusters





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Hot Intra-Cluster Medium

- Baryons trapped into cluster/group potential well.
- Gas heated mainly because of gravity (10^7-10^8K)
- X-ray emission: Bremmstrahlung radiation

Virial Theorem:

$$U_{kin} = -\frac{1}{2}\Omega_{pot} \Rightarrow \frac{1}{2}m_p v^2 = \frac{1}{2}\frac{GMm_p}{R}$$

Assume ideal monoatomic gas (hydrogen)

$$\frac{1}{2}m_p v^2 = \frac{3}{2}kT \Rightarrow T \sim \frac{GMm_p}{kR}$$

For cluster with $M = 10^{14} M_{solar}$ and $R = 100\text{kpc}$

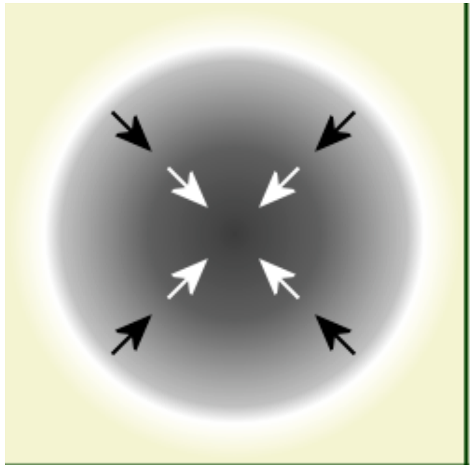
$$T \sim 5\times10^7 K$$

Self-similar scaling relations

Basic Assumptions:

1. Clusters form via gravitational collapse.

2. The only source of energy is gravitational energy.



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Clusters are self-similar: Their properties scale up or down depending on their Mass.

Derive simple scaling relations between cluster observables to test the assumptions above

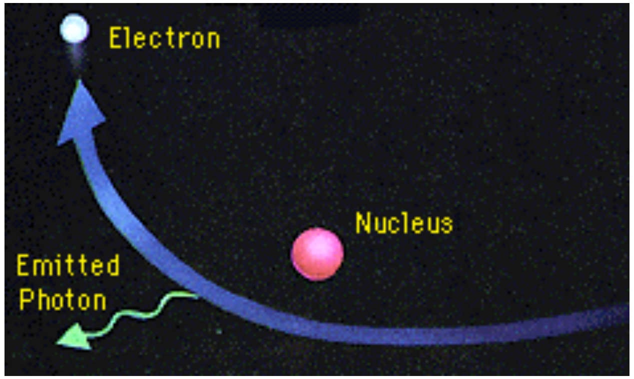
Hot gas: Bremsstrahlung

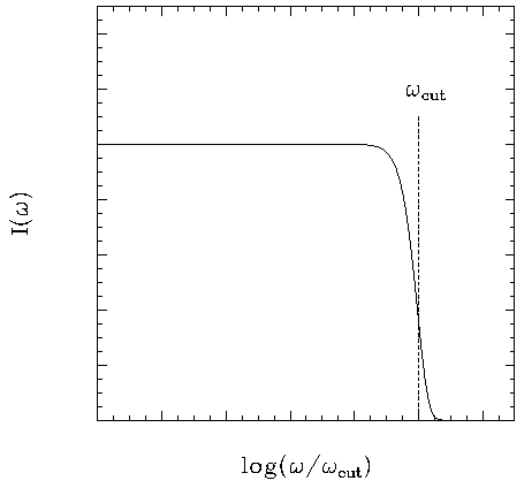
- Gas temperature T~10^7-10^8K: Hydrogen fully ionised
- Bremsstrahlung or braking radiation: emitted by a charged particle when accelerating in electric field.
- In the case of X-rays, e^- in Coulomb collision charge of Z protons
- The resulting spectrum is **flat** with an **upper cutoff** ω_{cut}, related to the interaction time, $\Delta t = v/b$, or interaction frequency $\omega = 1/\Delta t = b/v$

$$I = \frac{8Z^2e^6}{3\pi c^3 m_e^2 v^2 b^2},$$

where v electron velocity,

b the impact paramater.





Hot gas: thermal Bremsstrahlung

- In astrophysically interesting cases, electrons have velocity distribution.
- In the case of plasma with uniform temperature *T*, Maxwell distribution
- Thermal Bremsstrahlung falls off exponentially at high energies
- X-ray luminosity proportional to gas mass, gas density and $T^{1/2}$

$$f(v) = 4\pi\left(\frac{m_e}{2\pi kT}\right)^{3/2} v^2\, e^{-\frac{m_e v^2}{2kT}}$$

emitted power per unit volume and unit frequency:

$$e_{ff} = g_{ff}\,\frac{2^5 \pi e^6}{2m_e c^3}\left(\frac{2\pi}{3m_e k}\right)^{1/2} Z^2\, n_e\, n_i\, T^{-1/2} e^{-h\nu/kT}$$

integrating in frequency:

$$e^{ff} = 1.4\times 10^{-27} g_B Z^2\, n_e\, n_i\, T^{1/2} \text{ in erg s}^{-1}\text{ cm}^{-3}$$

$$L_X = \int e^{ff}\, dV \propto M_{gas}\rho_{gas}T^{0.5}$$

Self-similar scaling relations

Dark Matter Halo:

Mass *M*, Density *ρ*

Cluster Gas:

Mass M_{gas}, Density: ρ_{gas}, Temperature *T*

Virial Theorem:

$$U_{kin} = -\frac{1}{2}\Omega_{pot} \Rightarrow \frac{3}{2}kT = \frac{1}{2}\frac{GMm_p}{r} \Rightarrow$$

$$T \sim Mr^{-1} \xrightarrow{\rho \sim M/r^3} \mathbf{T \sim M^{2/3} \rho^{1/3}}$$

Also assume

$$\rho_{gas} \sim \rho$$

$$M_{gas} \sim M$$

Using the above derive scaling relation for L_X :

$$L_X \propto M_{gas}\rho_{gas}T^{0.5} \Rightarrow L_X \propto \rho^{0.5}T^2$$

Self-similar scaling relations

How is ρ defined?

We have to decide radius within which ρ is measured.

Choose radius at which the local density is a fixed multiple of the critical density of the Universe.

$$\rho = \Delta \times \rho_c \Rightarrow \rho = \Delta \times \frac{3H(z)^2}{8\pi G}$$

For smaller clusters $\rho = \Delta \times \rho_c$ will correspond to smaller radii.

Scaling relation for L_X :

$$L_X \propto \rho^{0.5} T^2 \Rightarrow L_X \propto \Delta^{0.5} \rho_c^{0.5} T^2 \Rightarrow$$

$$L_X \propto T^2 \rho_c^{0.5}(z)$$

$$\rho_c(z) = \frac{3H(z)^2}{8\pi G}, \quad H(z)^2 = H_O^2\left(\Omega_M (1+z)^3 + \Omega_\Lambda\right)$$

After accounting for redshift and mass of different clusters we expect :

$$L_X \propto T^2$$

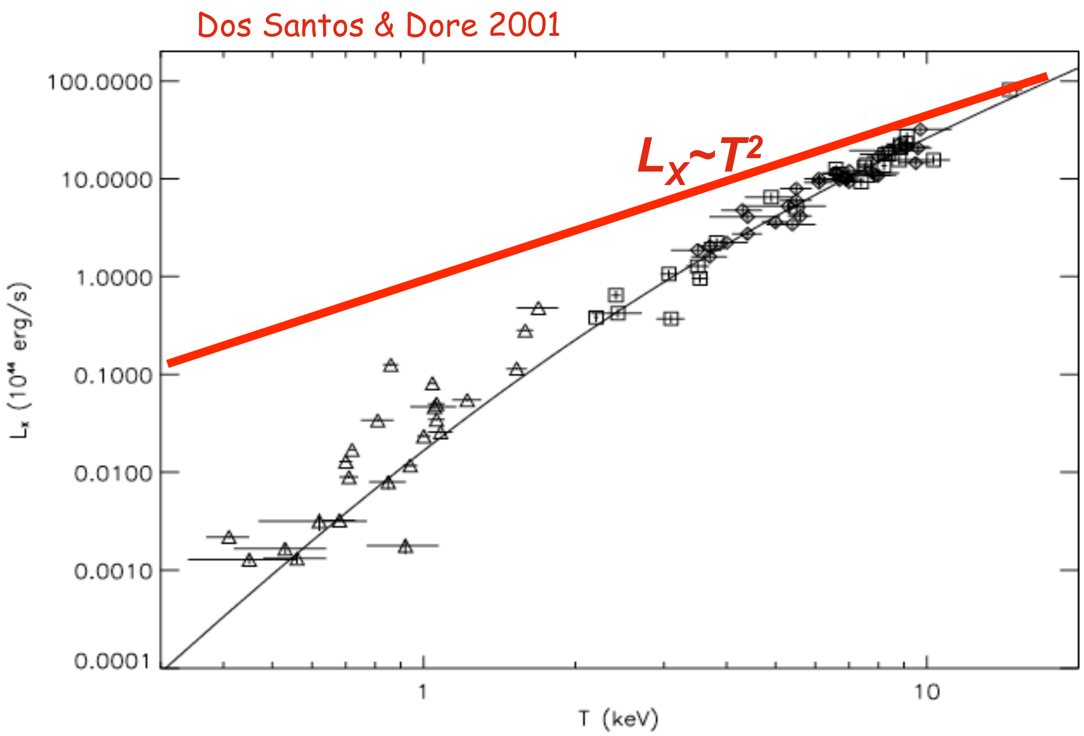
Departure from self-similar scaling relations

Observed L_X-T relation deviates from self-similarity.

Departure from self-similarity is more pronounced for less massive clusters/groups

Evidence for non-gravitational source of heating that raises T at a given L_X.

Additional heating needed ~1keV per particle.



Cluster gas cooling time: overcooling problem

Hot gas cools via thermal Bremsstrahlung radiation.

At the cluster outskirts typical values $n_p \sim 10^{-4}$cm^{-3}, $T \sim 10^7$K:

$t_{cool} \sim 10^{11}$yr >>Age of the Universe

BUT: at cluster core typical values $n_p \sim 10^{-2}$cm^{-3}, $T \sim 10^7$K:

$t_{cool} \sim 2\times 10^9$yr, i.e. fast cooling

Thermal Bremsstrahlung emissivity

$$e^{ff} = 1.4 \times 10^{-27} g_B Z^2 \, n_e \, n_i \, T^{1/2} \quad \text{in erg s}^{-1} \text{ cm}^{-3}$$

For a perfect monoatomic gas at temperature T

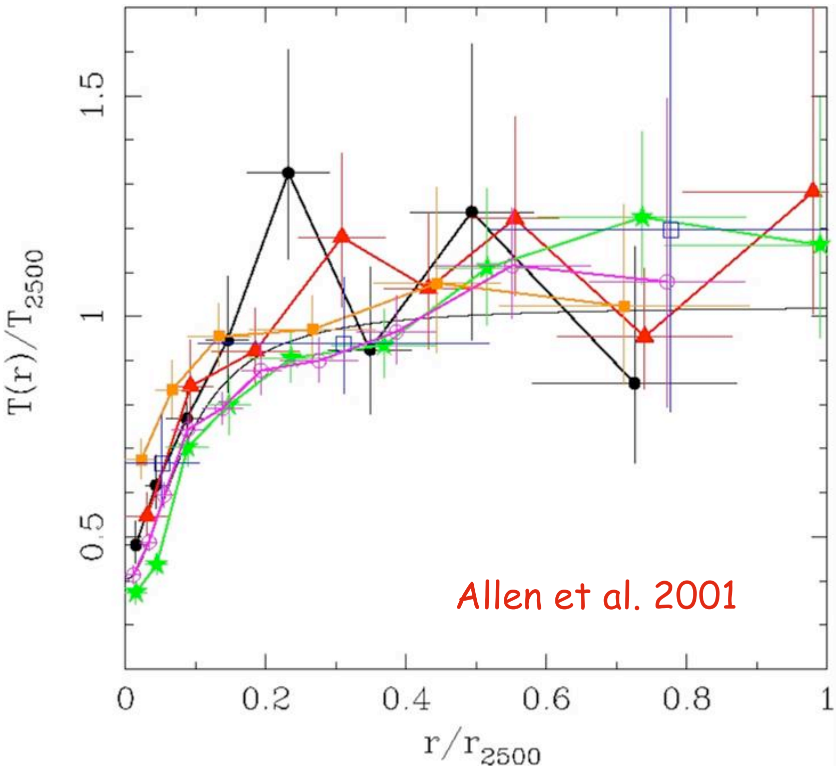
$$\text{U} = \frac{3}{2} kTn_e$$

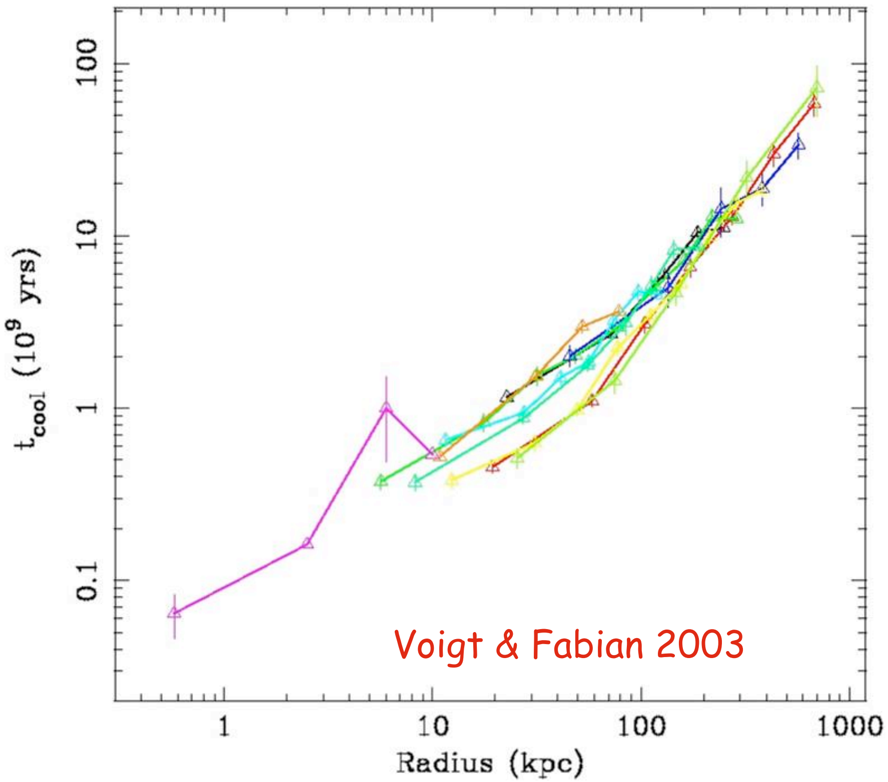
So the time required to radiate this energy:

$$t_{cool} = \frac{3}{2} kTn_e / e^{ff} \Rightarrow$$

$$t_{cool} = 8.5 \times 10^{10} \left(\frac{n_p}{10^{-3} cm^3} \right)^{-1} \left(\frac{T}{10^8 K} \right)^{1/2} yr$$

Overcooling problem





There should be a reservoir of cool gas & star-formation in the central cluster galaxy.

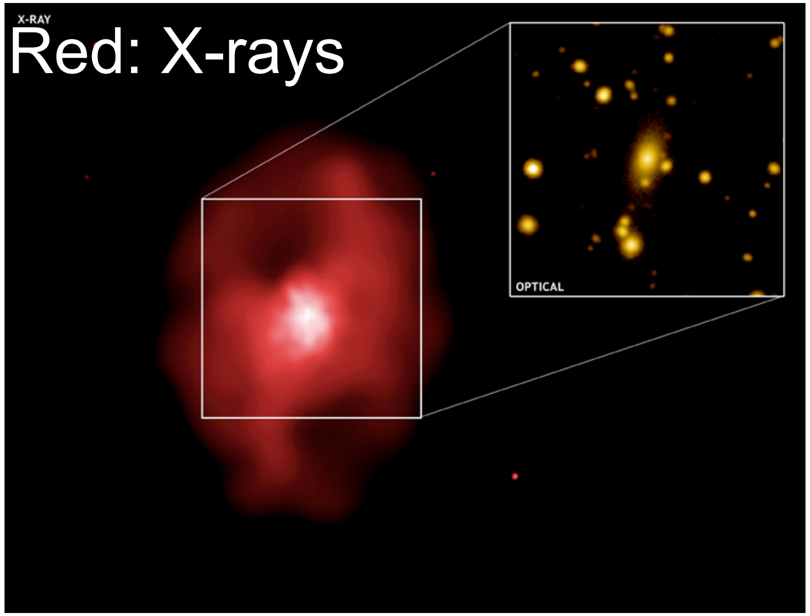
* Not all cooling flow clusters show evidence for SF.
* In many clusters SF rate << than cooling mass rate
* Cold gas is 10 times less than expected

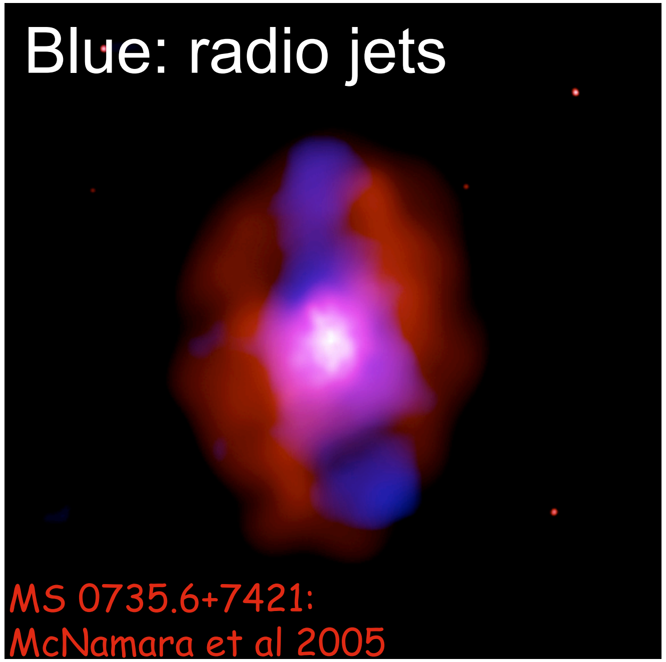
} some heating process suppress cooling

Heating history of clusters

- ICM properties suggest additional non-gravitational heating mechanism:
  - Departure from self-similarity (e.g. L_X–T relation)
  - Lack of cooling gas at the centre of clusters
- Could AGN provide the extra energy?

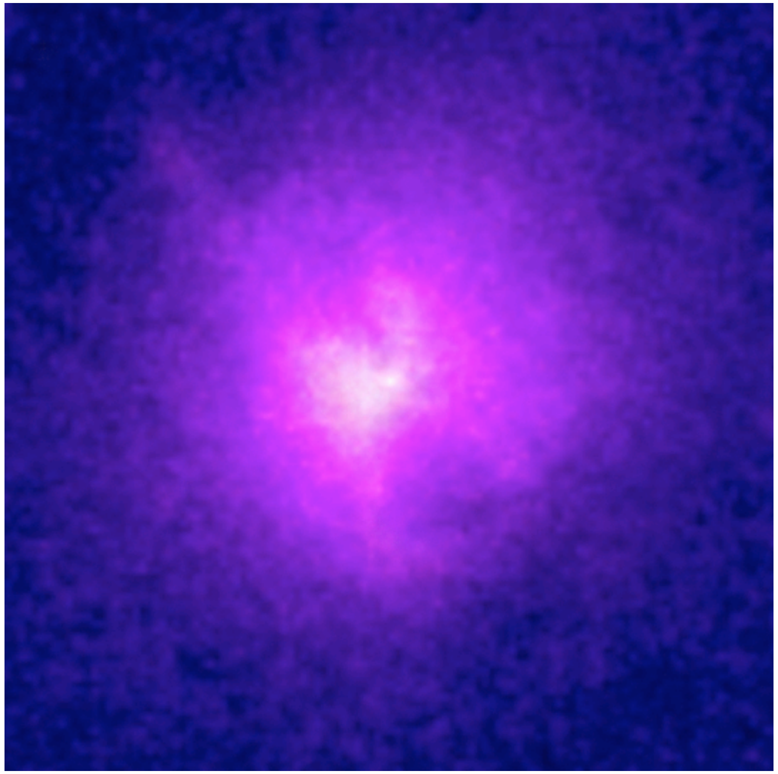
Evidence for AGN/ICM interaction

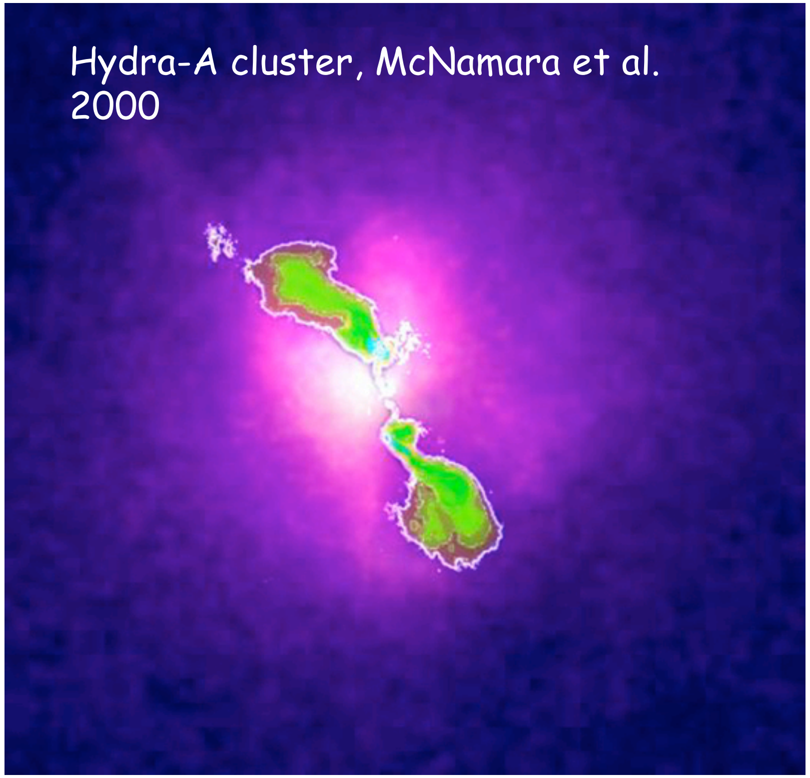




Cavities in the hot cluster gas created by radio jets coming from the super-massive black hole of the central cluster galaxy.

Evidence for AGN/ICM interaction





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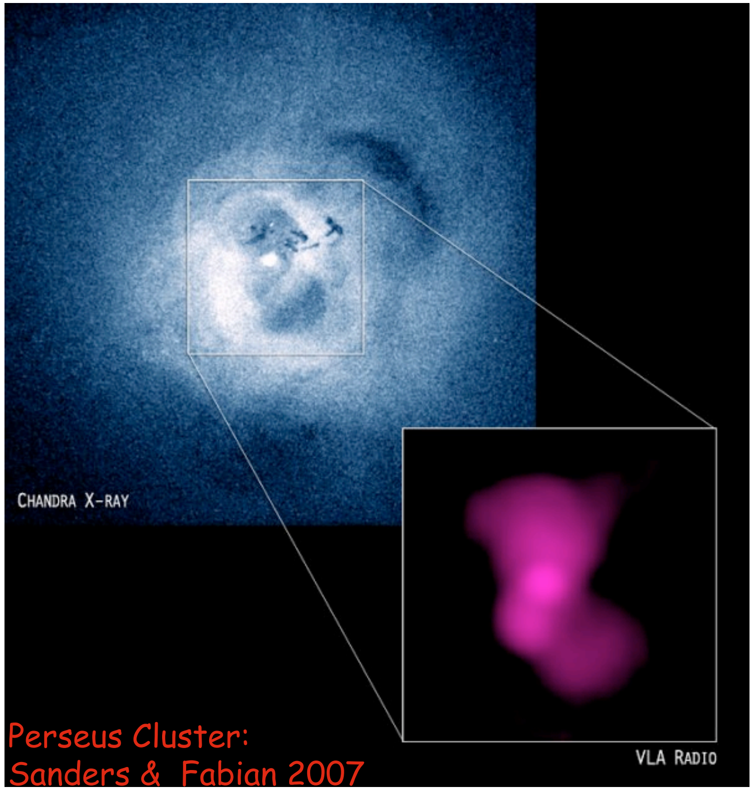
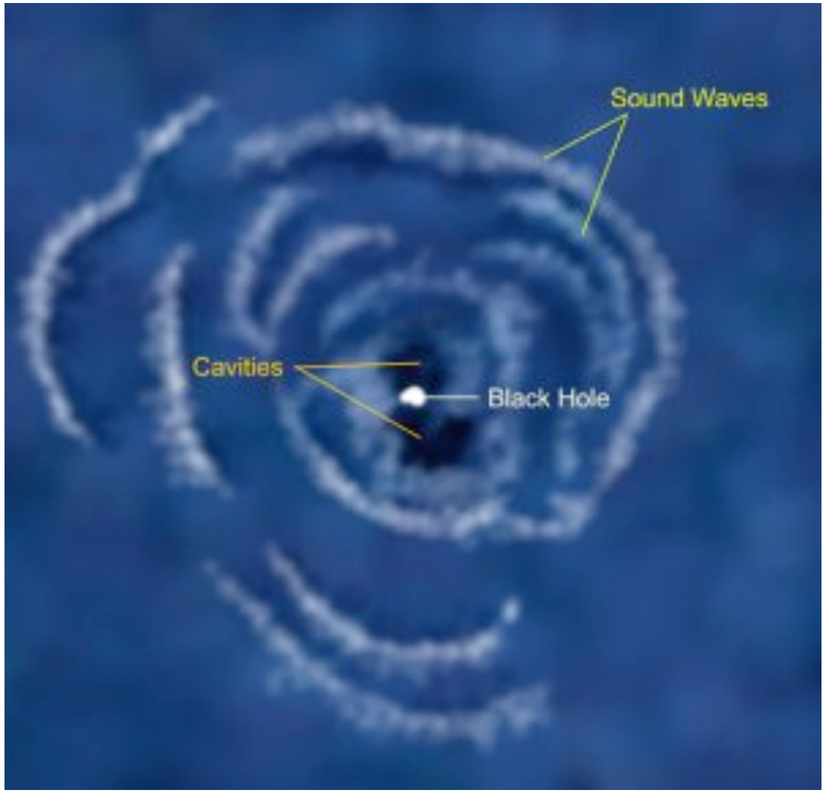




Energetics of AGN/ICM interaction

Is the energy injected by jets sufficient to (i) stop cooling flows and (ii) pre-heat the gas?

Heat (Q) injected to ISM is the sum of internal energy (U) plus work (PV) done by jets on ISM:

$Q = U + pdV \sim U + PV$

Assuming idea gas:

$U = 3/2NkT = 3/2PV$

Combining the relations above

$Q = 5/2PV$

Application to Hydra cluster:

bubble heating: $Q = 10^{60} erg$

AGN lifetime 10^{8} yr, so heating rate:

$\dot{Q} = 3 \times 10^{44}$ erg/s

Energetics of AGN/ICM interaction

Is the energy injected by jets sufficient to (i) stop cooling flows and (ii) pre-heat the gas?

YES: In the Hydra cluster, cooling luminosity equals the bubble heating luminosity.

Cooling rate of ISM:

$$Q = U + pdV \sim U + PV$$

Assuming idea gas:

$$U = 3/2NkT$$

Combining the relations above

$$Q = 5/2NkT = \frac{5}{2}\frac{M}{\mu m_p}kT$$

Cooling luminosity:

$$L_X = \frac{5}{2}\frac{\dot{M}}{\mu m_p}kT$$

Application to Hydra, $\dot{\mathrm{M}} = 100\mathrm{Msolar/yr}$

$$L_X = 3\times10^{44}\,\mathrm{erg/s}$$

Energetics of AGN/ICM interaction

Is the energy injected by jets sufficient to (i) stop cooling flows and (ii) pre-heat the gas?

ALMOST: In the Hydra cluster, the energy needed to explain L_X–T relation offset is ×2 larger than the bubble heating luminosity

An increase in the ISM energy per particle of $\sim 1\text{keV}$ is required to explain offset in the L_X - T relation:

$\Delta E_{particle} \sim 1\text{keV}$

For a cluster with gas mass M_{gas}

$$\Delta U = N \times \Delta E_{particle} = \frac{M_{gas}}{\mu m_p} \Delta E_{particle},$$

where N is the number of the ISM particles.

For the Hydra cluster, $\text{M} \sim 6 \times 10^{13} \text{M}_{\text{solar}}$,

$\Delta U = 2 \times 10^{62} \text{erg}$

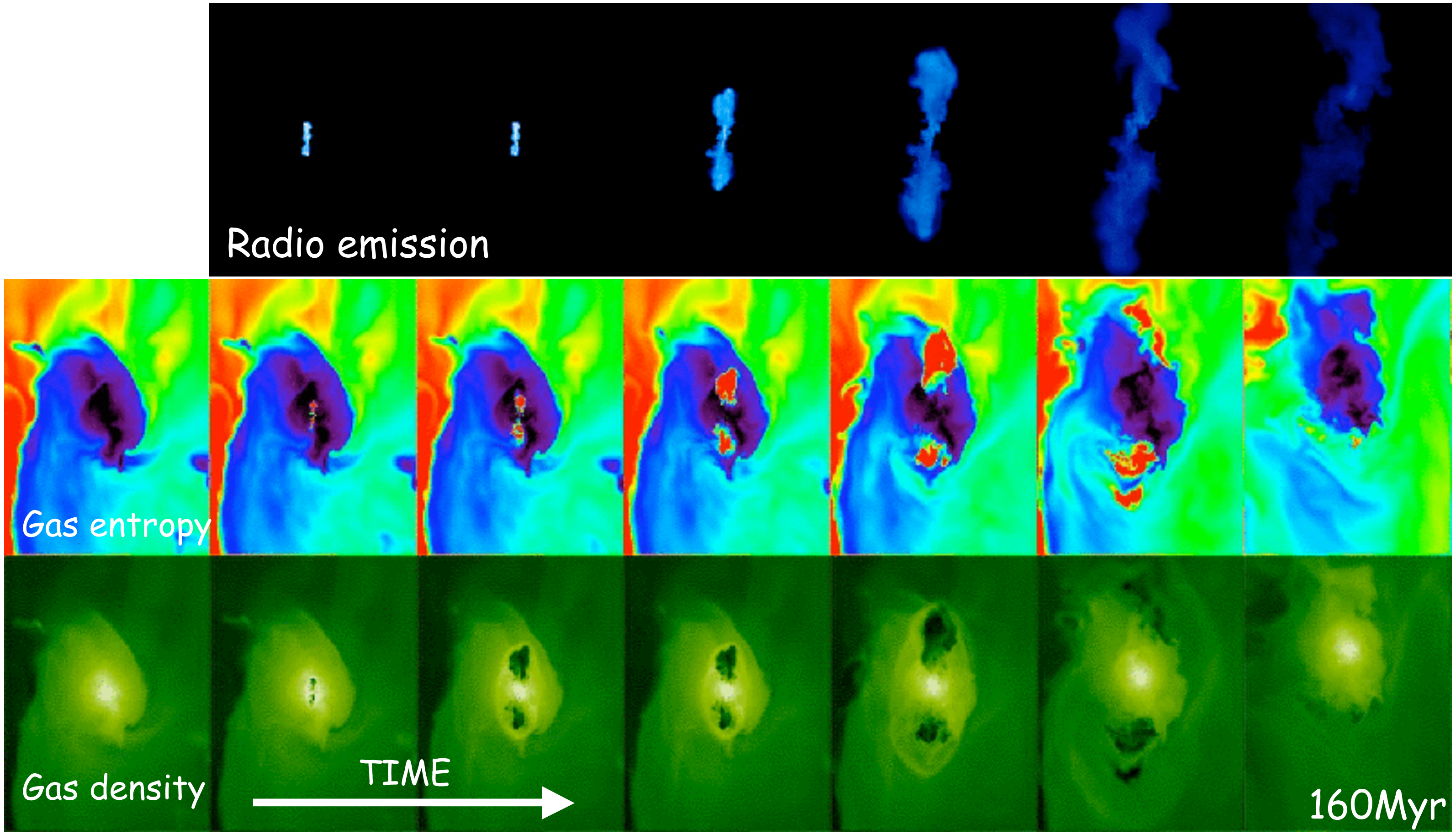
Assuming that this is deposited to the ISM by AGN over the lifetime of the Universe $\sim 10\text{Gyr}$, the energy injection rate is

$$\Delta U / \Delta t = 7 \times 10^{44} \text{erg/s}$$

Problems and ongoing research

- Is jet energy deposited at the right place to offset cooling flows?
- How is jet energy dissipated in the ICM?
- How frequent are AGN outbursts in clusters?
- How radio jets form?
- How is accretion on the SBH of cluster galaxies triggered?
- Are jets the only way of heating ICM?

Jet/ICM interaction simulations



Heinz et al. 2006

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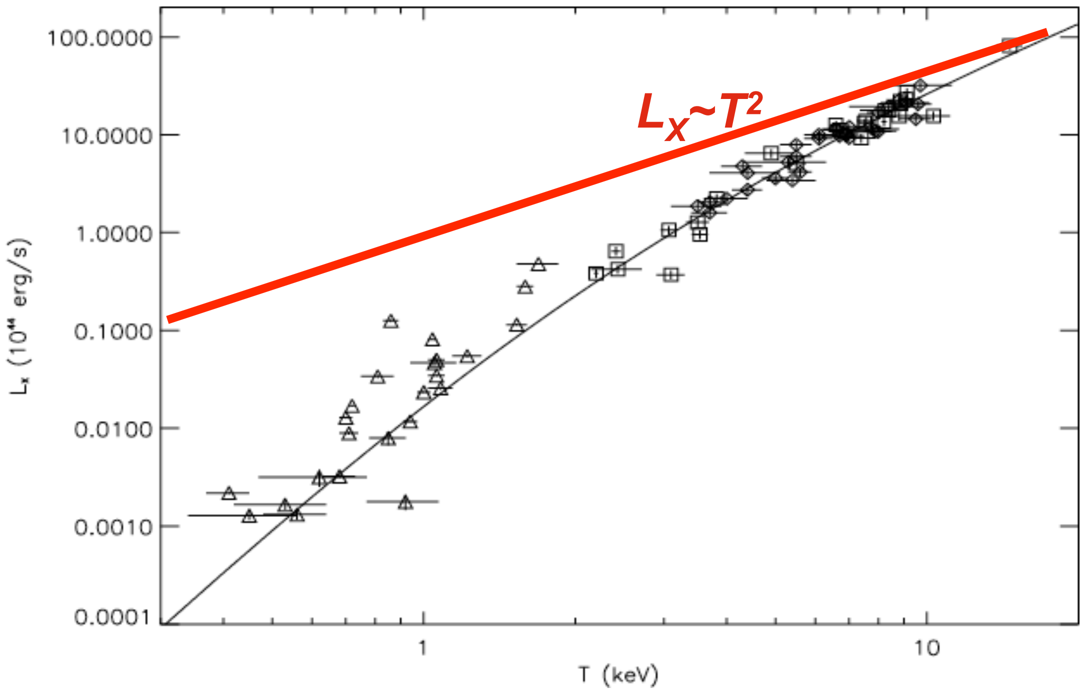
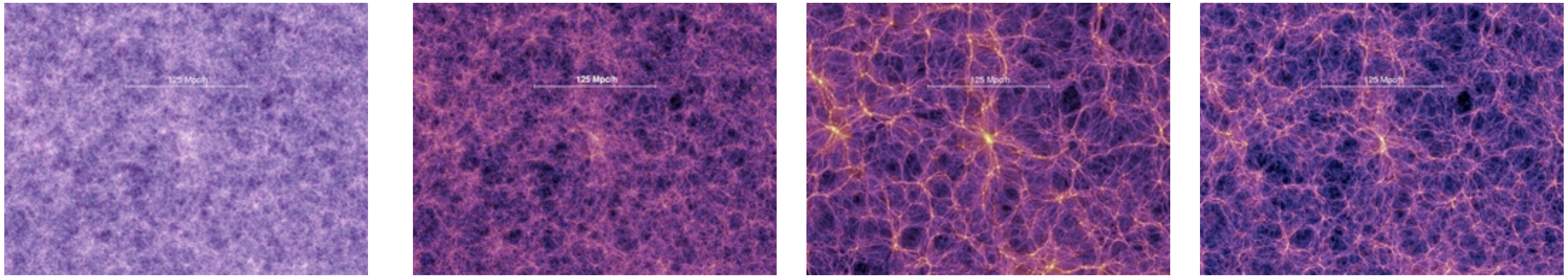
Dos Santos & Dore 2001



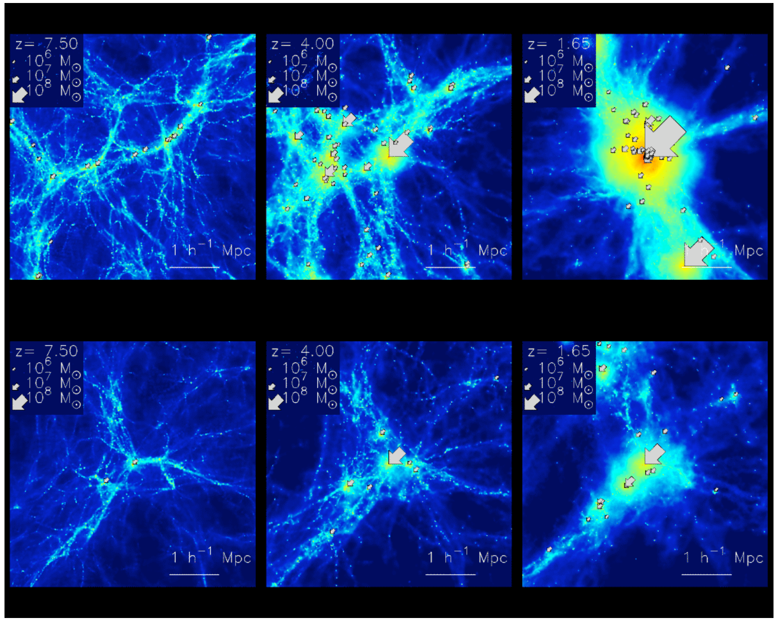
Cosmological simulations of galaxy formation

z=18.3 *z*=5.7 *z*=1.4 *z*=0

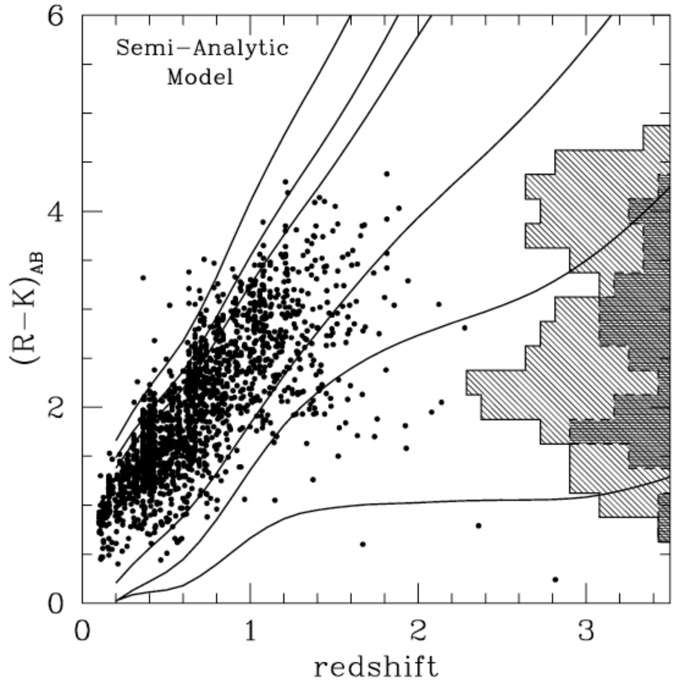


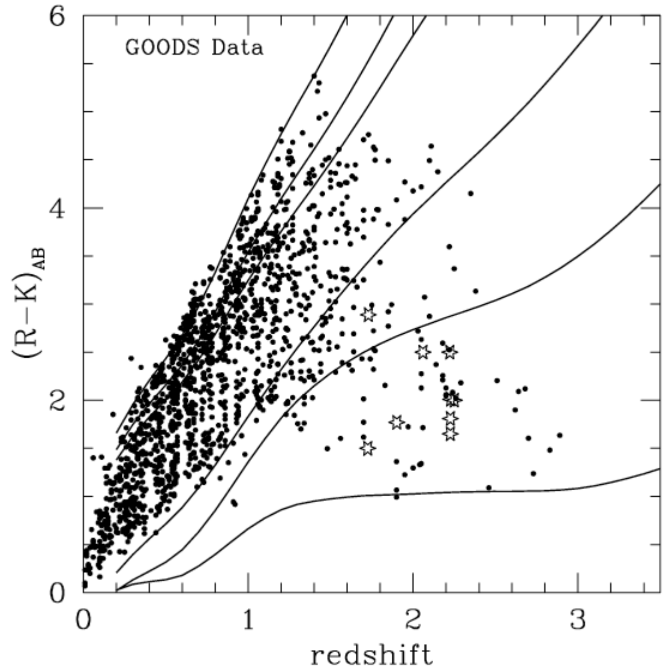
Millennium Simulation, Springel et al. 2005

- Cold Dark Matter
- Λ–cosmology
- Evolution of dark matter haloes
- Gravity only



Implications for cosmological simulations for galaxy formation





Cosmological simulations: too many massive blue (star-forming) galaxies at z~1

Need to suppress star-formation in massive galaxies at z~1: AGN feedback via radio jets can solve the problem

Summary

- AGN have a strong impact on the large scale environment of galaxies
- Radio Jet/ICM interaction can explain
  - The departure of clusters/groups from self-similarity
  - The lack of cool gas in cooling flow clusters
- AGN feedback important for cosmological simulations for galaxy formation

References for further study

- McNamara & Nulsen ARA&A, 2007, 45, 117 (arXiv:0709.2152)
- Fabian A. C., 1994, ARA&A, 32, 277
- "Cosmological Aspects of X-ray Clusters of Galaxies", 1994, NATO ASI series, edited by W. C. Seiter
- "Heating versus Cooling in Galaxies and Clusters of Galaxies", proceedings of the MPA/ESO/MPE/USM Joint Astronomy Conference, Garching 2006, editors Boringer, Pratt, Finoguenov, Schuecker.

Self-similar scaling relations

Entropy of estimates the heating history of the gas:

$$S \sim \ln(\frac{T^{3/2}}{\rho_{gas}})$$

Assumes ideal monoatomic gas.

Evidence for non-gravitational source of heating that raises entropy of the gas