# *The many lives of AGN:* black hole growth and the colors of galaxies


*Croton et al., 2006*

# The Problem

## Success of Λ-CDM

- CMB
LSS
BBN elements
Accelerating expansion

## Difficulties of Λ-CDM

- Hierarchical merging of DM halos for structure growth (White & Rees 1978)

↓

- Over predicts high and low luminosity galaxies
- Under predicts MW-size galaxies

**Cooling inefficiencies?**
**Nope.**

Optical (Hubble)

# The Solution

"we argue that radio sources may provide the required feedback, while at the same time solving two other longstanding puzzles"

**cooling flow problem**

**massive ellipticals have the oldest stars**

Optical (Hubble)

# cooling flow puzzle

→ Gas in clusters SHOULD be cooling extremely rapidly

→ observations show that the gas is NOT condensing into stars

$t_{cool} \sim 1$ Gyr

**key insight:**

every cluster with a strong cooling flow also contains a massive and active central radio galaxy (Burns, Gregory & Holman 1981)

Optical (Hubble)

# massive elliptical puzzle

## lookback studies:

SFR and AGN activity peak around z ~ 2 in highest mass systems, leading to more growth EARLY

## hierarchical merging:

massive dark haloes assemble at lower redshift than lower mass haloes, central galaxies growing through accretion and cooling flow

## key insight:

Radio galaxies prevent accretion, limiting the mass growth from star formation. Mergers change mass and morphology.

Optical (Hubble)

# how do we proceed?

full simulations of diffuse gas + DM with AGN feedback

Simulate DM distribution once (expensive) (1)

+

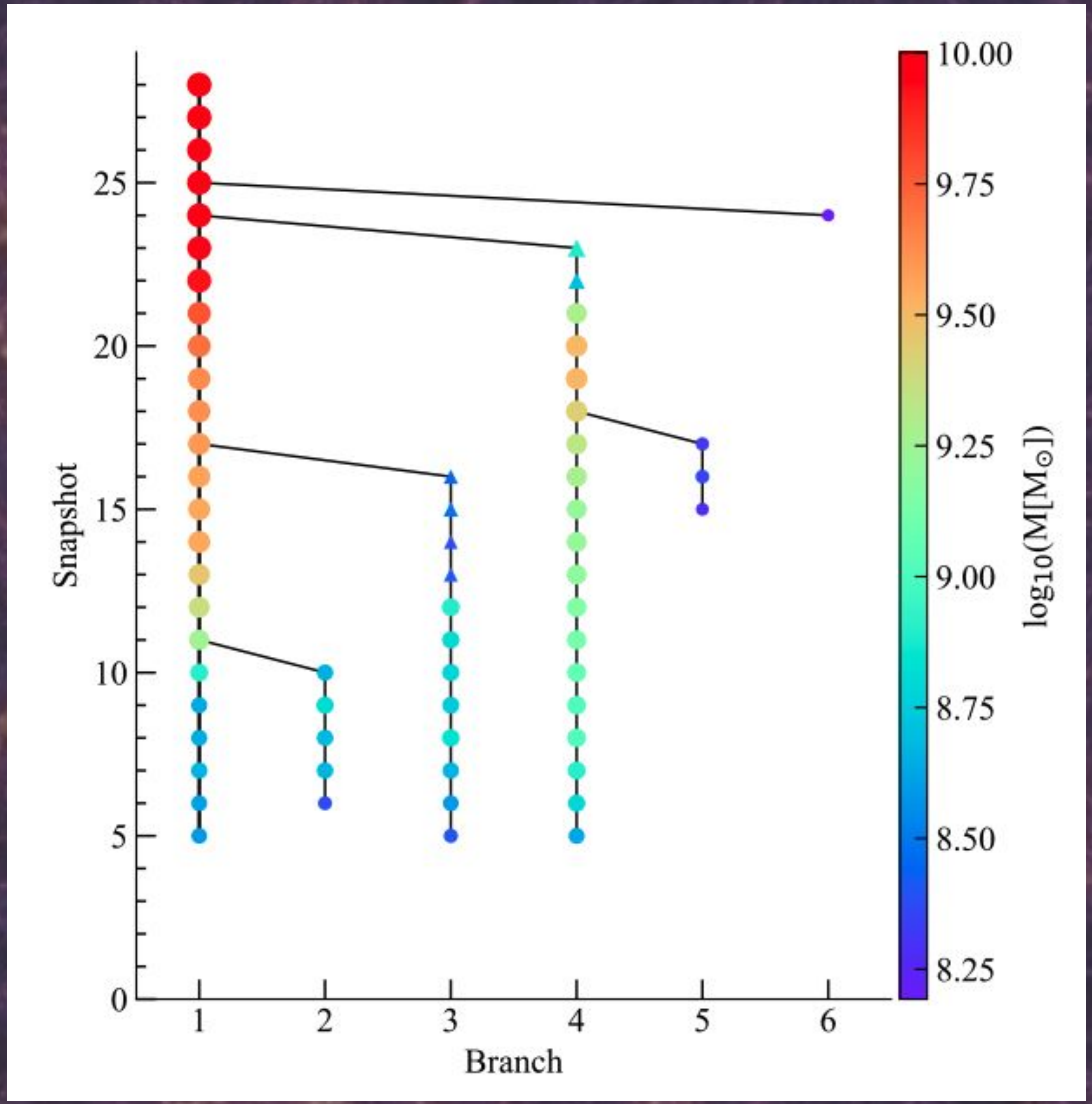
Apply semi-analytic recipes for baryons at each time step (cheap) [Kauffman+1999] (2)

Optical (Hubble)

# (1) The Dark Matter Skeleton: The Millenium Run

Springel+2005b

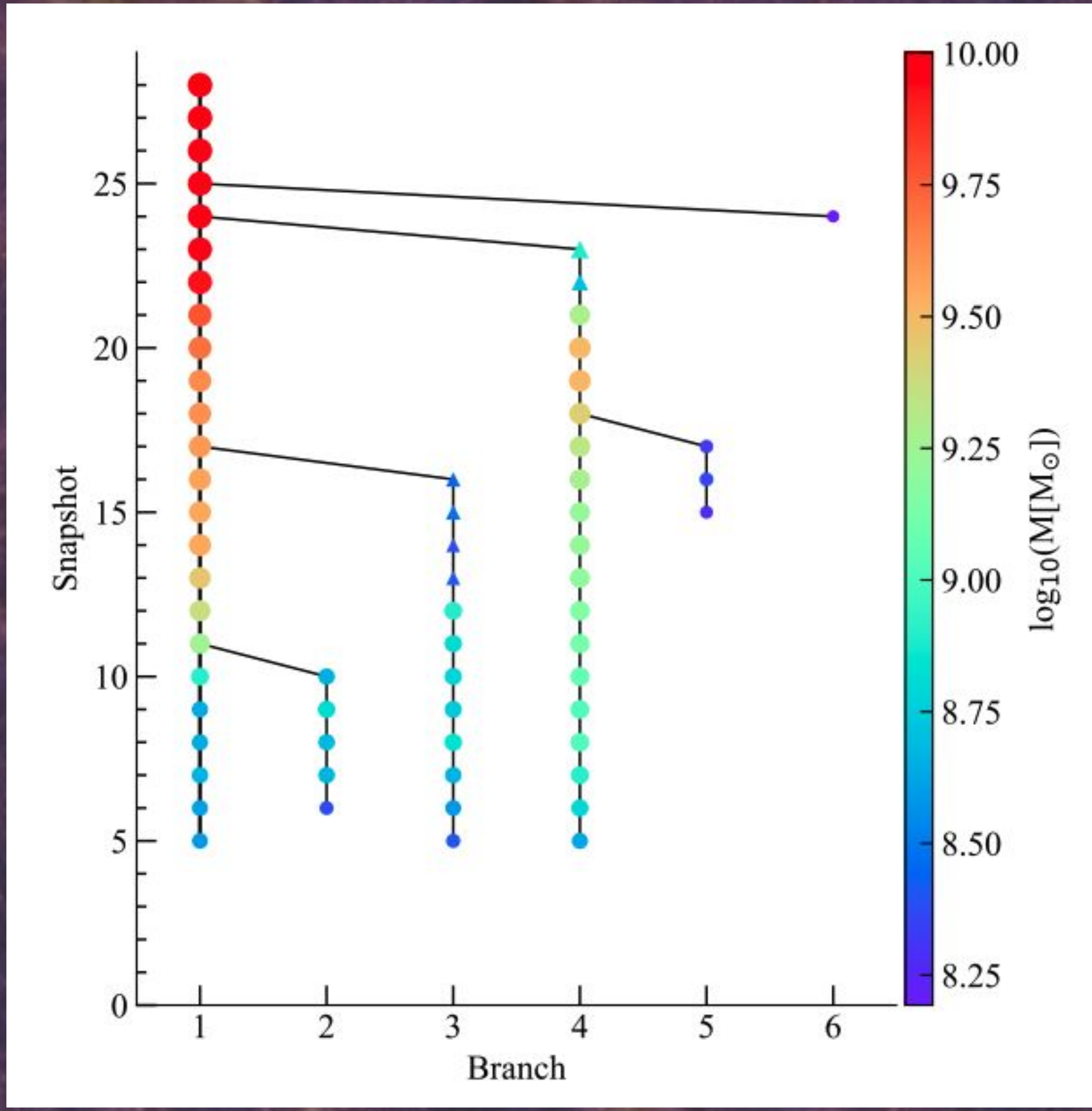
- very large dark matter simulation in ΛCDM cosmology
- $10^{10}$ particles of mass ~ $10^9\ M_{sun}$
- periodic box 2 billion light years on each side
- 64 snapshots from z ~ 127 to identify DM haloes and subhaloes




Example Merger Tree for a galaxy at z = 0

*see Massimo's TNG100 Presentation

# (1) The Dark Matter Skeleton: The Millenium Run




Example Merger Tree for a galaxy at z = 0

applying physical models with semi-analytic recipes (and exploring parameter space) tree-for-tree is computationally cheap

*see Massimo's TNG100 Presentation

# (2) Semi-Analytic Models

**gas infall and cooling:**
(White & Frenk 1991;
De Lucia, Kauffmann & White 2004)

**reionization:**
(Kravtsov, Gnedin & Klypin 2004)

**star formation:**
(Kauffman+1996)

**spectroscopic evolution & dust:**
(Bruzual & Charlot 2003, De Lucia+2004)

**SN feedback:**
(Springel+2001a, De Lucia+2004)

**morphology, mergers, and starbursts**
(Mo+1996, Sommerville+2001)

**metal enrichment:**
(De Lucia+2004)

**black hole growth, AGN outflows, and cooling:**
(this paper, Croton+2006)

***"most...follows earlier work, … but we introduce a 'radio' feedback mode, based on simple physical models"***

Optical (Hubble)

# (2) Semi-Analytic Models

***"Our parameters have been chosen to reproduce local galaxy properties"***

- luminosity-color distribution
- stellar mass-stellar age relation
- color-magnitude relation of ellipticals
- bulge mass-black hole relation
- cosmic star formation history

*"plausible changes in one parameter or recipe can usually be accommodated through adjustment of the remaining parameters within their own plausible range."*

***"The particular model that we present is thus not unique."***

Optical (Hubble)

# (2) Semi-Analytic Model Parameter Table (skip)

**Table 1.** A summary of our main model parameters and their best values and plausible ranges, as described in the text. Once set, these values are kept fixed for all results presented in this paper, in particular for models in which AGN feedback is switched off.

| Parameter | Description | Best value | Plausible range |
|---|---|---|---|
| $f_{\mathrm{b}}$ | Cosmic baryon fraction (Section 3.3) | 0.17 | fixed |
| $z_0$, $z_{\mathrm{r}}$ | Redshift of reionization (Section 3.3) | 8, 7 | fixed |
| $f_{\mathrm{BH}}$ | Merger cold gas BH accretion fraction (Section 3.4.1) | 0.03 | 002–004 |
| $\kappa_{\mathrm{AGN}}$ | Quiescent hot gas BH accretion rate ($\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$) (Section 3.4.2) | $6 \times 10^{-6}$ | $(4–8) \times 10^{-6}$ |
| $\alpha_{\mathrm{SF}}$ | Star formation efficiency (Section 3.5) | 0.07 | 005–015 |
| $\epsilon_{\mathrm{disc}}$ | SN feedback disc reheating efficiency (Section 3.6) | 3.5 | 1–5 |
| $\epsilon_{\mathrm{halo}}$ | SN feedback halo ejection efficiency (Section 3.6) | 0.35 | 01–05 |
| $\gamma_{\mathrm{ej}}$ | Ejected gas reincorporation efficiency (Section 3.6) | 0.5 | 01–10 |
| $T_{\mathrm{merger}}$ | Major merger mass ratio threshold (Section 3.7) | 0.3 | 02–04 |
| $R$ | Instantaneous recycled fraction of SF to the cold disc (Section 3.9) | 0.3 | 02–04 |
| $Y$ | Yield of metals produced per unit SF (Section 3.9) | 0.03 | 002–004 |

# Gas Infall and Cooling

(White & Frenk 1991)

—> infalling gas shocks to virial temperature

two fates:

late times, massive systems:

$$\dot{m}_{\rm cool} = 0.5 m_{\rm hot} \frac{r_{\rm cool} V_{\rm vir}}{R_{\rm vir}^2}.$$

$r_{\rm cool} < R_{\rm vir}.$

hot atmosphere forms, accretion onto central object via cooling flow

"STATIC HOT HALO"

early times, less massive systems:

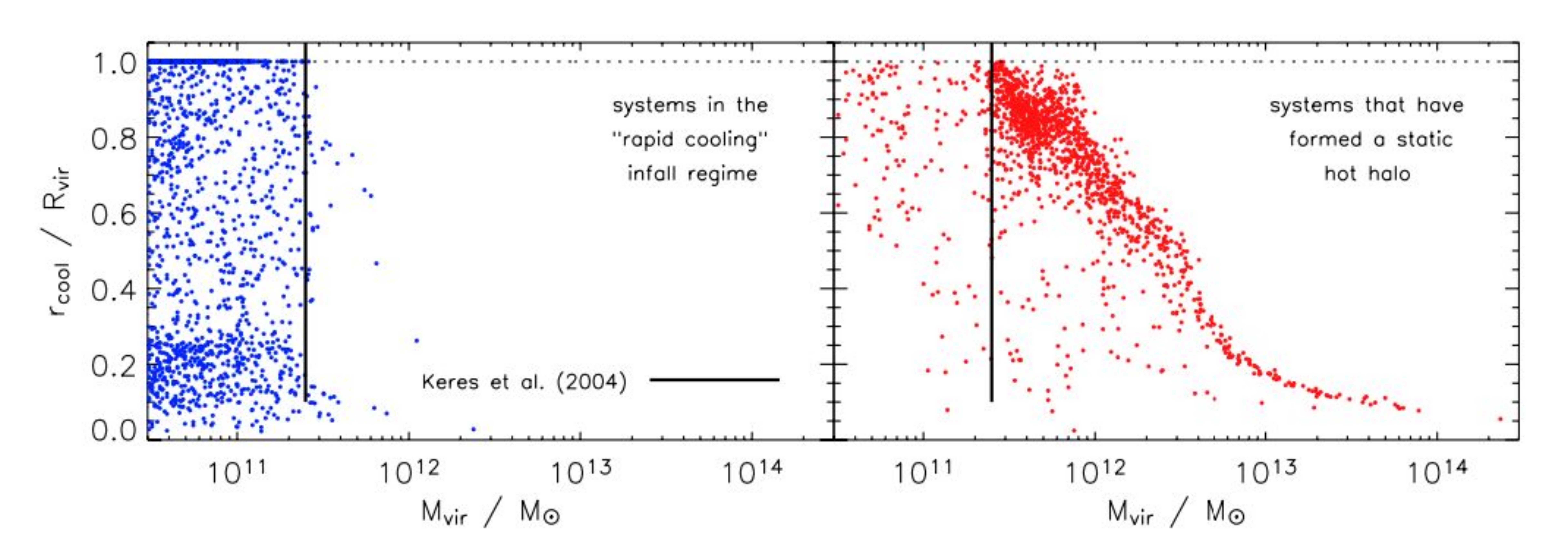
post-shock gas rapidly cools onto object

**"RAPID COOLING"**

Optical (Hubble)

# Gas Infall and Cooling

**semi-analytic model recovers Keres+2003 fully 3D simulations**



# Reionization of IGM

(Kravtsov, Gnedin & Klypin+2004)

**dwarf galaxies contain a small fraction of all condensed baryons**

define a "filtering mass," below which you reduce the baryon fraction:

$$f_{\rm b}^{\rm halo}(z, M_{\rm vir}) = \frac{f_{\rm b}^{\rm cosmic}}{[1 + 0.26 M_{\rm F}(z)/M_{\rm vir}]^3}.$$

$M_F \sim 4 \times 10^9\ M_{sun}$

(Gnedin+2000)

**photoionization of IGM affects gas content of haloes**

Optical (Hubble)

# Star Formation

(Kauffman+1996)

surface density + mass **threshold** for star formation

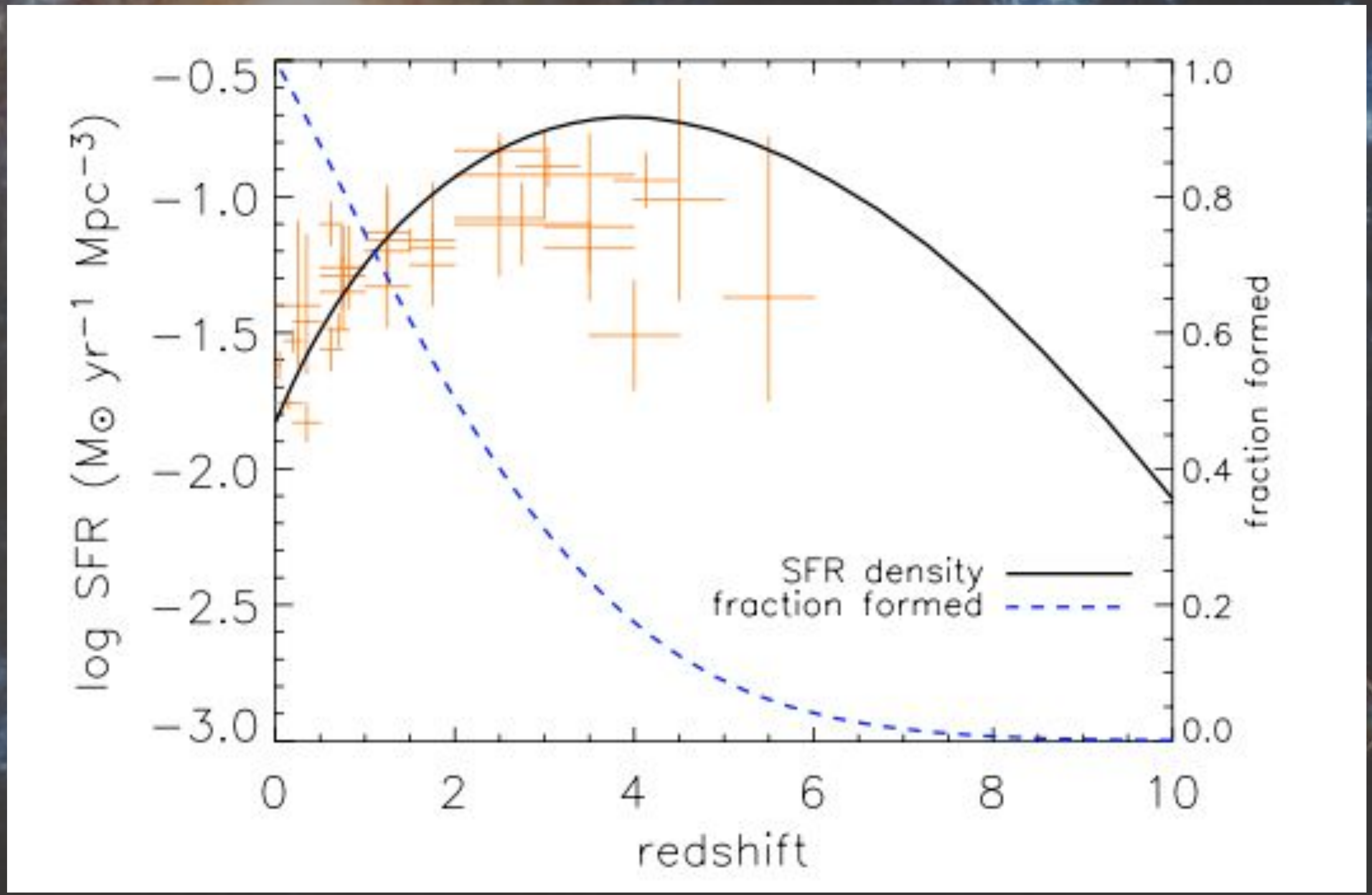
$$\Sigma_{\rm crit}(R) = 120\left(\frac{V_{\rm vir}}{200\ {\rm km\ s^{-1}}}\right)\left(\frac{R}{\rm kpc}\right)^{-1} {\rm M_\odot\ pc^{-2}}.$$

$$m_{\rm crit} = 3.8\times10^{9}\left(\frac{V_{\rm vir}}{200\ {\rm km\ s^{-1}}}\right)\left(\frac{r_{\rm disc}}{10\ {\rm kpc}}\right){\rm M_\odot},$$

↓

$$\dot{m}_* = \alpha_{\rm SF}(m_{\rm cold} - m_{\rm crit})/t_{\rm dyn,disc},$$

star formation rate leading to episodic star formation



# SN Feedback

(Springel+2001a, De Lucia + 2004)

$$\Delta m_{\text{ejected}} = \underbrace{\left( \epsilon_{\text{halo}} \frac{V_{\text{SN}}^2}{V_{\text{vir}}^2} - \epsilon_{\text{disc}} \right)}_{\text{efficiency term}} \Delta m_*$$

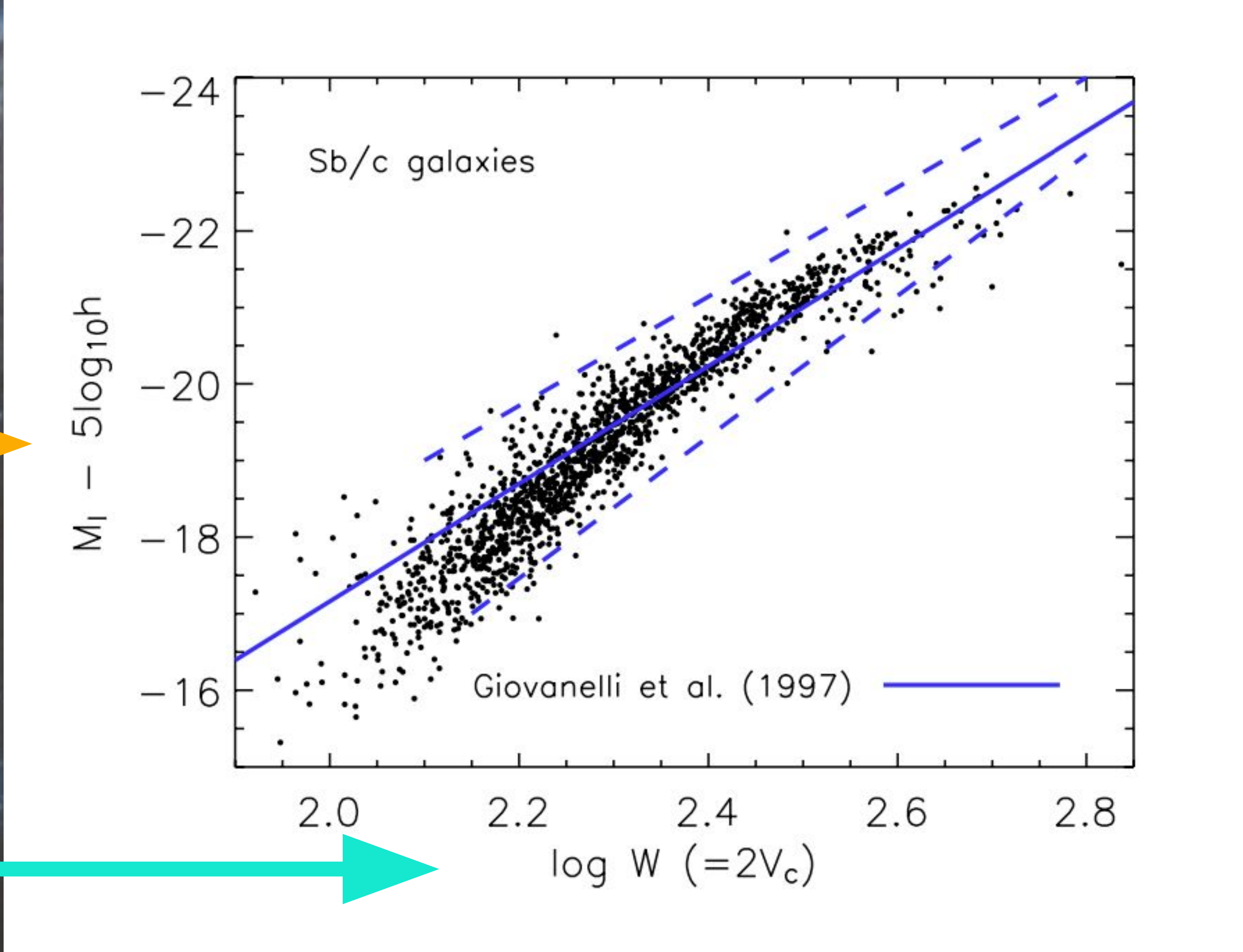
$$\dot{m}_{\text{ejected}} = -\gamma_{\text{ej}} m_{\text{ejected}} / t_{\text{dyn}},$$

**SN eject material into the hot halo (not necessarily permanently)**

**SN feedback + star formation models recover Tully-Fisher relation**

**related to SF**

**related to SN feedback**



# Morphology, Mergers, and Starbursts

(Sommerville+2001)

**morphology:**
assumed to be controlled by bulge-to-total luminosity ratio

$T_{merger} = 0.3$

**Minor Merger**

cold gas from satellite added to central bulge, along with stars from minor subsequent starburst

**Major Merger**

more significant starburst, discs destroyed to form spheroid

$$e_{\rm burst} = \beta_{\rm burst}(m_{\rm sat}/m_{\rm central})^{\alpha_{\rm burst}},$$

# Black Hole Growth, AGN Outflows, and Cooling Suppression

(this paper, Croton+2006)

two mechanisms for BH growth and accretion:

**radio mode suppresses cooling flows in massive systems**

## “quasar mode”

- rapid cooling -

$$\Delta m_{\mathrm{BH,Q}} = \frac{f'_{\mathrm{BH}} m_{\mathrm{cold}}}{1 + (280\ \mathrm{km\ s^{-1}}/V_{\mathrm{vir}})^2},$$

**mass accreted:**

- **proportion to total cold gas present**
- **less efficient in low mass systems and unequal mergers**

## “radio mode”

- static hot halo -

**mass accreted**

$$\dot{m}_{\mathrm{BH,R}} = \kappa_{\mathrm{AGN}} \left(\frac{m_{\mathrm{BH}}}{10^8\ \mathrm{M_{\odot}}}\right)\left(\frac{f_{\mathrm{hot}}}{0.1}\right)\left(\frac{V_{\mathrm{vir}}}{200\ \mathrm{km\ s^{-1}}}\right)^3,$$

**mechanical heating from black hole**

$$L_{\mathrm{BH}} = \eta \dot{m}_{\mathrm{BH}} c^2,$$

Optical (Hubble)

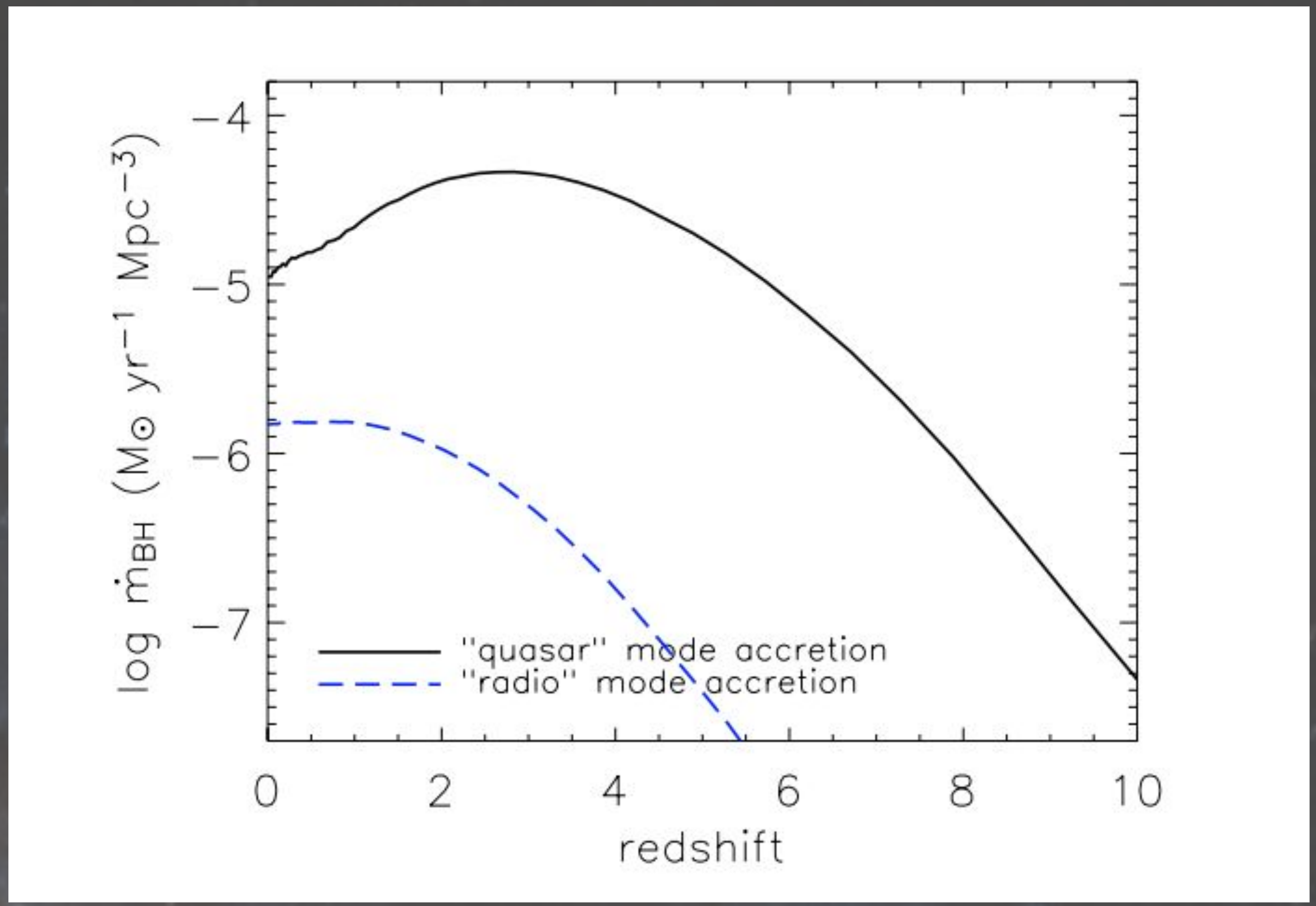
# Black Hole Growth, AGN Outflows, and Cooling Suppression

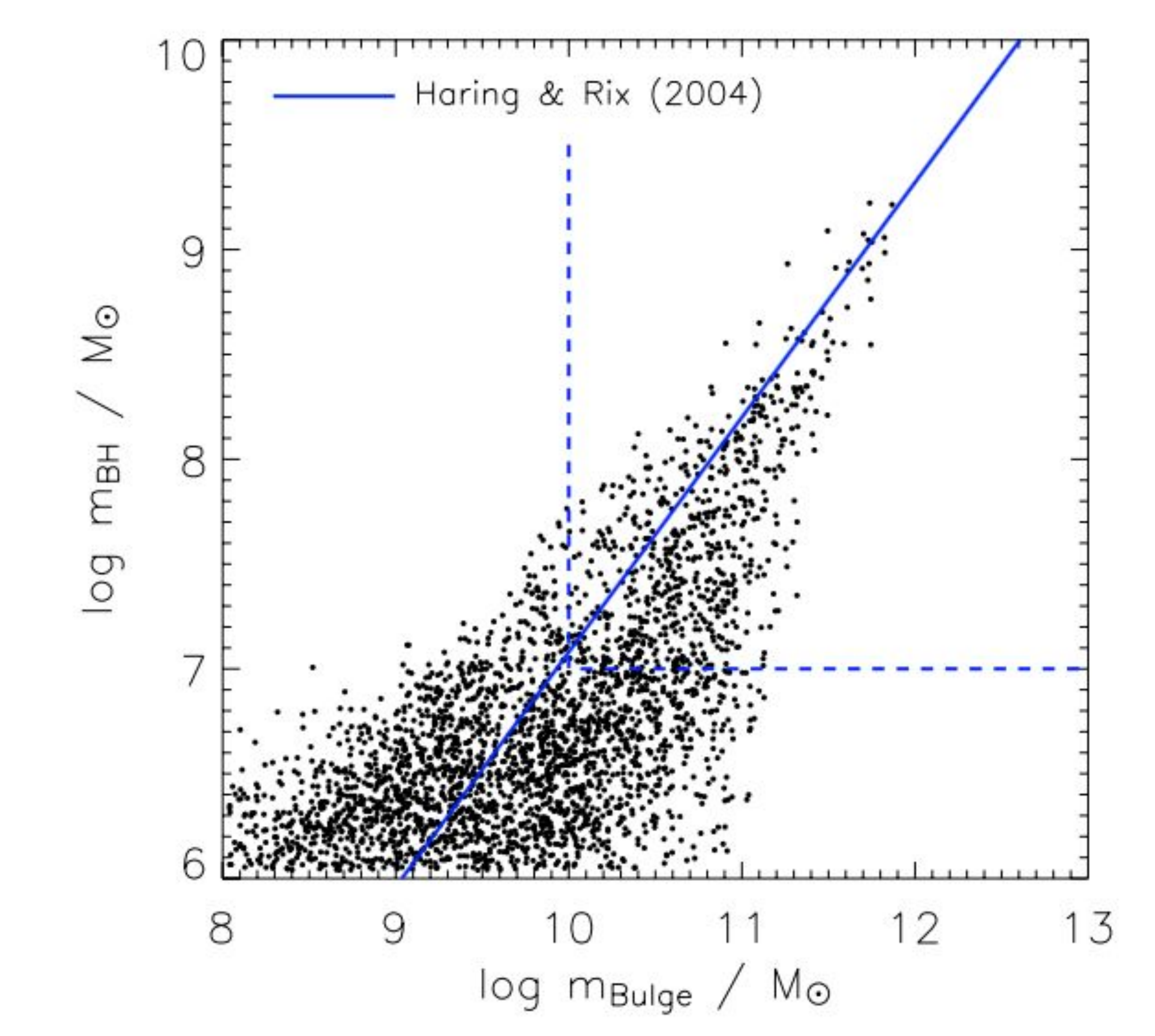
(this paper, Croton+2006)

black hole growth is dominated by mergers at early times

radio mode significant at late times

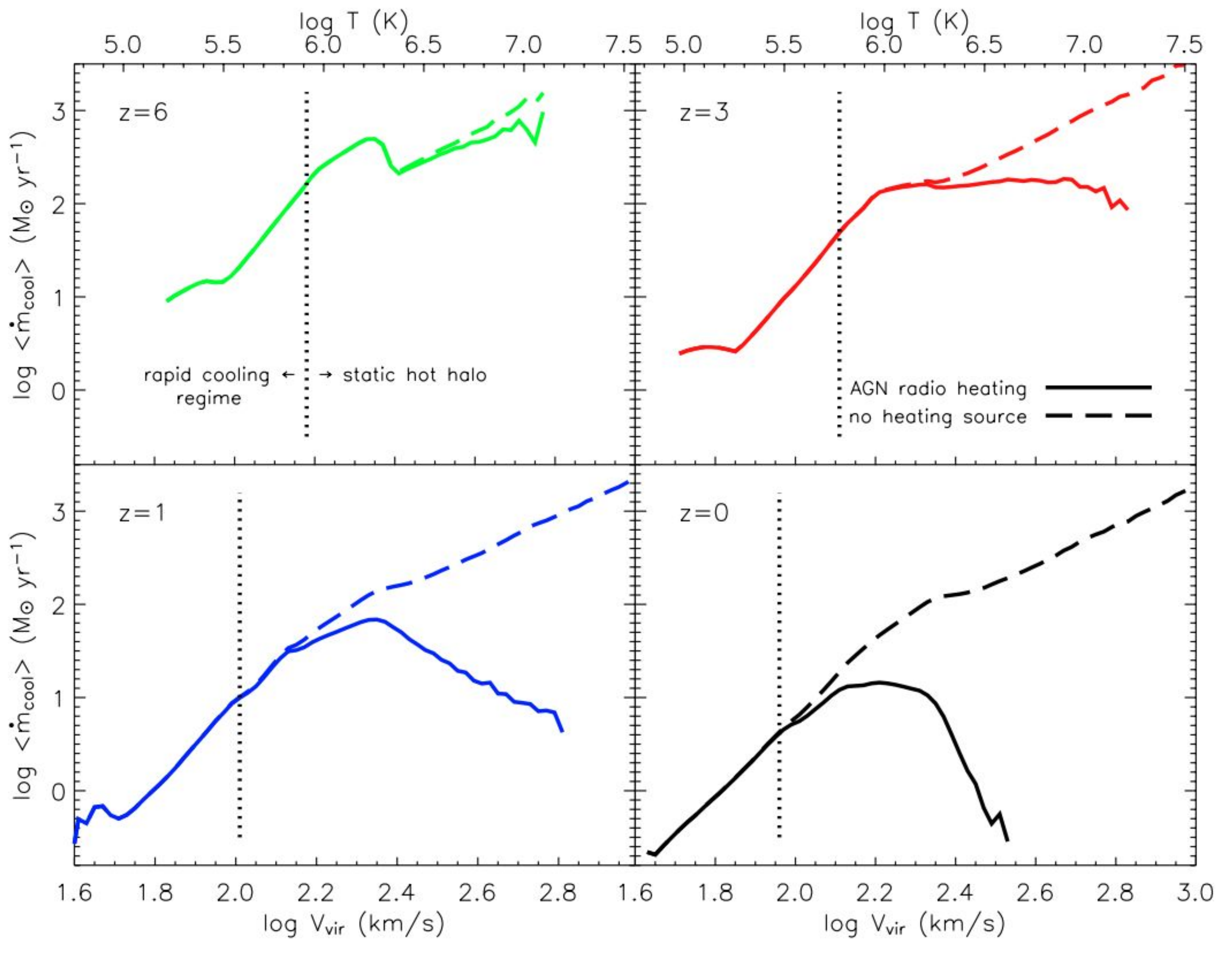
this feedback is strong enough to reproduce luminosities and colors of galaxies



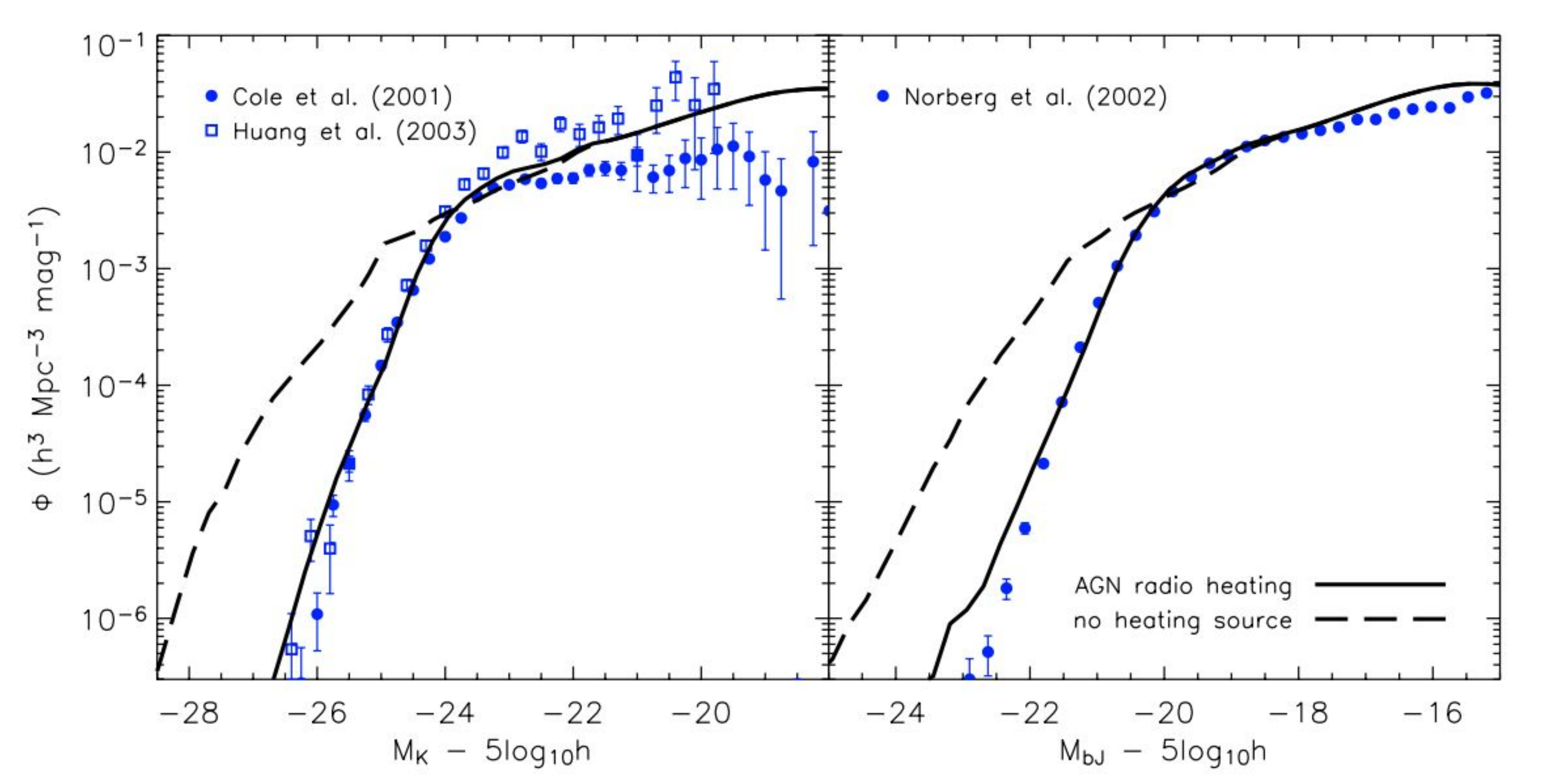
# Cooling Flow Suppression

**with radio mode, condensation rate is suppressed at present in massive ellipticals in clusters**



# Galaxy Properties with Suppressed Condensation

**radio mode reduces the luminosities of bright galaxies**



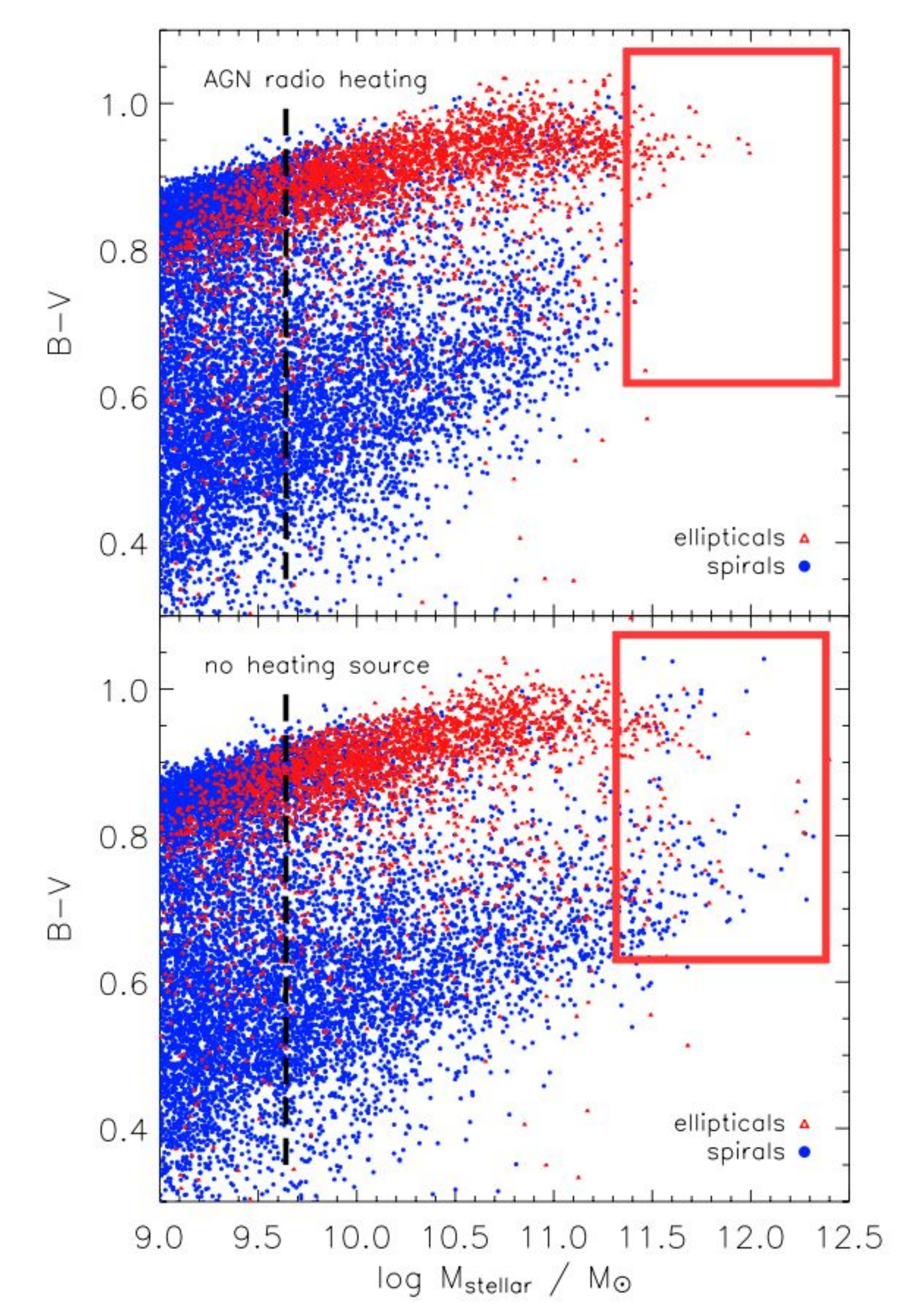
# Galaxy Properties with Suppressed Condensation

**with radio mode heating:**

- **most massive galaxies are red and elliptical**
- **growth through mergers, cooling halts star formation**

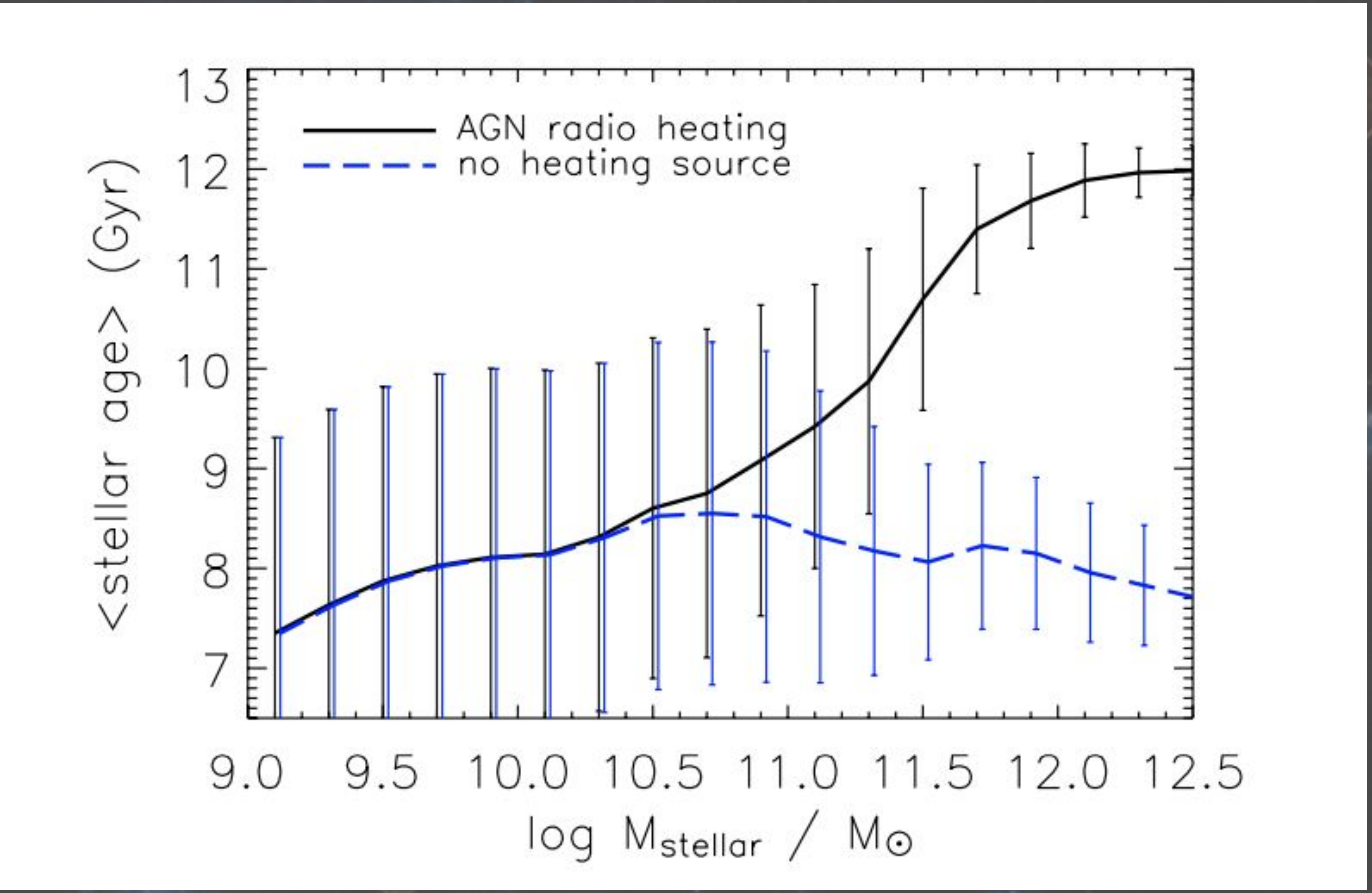
without radio mode:

- most massive galaxies are blue and have discs



# Galaxy Properties with Suppressed Condensation

**cooling flow suppression increases mean age of stars in high mass galaxies**




Optical (Hubble)

# What's really going on…

**from earlier:** a model for black hole accretion in systems with a static hot halo

$$\dot{m}_{\mathrm{BH,R}} = \kappa_{\mathrm{AGN}} \left( \frac{m_{\mathrm{BH}}}{10^8\ \mathrm{M}_\odot} \right) \left( \frac{f_{\mathrm{hot}}}{0.1} \right) \left( \frac{V_{\mathrm{vir}}}{200\ \mathrm{km\ s^{-1}}} \right)^3,$$

**what physical model can reproduce these scalings?**

**cold cloud accretion** (1)

**bondi accretion** (2)

Optical (Hubble)

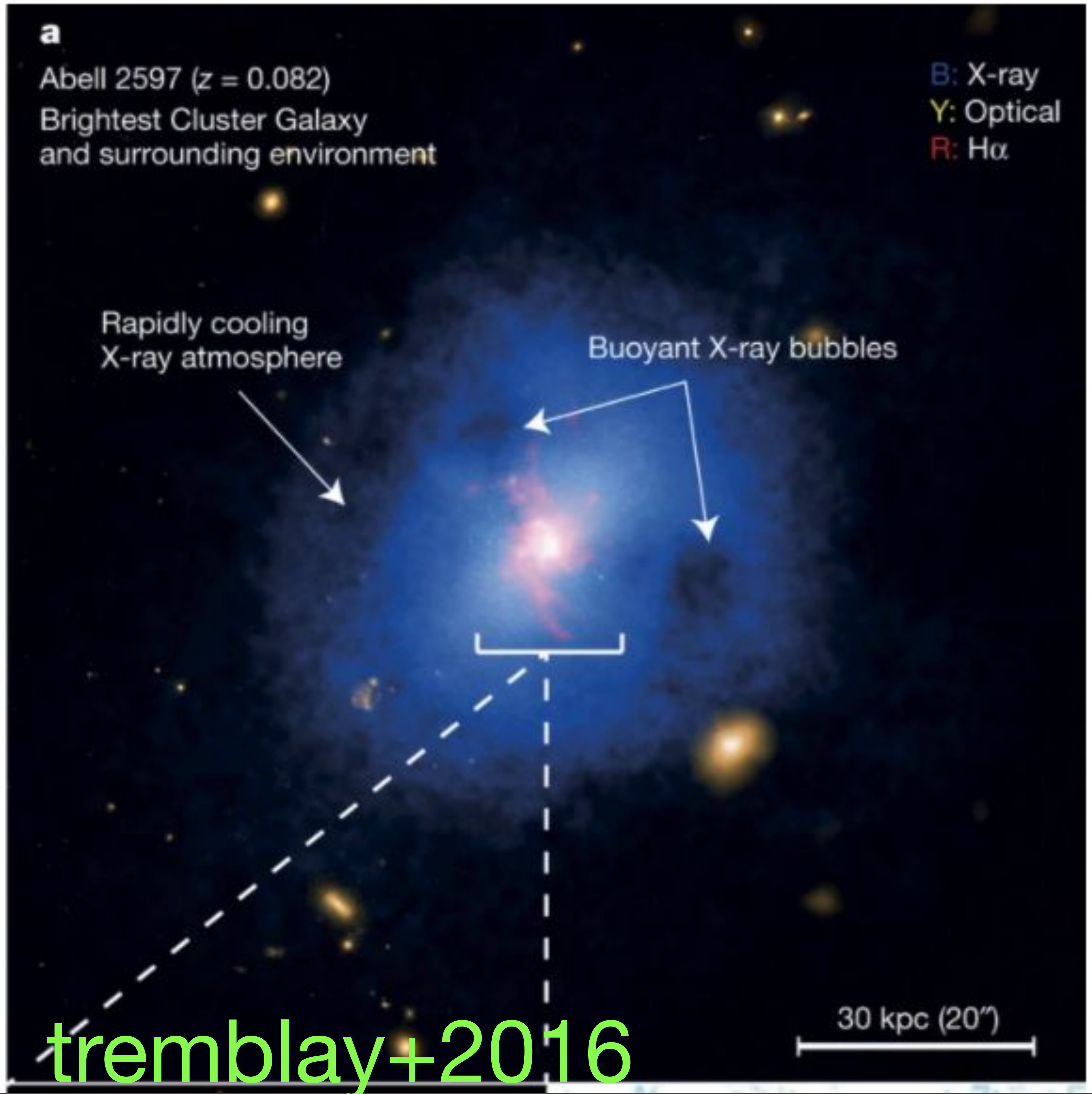
# Cold Cloud Accretion
(Bertschinger+1989)

fragmentation into clouds

deep gravitational wells rapidly accelerate the cooling flow as it enters free fall

$$r_{BH} = \frac{G m_{BH}}{V_{vir}^2}$$

Figure 1: A multiwavelength view of the Abell 2597 BCG.



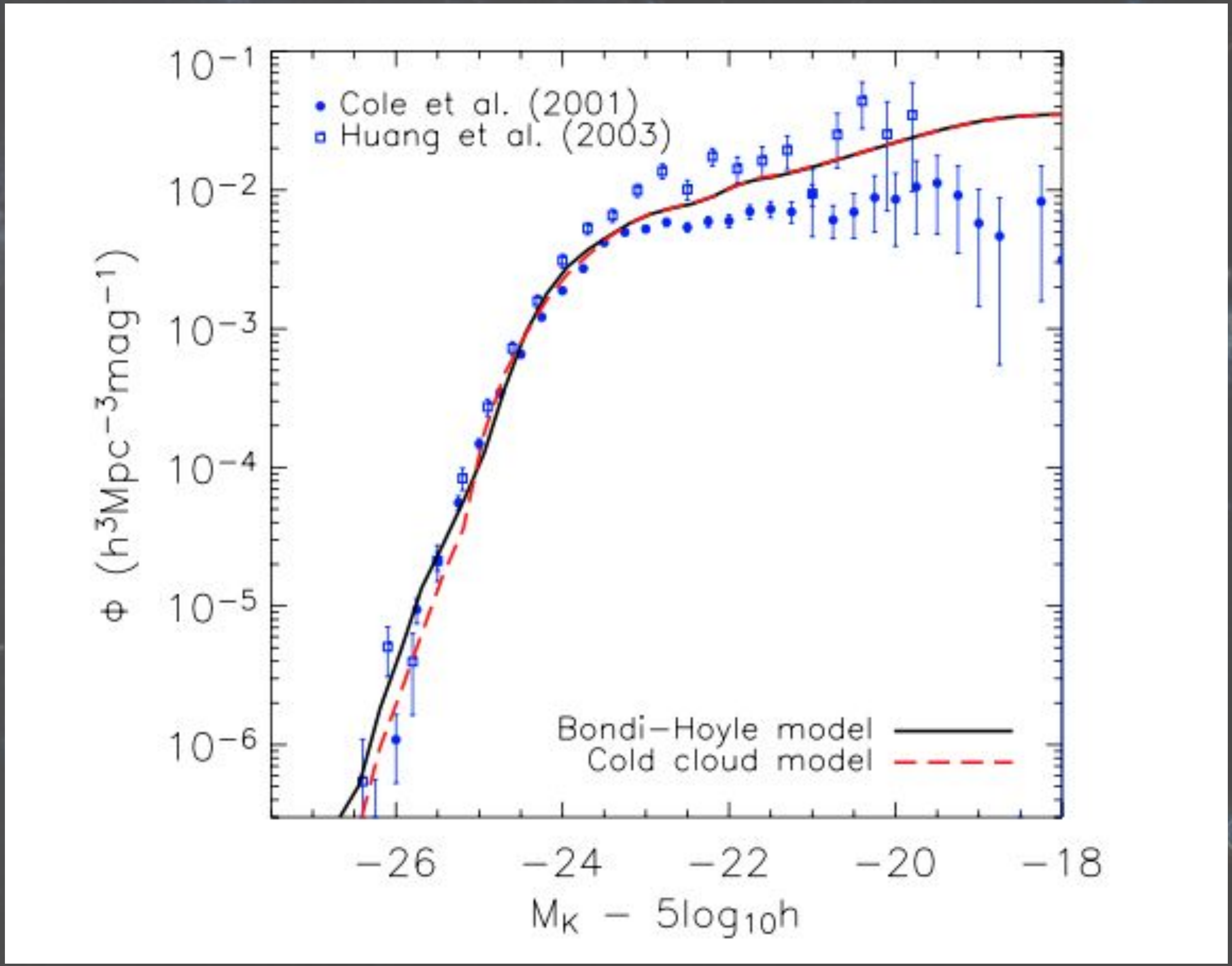

tremblay+2016

# Bondi Accretion

(Bondi+1952, Churazon+2005)

$$\dot{m}_{\mathrm{Bondi}} = 2.5\pi \mathrm{G}^2 \frac{m_{\mathrm{BH}}^2 \rho_0}{c_s^3}.$$

neither model can be ruled out right now




maximal cooling flow model
of Nulsen & Fabian 2000

$$\dot{m}_{\mathrm{Bondi}} \approx \mathrm{G}\mu m_{\mathrm{p}} \frac{kT}{\Lambda} m_{\mathrm{BH}}.$$

# Quick Recap

***introducing "radio feedback" in semi-analytic models of galaxy formation suppresses cooling flows, explaining:***

*(a) cooling flow problem*
*(b) massive, old ellipticals*
*(c) color-mass distribution*
*(d) a host of other galaxy properties*

Optical (Hubble)