
Quasar Feedback in
Structure Formation
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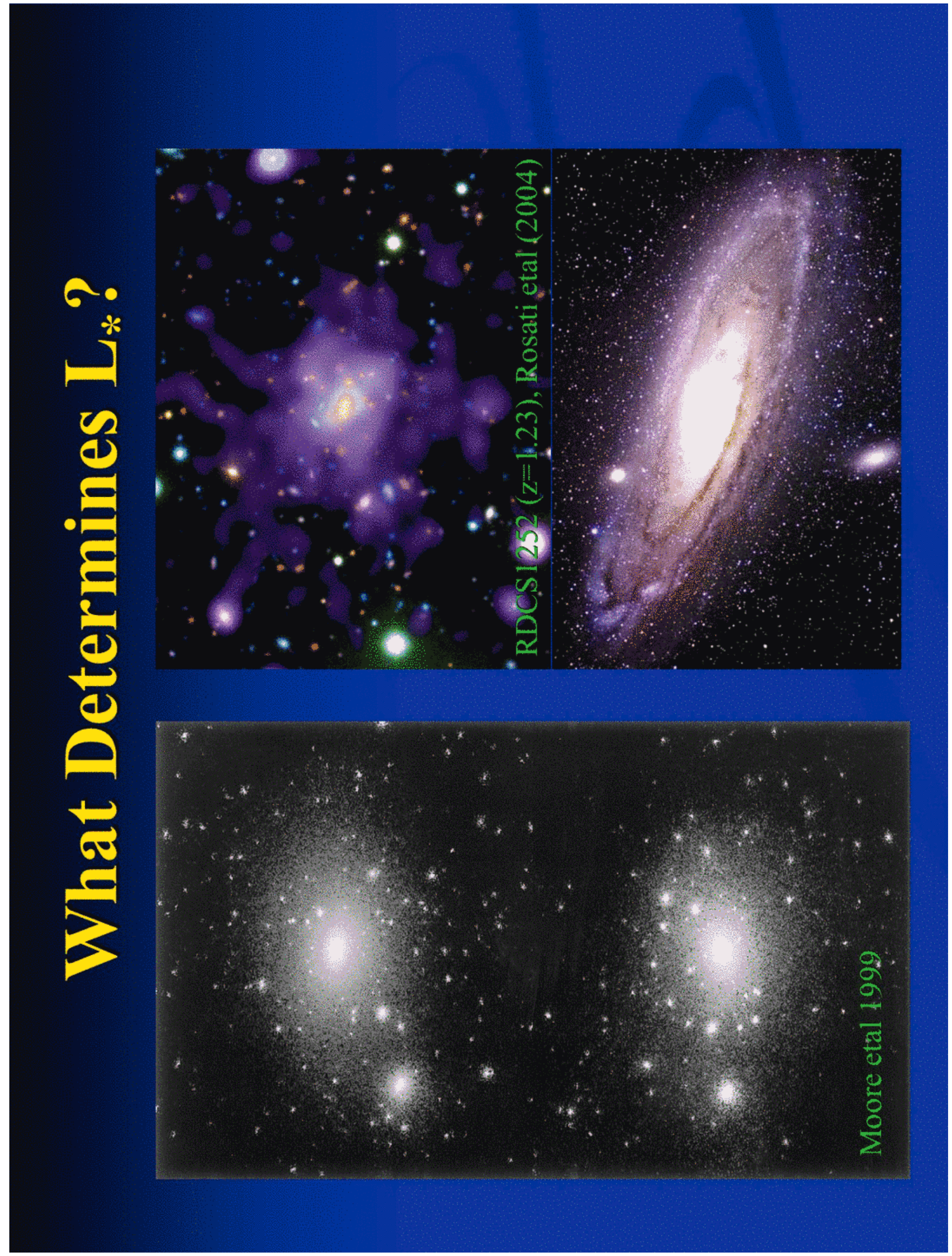
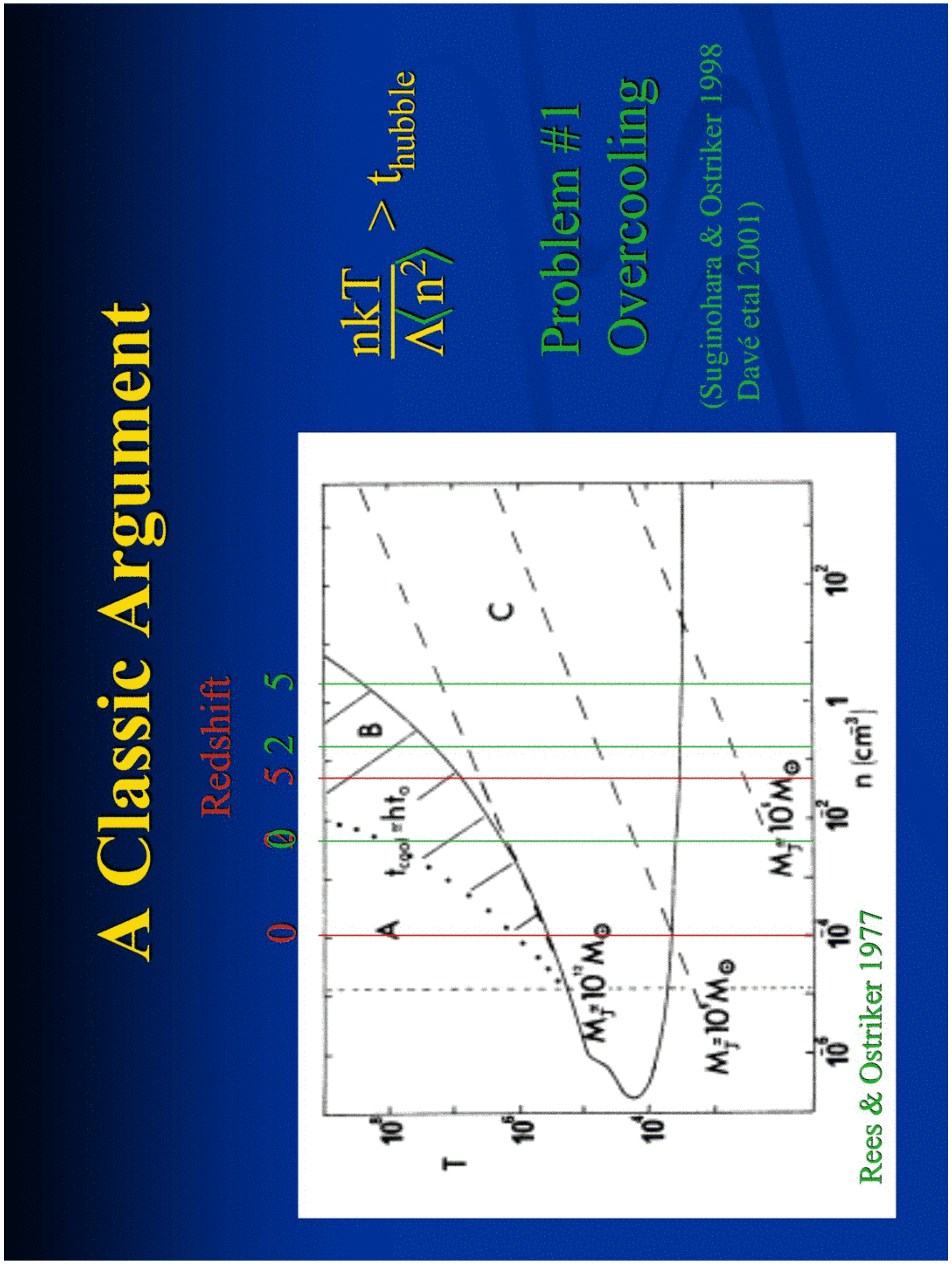
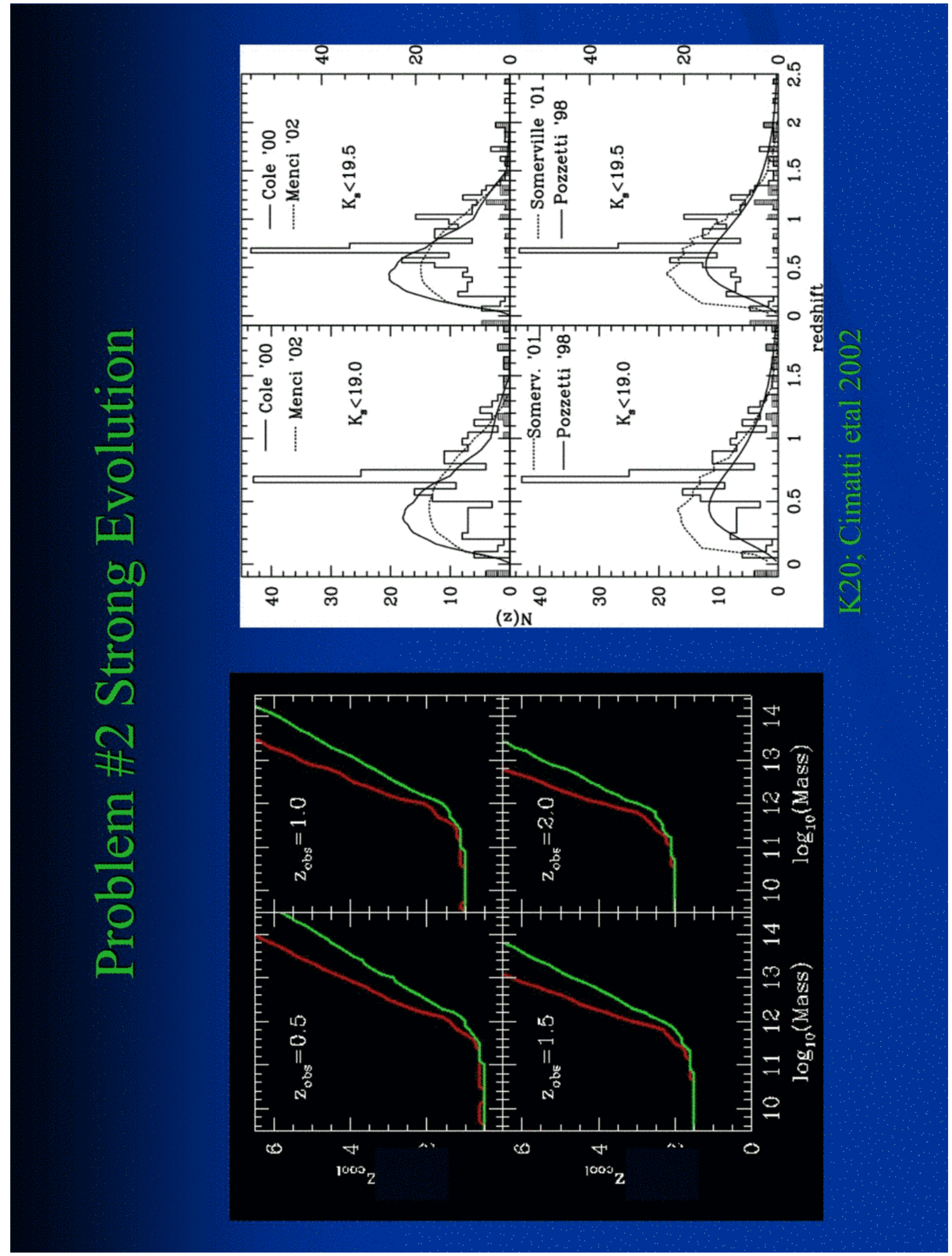
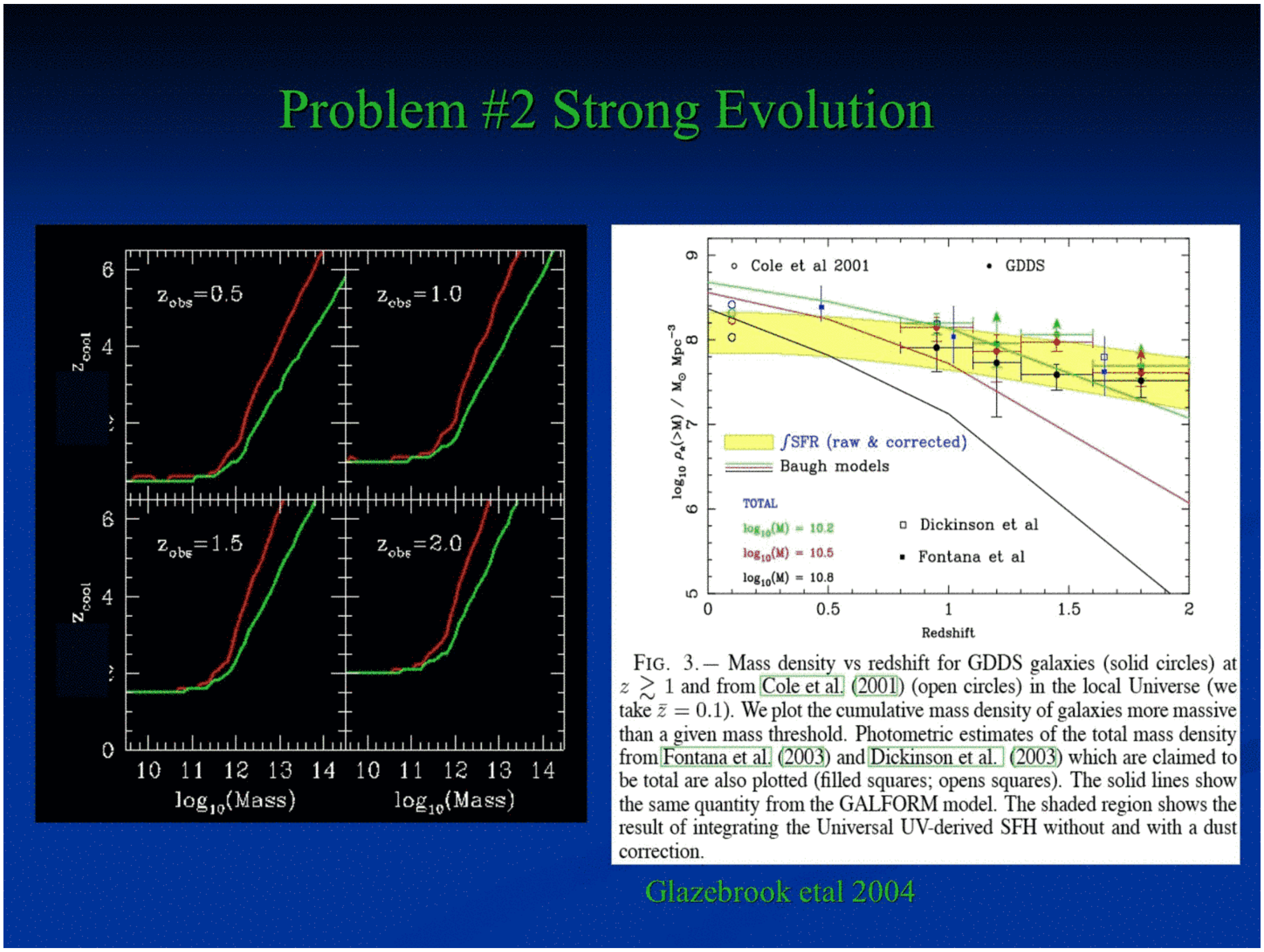
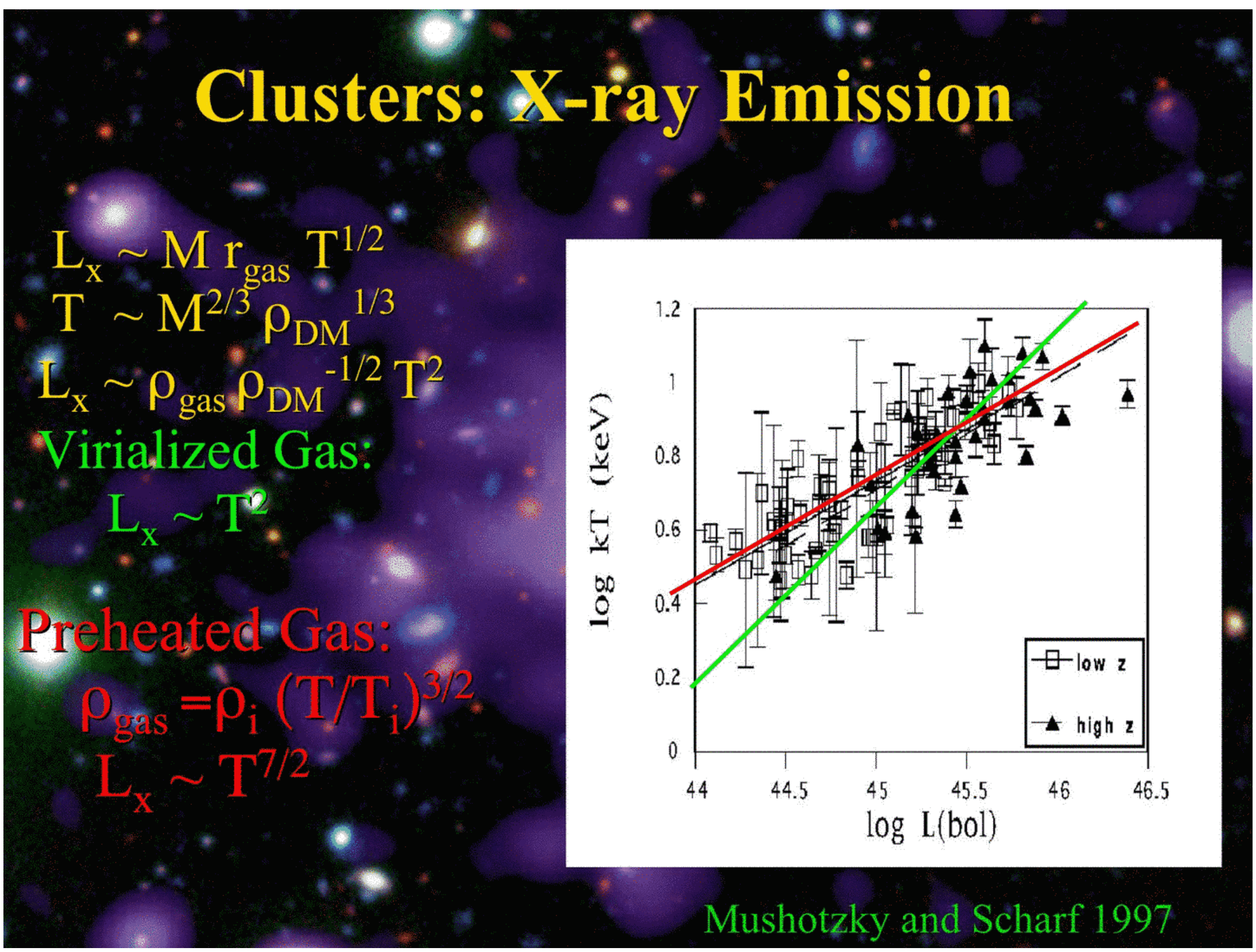
KITP
ES & Peng Oh: ApJ 608, 62; astro-ph/0401087

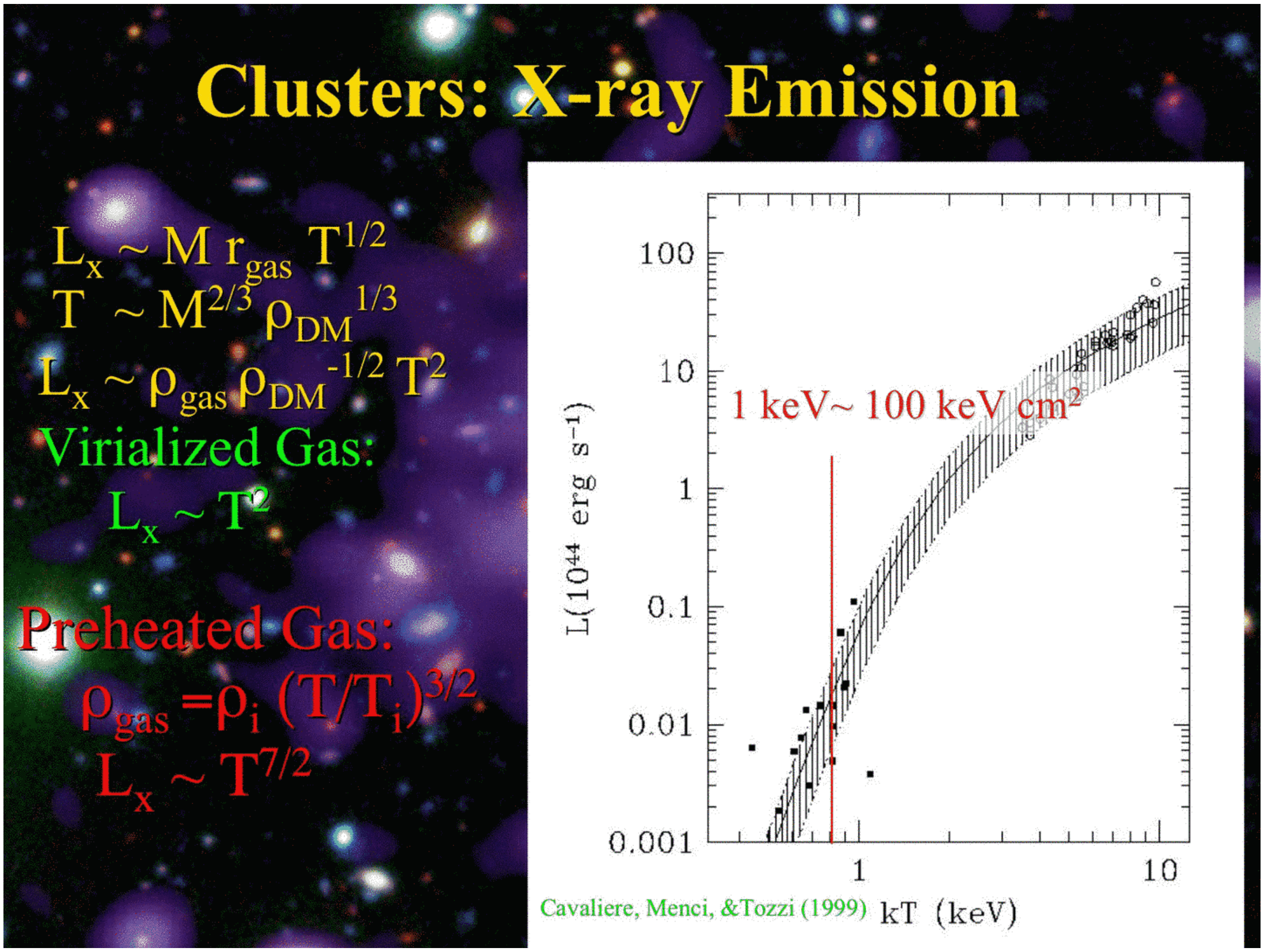

What Determines L*?
RDCS1252 (z=1.23), Rosati etal (2004)
Moore etal 1999

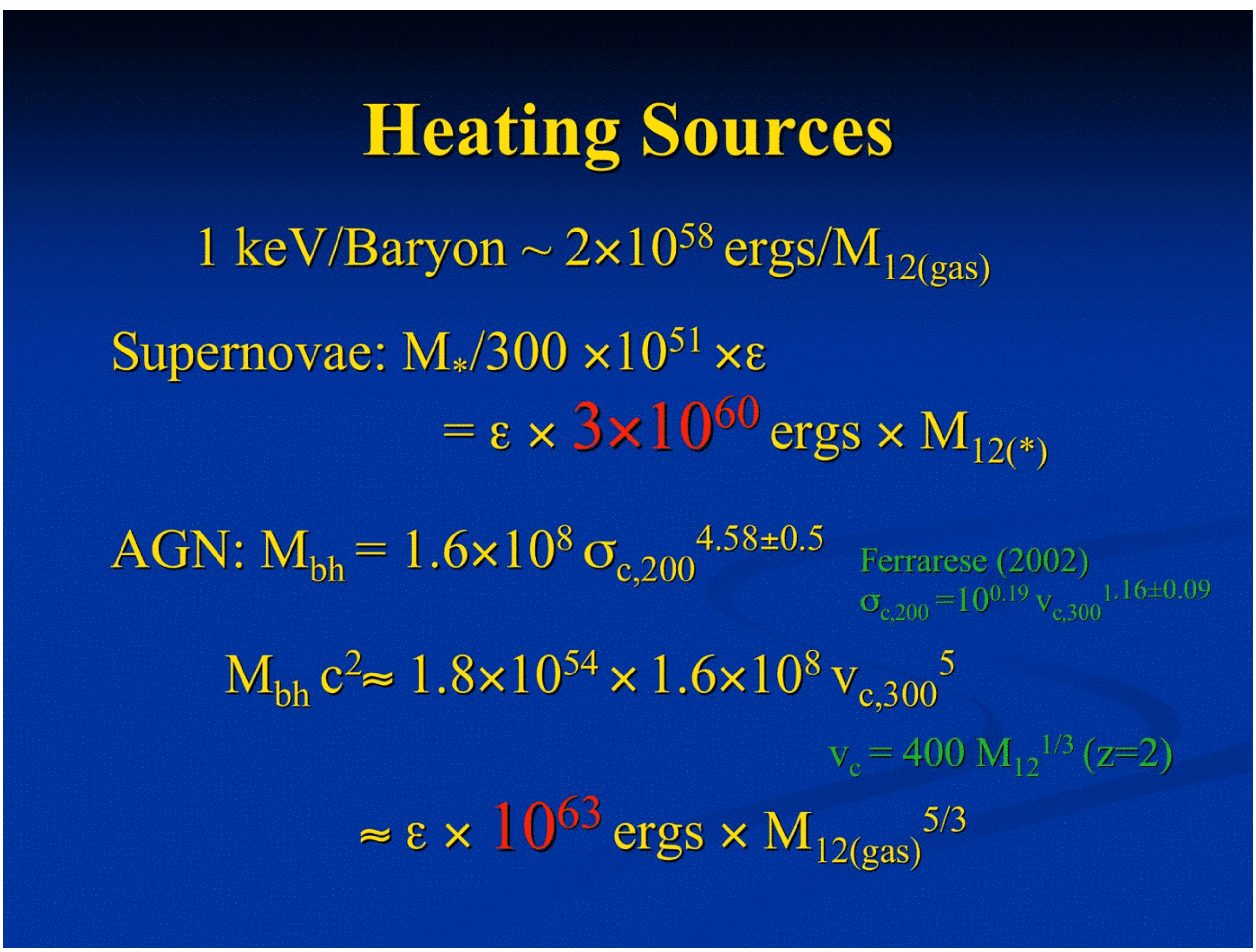

A Classic Argument
Redshift
0 0 5 2 5
$\frac{nkT}{\Lambda\langle n^2\rangle} > t_{hubble}$
Problem #1
Overcooling
(Suginohara & Ostriker 1998
Davé etal 2001)
T
n (cm⁻³)
A
B
C
$t_{cool} = ht_0$
Rees & Ostriker 1977

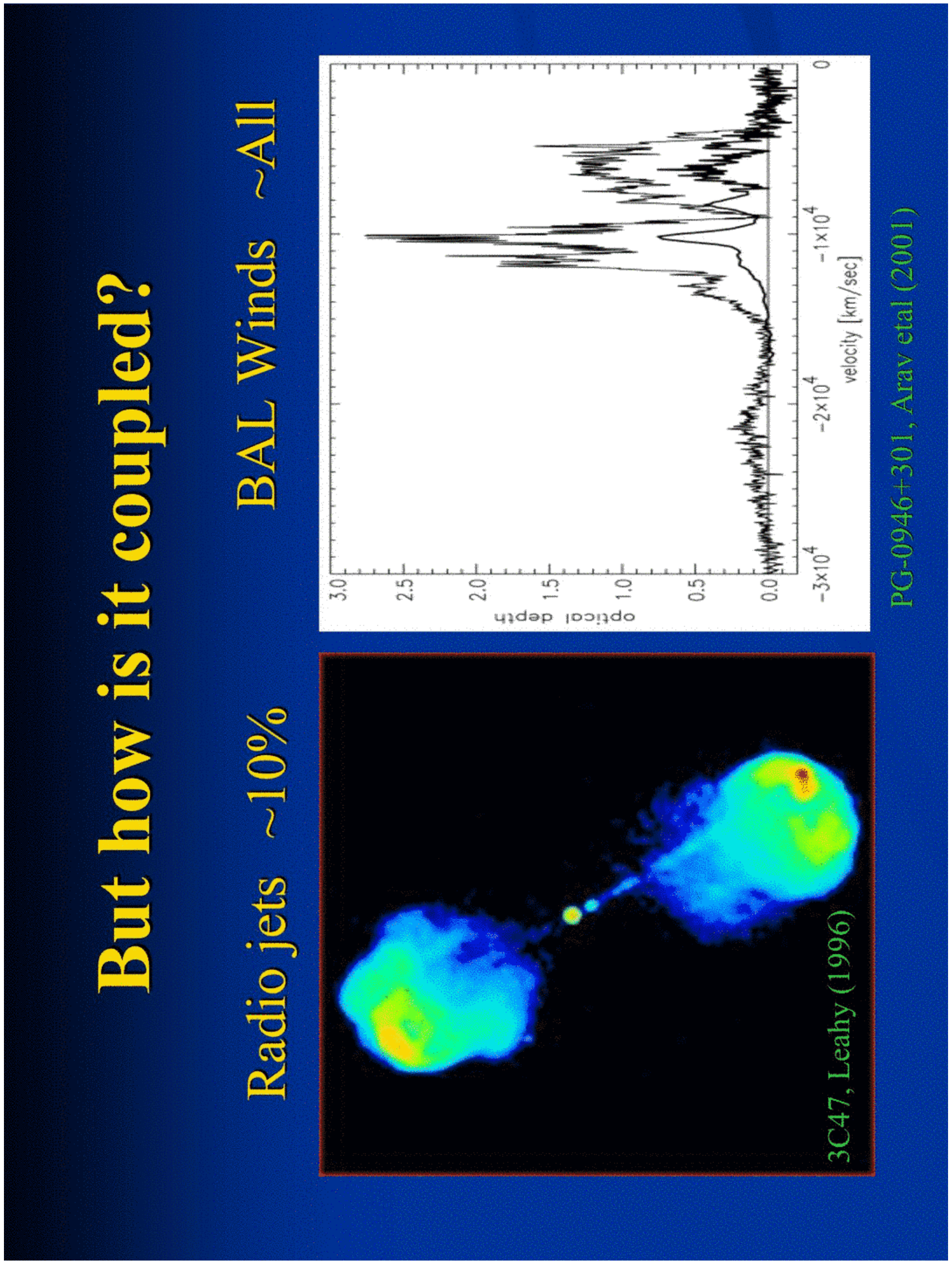

Problem #2 Strong Evolution
$z_{obs}=0.5$
$z_{obs}=1.0$
$z_{obs}=1.5$
$z_{obs}=2.0$
$\log_{10}$(Mass)
Cole '00
Menci '02
Somerville '01
Pozzetti '98
$K_s<19.0$
$K_s<19.5$
N(z)
redshift
K20; Cimatti etal 2002

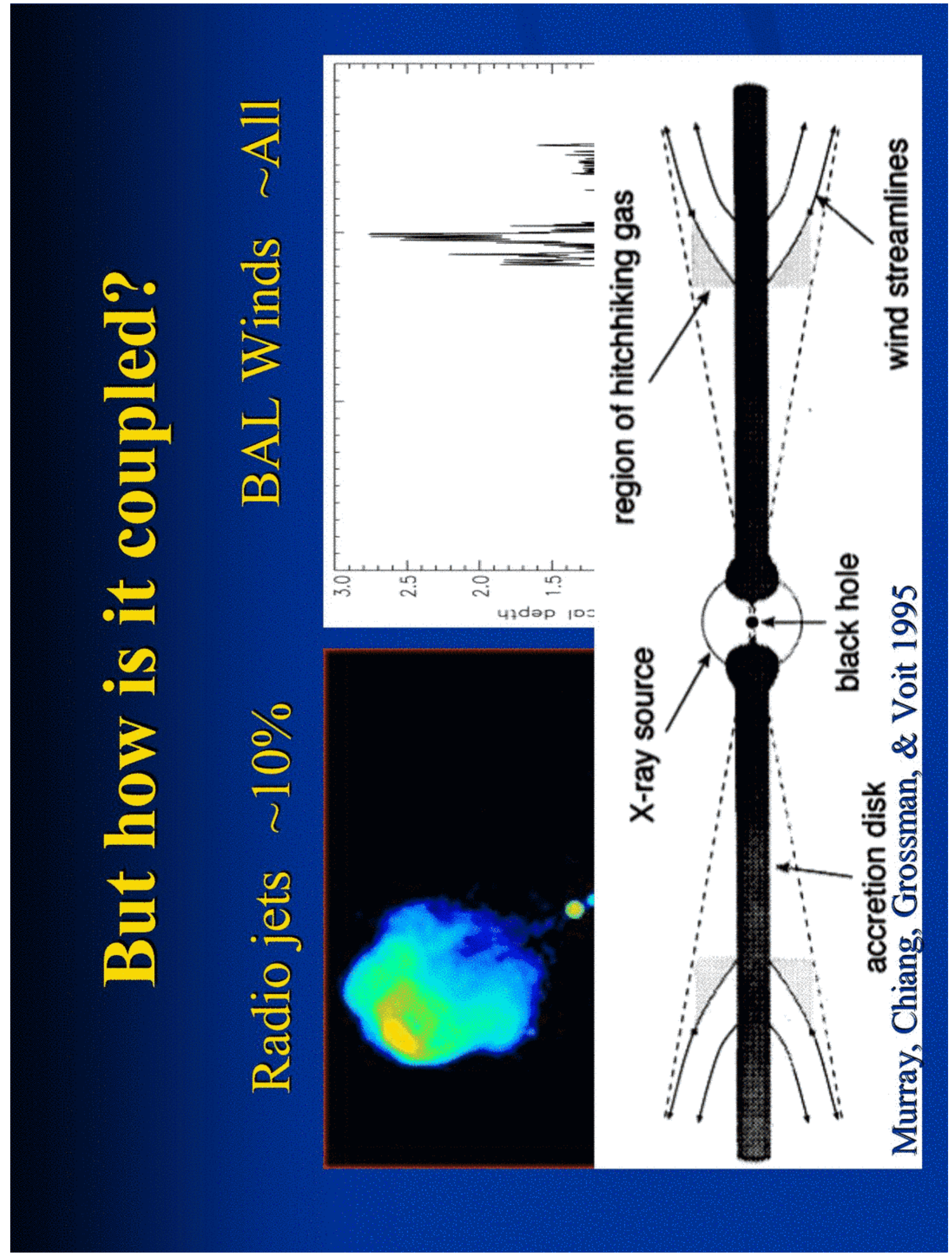

Problem #2 Strong Evolution
z_{obs}=0.5
z_{obs}=1.0
z_{obs}=1.5
z_{obs}=2.0
z_{cool}
$\log_{10}$(Mass)
Cole et al 2001
GDDS
∫SFR (raw & corrected)
Baugh models
TOTAL
$\log_{10}(M)$ = 10.2
$\log_{10}(M)$ = 10.5
$\log_{10}(M)$ = 10.8
Dickinson et al
Fontana et al
$\log_{10} \rho_*(>M)$ / $M_\odot$ Mpc^{-3}
Redshift
FIG. 3.— Mass density vs redshift for GDDS galaxies (solid circles) at $z \gtrsim 1$ and from Cole et al. (2001) (open circles) in the local Universe (we take $\bar{z} = 0.1$). We plot the cumulative mass density of galaxies more massive than a given mass threshold. Photometric estimates of the total mass density from Fontana et al. (2003) and Dickinson et al. (2003) which are claimed to be total are also plotted (filled squares; opens squares). The solid lines show the same quantity from the GALFORM model. The shaded region shows the result of integrating the Universal UV-derived SFH without and with a dust correction.
Glazebrook etal 2004

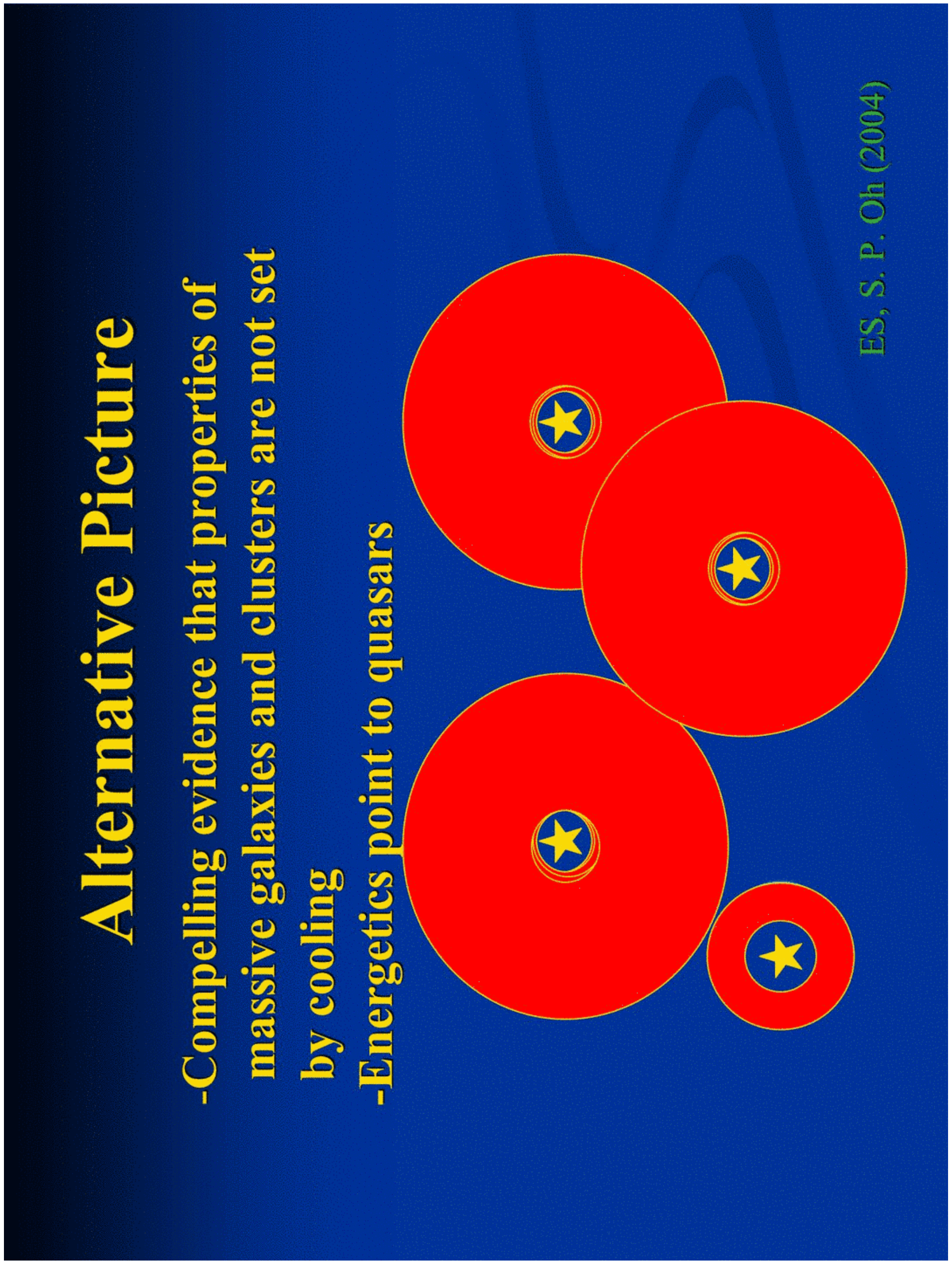

Clusters: X-ray Emission
$L_x \sim M\, r_{gas}\, T^{1/2}$
$T \sim M^{2/3} \rho_{DM}^{1/3}$
$L_x \sim \rho_{gas} \rho_{DM}^{-1/2} T^2$
Virialized Gas:
$L_x \sim T^2$
Preheated Gas:
$\rho_{gas} = \rho_i (T/T_i)^{3/2}$
$L_x \sim T^{7/2}$
log kT (keV)
log L(bol)
low z
high z
Mushotzky and Scharf 1997

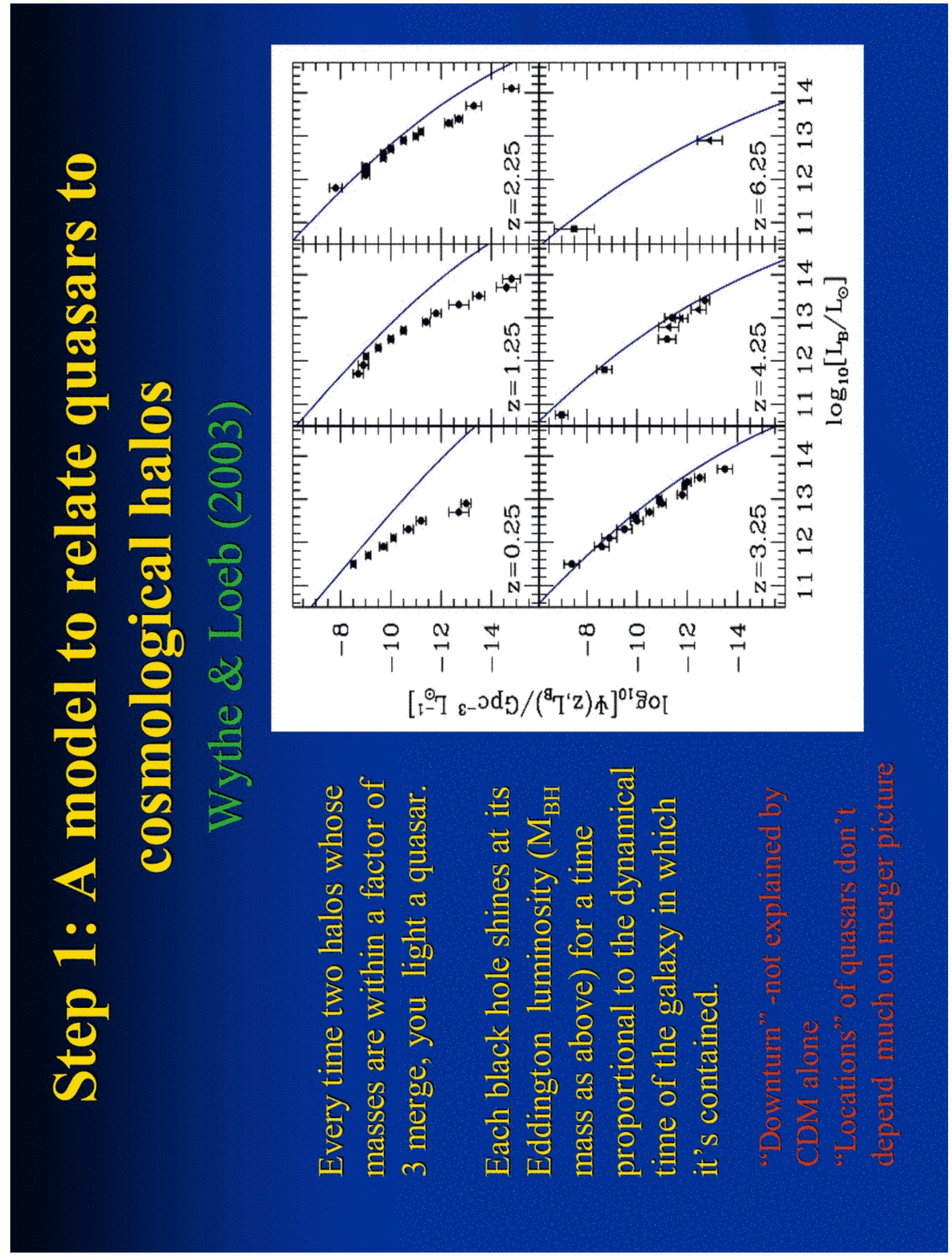

Clusters: X-ray Emission
$L_x \sim M\, r_{gas}\; T^{1/2}$
$T \sim M^{2/3}\, \rho_{DM}^{\;1/3}$
$L_x \sim \rho_{gas}\, \rho_{DM}^{\;-1/2}\, T^2$
Virialized Gas:
$L_x \sim T^2$
Preheated Gas:
$\rho_{gas} = \rho_i\, (T/T_i)^{3/2}$
$L_x \sim T^{7/2}$
$L(10^{44}$ erg $s^{-1})$
100
10
1
0.1
0.01
0.001
1 keV~ 100 keV cm^2
1
10
kT (keV)
Cavaliere, Menci, &Tozzi (1999)


Heating Sources
1 keV/Baryon ~ 2×10^{58} ergs/$M_{12(gas)}$
Supernovae: $M_*/300 \times 10^{51} \times \varepsilon$
$= \varepsilon \times 3\times10^{60}$ ergs $\times M_{12(*)}$
AGN: $M_{bh} = 1.6\times10^8\, \sigma_{c,200}^{\;4.58\pm0.5}$
Ferrarese (2002)
$\sigma_{c,200} = 10^{0.19}\, v_{c,300}^{\;1.16\pm0.09}$
$M_{bh}\, c^2 \approx 1.8\times10^{54} \times 1.6\times10^8\, v_{c,300}^{\;5}$
$v_c = 400\, M_{12}^{\;1/3}$ (z=2)
$\approx \varepsilon \times 10^{63}$ ergs $\times M_{12(gas)}^{\;5/3}$


But how is it coupled?
Radio jets ~10%
BAL Winds ~All
3C47, Leahy (1996)
optical depth
velocity [km/sec]
PG-0946+301, Arav etal (2001)


But how is it coupled?
Radio jets ~10%
BAL Winds ~All
region of hitchhiking gas
wind streamlines
X-ray source
black hole
accretion disk
Murray, Chiang, Grossman, & Voit 1995


Alternative Picture
-Compelling evidence that properties of massive galaxies and clusters are not set by cooling
-Energetics point to quasars
ES, S. P. Oh (2004)


Step 1: A model to relate quasars to cosmological halos
Wythe & Loeb (2003)
z=0.25
z=1.25
z=2.25
z=3.25
z=4.25
z=6.25
$\log_{10}[\Psi(z,L_B)/\mathrm{Gpc}^{-3}\,L_\odot^{-1}]$
$\log_{10}[L_B/L_\odot]$
Every time two halos whose masses are within a factor of 3 merge, you light a quasar.
Each black hole shines at its Eddington luminosity (M_{BH} mass as above) for a time proportional to the dynamical time of the galaxy in which it's contained.
“Downturn” -not explained by CDM alone
“Locations” of quasars don't depend much on merger picture

Step 2: Sedov-Taylor Blast Waves

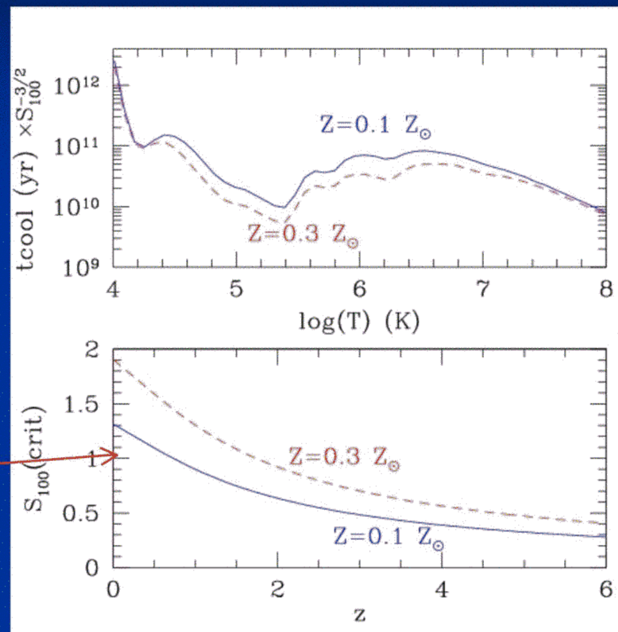
$E_{60} = 1.2\ \varepsilon_k M_{12}^{5/3} (1+z)$

$R = 1.7\ \mathrm{Mpc}\ E_{60}^{1/5}\ t_{Gyr}^{2/5} \times \delta^{-1/5} (1+z)^{-3/5}$

Critical Entropy

Oh & Benson (2003)

100 keV cm^2



$S = 2 \times 10^4\ \mathrm{keV\ cm^2}\ E_{60}\ R_{Mpc}^{-3}\ \delta^{-5/3} (1+z)^{-5}$

Step 3: Feedback

To compute the average number of supercritical impacting a random point in space, you just count bubbles:

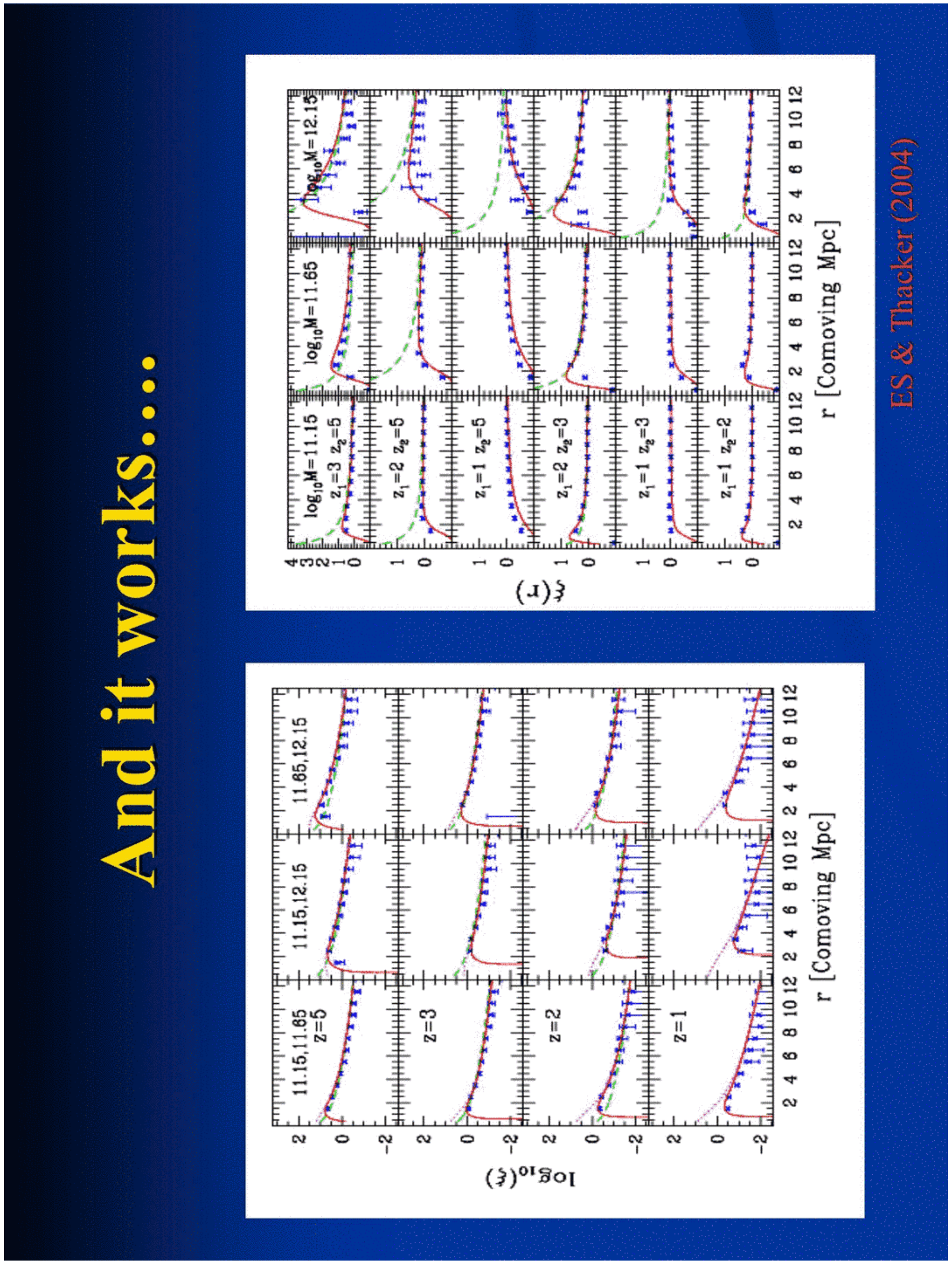
$$N_S(z) \propto \int_z^\infty dz' \int_{M_{min}}^\infty dM\ R_S^3(z,z',M)\ n(z',M)$$

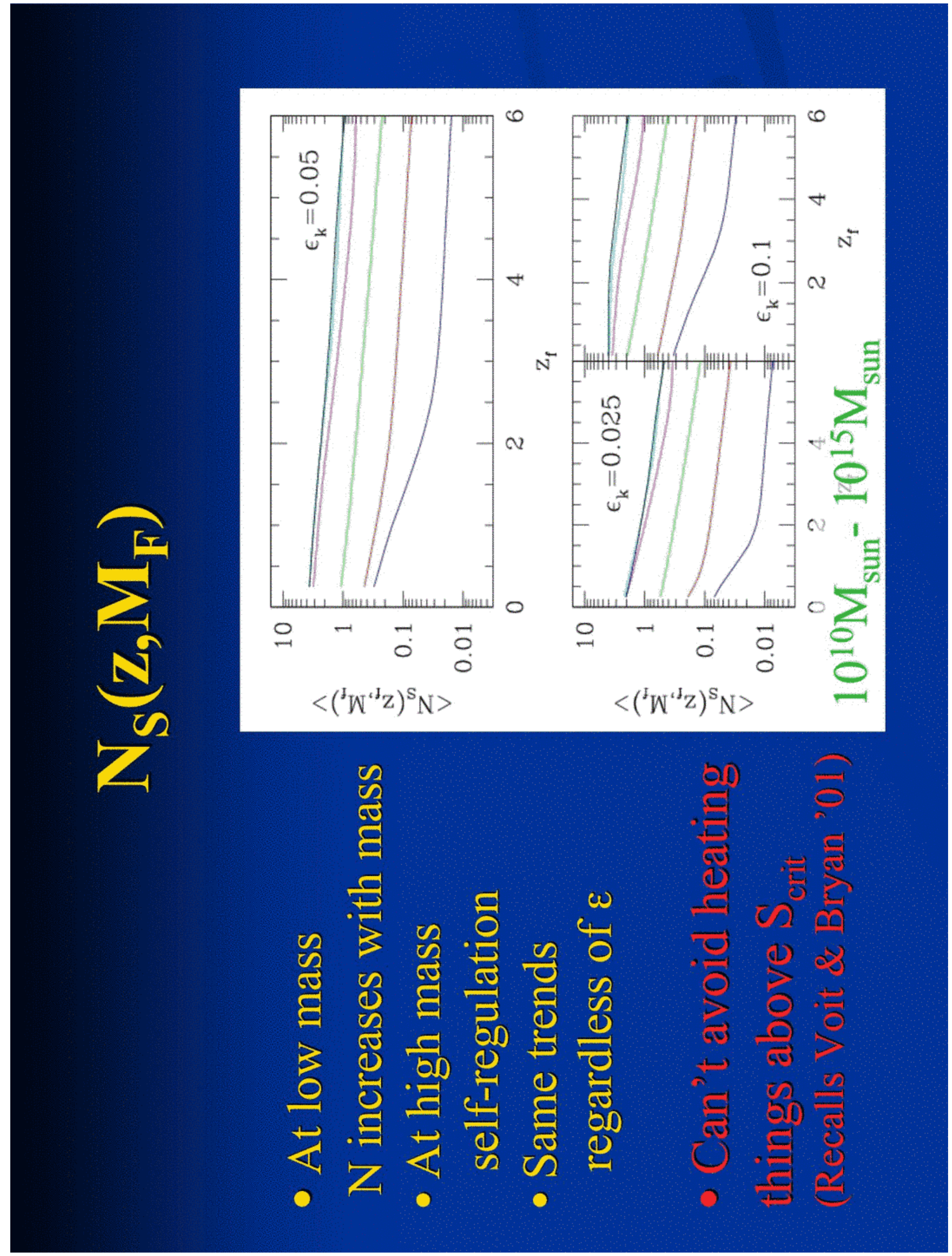
To compute the average number impacting a forming object, you have to account for clustering:

$$N_S(z,M_F) \propto \int_z^\infty dz' \int_{M_{min}}^\infty dM\ b(z,z',M,M_F)\ R_S^3(z,z',M)\ n(z',M)$$

$$\text{Fraction surviving} = 1-\exp[-N_S(z,M_F)]$$

$b(z,z',M,M_F)$ from ES & Barkana (2002)

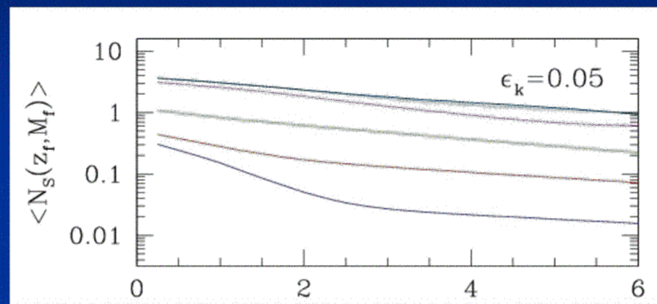

And it works….
$\log_{10}(\xi)$
r [Comoving Mpc]
$\xi(r)$
r [Comoving Mpc]
ES & Thacker (2004)


$N_S(z,M_F)$
• At low mass
N increases with mass
• At high mass
self-regulation
• Same trends
regardless of ε
• Can't avoid heating
things above S_{crit}
(Recalls Voit & Bryan '01)
$\epsilon_k=0.05$
$\epsilon_k=0.025$
$\epsilon_k=0.1$
$<N_S(z_f,M_f)>$
z_f
$10^{10}M_{sun}$ - $10^{15}M_{sun}$

$N_S(z,M_F)$

- At low mass
  N increases with mass
- At high mass
  self-regulation
- Same trends
  regardless of ε

- Can't avoid heating things above S_{crit}
  (Recalls Voit & Bryan '01)



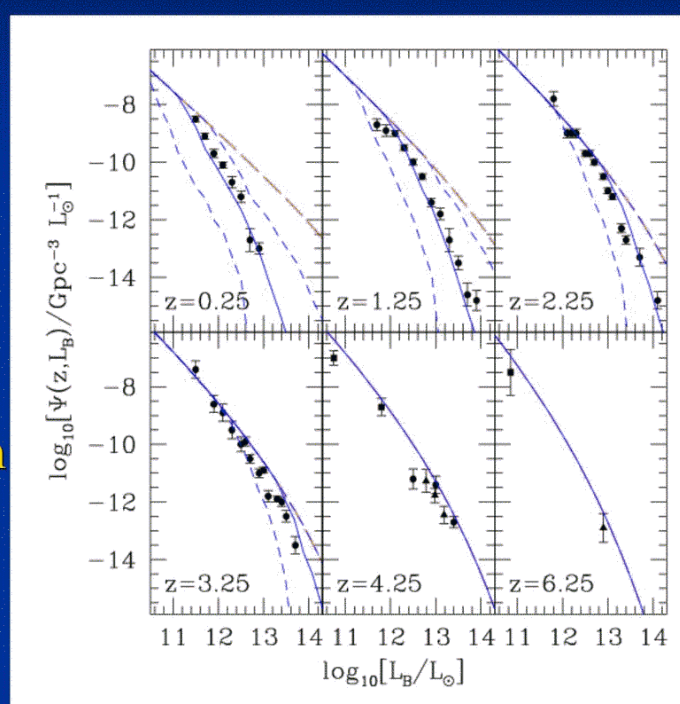
But you put the entropy floor in at the group scale, which smooths things out early to get the profiles at larger radii.

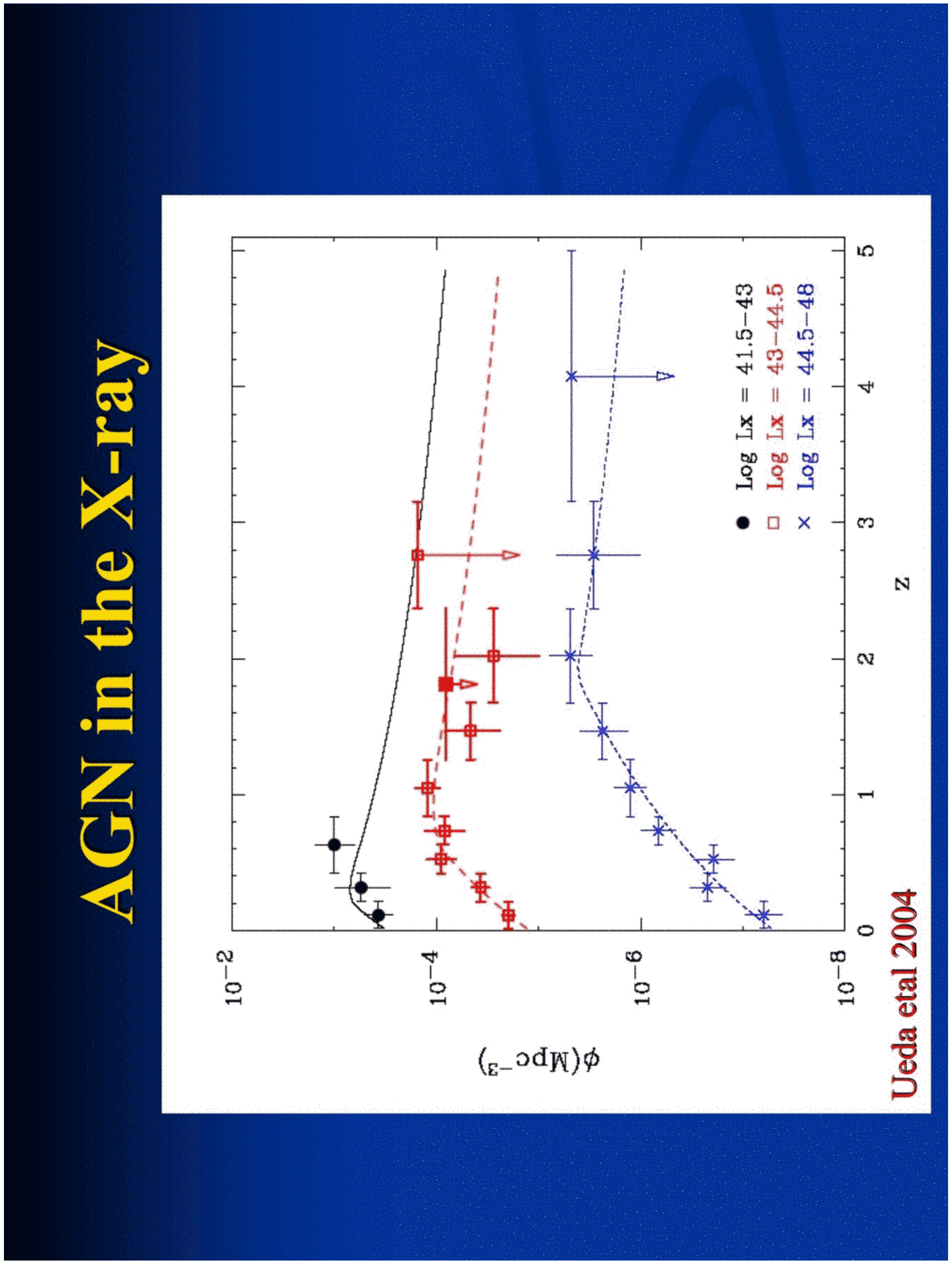
Quasar Luminosity Function

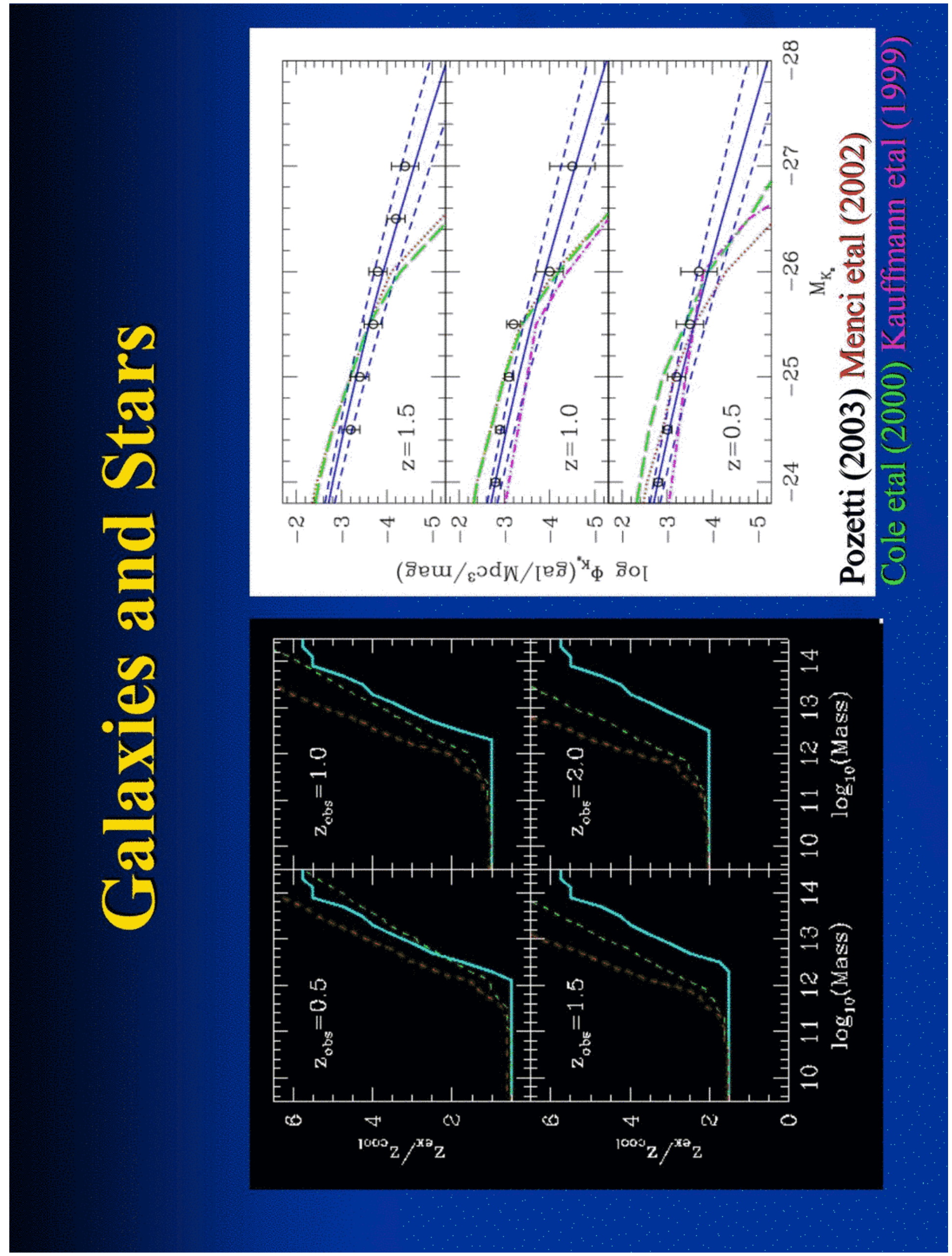
One free parameter reproduces **two** major features:
Turnover redshift
Turnover luminosity

Top Down:

Size of progenitor that can raise S> S_crit becomes smaller as mean density goes down.




AGN in the X-ray
Log Lx = 41.5−43
Log Lx = 43−44.5
Log Lx = 44.5−48
z
φ(Mpc⁻³)
Ueda etal 2004


Galaxies and Stars
z=1.5
z=1.0
z=0.5
log10(Mass)
Pozetti (2003) Menci etal (2002)
Cole etal (2000) Kauffmann etal (1999)

DEEP1/2 and COMBO-17

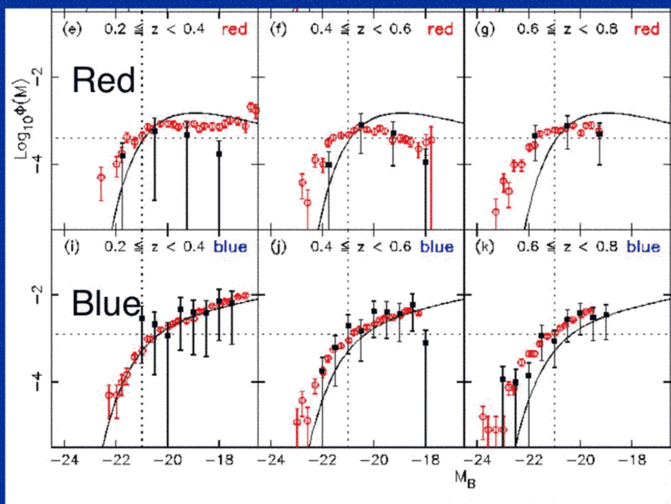
Deep1/2

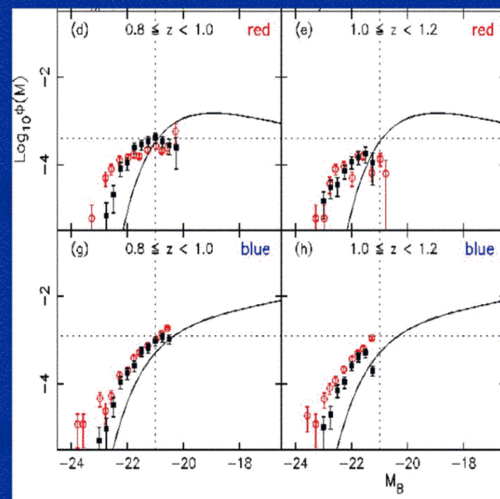
Combo 17

Restframe B band

Red galaxies: L* brightens by about 1.6 mag at z ~ 1, but number density is lower.

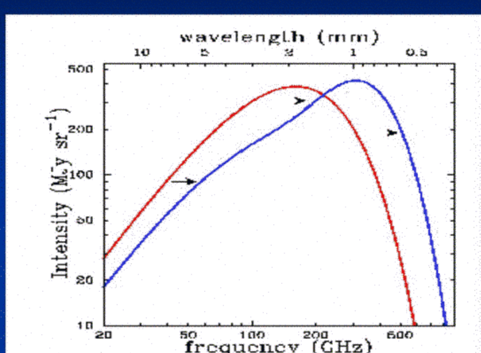
- Blue galaxies: L* brightens by about 0.8 mag at z ~ 1, but number density is constant.





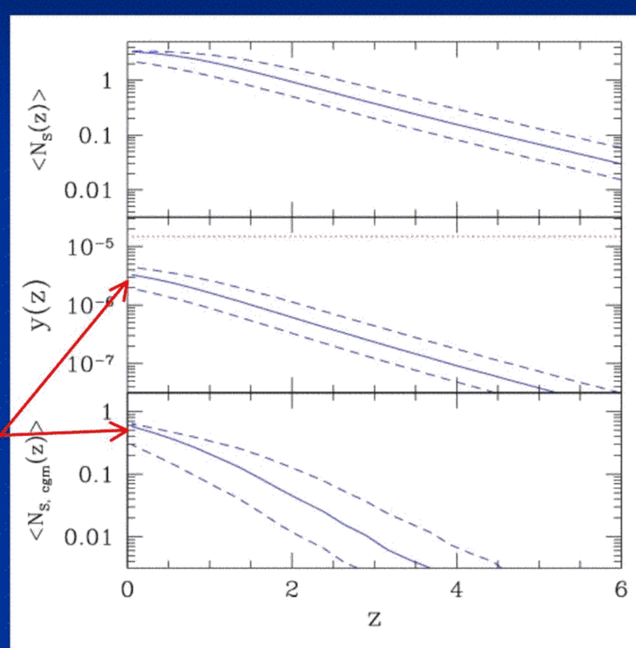
Willmer et al. 2004

Intergalactic Medium



- By z~0 $N_{CGM}(z)$~1, could drastically change "WHIM"

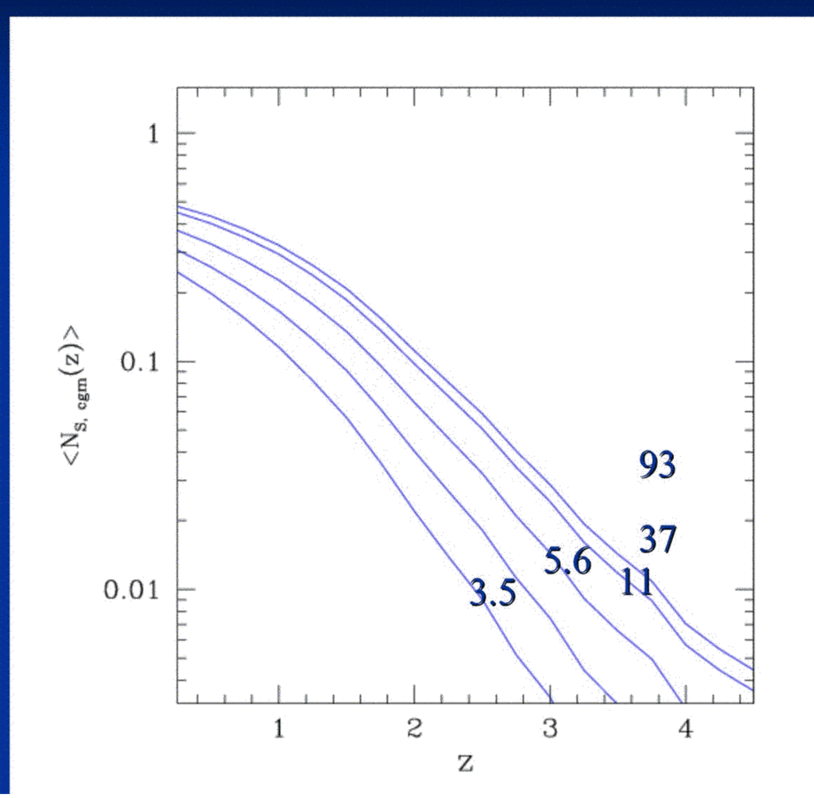
SZ constraints ~10 μK



Conclusions

- Quasar outflows are likely to play a key role in structure formation and IGM physics, much as SNe play a key role in the physics of the ISM.
- On quasar scales, outflows inhibit their own formation, reproducing the characteristic turn over redshift and luminosity in $\Psi(z,L_B)$
- On galaxy scales, quasar outflows fixes L* as the nonlinear scale at the redshift of strong feedback. Afterwards little evolution is expected (as observed)
- On cluster scales, quasar outflows explain why the ICM has been heated to the magic value of 100 keV cm^2cm
- This heating has imposes number of observable features: including CMB distortions, WHIM properties, lack of evolution in X-ray group prop., direct X-ray measurements

Impact as a function of overdensity

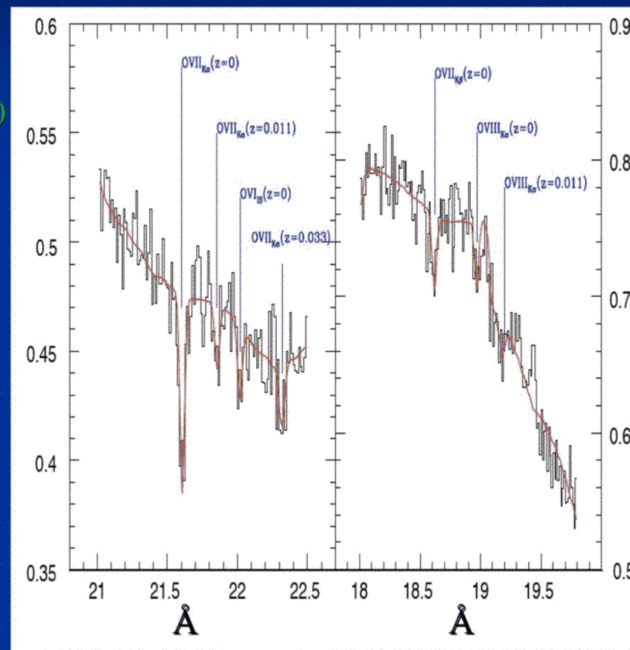


Other Observables

Evolution of disk sizes
$R \propto M^{-1/3} H(z)^{-2/3}$ Mo, Mao, White (1998)
$\propto M^{-1/3} [\Omega_\Lambda + \Omega_\Lambda (1+z)^3]^{2/3}$

cluster sizes do not evolve with redshift, first hint of preheating

May be an important heating source for the local WHIM: UV measurements, X-ray forest



Nicastro etal (2003)