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Simulations of Galaxy Clusters with Feedback from Semi-Analytic Models

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Introduction

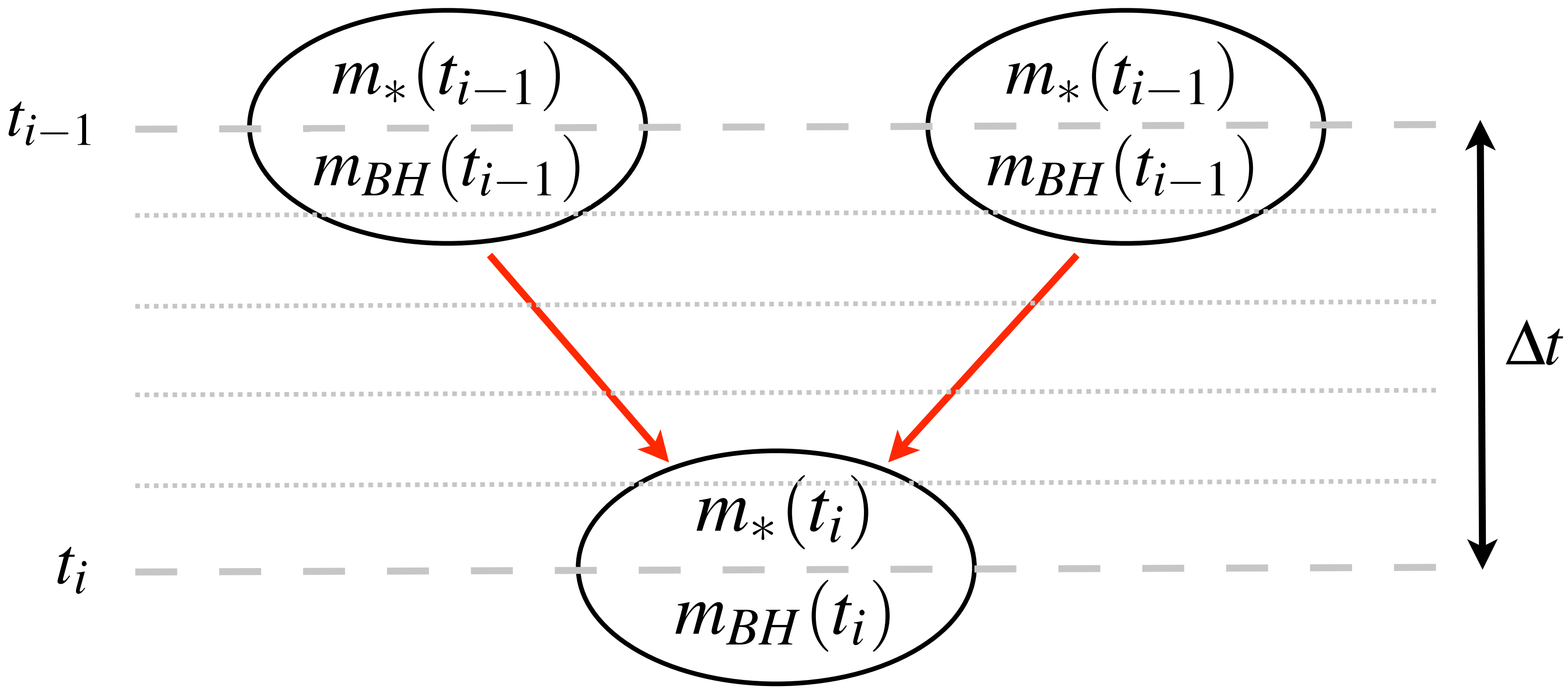
- **Feedback** from galaxies (**star formation**, **SN**, **AGN**, etc) is essential to prevent the overcooling of gas in simulations of galaxy clusters
- Direct high-resolution NB+SPH simulations capable of resolving individual galaxies are not currently practical in cosmological volumes
- Feedback included in direct NB+SPH simulations using simple models
- **Semi-analytic models** (SAMs) provide a powerful tool for studying galaxy formation
- SAMs incorporate feedback processes via a set of physically motivated recipes
- Combine direct and semi-analytic approaches by using predictions from SAMs as a model for sub-resolution physics in NB+SPH simulations
- Aim to investigate what SAMs predict for the intracluster medium (ICM)

Methodology

- Construct initial conditions identical to the **Millennium simulation**, but with the lower mass resolution of the **Millennium gas run**
- SAMs built on dark matter **merger trees** constructed from the Millennium simulation
- Assume the gas particles have **zero** gravitational mass
- Evolve the initial conditions with **Gadget 2**, assigning the correct mass to gas particles for SPH calculations
- Neglect **radiative cooling** since the bulk of the gas in clusters has a long cooling time
- At each Millennium output, use data from the SAMs to calculate feedback from SN, AGN, etc, and inject this energy into the gas
- Examine resulting properties of galaxy clusters and the ICM

Feedback from SAMs

- Properties of all the galaxies formed in the **L-Galaxies/GalForm** SAMs are stored in the GAVO SQL database `http://www.g-vo.org`



$$\Delta m_* = m_*(t_i) - \sum_{prog.} m_*(t_{i-1})$$

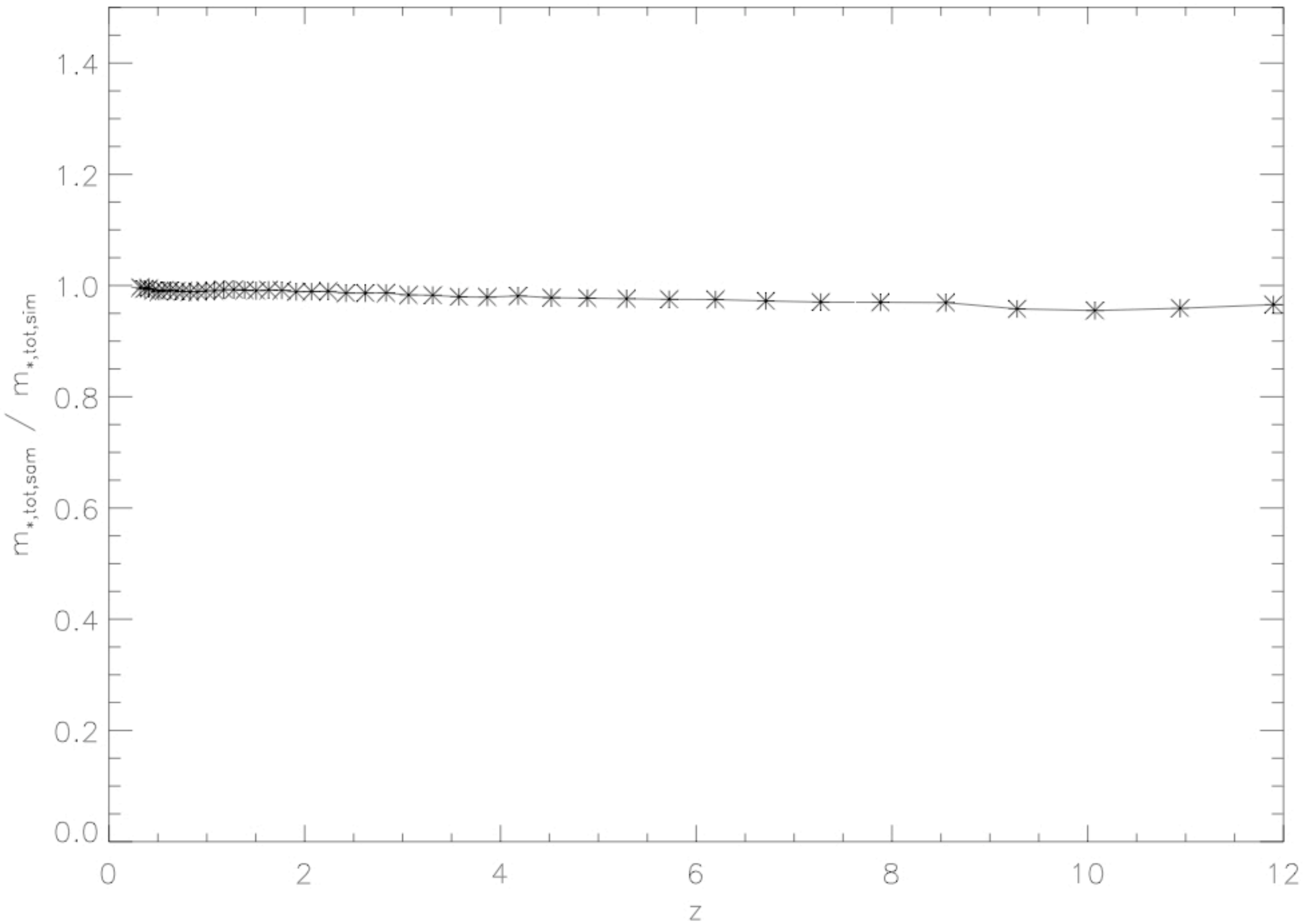
$$\Delta m_{BH} = m_{BH}(t_i) - \sum_{prog.} m_{BH}(t_{i-1})$$

Star Formation

- For each galaxy we know the mass in new stars Δm_*
- Number of gas particles to convert to **collisionless** star particles is

$$N_{stars} = \frac{\Delta m_*}{m_{gas}}$$

- If N_{stars} is not an integer, we use a probabilistic method to determine how many star particles to form
- Total mass of stars formed in simulation agrees very well with SAM prediction



Type II SN Feedback

- In L-Galaxies, the energy released by type 2 supernovae is

$$\Delta E_{SN} = \frac{1}{2}\varepsilon_{halo}\Delta m_* v_{SN}^2$$

where $\varepsilon_{halo} = 0.35$ is the efficiency with which cold disc gas is reheated

- The energy used to reheat cold gas is

$$\Delta E_{hot} = \frac{1}{2}\varepsilon_{disc}\Delta m_* v_{vir}^2$$

where $\varepsilon_{disc} = 3.5$ controls the amount of cold gas reheated by supernovae

- Hot gas is **ejected** from the halo in a wind if

$$\Delta E_{ejected} = \Delta E_{SN} - \Delta E_{hot} > 0$$

- No hot gas is ejected for halos with $v_{vir} > (\varepsilon_{halo}/\varepsilon_{disc})^{1/2} v_{SN} \approx 200$ km/s

AGN Feedback

- In L-Galaxies, black holes accrete matter in two ways:

  (i) Mergers funnel cold gas towards central black hole - **quasar mode**

  (ii) Quiescent accretion of hot gas from static hot halo - **radio mode**

- **Ignore** energy released by radio mode accretion since it only reduces the cooling rate of hot gas within the halo

- Assume a fraction ε_f of the bolometric luminosity couples **thermally** and **isotropically** to surrounding gas particles (e.g. Sijacki *et al* 2007):

$$\Delta E_{BH,quas} = \varepsilon_f \eta \Delta m_{BH,quas} c^2$$

- The mass accreted in the quasar mode is $\Delta m_{BH,quas} = \Delta m_{BH} - \Delta m_{BH,rad}$ where

$$\Delta m_{BH,rad} = \kappa_{AGN} \left(\frac{m_{BH}}{10^8 M_{\odot}} \right) \left(\frac{f_{hot}}{0.1} \right) \left(\frac{v_{vir}}{200\ \mathrm{km/s}} \right)^3 \Delta t$$

Heating Models

- Two physically motivated models for injecting feedback energy into gas:

  (i) Heat N nearest gas particles by the halo **virial temperature** so they become buoyant and move outwards, where

  $$N = \frac{\Delta E_{feed}}{3 m_{gas} k_B T_{vir} / 2 \mu m_H}$$

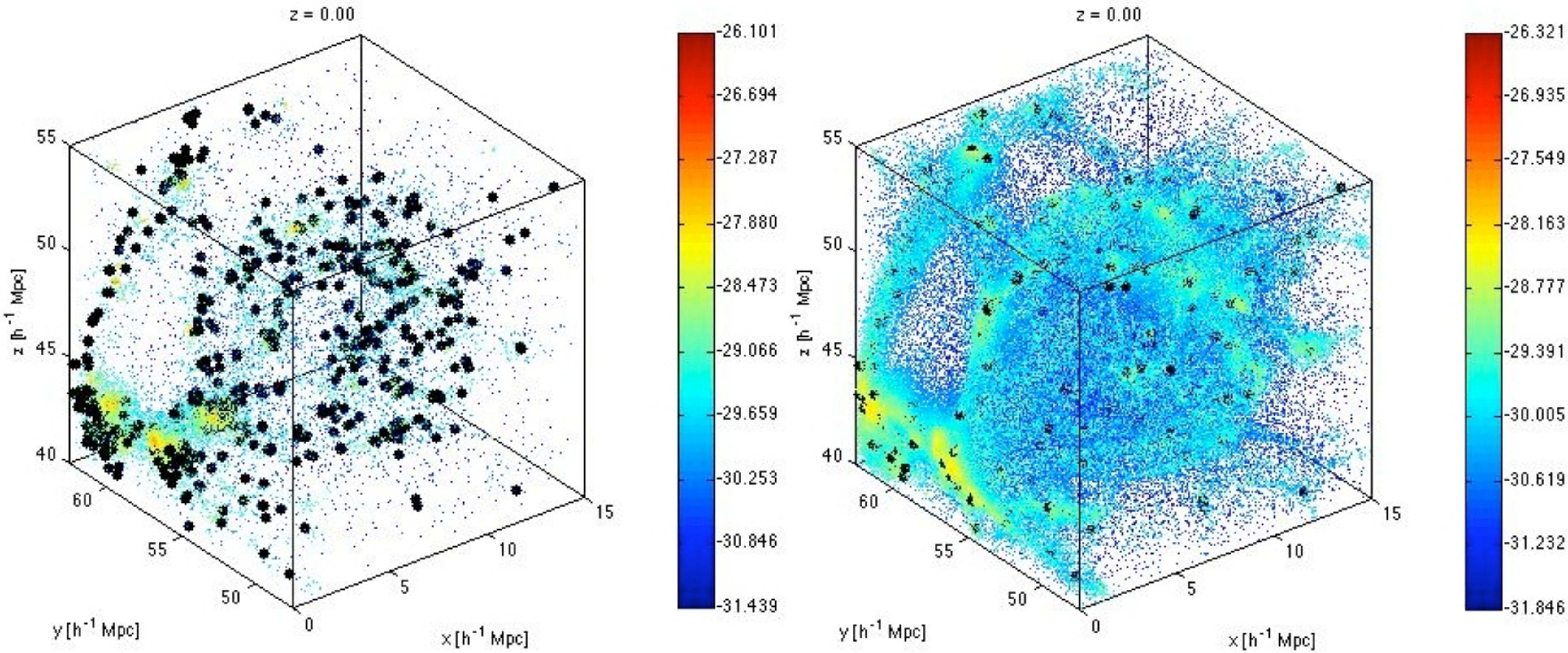
  (ii) Heat gas particles within a radius $R = v_{vir} \Delta t$ since this is of the order of the distance over which disturbances in the gas can propagate in a timestep

- Gas particles are heated by giving them an entropy boost

$$\Delta A(S) = \frac{P}{\rho^{\gamma}} = \frac{(\gamma - 1)\Delta E_{feed}}{N m_{gas} \rho^{(\gamma-1)}}$$

- Incorporated these feedback models into Gadget2

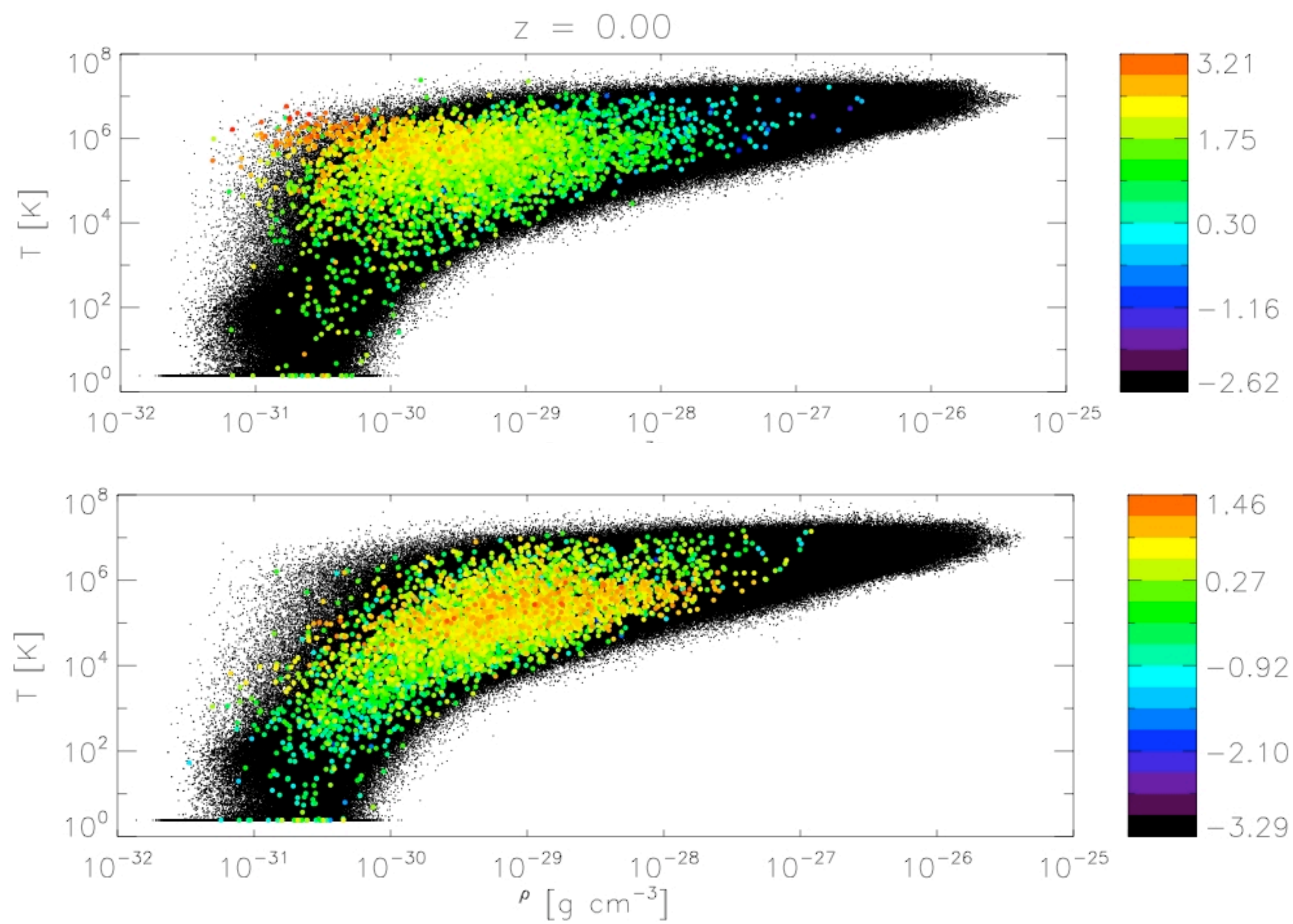
Resolution Issues



Resolution Issues

- Gas in artificial low-density regions heated too much
- Assume gas is at the **virial (gas) density** of the halo
- Entropy boost is then

$$\Delta A(S) = \frac{(\gamma - 1)\Delta E_{feed}}{N m_{gas} \rho_{vir}^{(\gamma-1)}}$$

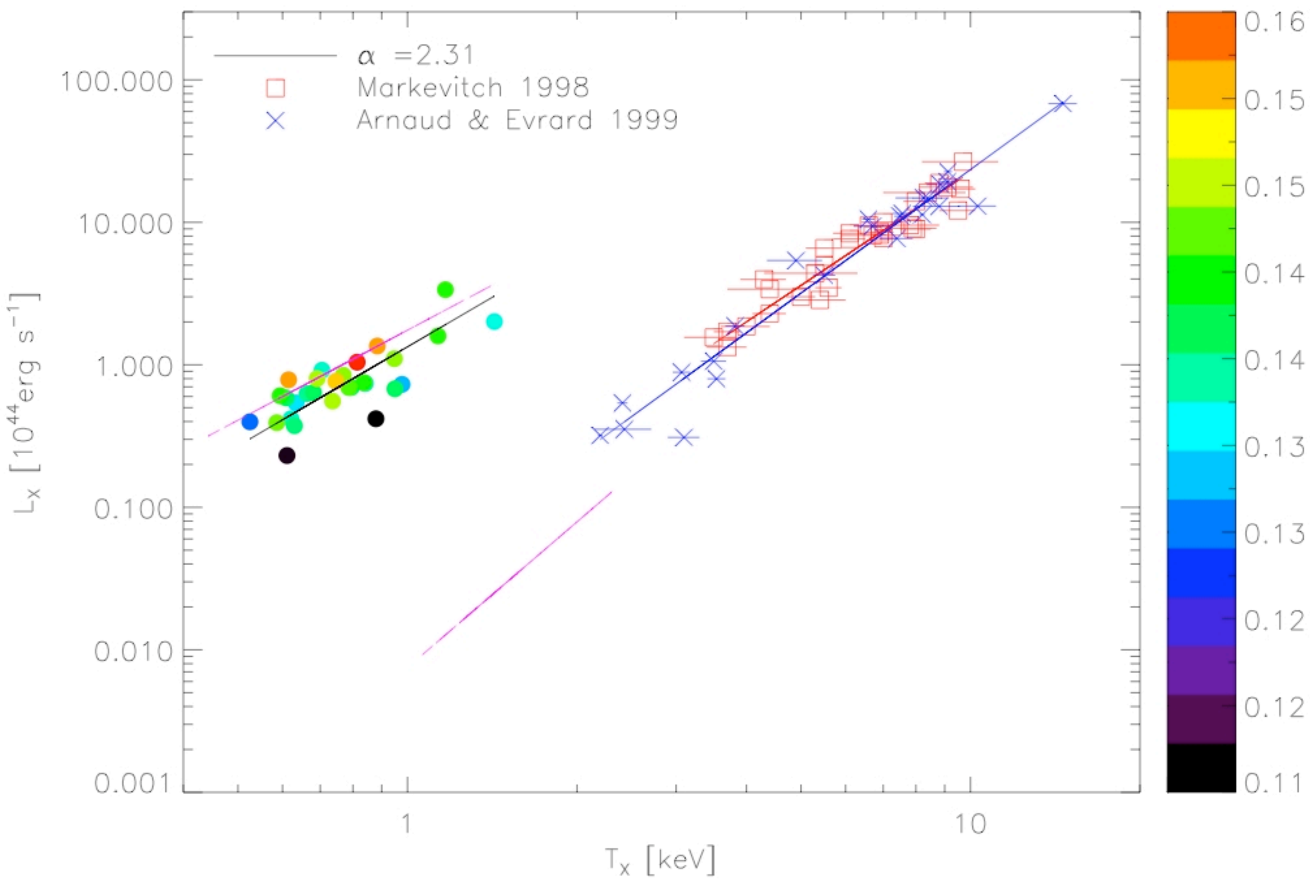


- Justification:

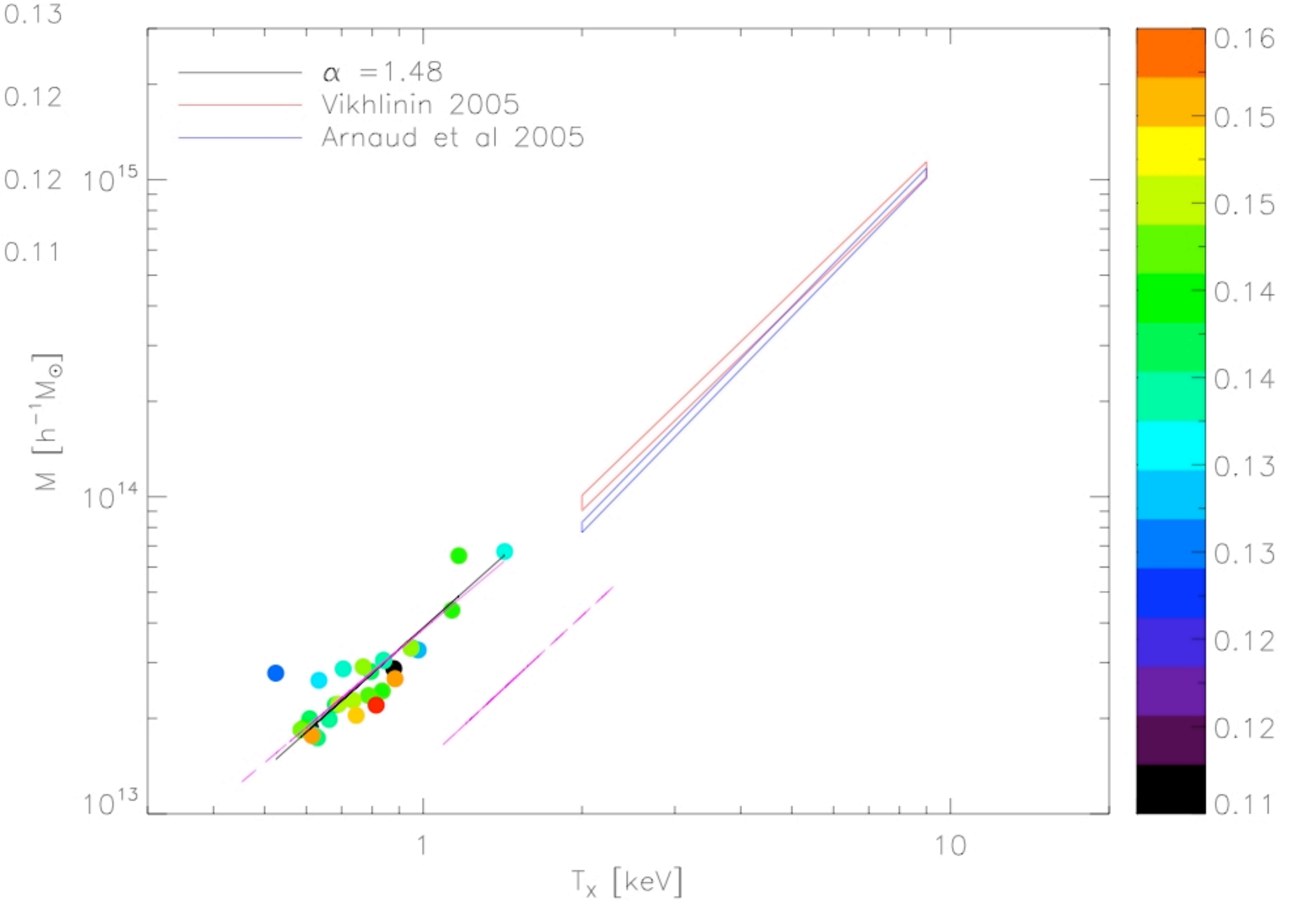
(i) Energy would be used up in full simulation since gas density higher

(ii) Reduce number of particles heated in overdense regions so as not to use more energy than available

Preliminary Results

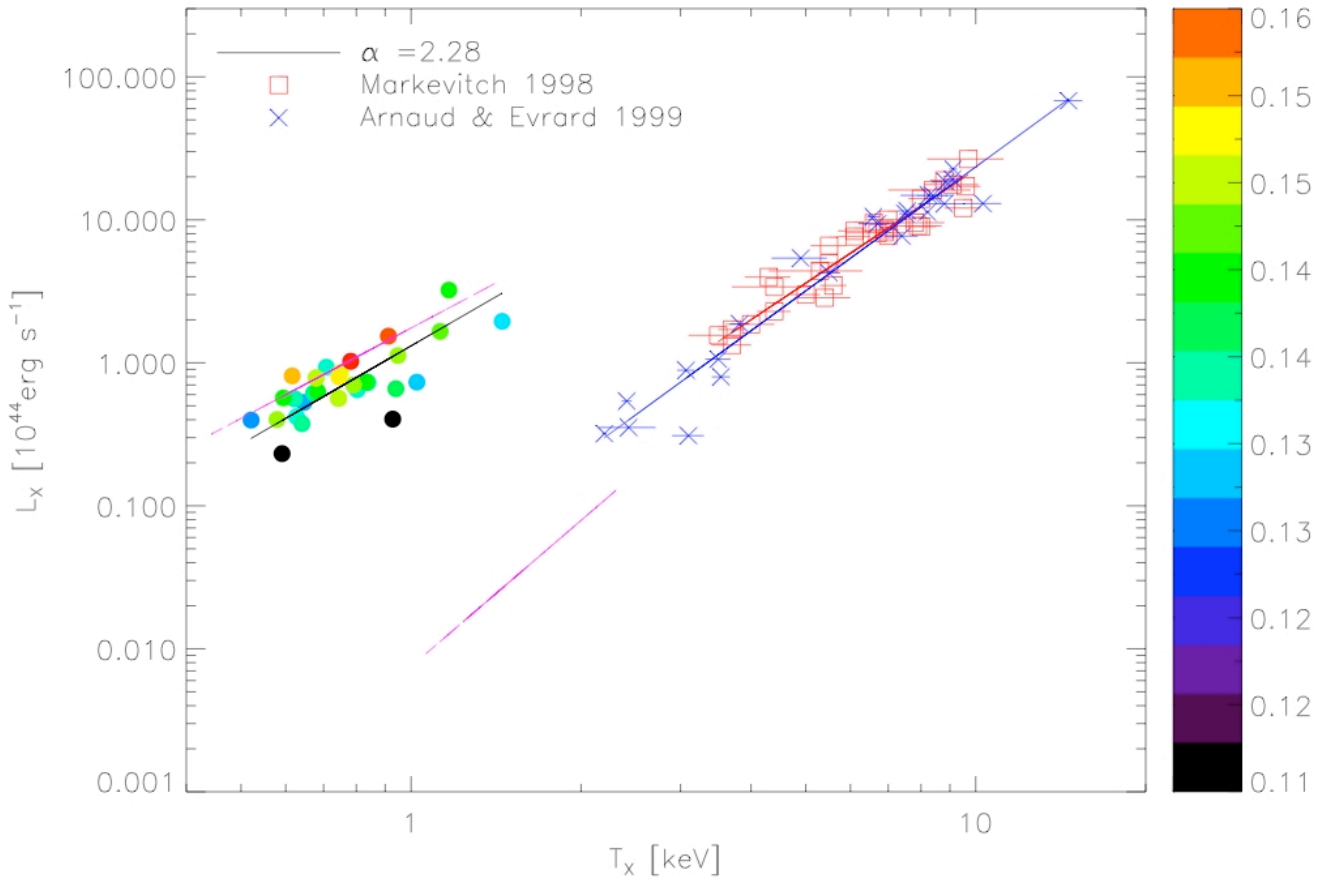


- MilliMillennium size simulation: $L = 62.5\mathrm{h}^{-1}\mathrm{Mpc}, N_{dm} = N_{gas} = 10^6$
- Results are shown for virial temperature model



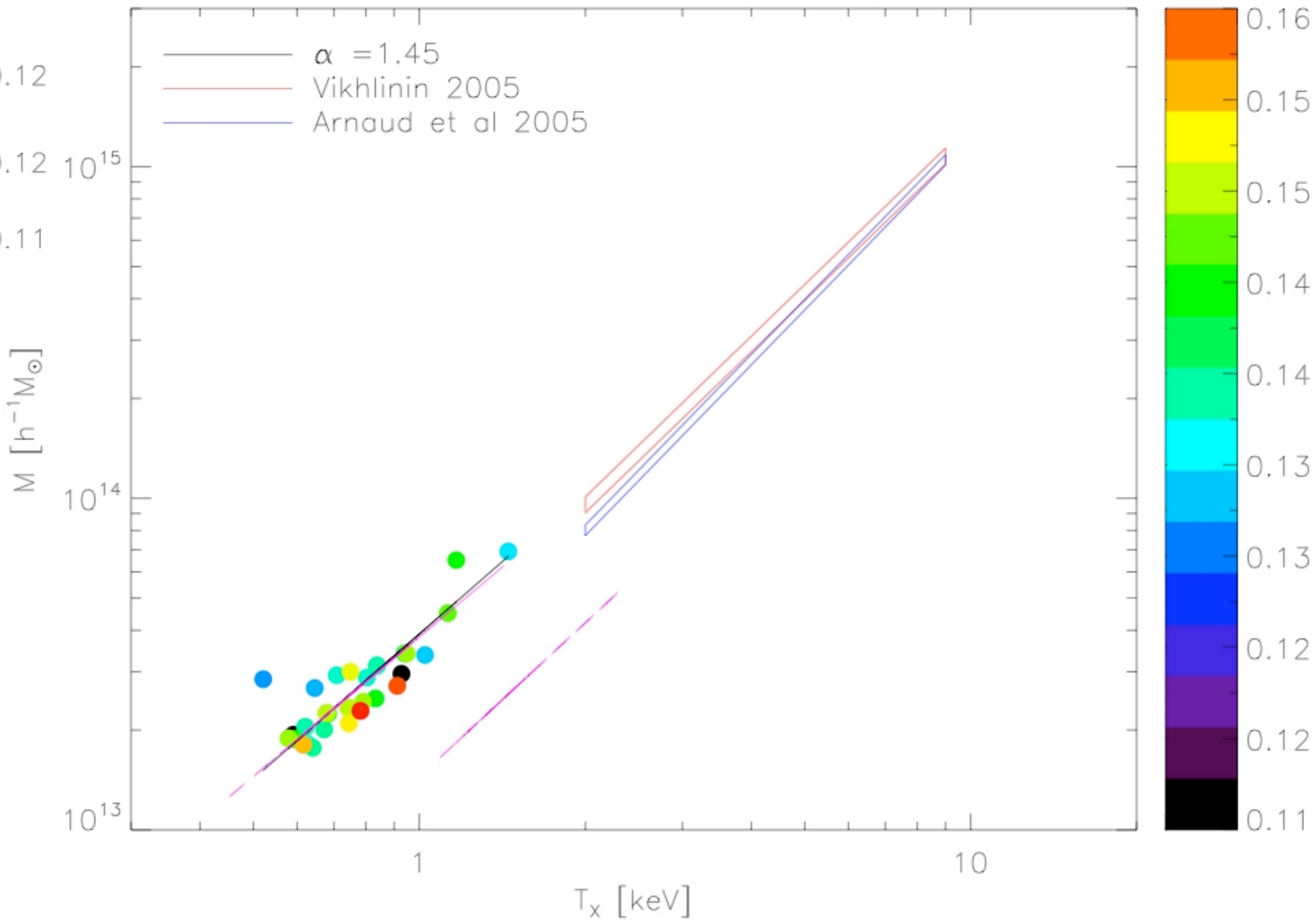
- All cluster properties calculated at R_{500}
- Star formation only

Preliminary Results

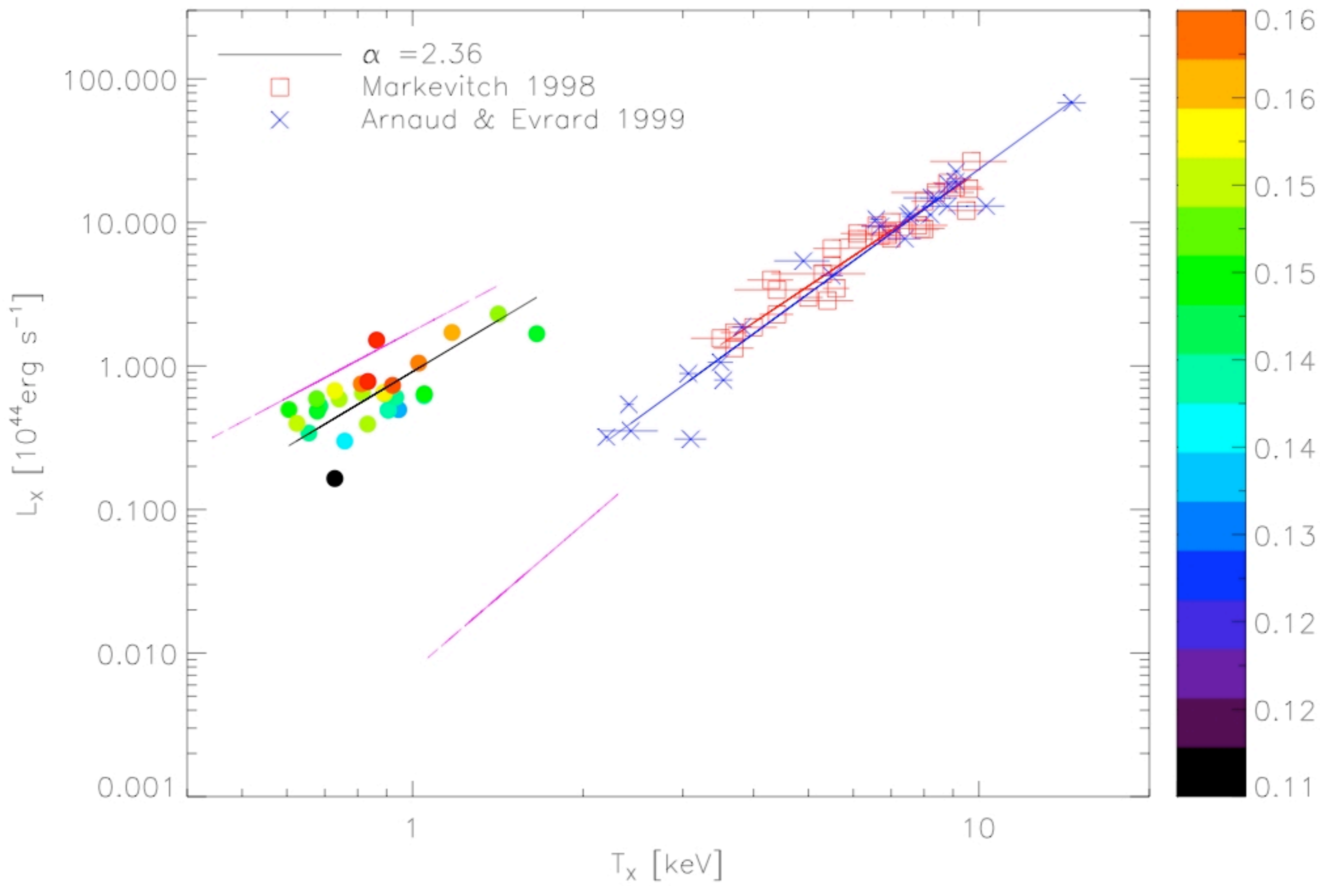


- Star formation and supernova feedback

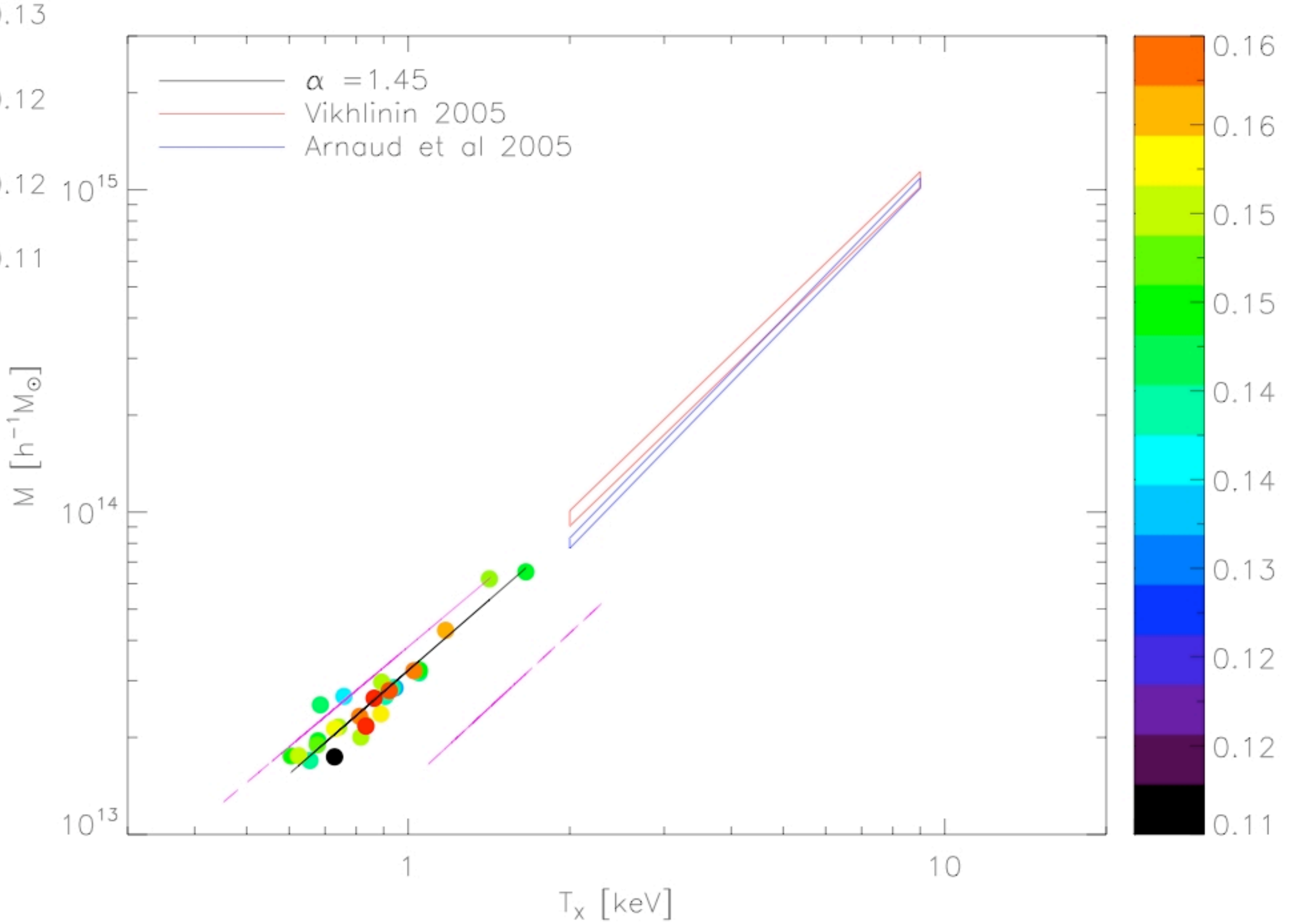
- Supernova feedback has a negligible effect on scaling relations!



Preliminary Results

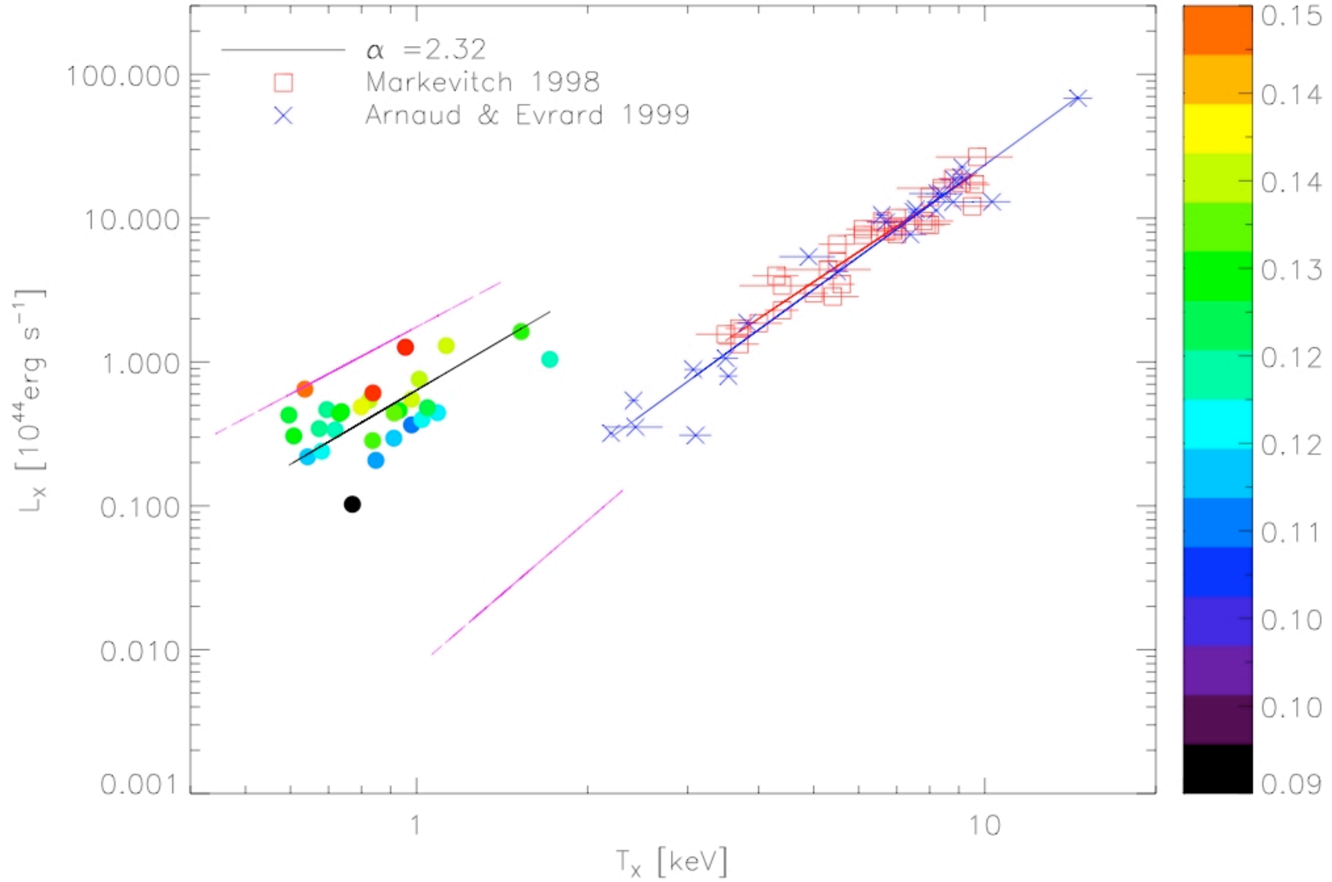


- AGN feedback only
- $\varepsilon_f = 0.05$

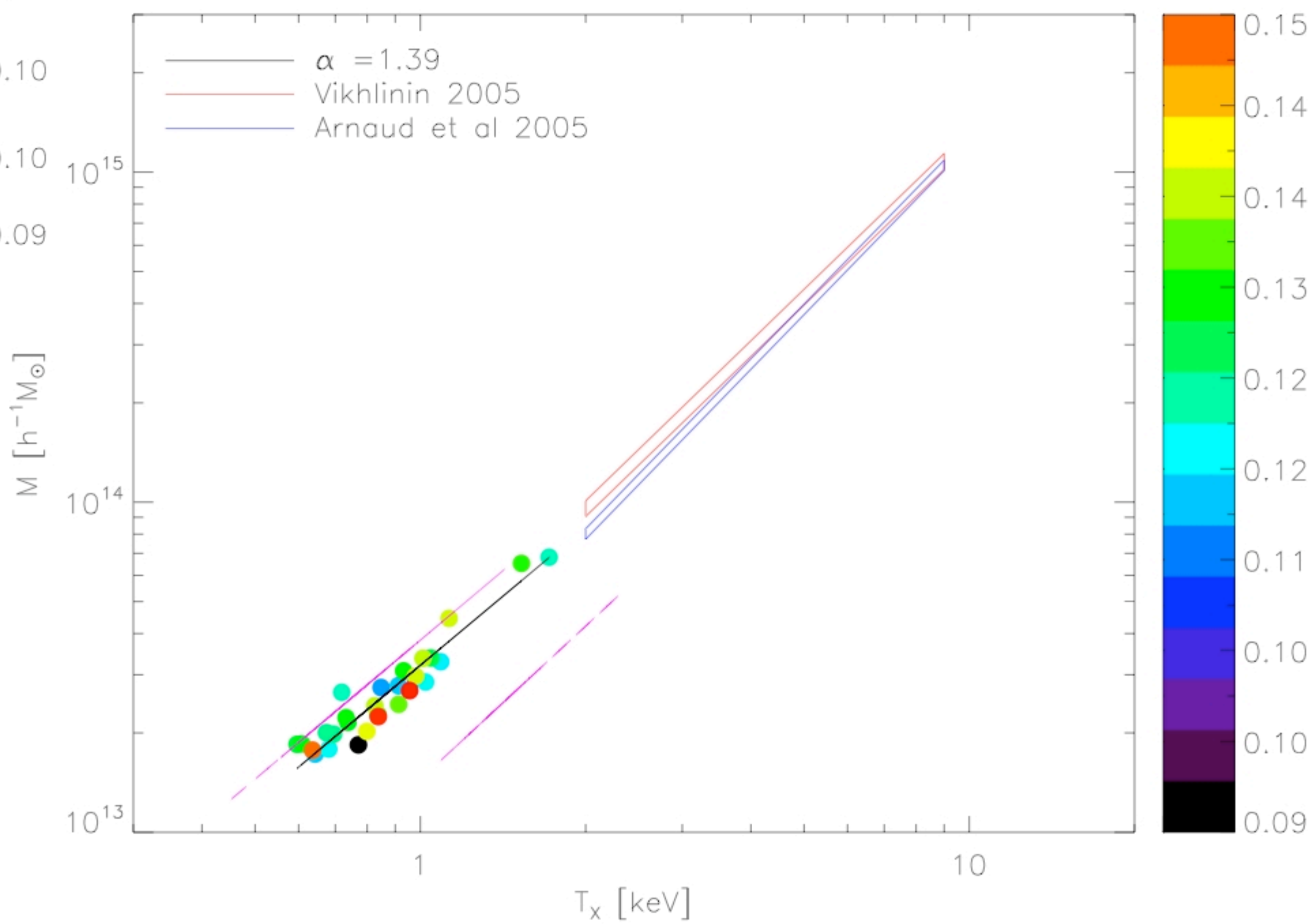


- Quasar mode feedback from AGN has the biggest impact on scaling relations

Preliminary Results

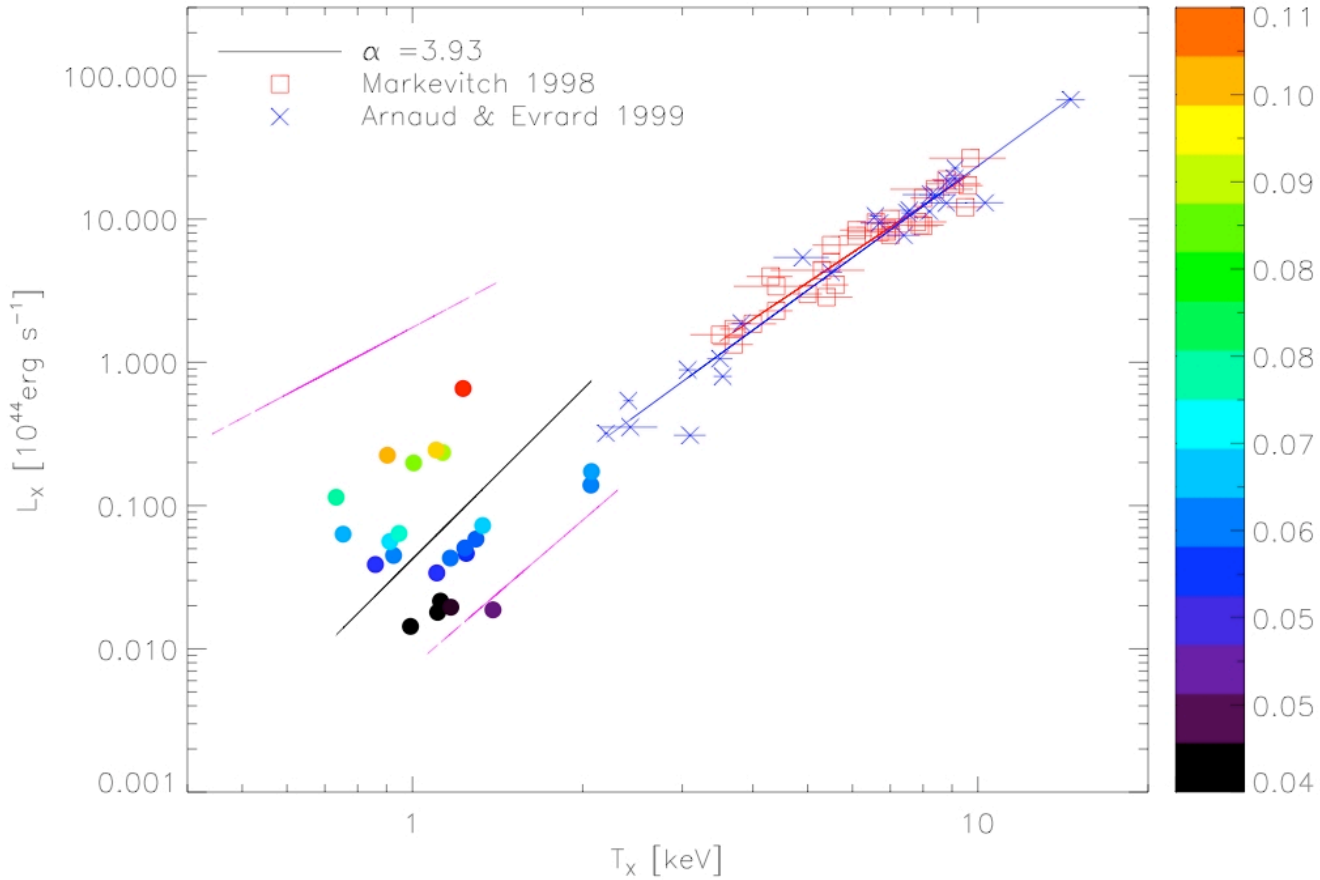


- Star formation plus supernova and AGN feedback
- $\varepsilon_f = 0.05$

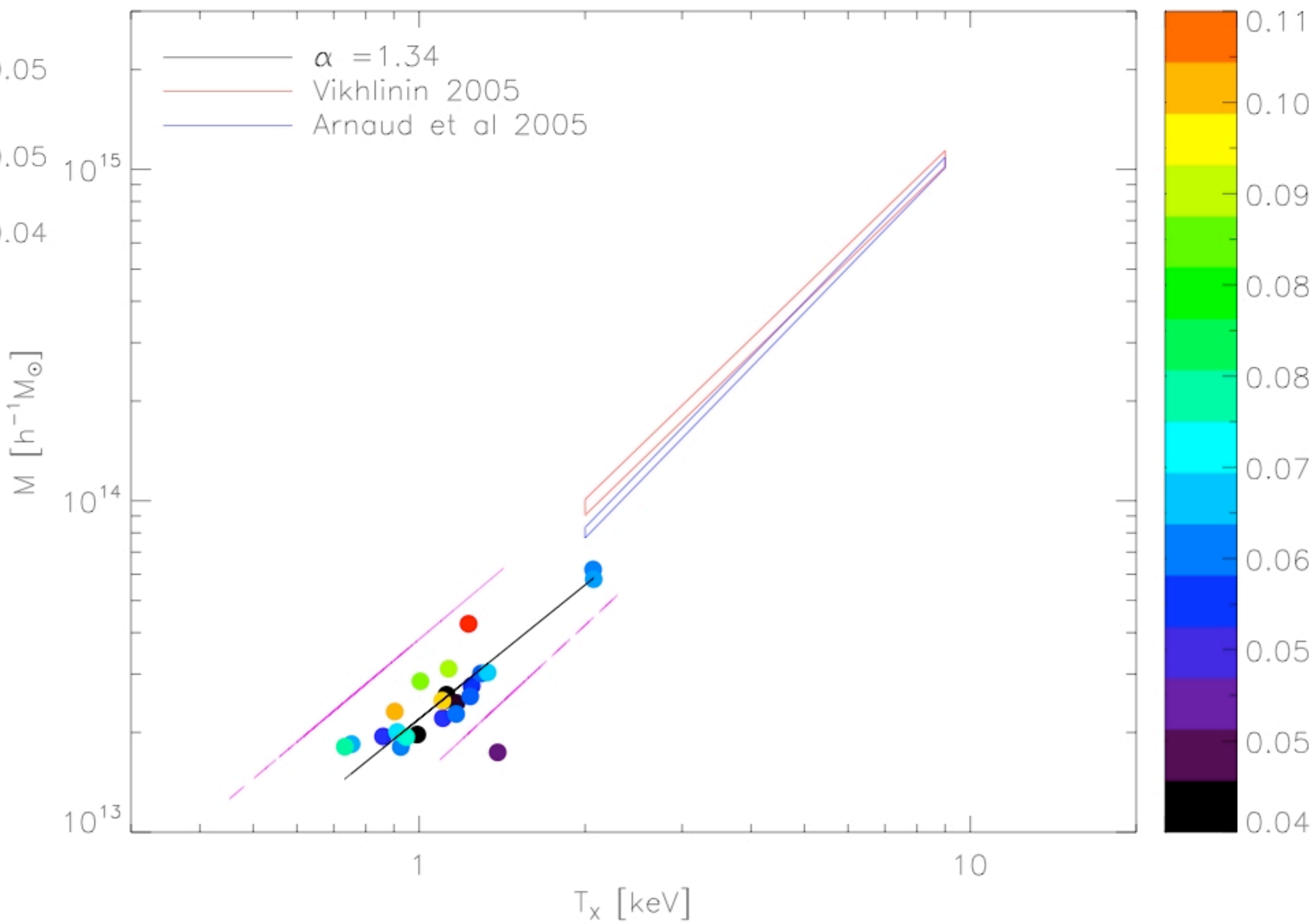


- Still need to drop about an order of magnitude in L_X

Preliminary Results



- Star formation plus supernova and AGN feedback
- $\varepsilon_f = 0.4$



- Can be viewed as a crude attempt at including radio mode feedback

What is Wrong?

- Issues:

  (i) Why do our L_X-T_X scaling relations disagree with observational data so much?

  (ii) Why does supernova feedback have so little effect?

- Several possibilites:

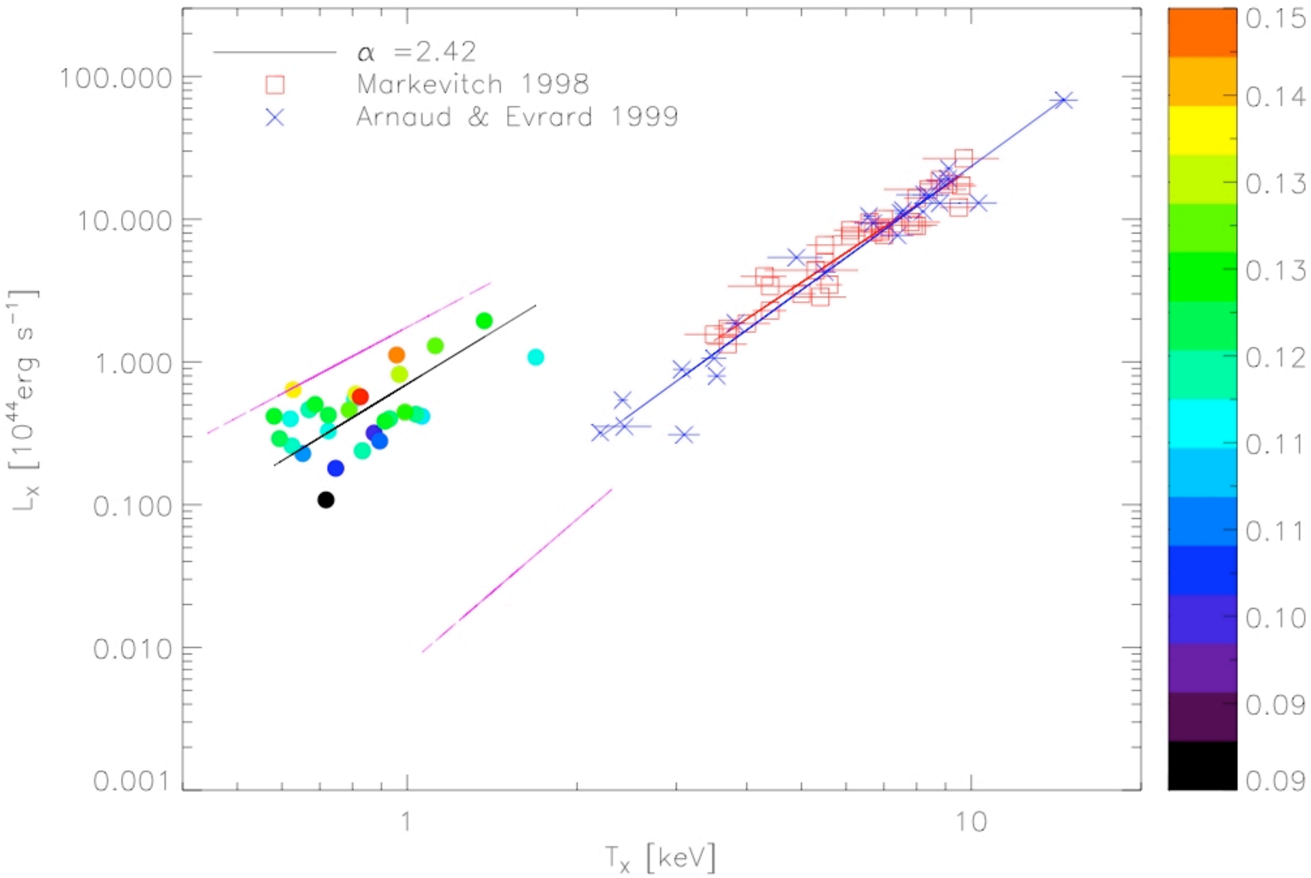
  (i) Feedback energy could be injected at the wrong locations because we are using a lower resolution simulation

  (ii) Our simple physically-motivated heating models do not work

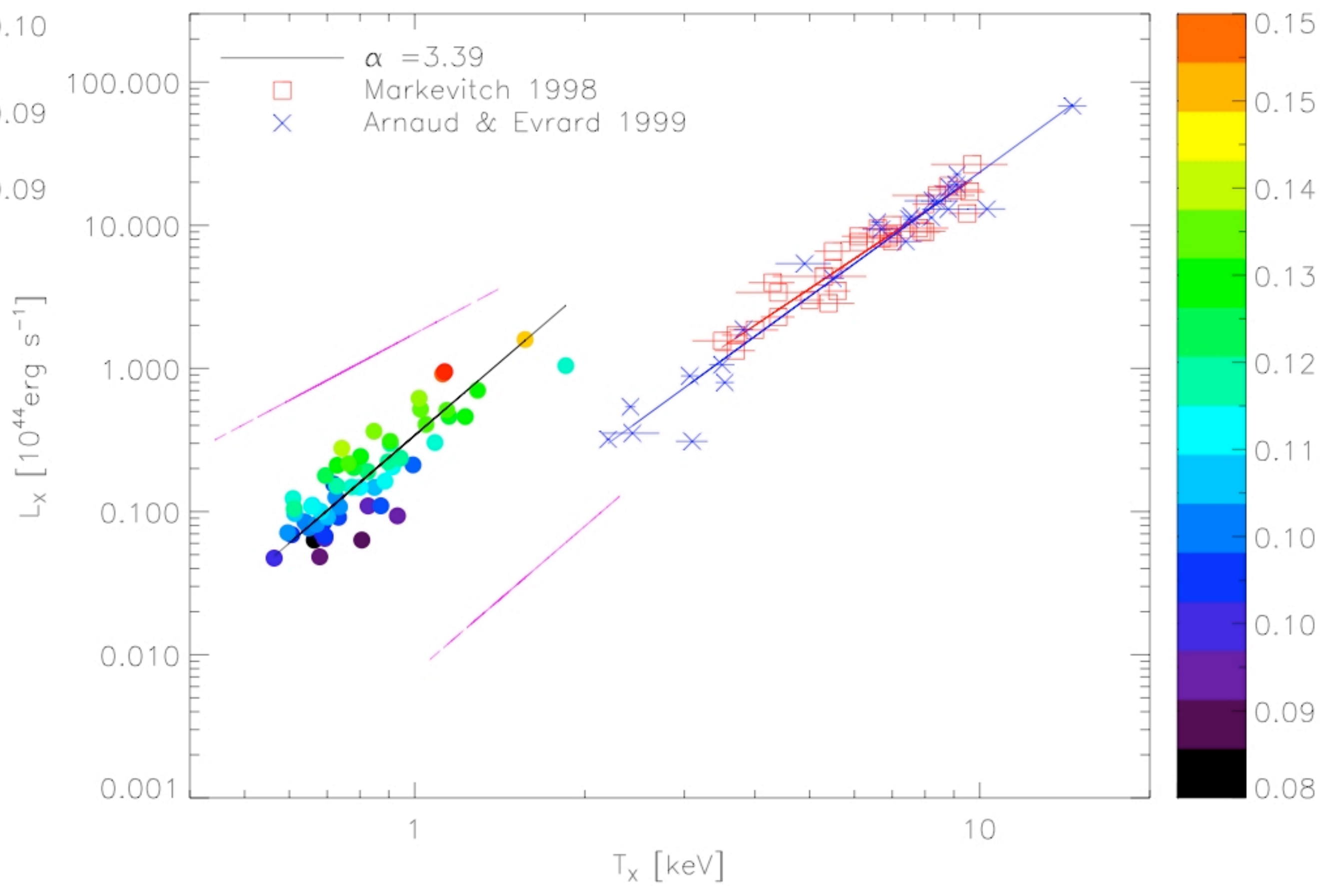
  (iii) SAMs do not release enough energy into the IGM/ICM

  (iv) No radio mode feedback - important at low redshift in central regions of clusters

Resolution Issues Revisited



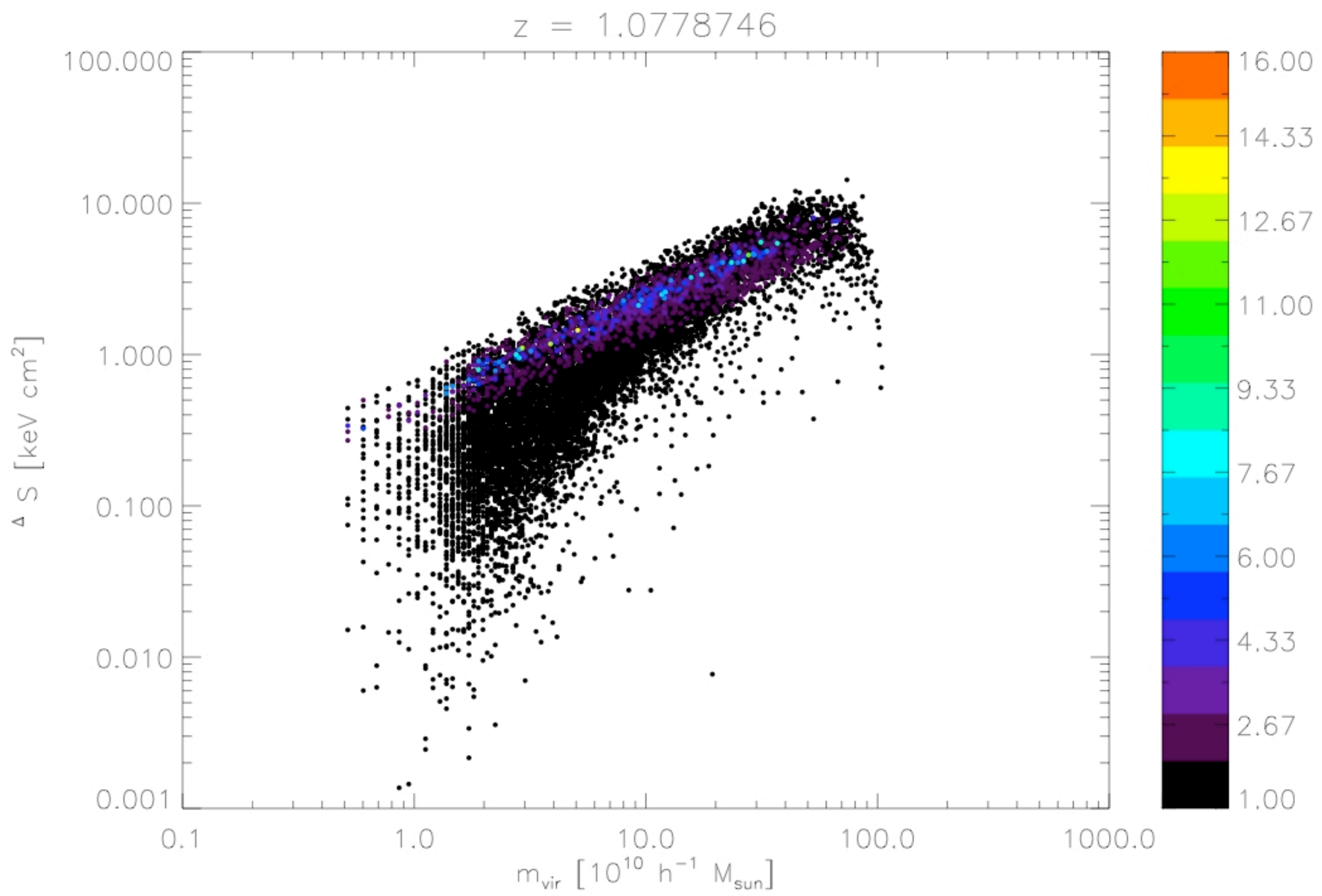
- Star formation plus supernova and AGN feedback
- $\varepsilon_f = 0.05$



- Repeated with **both** dark matter and gas at the higher resolution of the Millennium simulation
- Significant effect!

Heating Model Problems

- In our virial temperature model, large ΔE_{feed} leads to the heating of many neighbours over unphysical distances
- **'Strong'** feedback model of Kay *et al* 2004 raises the entropy of a particle by $\Delta S = 1000\mathrm{keV\ cm}^2$
- Heats particles to **very** high temperatures in dense regions
- Maybe necessary to obtain correct scaling relations
- Empirical model!



Supernova Energetics

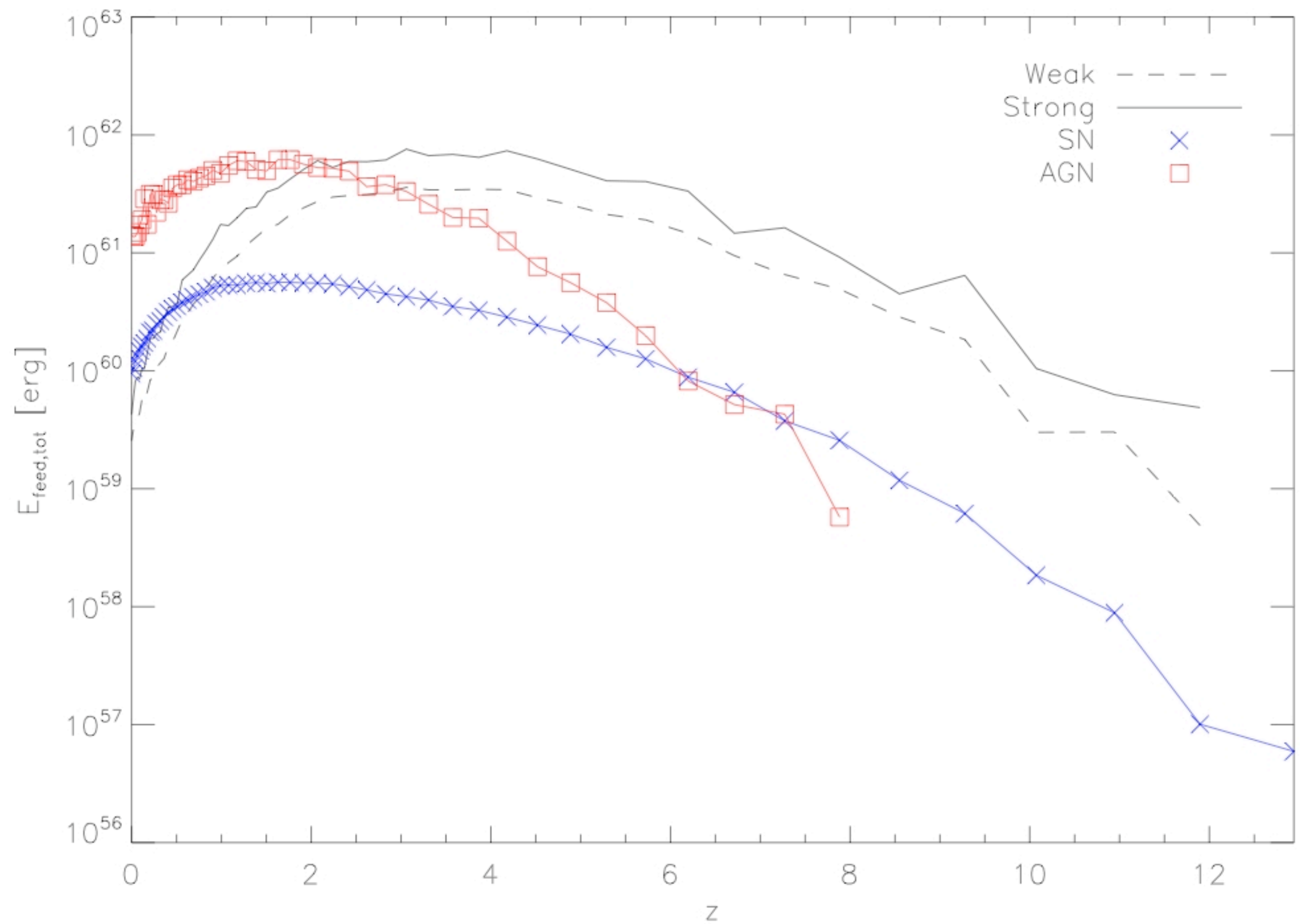
- In L-Galaxies, the energy of ejecta per solar mass of stars formed is

$$\Delta E_{ejected} \approx 10^{43} \left[\varepsilon_{halo} \left(\frac{v_{SN}}{\mathrm{km\ s^{-1}}} \right)^2 - \varepsilon_{disc} \left(\frac{v_{vir}}{\mathrm{km\ s^{-1}}} \right)^2 \right] \left(\frac{\Delta m_*}{M_\odot} \right) \mathrm{erg}$$

- In the strong feedback model of Kay *et al* 2004, the amount of energy released by type 2 supernovae per solar mass of stars formed is

$$\Delta E_{SN} \approx 5 \times 10^{48} \left(\frac{\Delta m_*}{M_\odot} \right) \mathrm{erg}$$

- Between 4 and 740 times greater!



Conclusion and Future Work

- Clearly some way to go before we can recover correct cluster scaling relations
- Short-term goal:

  (i) Implement heating model where particles are given a fixed entropy boost
- Long-term goals:

  (i) Allow for radio mode feedback from AGN

  (ii) Include feedback from type Ia supernovae and AGB stars

  (iii) Incorporate metal enrichment of ICM (c.f. Cora *et al* 2008)

  (iv) Repeat using GalForm to explore the different predictions for the ICM made by the two SAMs

  (v) Perform simulations with a larger dynamic range