How AGN Terminate Galaxy Formation

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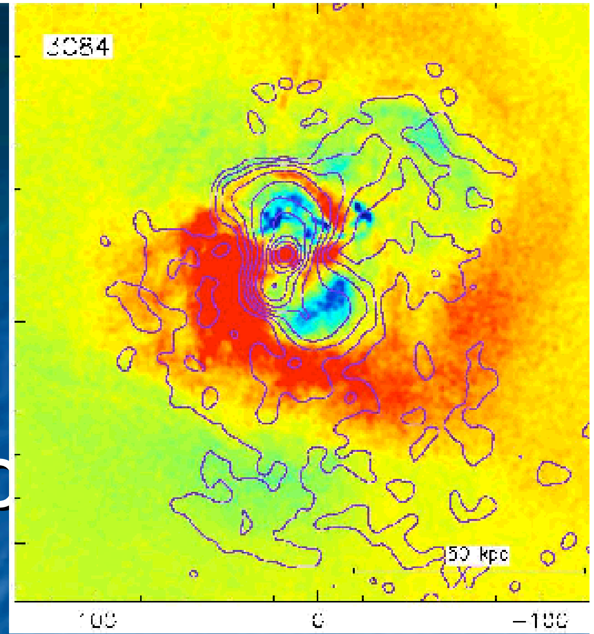
Introduction



- XMM spectra show `cooling-flo cooling (T_{min}' $T_{vir}/3$)
- Chandra makes impact of radio galaxies evident
- By what mechanism does an AGN thermostat the ICM?
- What implications does this mechanism have for galaxy formation? (astro-ph/0308172; astro-ph/0407238)

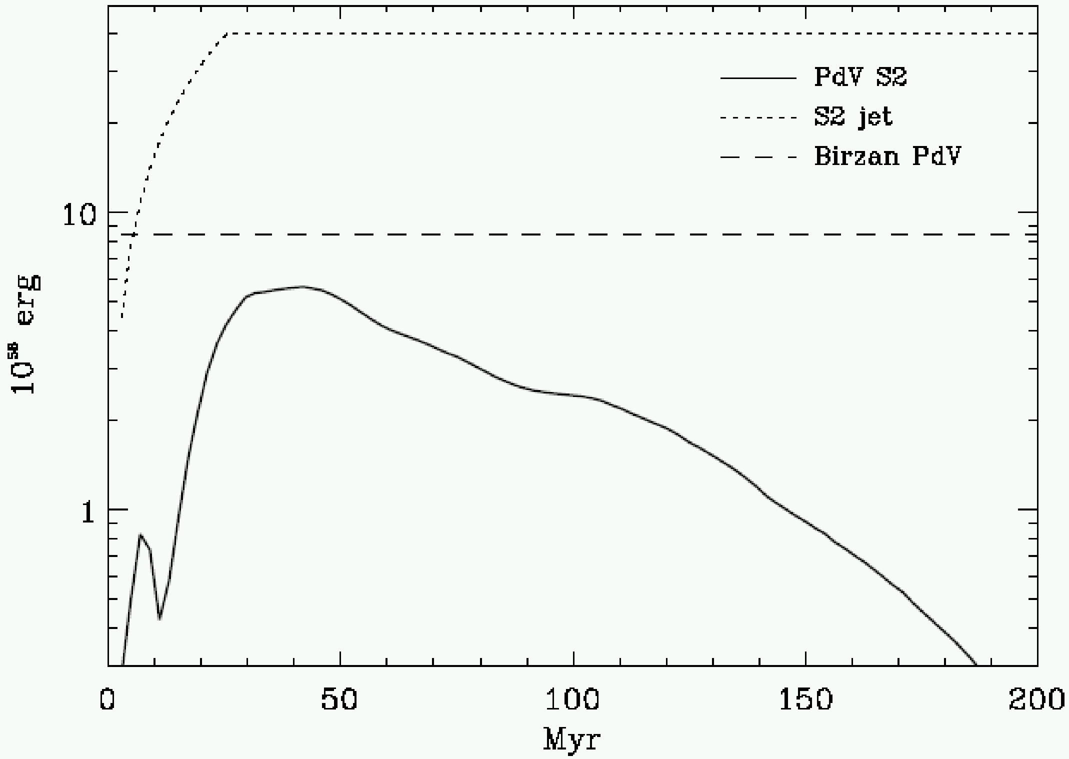
Anisotropic heating

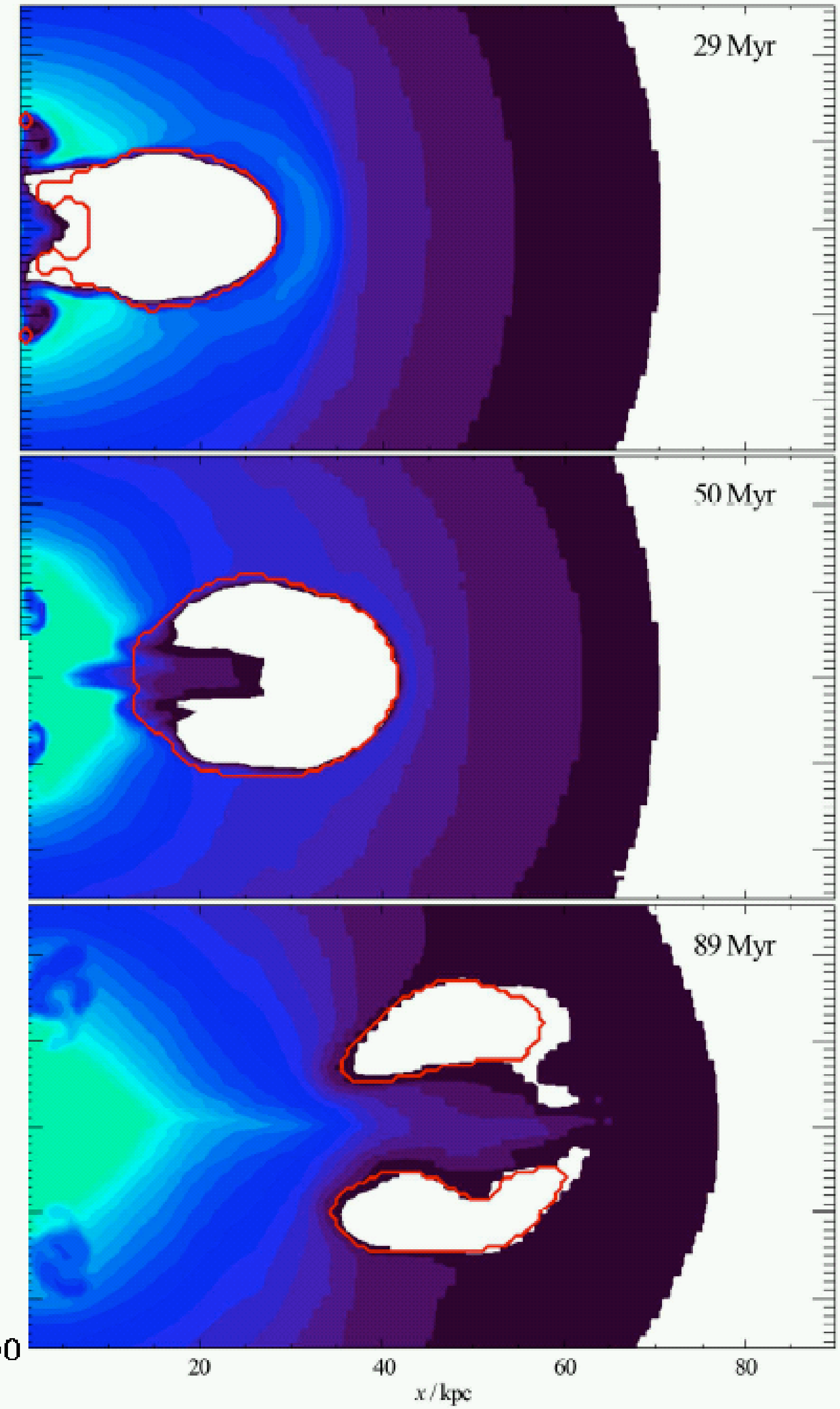
- Absence of isentropic cores implies energy thermalized at many radii simultaneously
- Expected of jet heating

Bubble dynamics

- Omma et al (2004), Omma & Binney (2004) Omma (2005) PhD thesis 3D adaptive-grid hydro simulations with Bryan-Norman code ENZO (piecewise parabolic solver)
- Jets fired into radiatively cooling model of Hydra ICM at »2kpc (David et al 2000) movie

- Define cavities by $\rho<\rho_0/4$
- Evaluate PV
- Peaks at only 10% of actual input





Statistics of observed cavities

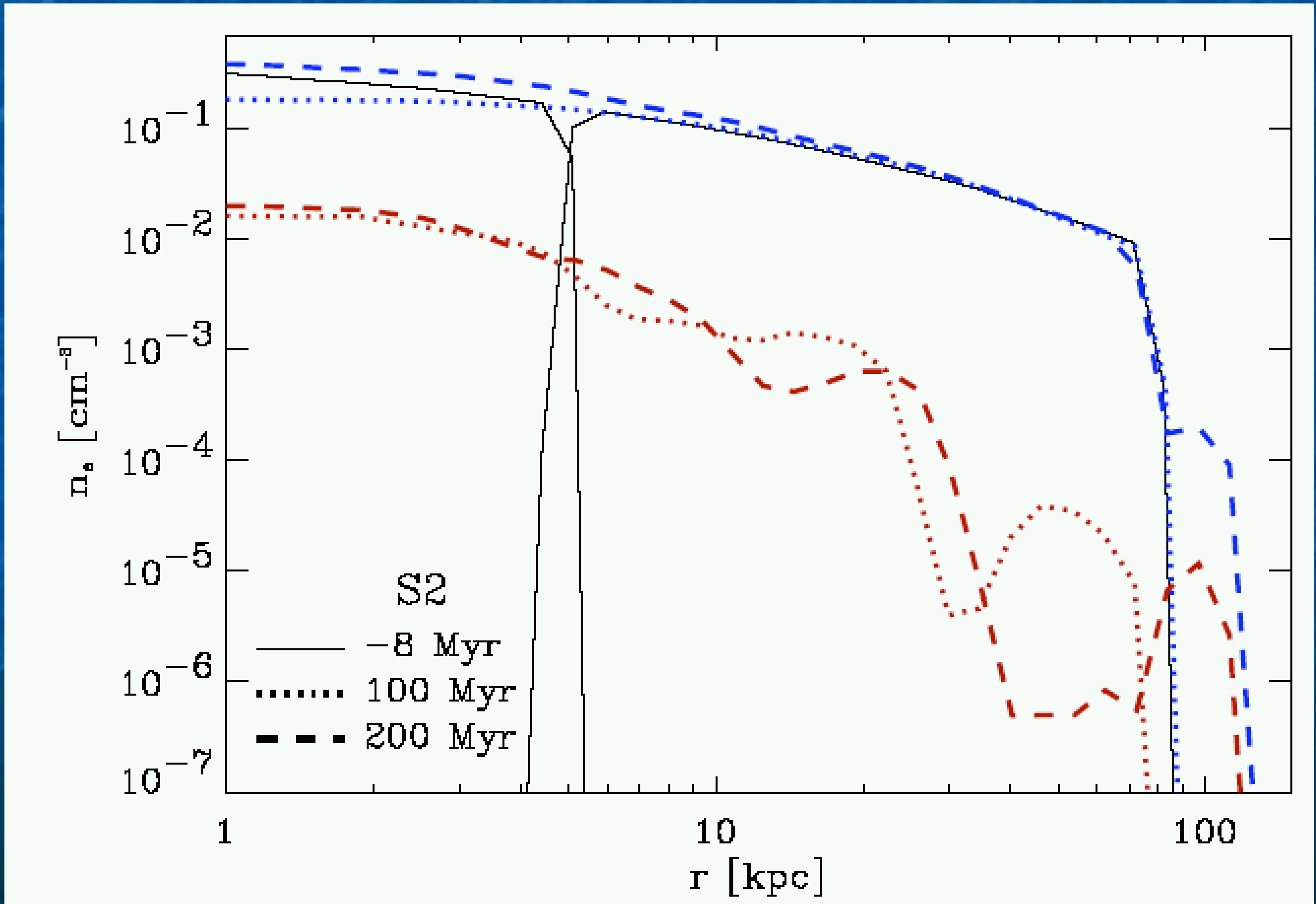
Table 1
Parameters for five clusters with cavities.

System	$PV/10^{58}$ erg	$L_X/10^{43}$ erg s^{-1}	τ / Myr	Reference
Hydra A	27	30	88	McNamara et al. (2000); Nulsen et al. (2002)
A2052	4	3.2	122	Blanton et al. (2001)
Perseus	8	27	29	Fabian et al. (2000); Allen et al. (1992)
A2597	3.1	3.8	79	McNamara et al. (2001)
A4059	22	18	119	Huang & Sarazin (1998); Heinz et al. (2002)

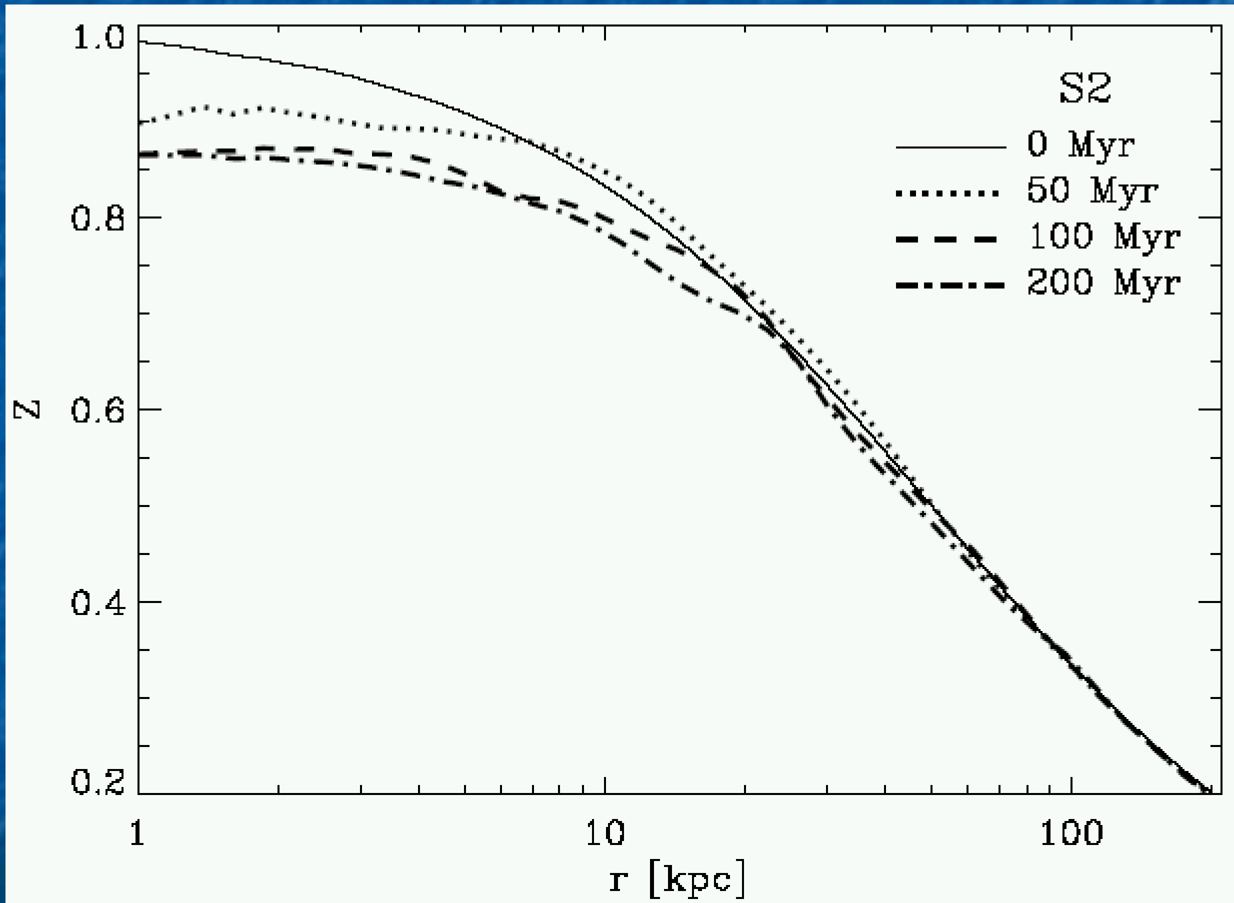
- Rate of heating by cavities ~ L_X for recurrence time > 100 Myr

Shifting gas around

- Follow tracer dye from (a) r<5kpc, and (b) 5<r<77 kpc



Effect on Z gradient

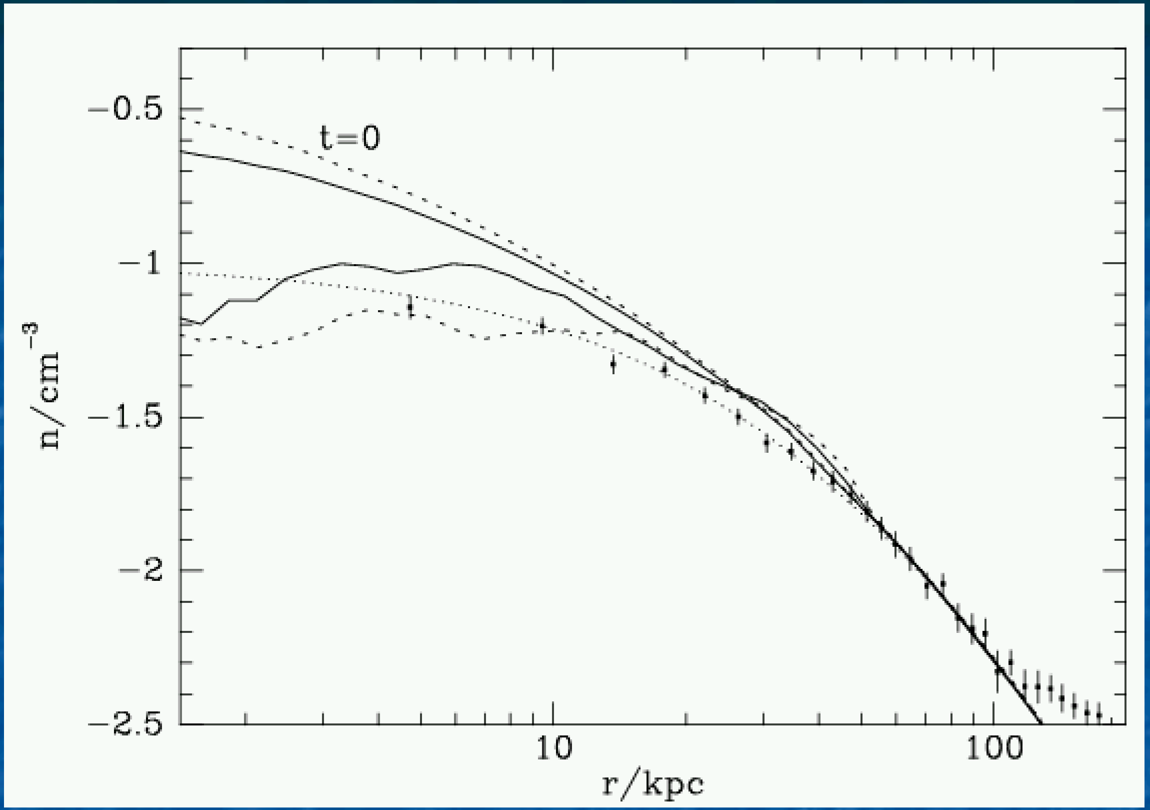


Fixing the radial density profile

- For steady state, E(r) must match $j_X(r)$
- A more powerful jet disrupts further out
- A more concentrated profile disrupts jet further in
- Later jet ignition _ bigger outburst
- Later ignition _ more centrally concentrated density profile

Two Simulations

- Start from present configuration of Hydra
- Wait (i) 262 Myr (ii) 300 Myr
- In (ii) extra $4x10^{59}$ erg lost to radiation, so add $8x10^{59}$ erg rather than $4x10^{59}$ erg as in (i)
- $E_{Bondi}=5(M/10^9M_{-})^2x10^{59}$erg in 262Myr; $E_{Bondi}=7(M/10^9M_{-})^2x10^{59}$erg in 300Myr



- Outbursts have undone 300 Myr of cooling
- System with later ignition ends less centrally concentrated
- Implies that systems can oscillate around an attracting profile

Conclusions so far

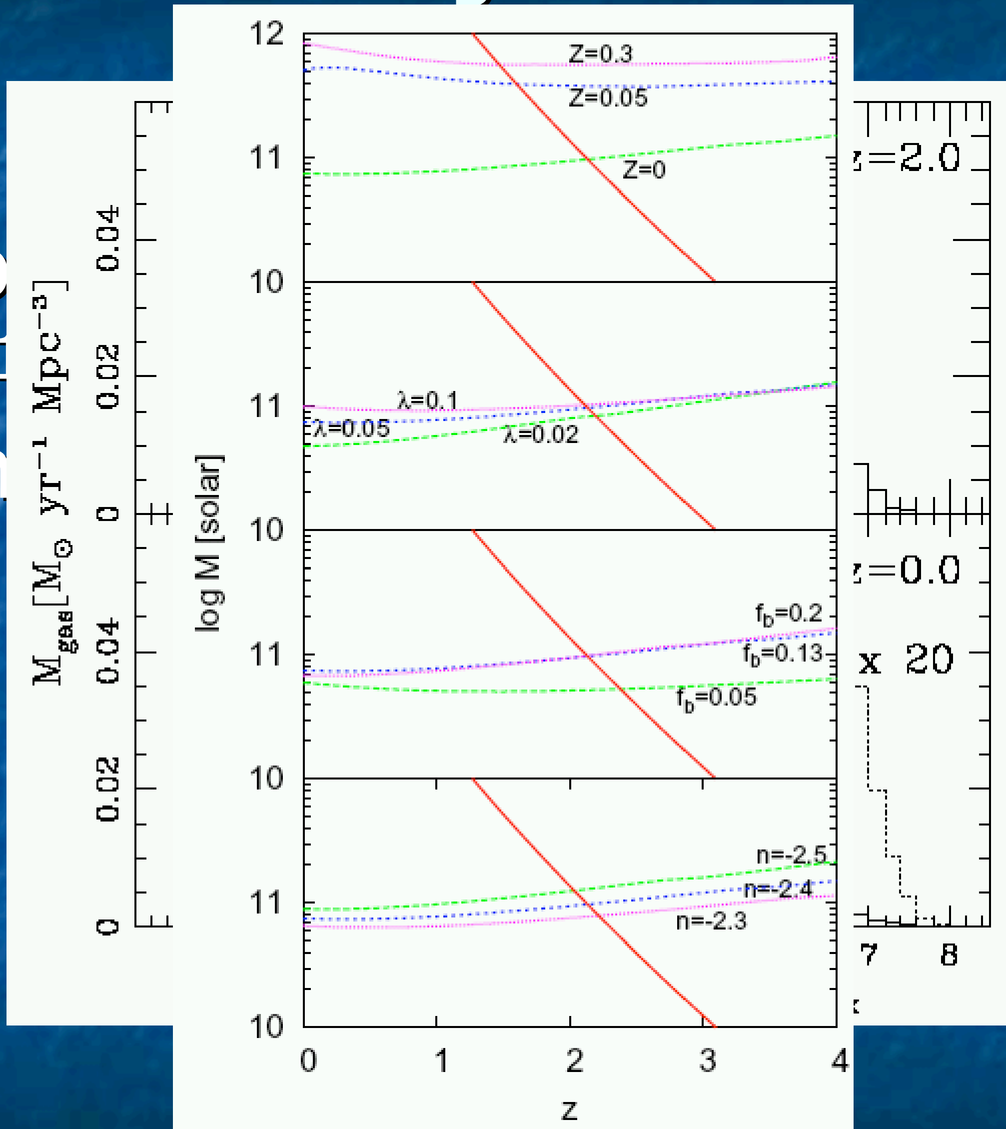
- Bubbles carry only a fraction of the energy injected by radio sources
- Radio sources can readily replace radiated energy
- If energy released in an outburst is proportional to energy radiated since last outburst, post-outburst density profile will oscillate around observed one
- Radio sources thermostat T_{vir} atmospheres

Implications for Galaxy Formation

- In classical theory, galaxies form by cooling of gas trapped at T_{vir}
- If new picture of cooling-flow dynamics correct, classical theory of GF false

So how *do* galaxies form?

- Fractio … at $T¿\ T_{vir}$
  (Binney 1 … ekel 2003)
- *f*~1 on … ow



Birnboim & Dekel 04

The Unnamed Killer

- W... plates
  & ...
- Ef... y with
  T...
- Sc... l to
  re... y
  wi...
- He... but
  clu...
- Lo... use
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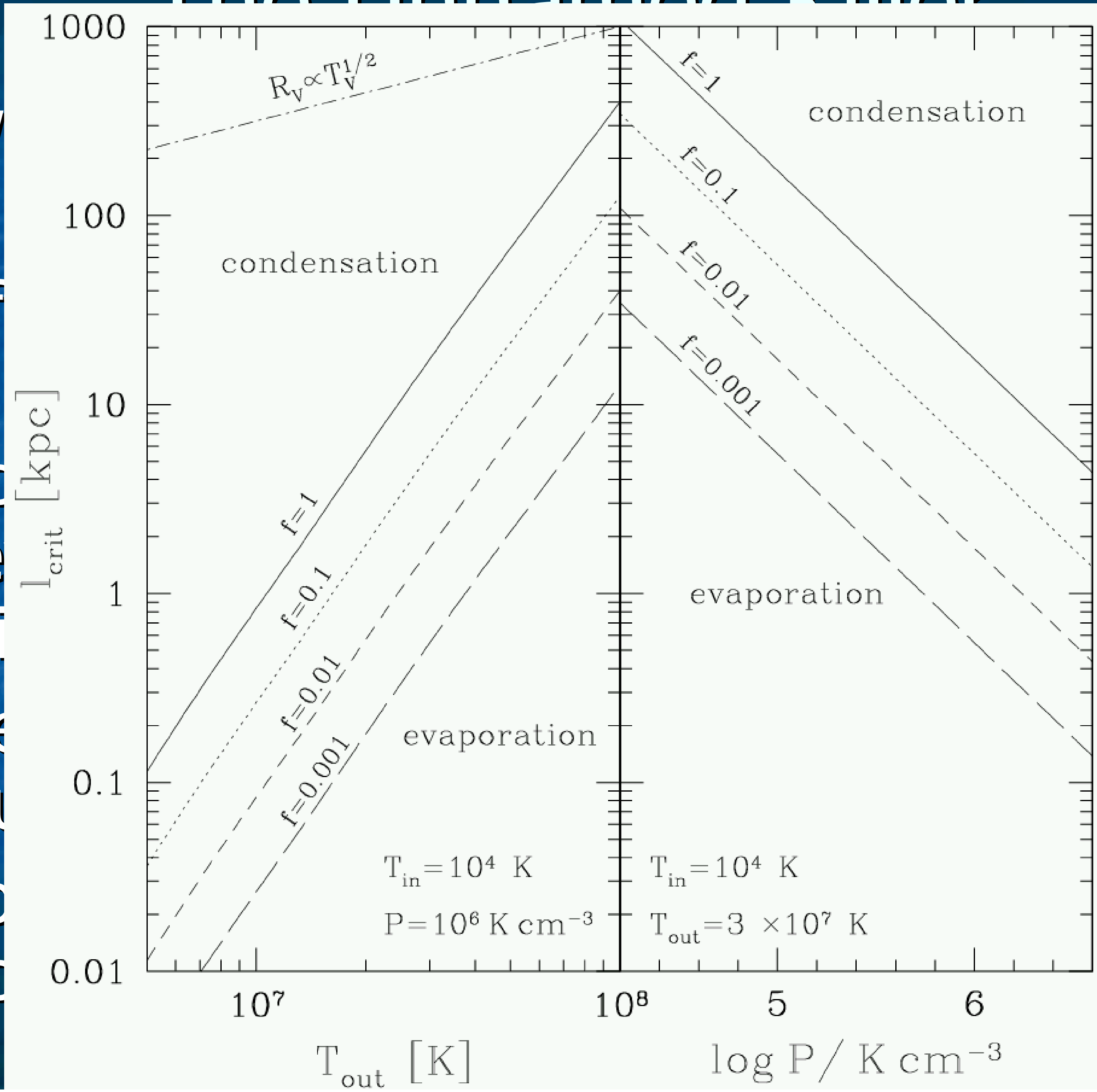


Connection with BH growth

- BH growth known to take place in bursts:
- Yu & Tremaine (2002) find
- (i) AGN have radiated in optical/UV as much E as released by all nuclear BHs;
- (ii) $L \sim L_{Edd}$ and _>0.1 needed to produce observed quasars from observed BHs

Lifecycle of supermassive BHs

- @L_{Edd} M~exp(t/$t_{Salpeter}$); $t_{Salpeter}$~25 Myr
- So M from 10^3M- to 10^9M- with 14t_S~0.4Gyr and 10Gyr at <0.05L_{Edd}
- Magorrian relation M~M_{bulge}, & high _/Fe of bulges, & high ages of bulges all imply L_{Edd} (quasar) phase associated rapid star formation
- Conjecture this is when there is cold gas @ centre
- Episodes end when well deep enough to trap 10^7K gas; then Mdot 0.002 to 0.02 M-/yr to offset 10^{43} – 10^{44} erg/s of L_X

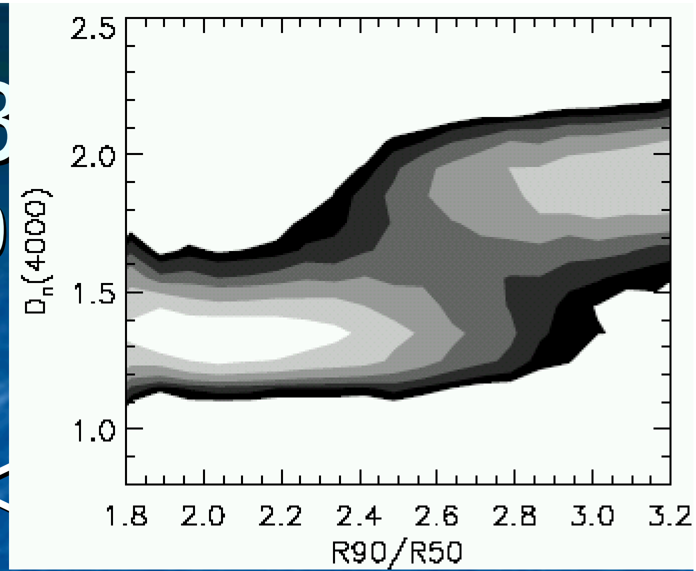
- Stars form from cold gas & then heat all gas
- When M<M*, heated gas expelled
- When M>M*, it accumulates (Larson 79; Dekel & Silk 86)
- Low M galaxies suppressed by photoionization, evaporation & SN feedback (Efstathiou 92; Dekel & Silk 86; Dekel 04)
- Without AGN heating ejected mass forms very massive objects later (Benson et al 03)
- AGN prevent hot gas cooling

Conclusions

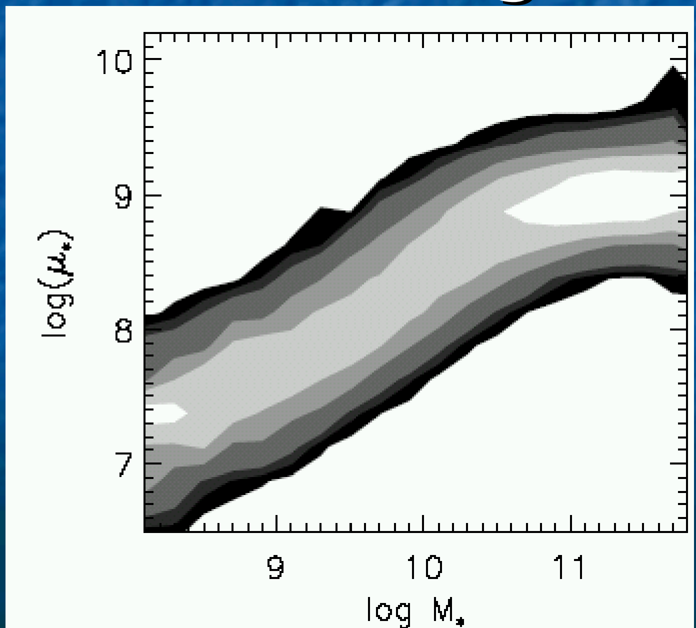
- A CF in most deep potential wells
- Is reheated every ~100 Myr
- Almost certainly jet heated – non-adiabatic
- CFs oscillate around a stable radial density profile
- Galaxies do not form from cooling gas
- BHs grow principally from cold gas simultaneously with rapid SF in bulge
- BHs heat CFs when in quiescent state
- Thermostatic control of CFs by AGN prevents formation of galaxies with M>M*

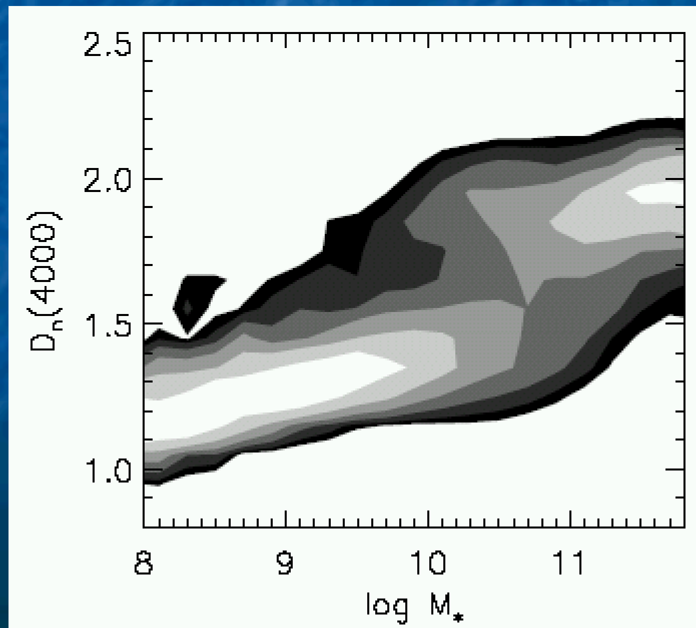
Characteristic M*=3

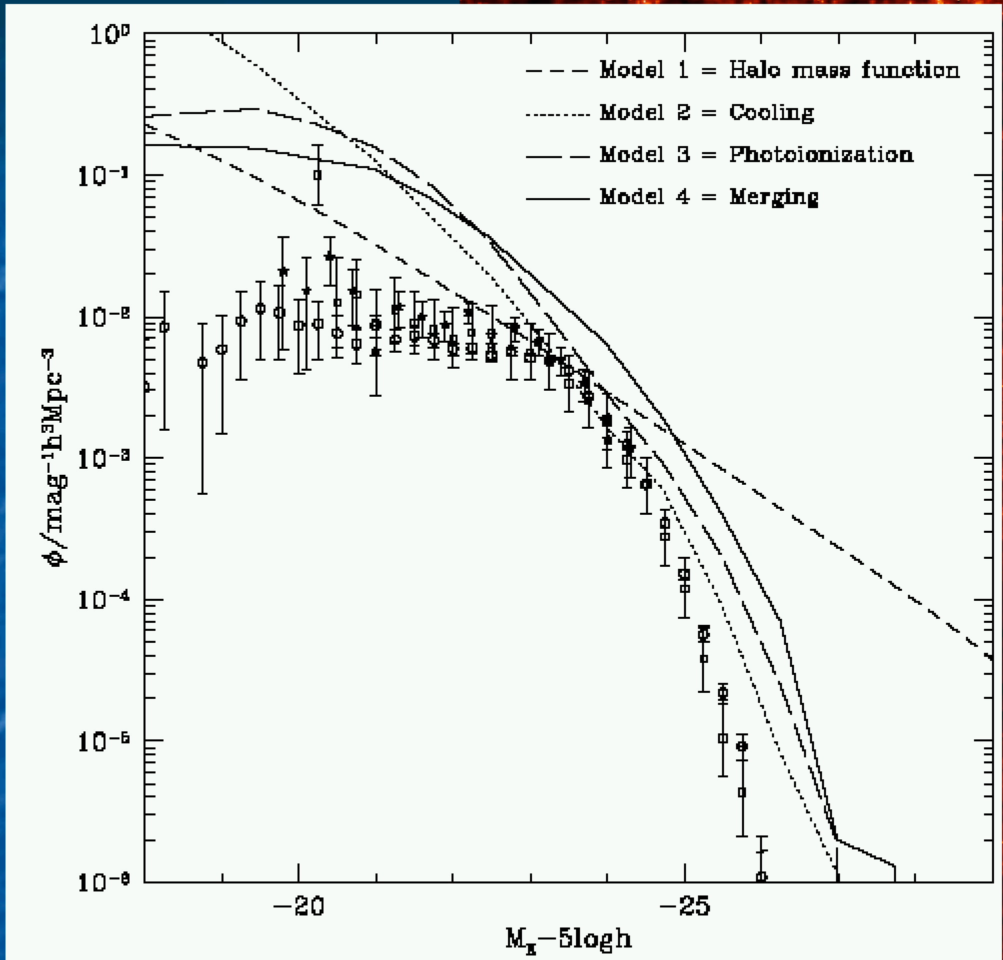
(Kauffmann et al 0



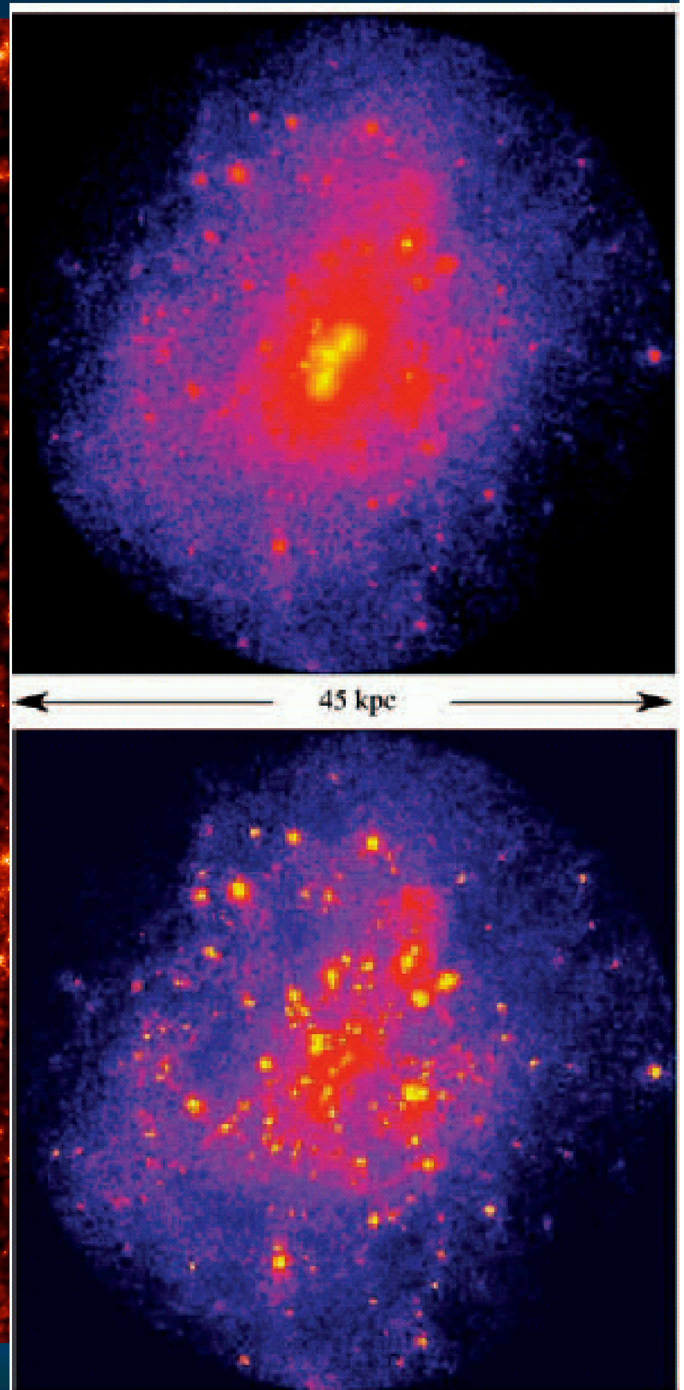
- At M>M* dSB/dM=0; at M<
- At M>M* galaxies old; at M<M* younger
- At M>M* light centrally concentrated







Model 1 = Halo mass function
Model 2 = Cooling
Model 3 = Photoionization
Model 4 = Merging
φ/mag⁻¹h³Mpc⁻³
M_K−5logh
−20
−25
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶



45 kpc

- Spectrum

Classical Theory of GF

- Gas heated to T_{vir} on falling into _
(Rees & Ostriker 1977; White & Rees 1978)
- Deep potential wells contain gas @ T_{vir}
- So we should be able to see galaxy formation!

BH – CF coupling

- Gross mismatch of timescales (t_{BH}~1yr; t_{CF}~100Myr)
- How can BH no bigger than solar system stabilize a system >100 kpc in size?
- Two part answer: (i) tight connection BH power to L_X; (ii) servo system for radial distribution of E

In M87

- Chandra resolves r_{Bondi}
- M_{Bondi} = 0.1 M./yr (Di Matteo et al 03)
- So L = 5×10^{44} erg/s if $0.1mc^2$ released
- L_X(<20kpc) = 10^{43} erg/s (Nulsen & Boehringer)
- L_X(AGN) < 5×10^{40} erg/s
- L_{Mech}(jet) = $10^{43} - 10^{44}$ erg/s (Reynolds et al 96; Owen et al 00)
- So BH accreting at near M_{Bondi} & heating on kpc scales with high efficiency (Binney & Tabor 95)

Bondi accretion

- Area of sonic flow

$$A = 4\pi \left(\frac{GMm_p}{k_B T_0} \right)^2$$

- Particle density

$$n \simeq P/k_B T_0$$

- Accretion rate

$$\dot{M} \simeq n m_p A c_s \simeq 4\pi P (GM)^2 \left(\frac{m_p}{k_B T_0} \right)^{5/2}$$

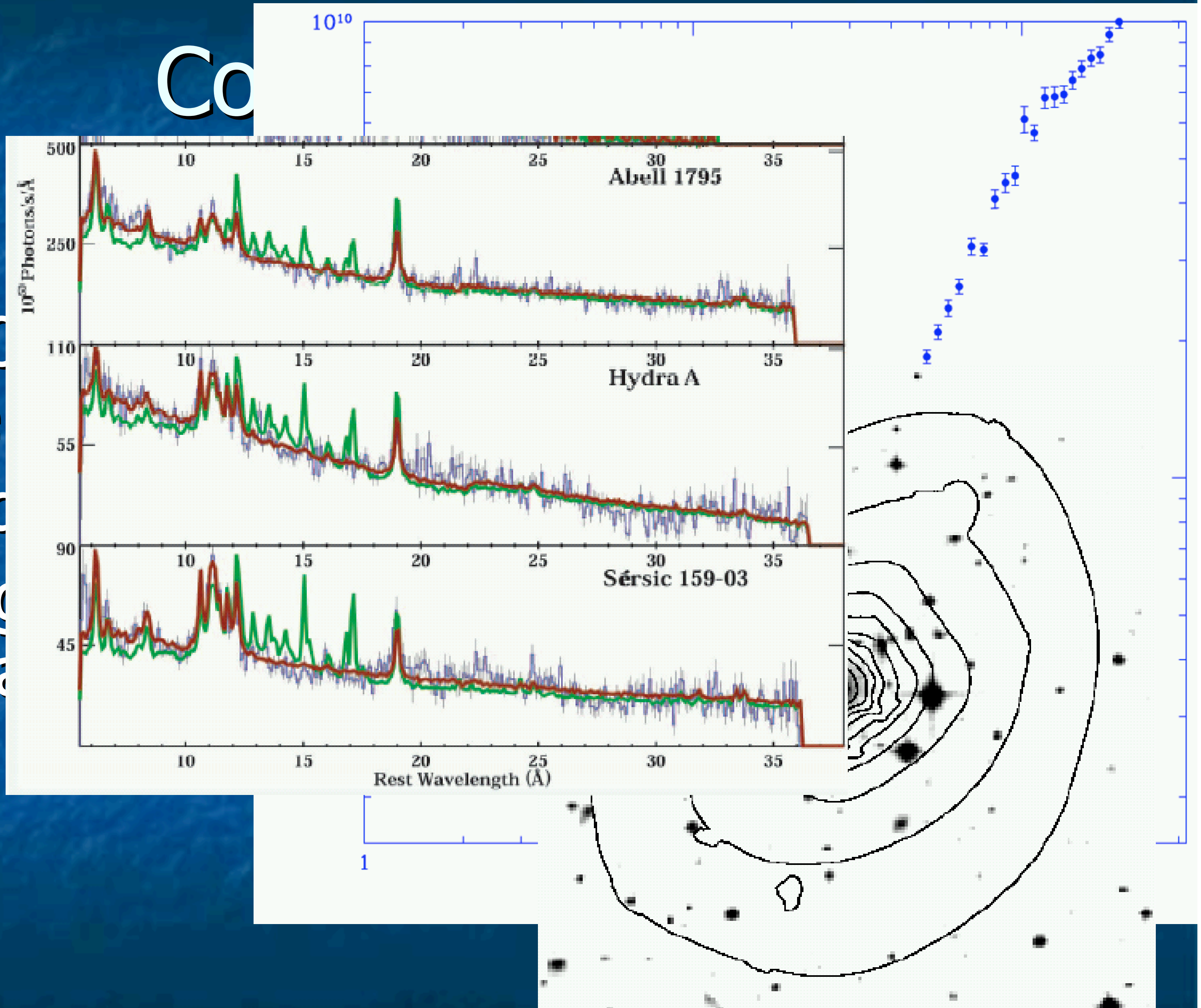
- Luminosity

$$L = \int d^3\mathbf{x}\, n^2 \Lambda(T) \simeq \int d^3\mathbf{x} \left(\frac{P}{k_B T} \right)^2 \Lambda$$

- So balance possible with E _ ∫ dt L_X

Co

- In >70
  centre
- t_{cool}=c
- But if g
  spectra



Heating CFs by BHs

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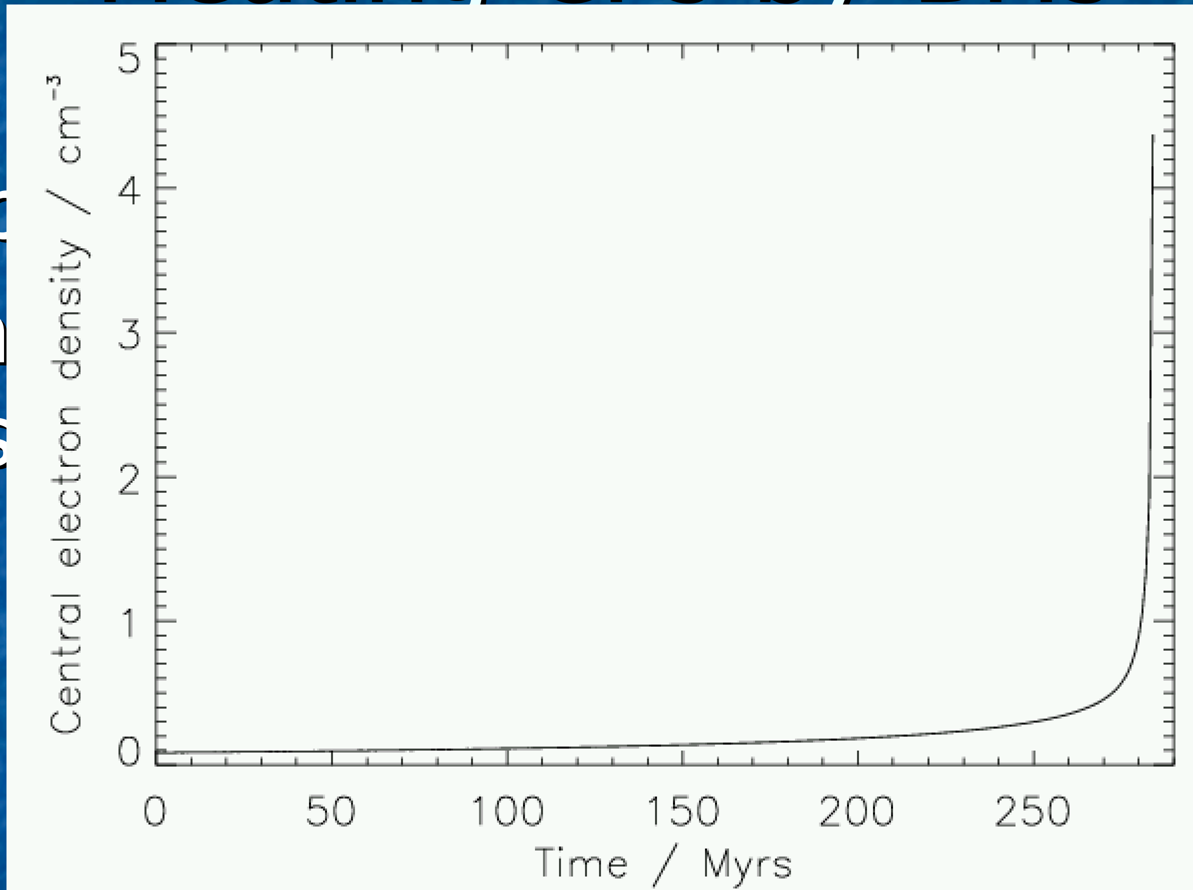
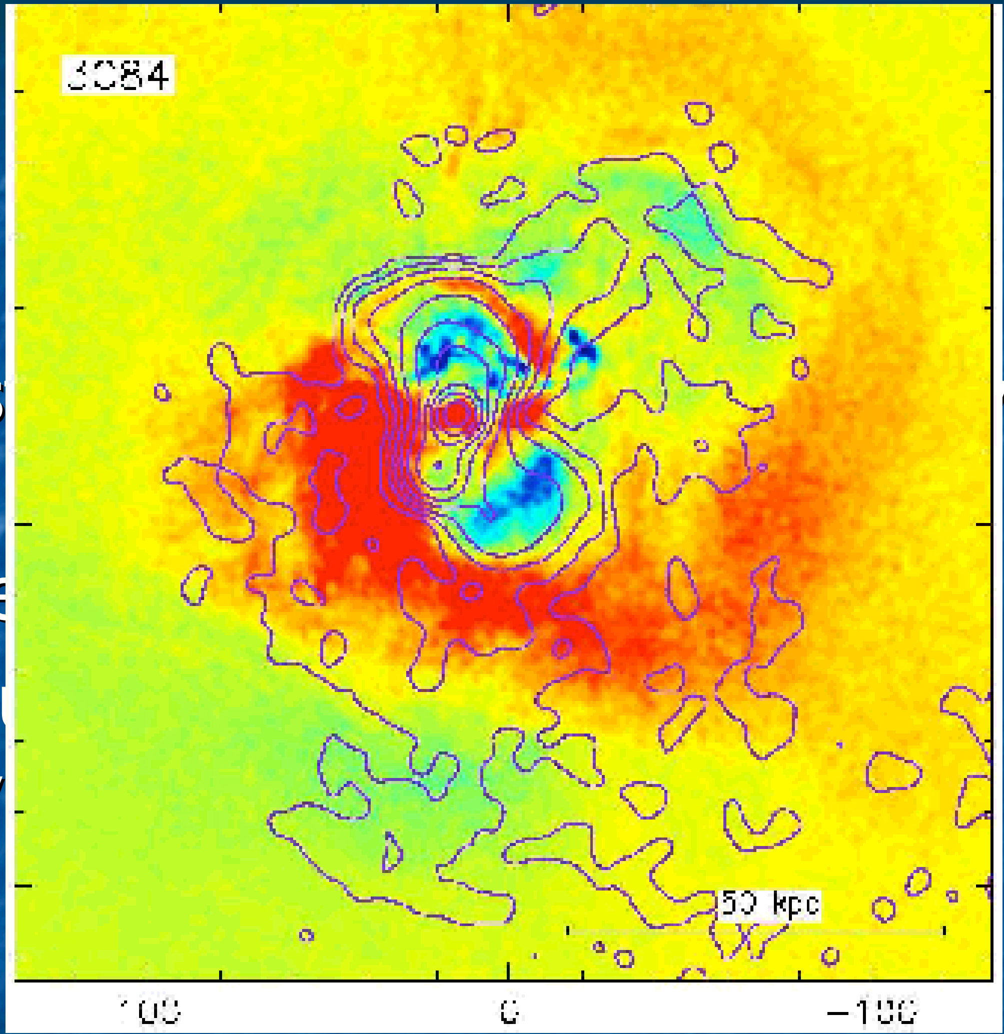
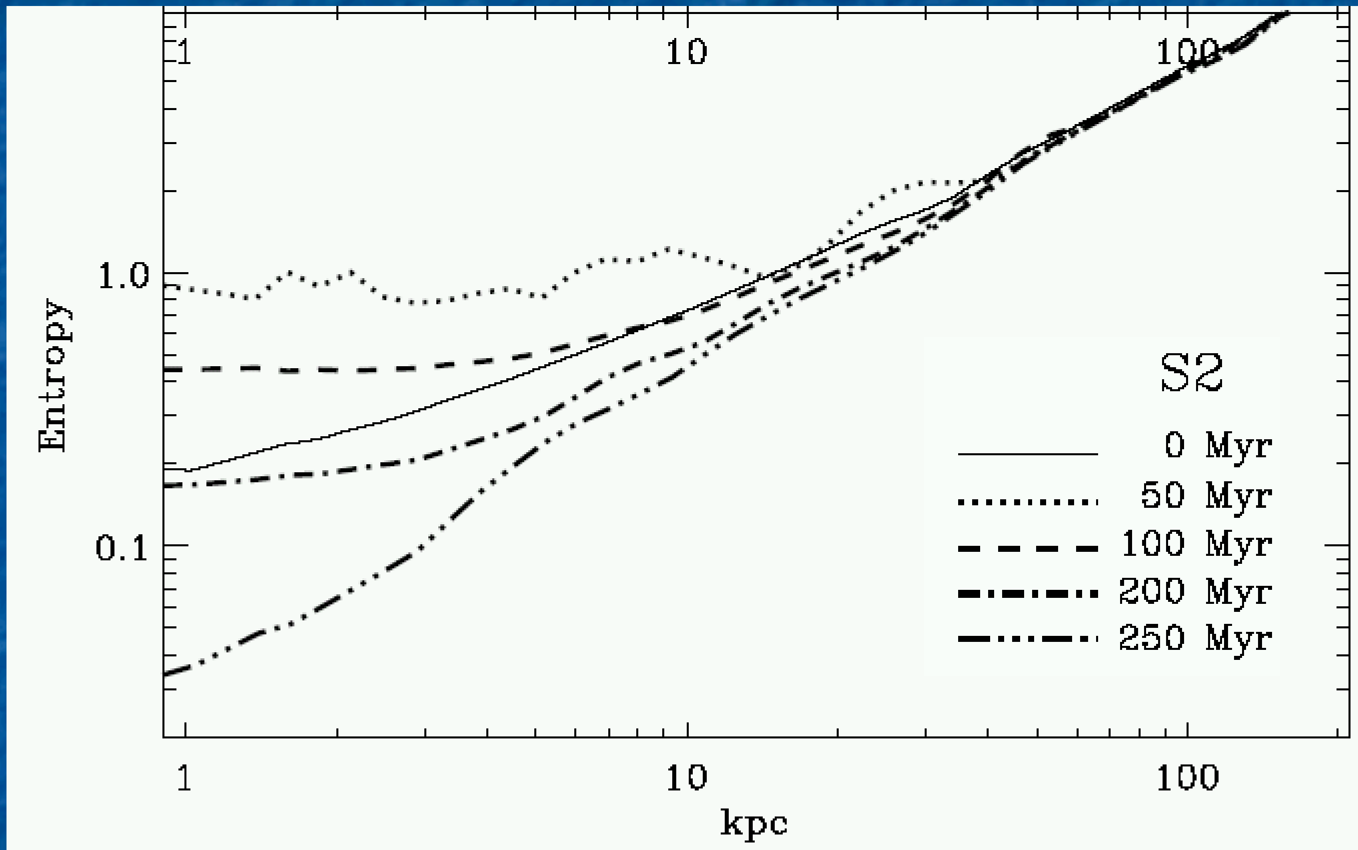
- Such … voke a res…



- Sugges[...] radii simulta[...]
- Expecte[...]
- Now mu[...] X-ray cav[...]





Entropy
kpc
1
10
100
1.0
0.1
S2
0 Myr
50 Myr
100 Myr
200 Myr
250 Myr