

Cosmological growth of supermassive black holes: constraints on radiative and kinetic energy feedback

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Outline

- SMBH as an evolving population: Integral constraints
- AGN downsizing: the role of accretion models
 - The “radio mode” of AGN growth
- Putting everything together: AGN evolution synthesis models
 - Radiative vs. kinetic energy output
- Open questions



I. AGN evolution: Integral constraints

AGN and Cosmology: (very) early developments

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LETTERS TO THE EDITOR

ASTRONOMY

Evidence on the Evolutionary Character of the Universe derived from Recent Red-shift Measurements

Hoyle and Burbidge¹ have recently examined the red-shifts of a number of quasi-stellar radio sources^{2,3} and have plotted their radio flux densities (S) against red-shift (z); they conclude that the results are inconsistent with a cosmological interpretation of these red-shifts.

This communication shows that this conclusion is not valid and that indeed the observed relationship between S and z provides valuable new information on the evolutionary nature of the Universe.

If, on the other hand, the flux density is attributed to a source of luminosity L , it must be modified by the evolution of the source. As shown, the luminosity L varies with epoch t by $L \propto t^{-\alpha}$ where α is the limiting value to be drawn. The types of evolutionary distribution of luminosity density have been carried out by Hoyle and Burbidge¹ restricted to $S_{178} \geq 8 \times 10^{-14} \text{ W m}^{-2}(\text{c/s})^{-1}$.

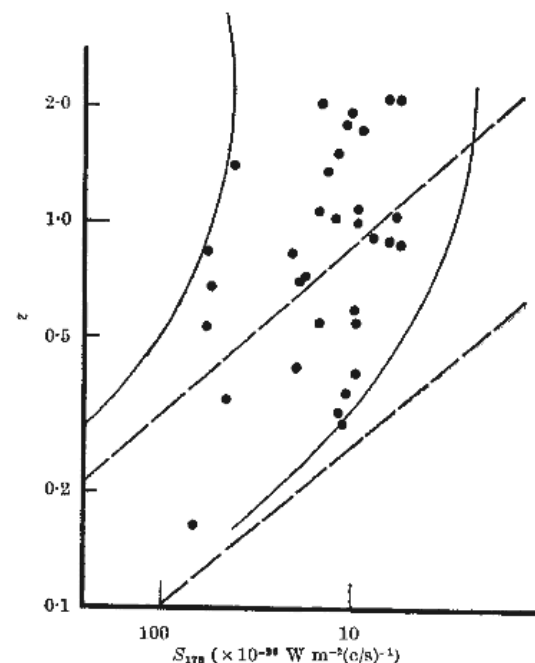
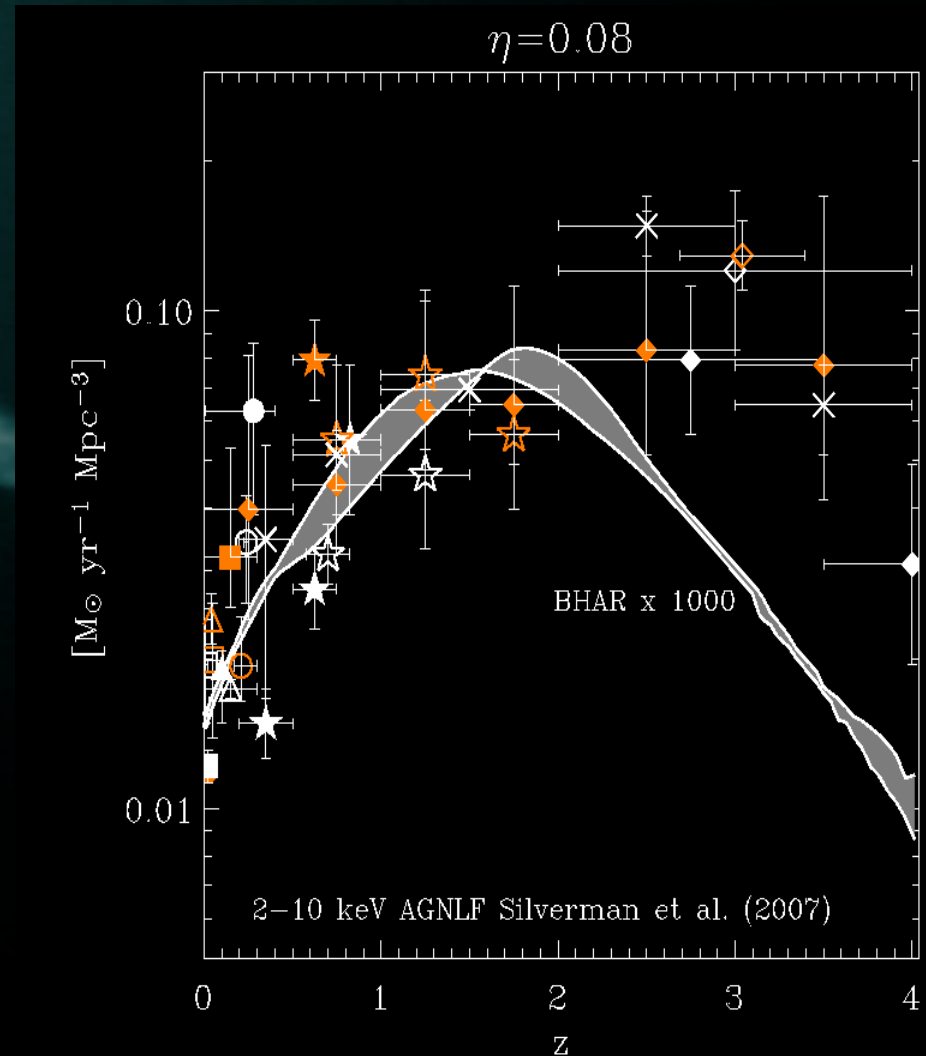


Fig. 1. The red-shift flux density plots expected in evolutionary cosmologies in which density evolution (dashed lines) and luminosity evolution (full lines) are included. The distribution of observational points is that presented by Hoyle and Burbidge restricted to $S_{178} \geq 8 \times 10^{-14} \text{ W m}^{-2}(\text{c/s})^{-1}$.

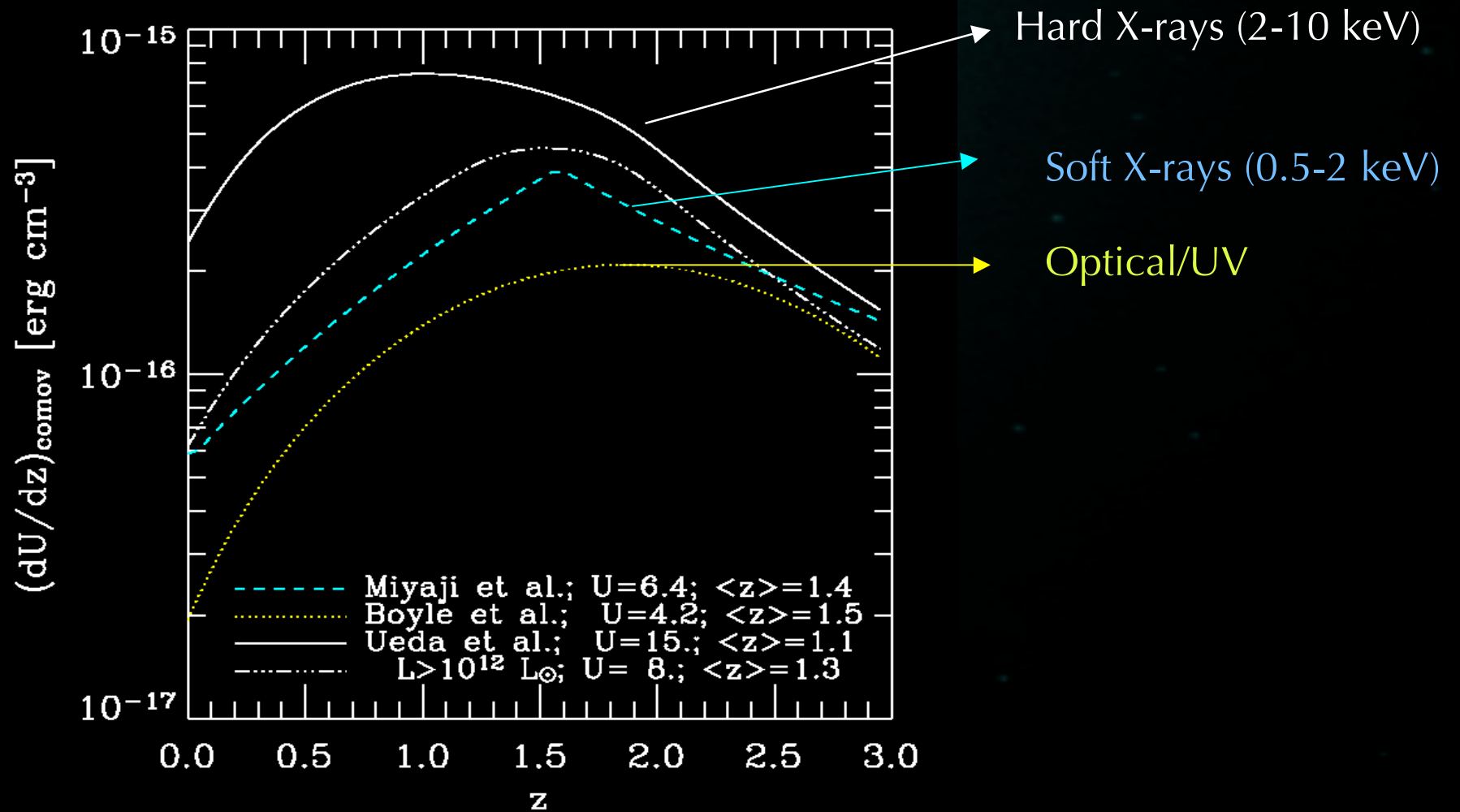
Longair 1966

AGN and Cosmology: a shift of paradigm

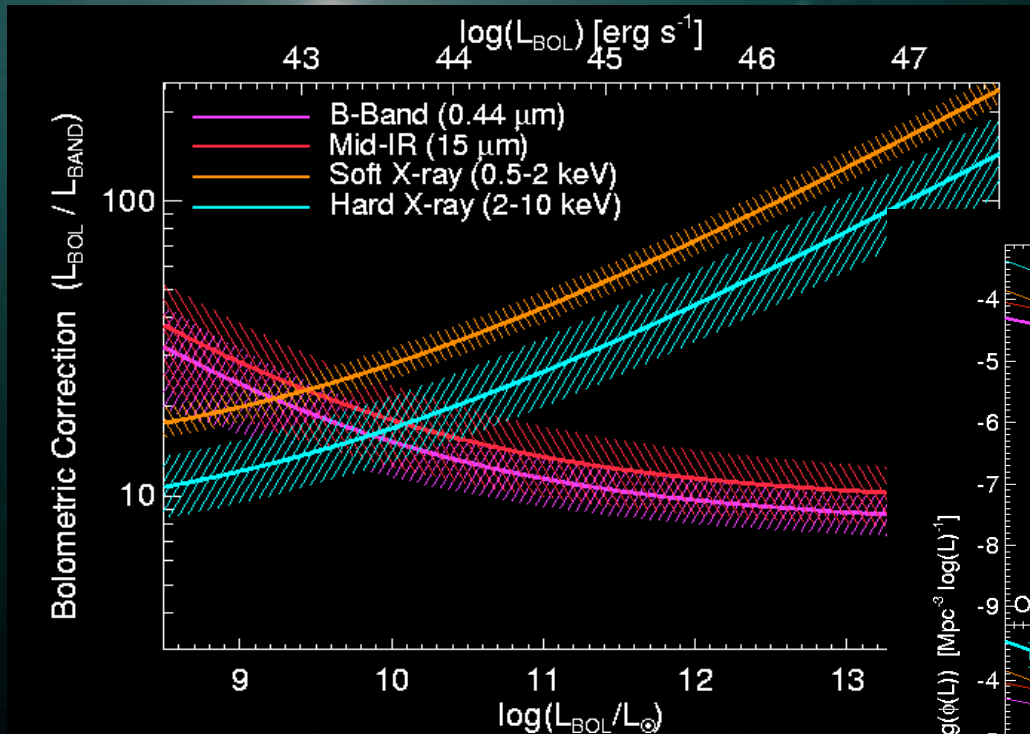
- Nowadays QSOs/AGN can:
 - Regulate galaxy formation
 - Stop cooling flows
 - “produce” early type galaxies with the right colors
 - Keep the universe ionized
- QSOs/AGN tracks the history of star formation in the Universe



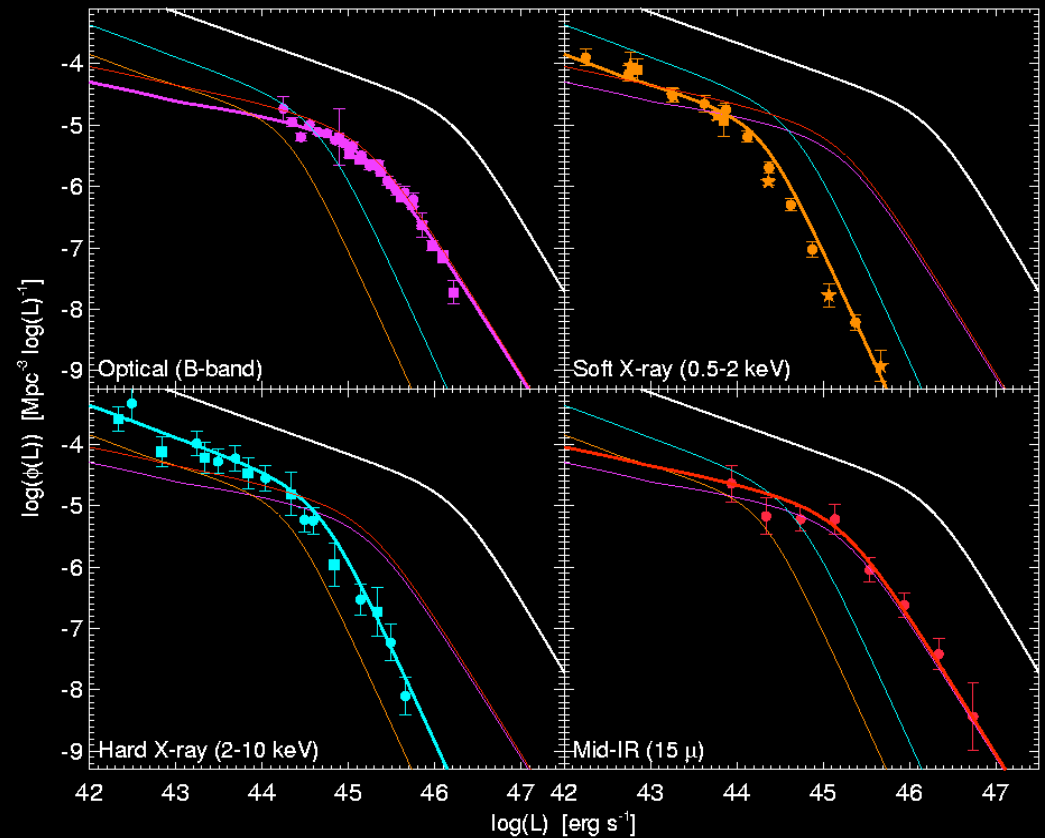
Recent progresses in AGN activity census



Bolometric corrections robustness



Crucial: varying X-ray bolometric correction with luminosity (Marcori et al 2004)



Hopkins et al 2006

Integral constraints

- Soltan (1982) first proposed that the mass in black holes today is simply related to the AGN population integrated over luminosity and redshift

$$L_{\text{bol}} = \epsilon \dot{M}_{\text{acc}} c^2 = \epsilon \dot{M}_{\bullet} c^2 / (1 - \epsilon)$$

Bolometric luminosity

Accretion rate

BH growth rate

Radiative efficiency

- The integrated X-ray background light (the band most strongly dominated by AGN radiation) can be used instead of the AGNLF

$$\rho_{\text{BH,XRB}}(z=0) = (1 + \langle z \rangle) \frac{(1 - \epsilon)}{\epsilon c^2} U_{\text{XRB}}^{\text{X}} \rightarrow \text{Bolometric correction}$$

Mean redshift of XRB sources

XRB energy density

Note: radiative efficiency vs. accretion efficiency

radiative efficiency

accretion efficiency (BH spin)

$$\epsilon \equiv \epsilon(a, \dot{m}, \dot{m}_{\text{cr}}) = \eta(a) f(\dot{m}, \dot{m}_{\text{cr}})$$

Non Spinning BH

$$0.06 \leq \eta(a) \leq 0.42$$

Maximally Spinning BH

$$f(\dot{m}, \dot{m}_{\text{cr}}) = \begin{cases} 1, & \dot{m} \geq \dot{m}_{\text{cr}} \\ \dot{m}/\dot{m}_{\text{cr}}, & \dot{m} < \dot{m}_{\text{cr}} \end{cases}$$

Determined by the complex physics of gas accretion

Integral constraints: early results

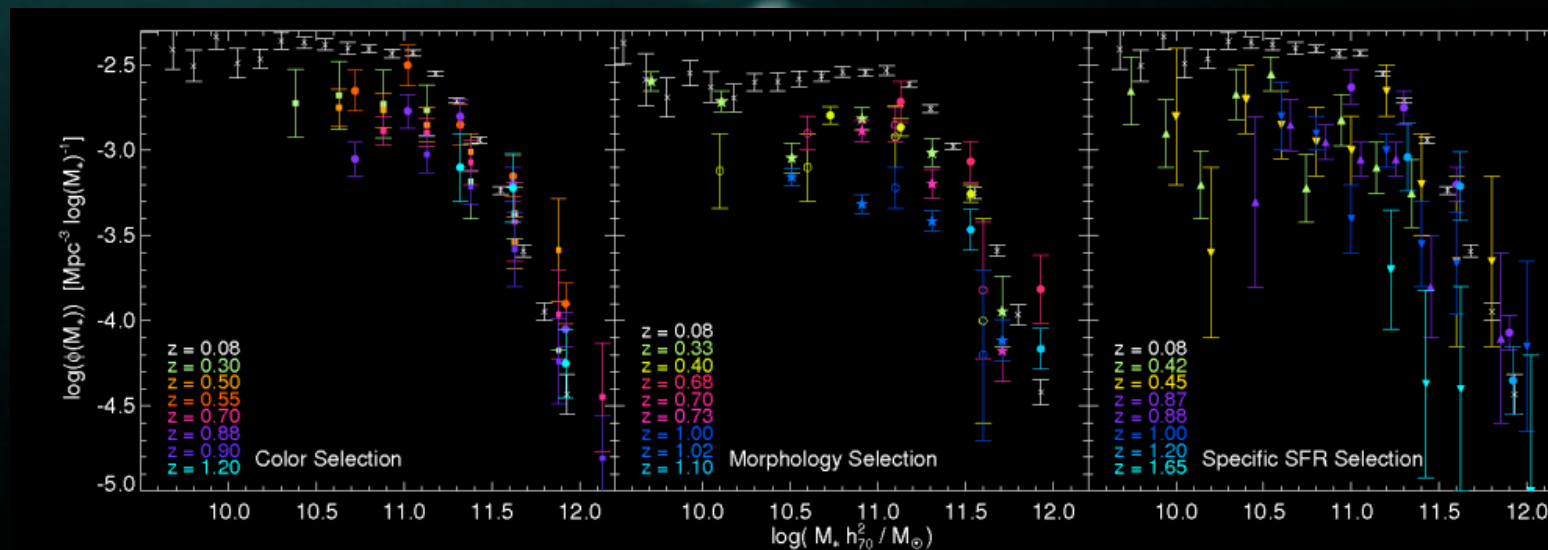
- Fabian & Iwasawa (1999) consistency between XRB and local BH mass density: no need for significant low-efficiency accretion
- Elvis, Risaliti & Zamorani (2002) compared XRB with local BH mass density: Need for high efficiency $\epsilon > 0.15$
- Yu & Tremaine (2002) compared local BH mass function with QSO LF evolution (2dF): high efficiency ($\epsilon > 0.1$) for luminous objects
- Marconi et al. (2004): Higher local BH mass function with hard X-ray selected AGN LF: $0.16 > \epsilon > 0.04$
- Merloni et al. (2004) degeneracy between ϵ and local relic mass function: $0.12 > \epsilon > 0.04$



**II. Beyond integral constraints: AGN
downsizing and radio vs. QSO modes**

Downsizing in galaxy evolution

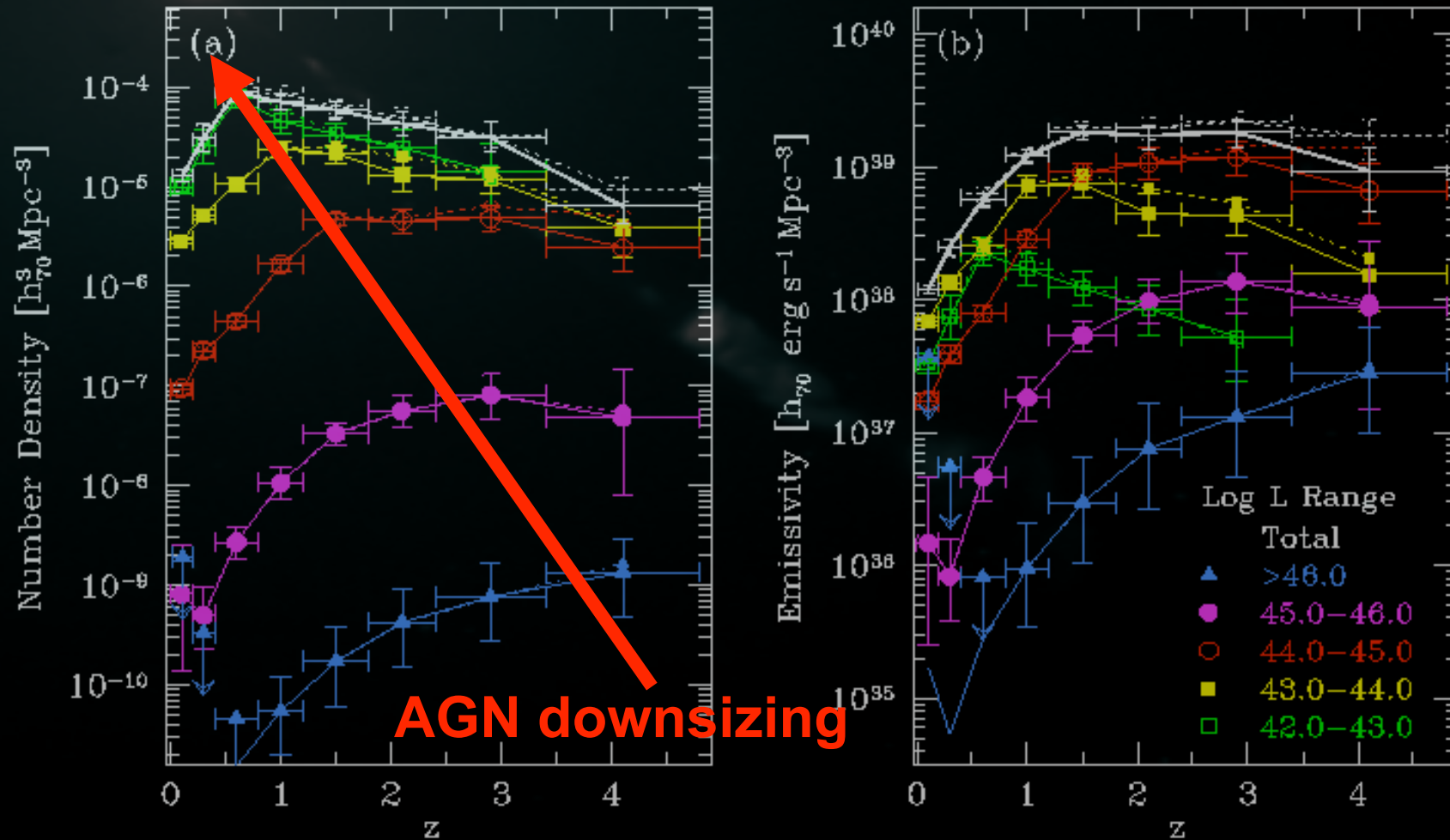
- **DOWNSIZING:** The most active star forming objects have smaller mass at lower redshift
- **ANTI-HIERARCHICAL:** Larger objects form (assemble) later
- NOTE: in principle, the observational fact that the most massive ellipticals have the oldest stellar population does not imply a anti-hierarchical evolution



Hopkins et al 2007

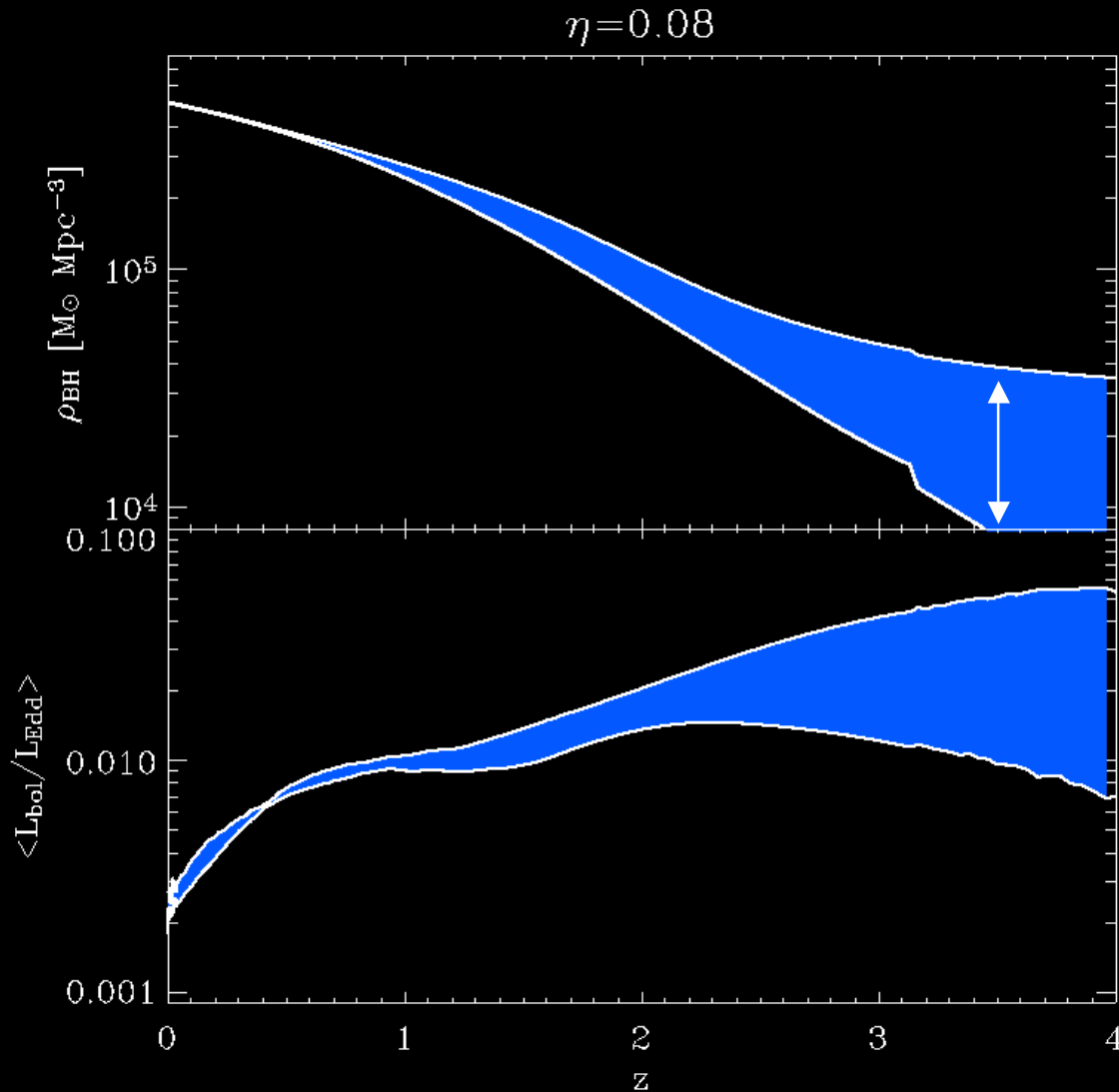
Cowie et al. 1996; Thomas et al. 2003; Heavens et al. 2004; Kodama et al 2004; Feulner et al. 2005; Juneau et al. 2005; Bundy et al. 2005; Treu et al. 2005; De Lucia et al. 2005; Perez-Gonzalez et al. 2005; Bundy et al. 2006; Cimatti et al. 2006; Neistein et al. 2006

AGN/SMBH downsizing: clues from X-rays



Ueda et al. 2003; Fiore et al. 2003; Barger et al. 2005; Hasinger et al. 2005

SMBH mass density and mean accretion rate



Uncertainty in BH mass density @ z_0
is the cumulative uncertainty in
XLF for $z < z_0$

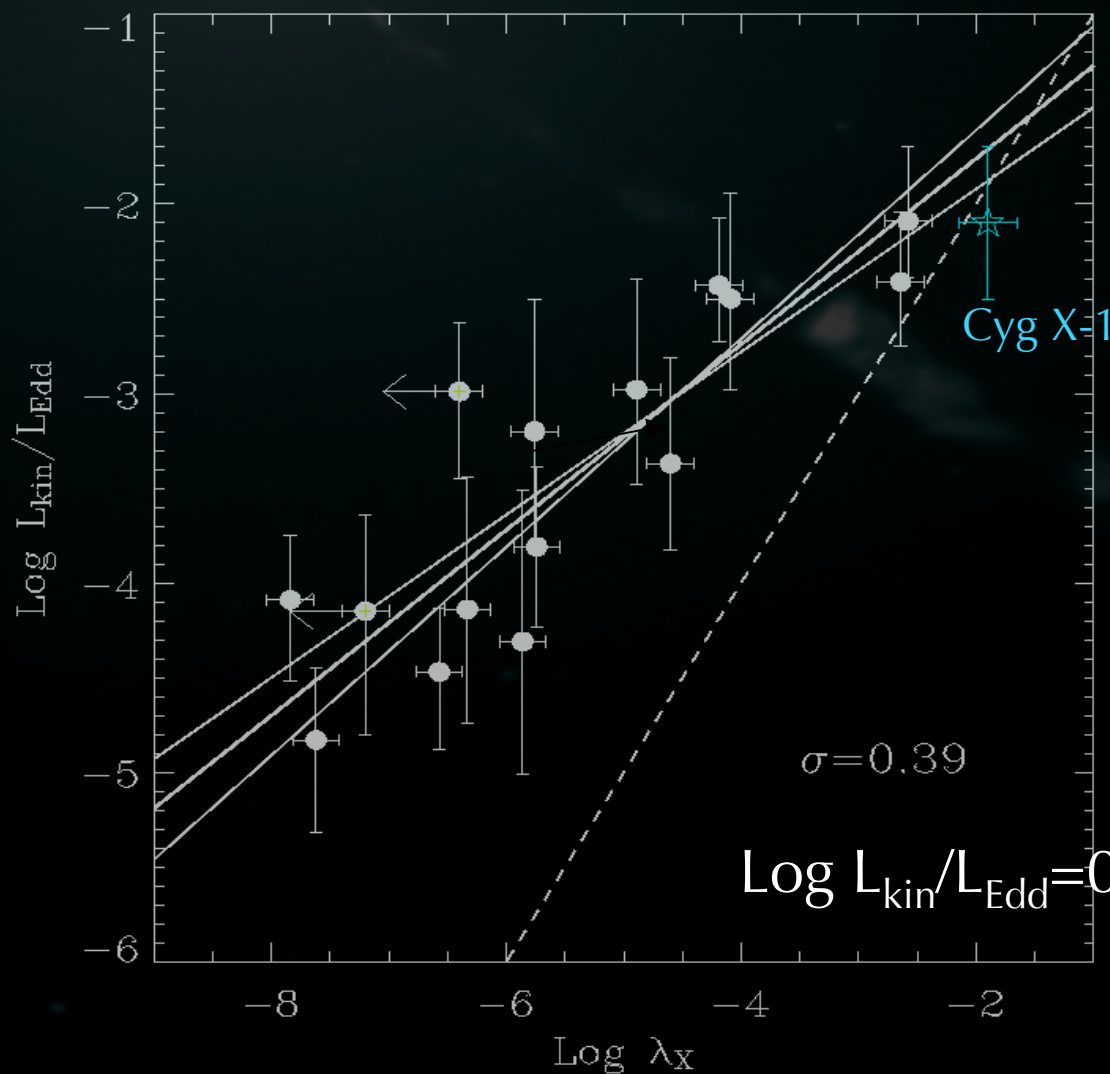
Ratio of radiative energy density
To black hole mass density

See e.g Merloni 2004

AGN downsizing: changing accretion modes

- SMBH must accrete at lower (average) rates at later times
- Accretion theory (and observations) indicate that
 - The energy output of an accreting BH depends crucially on its accretion rate
 - Low-accretion rate systems tend to be “jet dominated”
- It is important to distinguish between **bright Quasar** mode and **Radio mode**

Low Power AGN are jet dominated



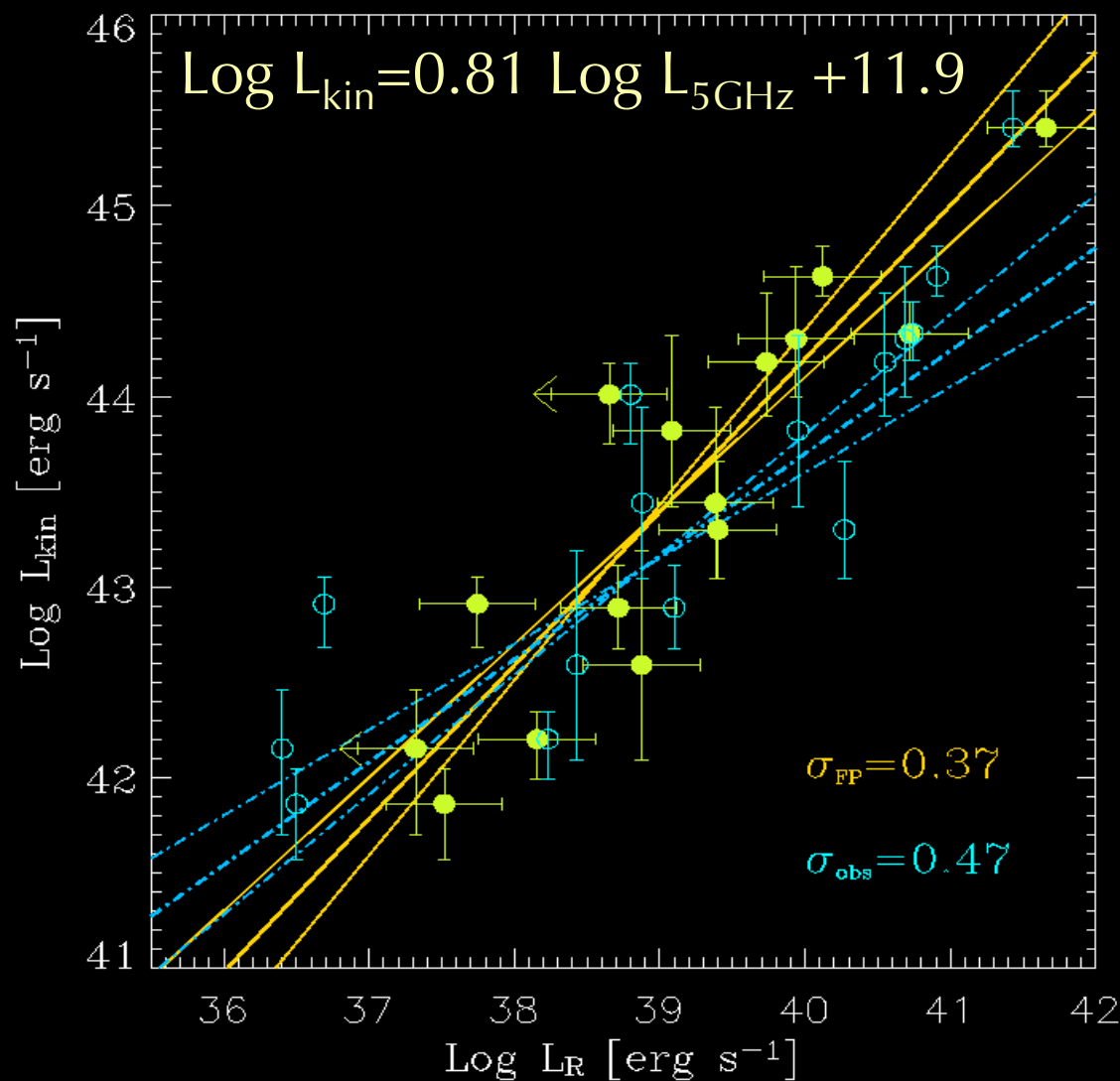
- By studying the nuclear properties of the AGN we can establish a link between jet power and accretion power
- The observed slope (0.50 ± 0.045) is perfectly consistent with radiatively inefficient “jet dominated” models (see E. Churazov’s talk)

Merloni and Heinz (2007)

What is the “radio mode” of AGN?

- The energy source that counterbalance cooling in the cores of groups and clusters. Prevents overproduction of massive galaxies at late times (a **FEEDBACK** mode; **Croton et al. 2006; Bower et al. 2006**)
 - **CANNOT** be associated to QSOs: their number density declines too fast
- A **FEEDING** mode (hot gas vs. cold gas, **Hardcastle et al. 2007**)
- That associated with bubbles, cavities and ripples seen in the hot X-ray emitting gas (=radio galaxies)
- **HERE**: The physical state of ALL black holes at low accretion rate ~less than a few % of the Eddington rate (an **ACCRETION** mode)

Core Radio/ L_{Kin} relation: effects of beaming



Slope=0.81

Slope=0.54

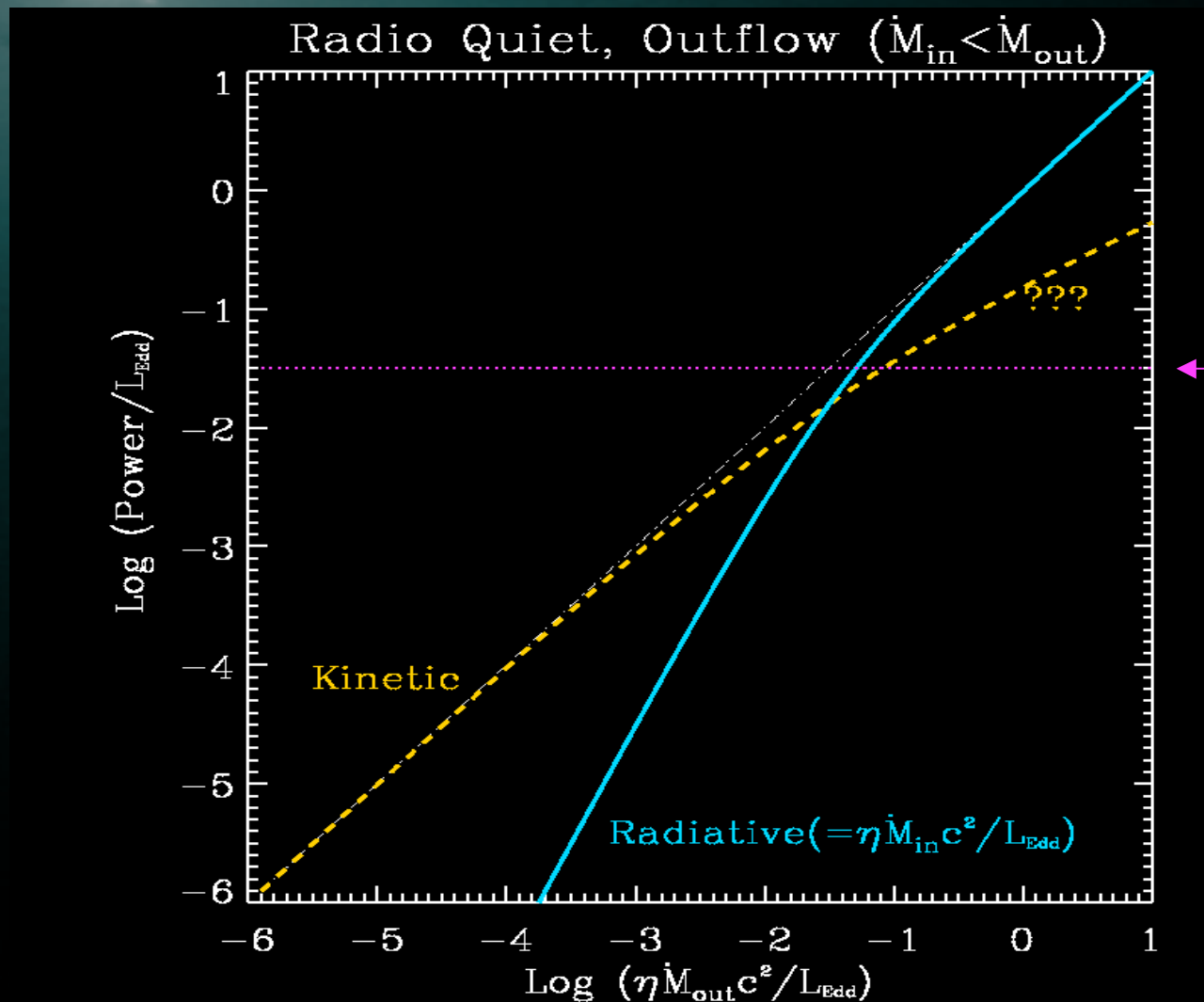
Observed L_{R} (beaming)
Derived from FP relation

Monte Carlo simulation:
Statistical estimates of
mean Lorentz Factor $\Gamma \sim 8$


Not a distance effect:
partial correlation analysis
 $P_{\text{nul}} = 2 \times 10^{-4}$

Merloni and Heinz (2007)

Accretion diagram for LMXB & AGN

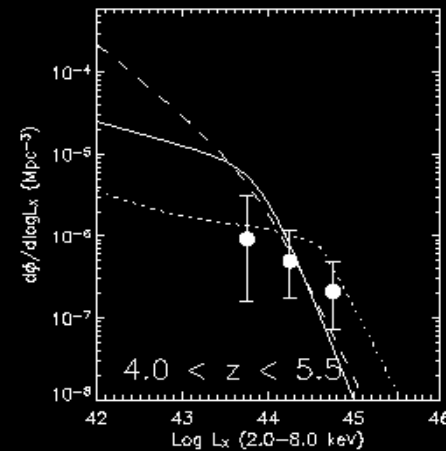
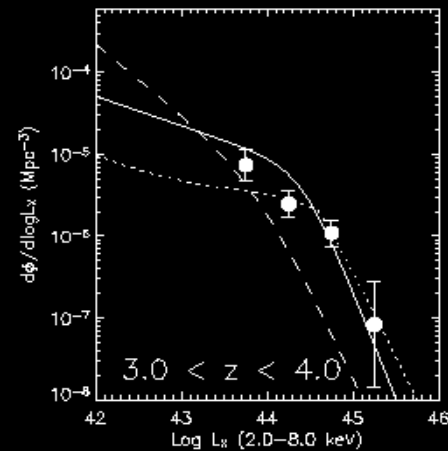
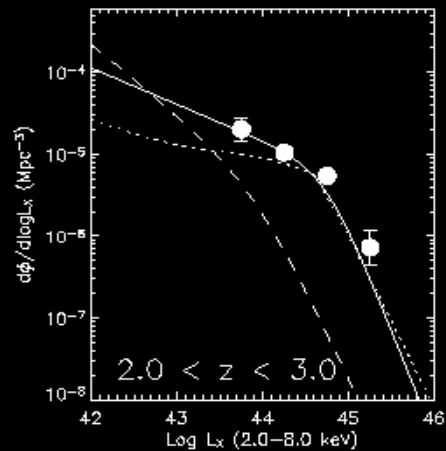
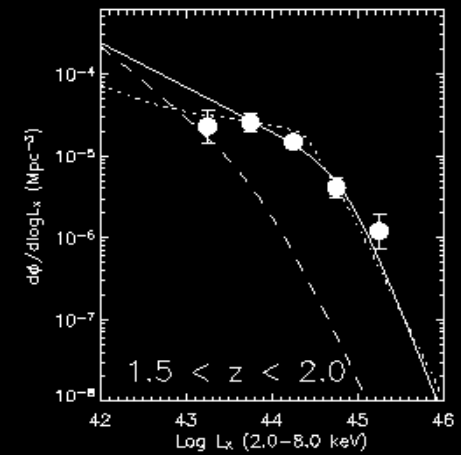
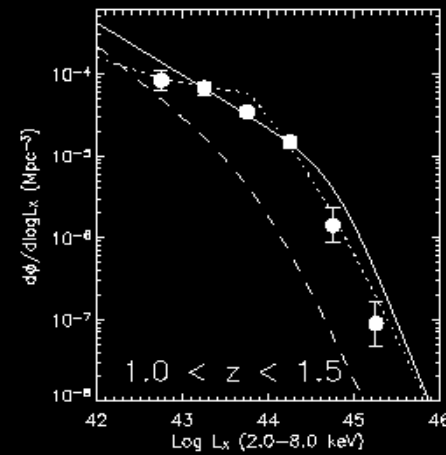
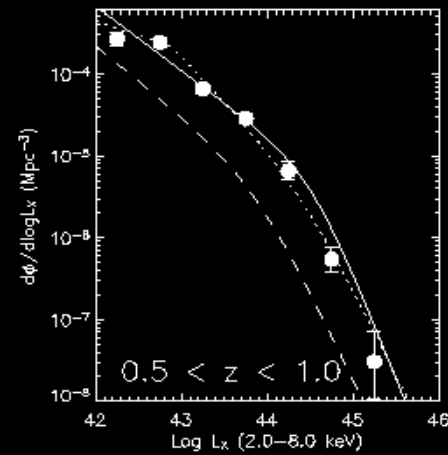
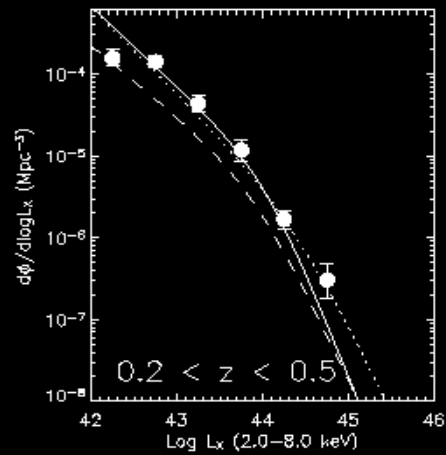


(Blandford & Begelman 1999)



**III. Putting everything together:
AGN evolution synthesis models**

2-10 keV Luminosity Functions of AGN

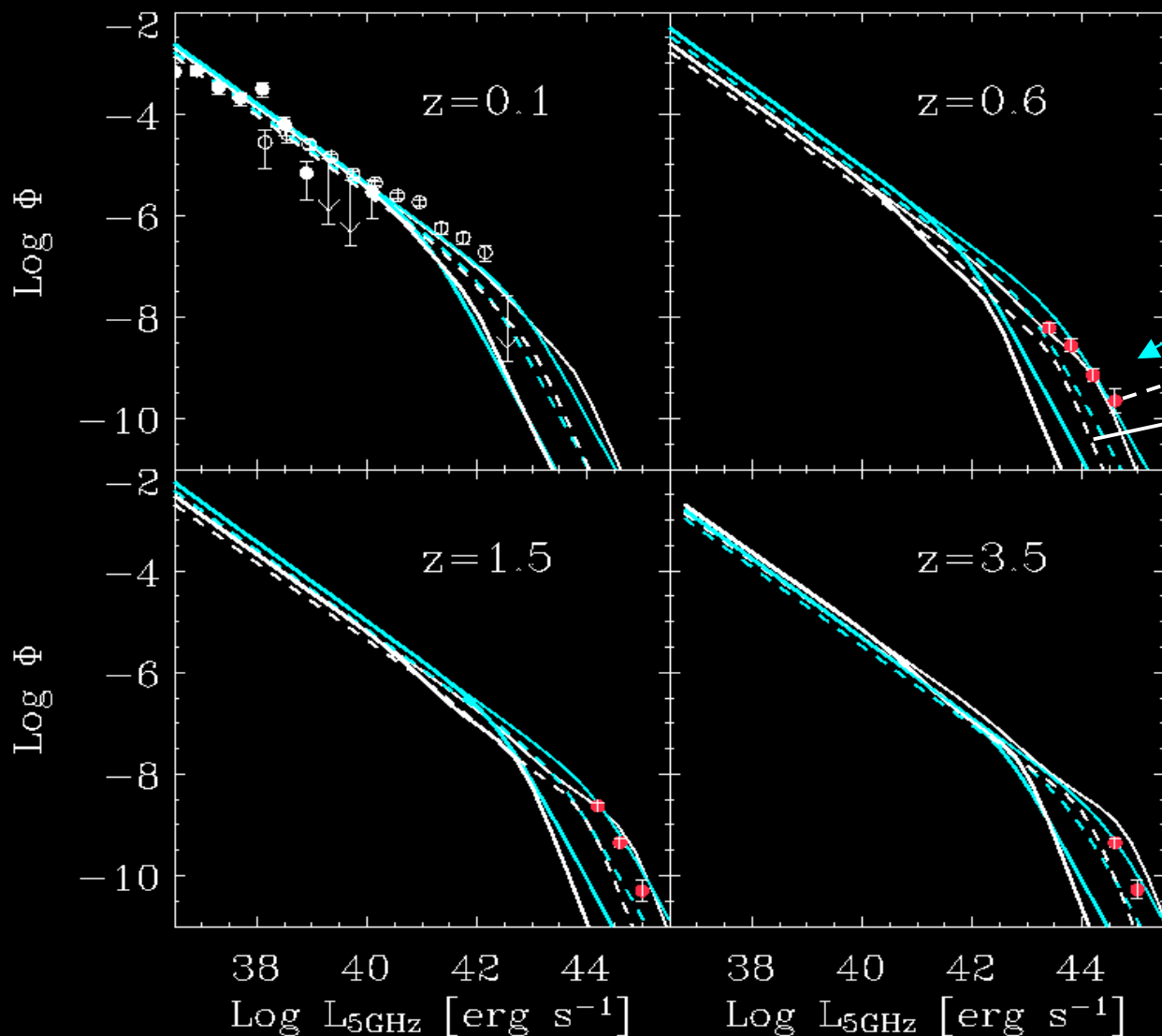


Solid lines: mod. PLE
Dotted lines: LDDE

(Silverman et al. 2007)

Corrected for absorption with Gilli et al. 2007 N_H distribution

Flat Spectrum radio LF: de-beaming



$$L^* \cong L^*_{,\text{obs}} / \delta_{\text{max}}^2$$

$$\Phi^* \cong \Phi^*_{,\text{obs}} / \Delta$$

$$\Delta \cong 2^{(2a-3)} \Gamma^{(2a-4)} / (2a-3)$$

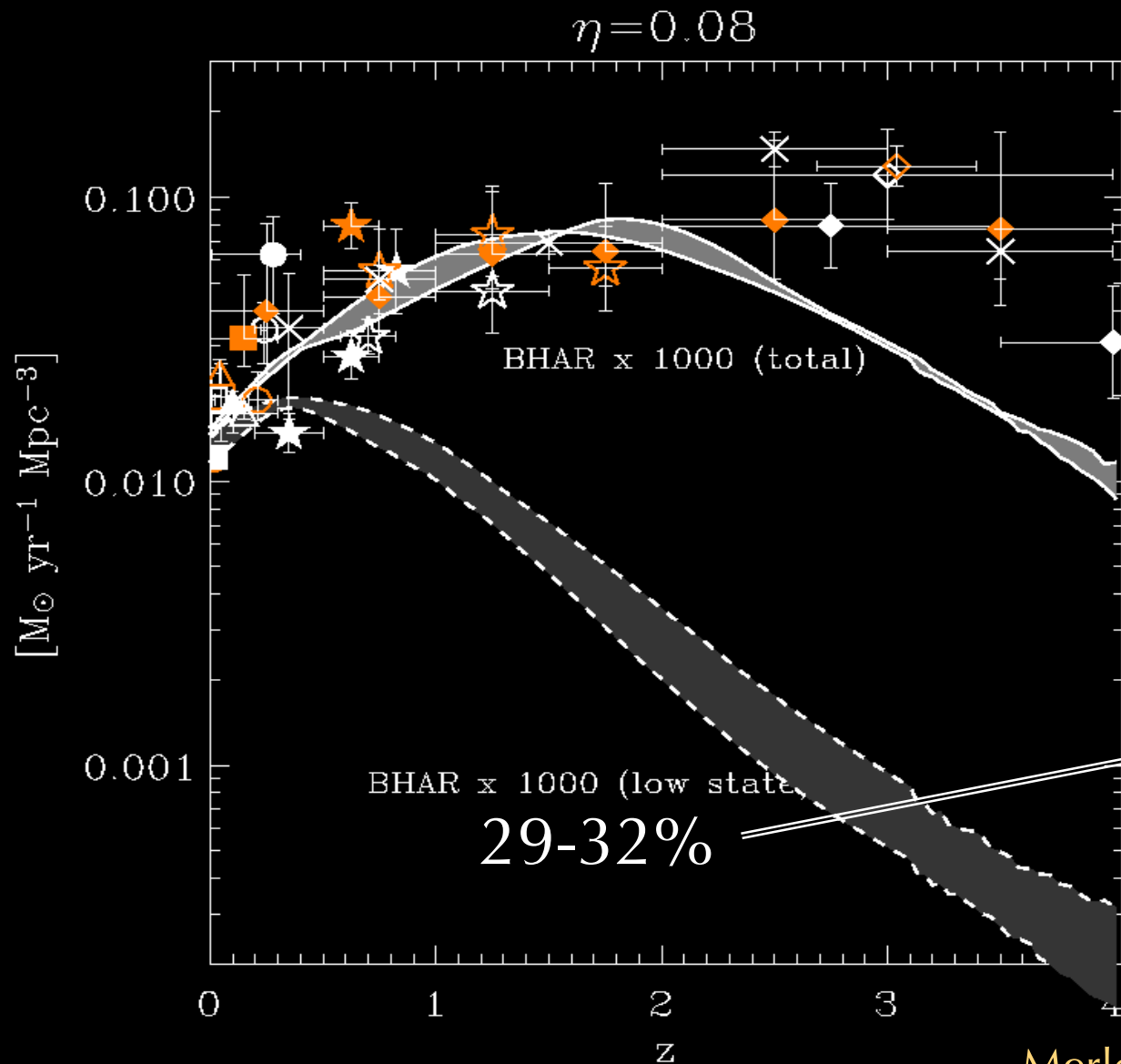
“Observed” FSRLFs

$\langle \Gamma \rangle = 2$

$\langle \Gamma \rangle = 8$

Local data points from
 Filho, Barthel & Ho (2006)
 High-z data
 Wall et al. (2005)
 RLF models from
 De Zotti et al. (2005)
 Dunlop & Peacock (1990)
 Beaming model from
 Urry & Schaefer (1984)
 Urry & Padovani (1991)

SMBH growth

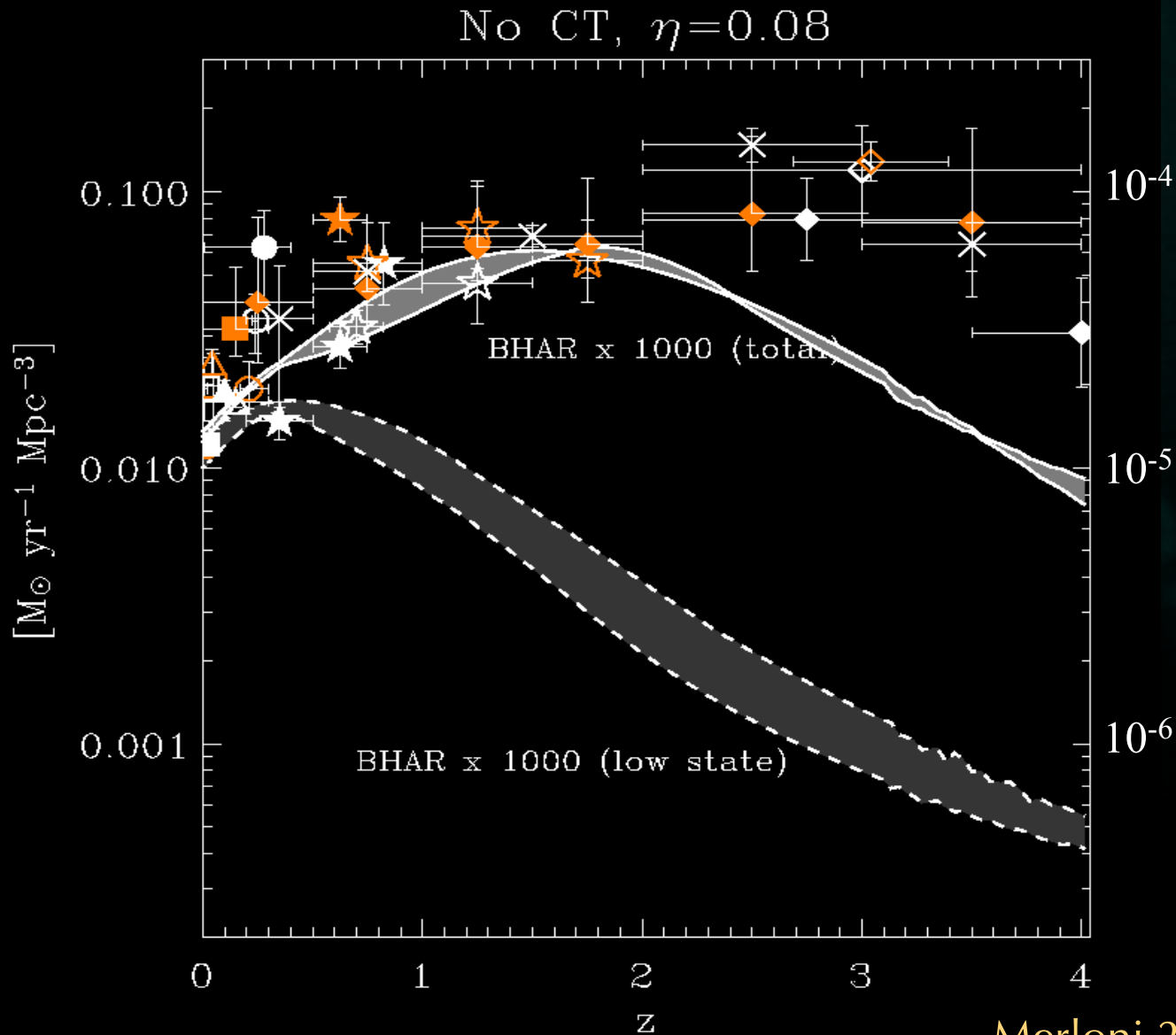


1) Most of
SMBH growth in
radiatively
efficient mode

$\epsilon \approx 0.04-0.05$
Marconi et al. (2004)

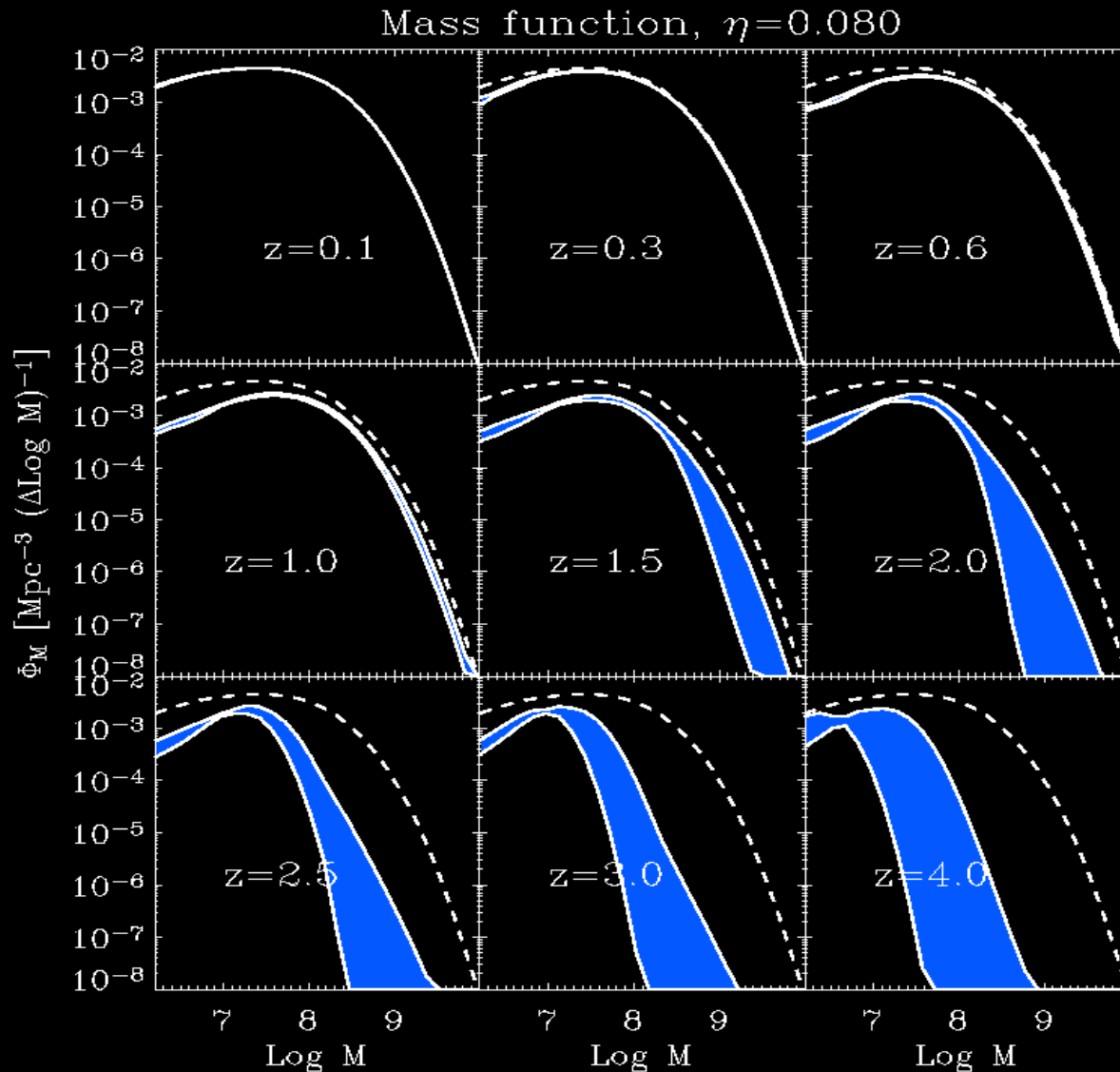
Merloni 2004; Merloni, in prep.

SMBH growth



2) Contribution of Compton Thick sources is about 15-20 % of accreted mass

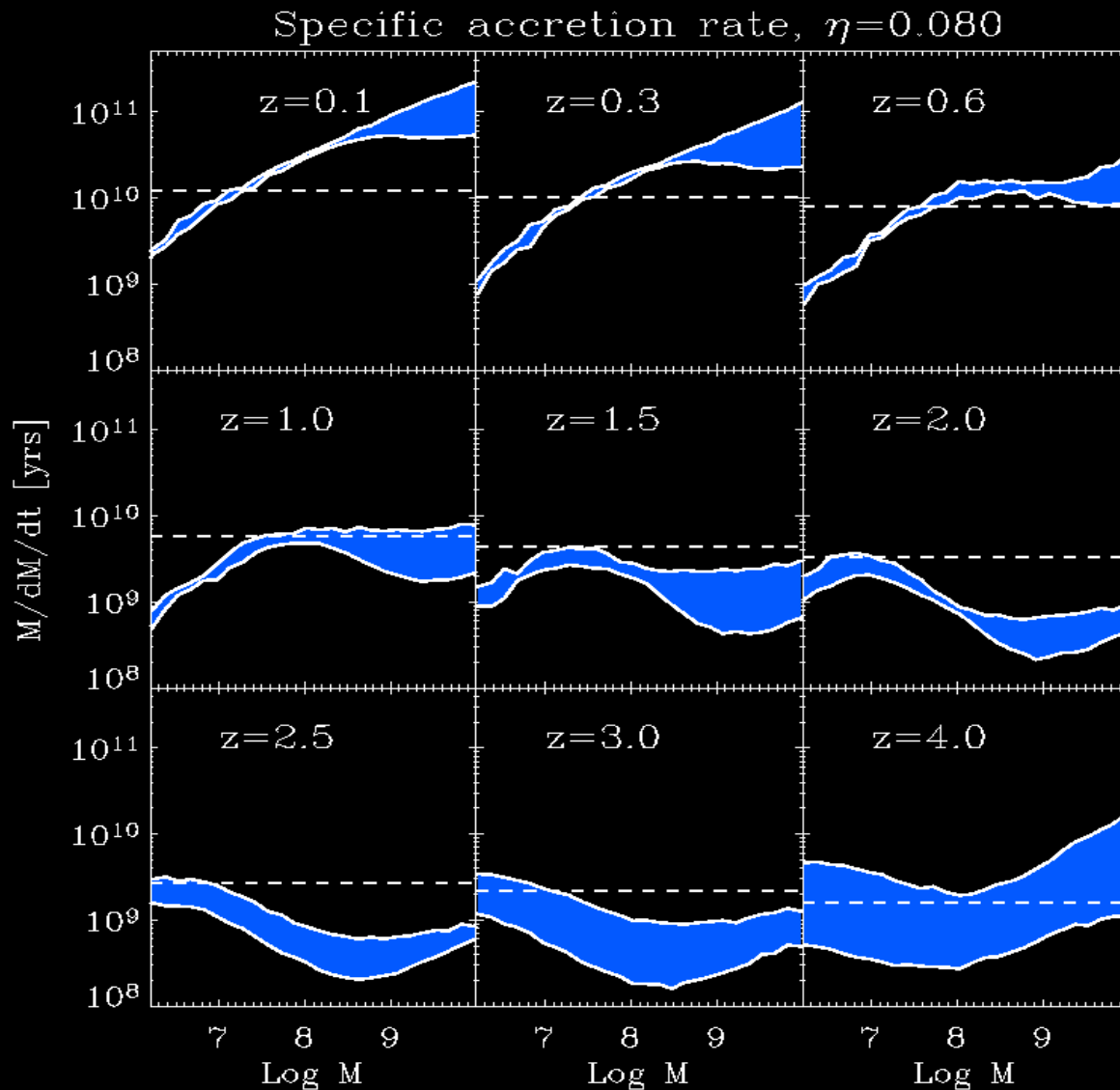
SMBH mass function



Solved continuity equation backwards in time (Small and Blandford 1992, Marconi et al. 2004)

Merloni in prep.

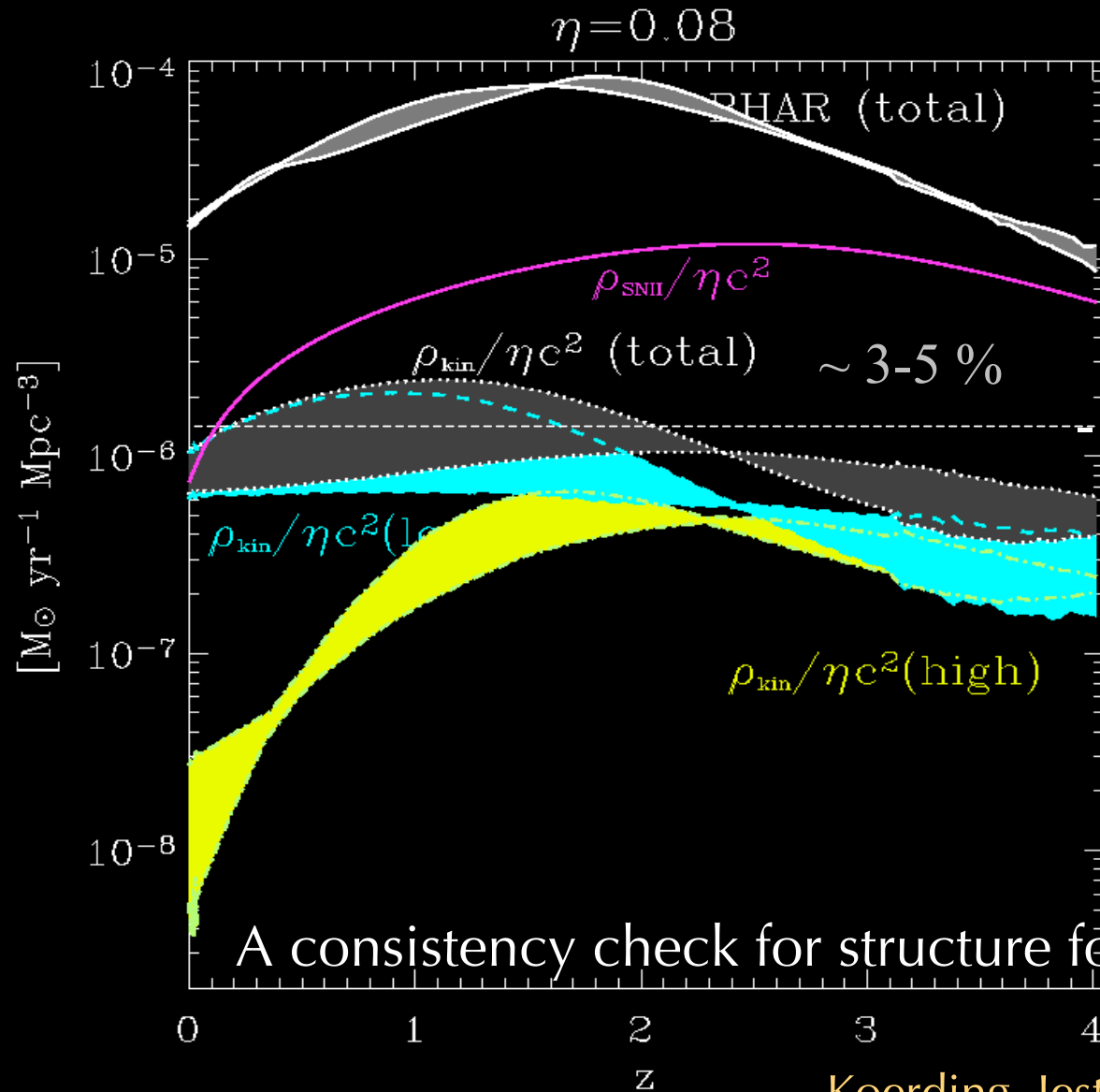
SMBH specific accretion rate



The anti-hierarchical evolution at low z seems **reversed** at high z

Merloni in prep.

Kinetic Energy output and SMBH growth



SN II K.E. output rate from SFR
(Hopkins & Beacom 2006)

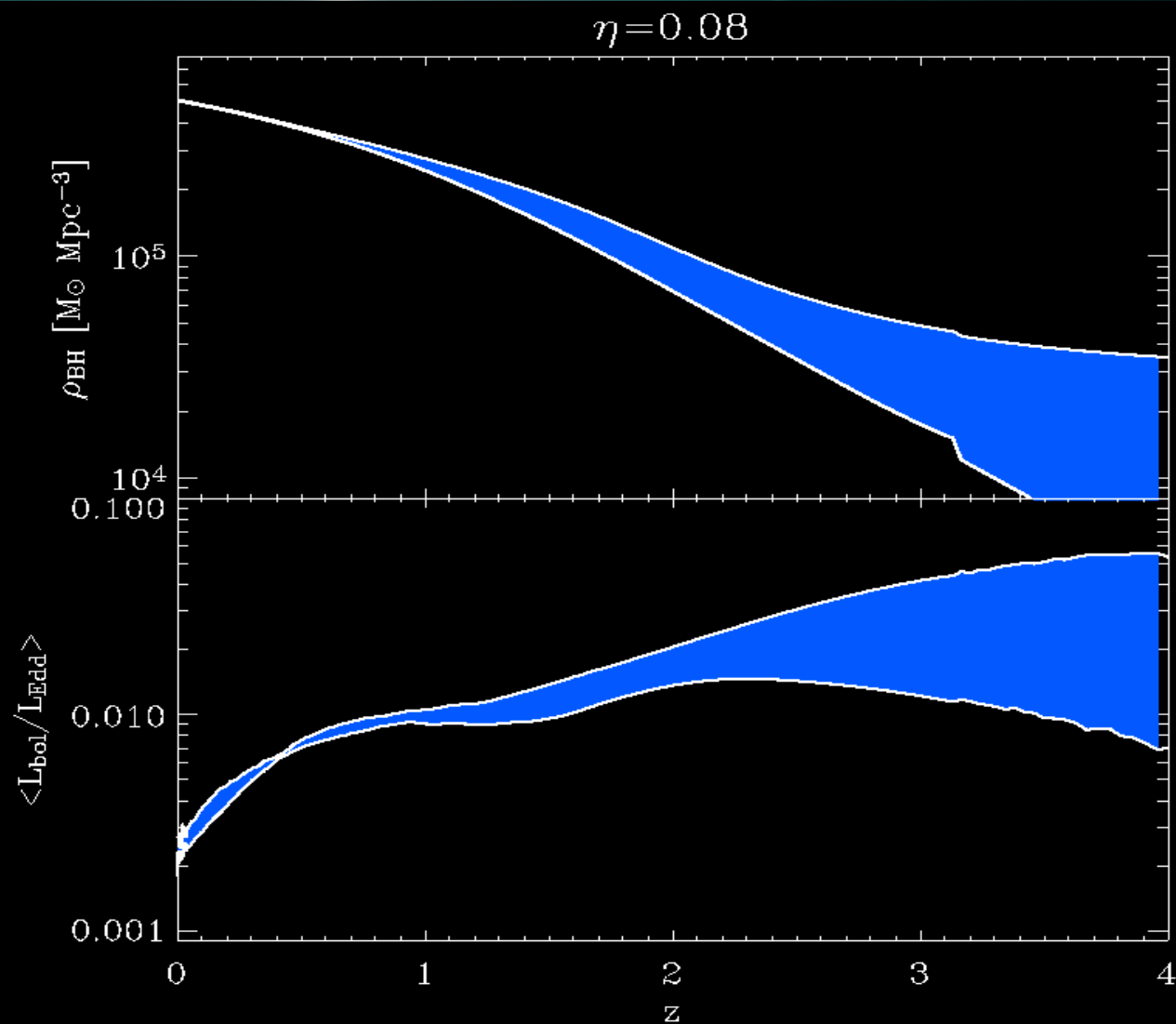
In the local universe,
kinetic feedback is
dominated by
low luminosity objects
("radio mode" AGN)

A consistency check for structure formation models

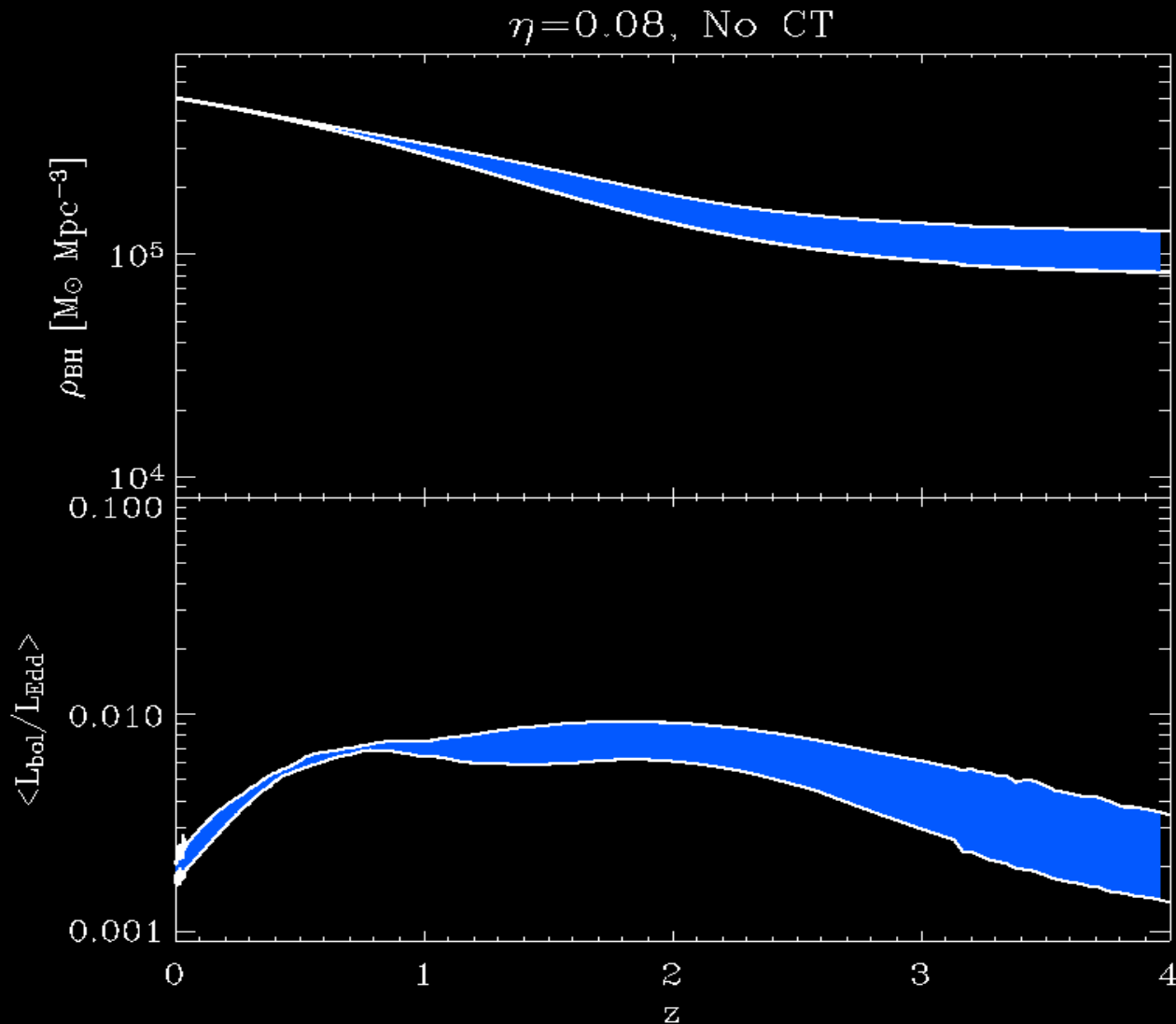
Conclusions

- Most of SMBH growth occurred in **radiatively efficient** episodes of accretion. CT sources contribute about 20% of the relic mass
- The anti-hierarchical trend is clearly seen in the low- z evolution of SMBH **mass function**. Reversal at higher z ?
- Constraints on the **physics of accretion/jet production** are crucial for our understanding of AGN feedback
- Feedback from “Low-luminosity AGN” are most likely **dominated by kinetic energy**
- The efficiency with which growing black holes convert mass into mechanical energy is **0.3-0.5%**, sensitive to the low-end slope of the FSRLF locally and at high- z

Open Questions: 1) CT sources

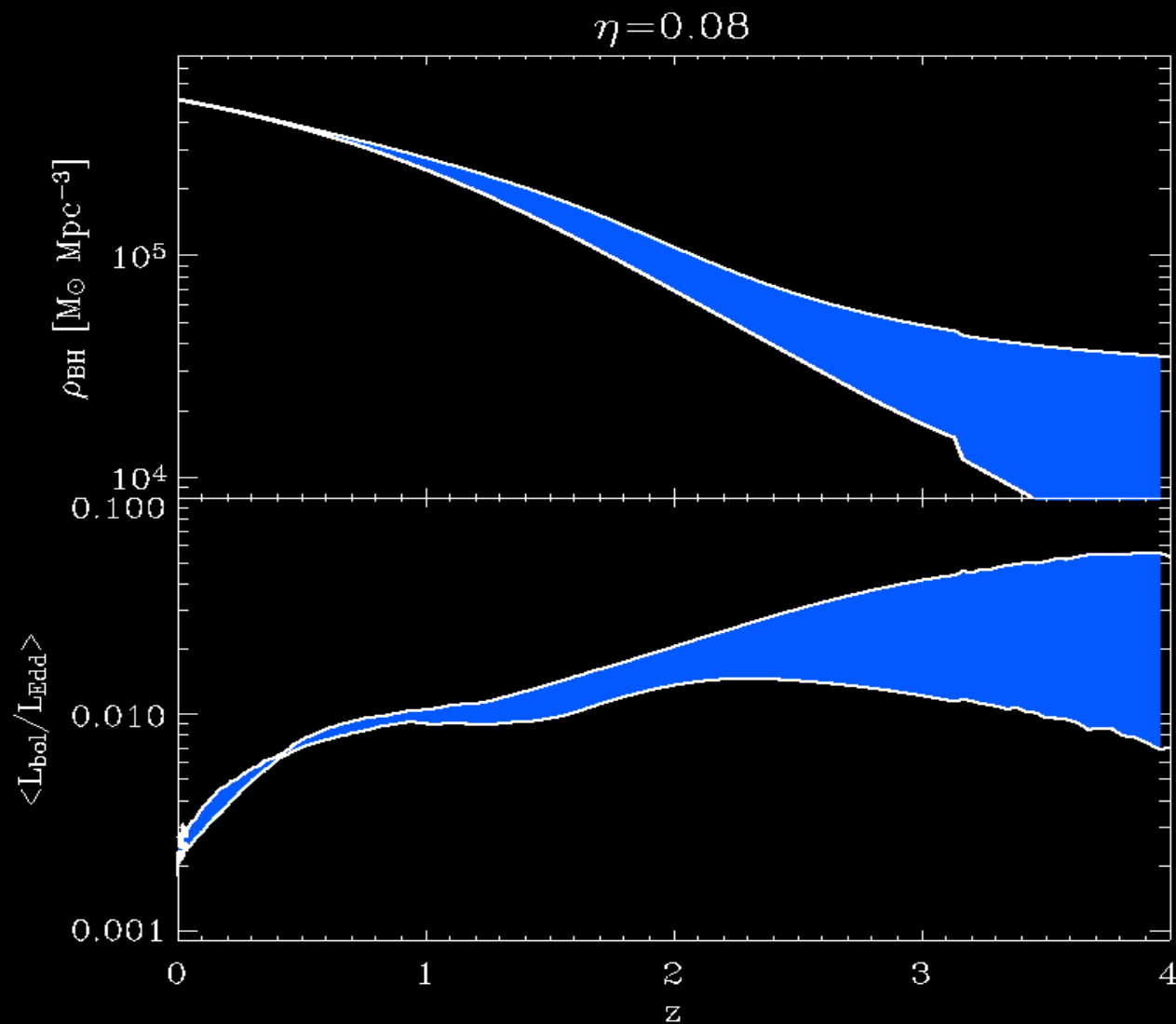


Open Questions: 1) CT sources

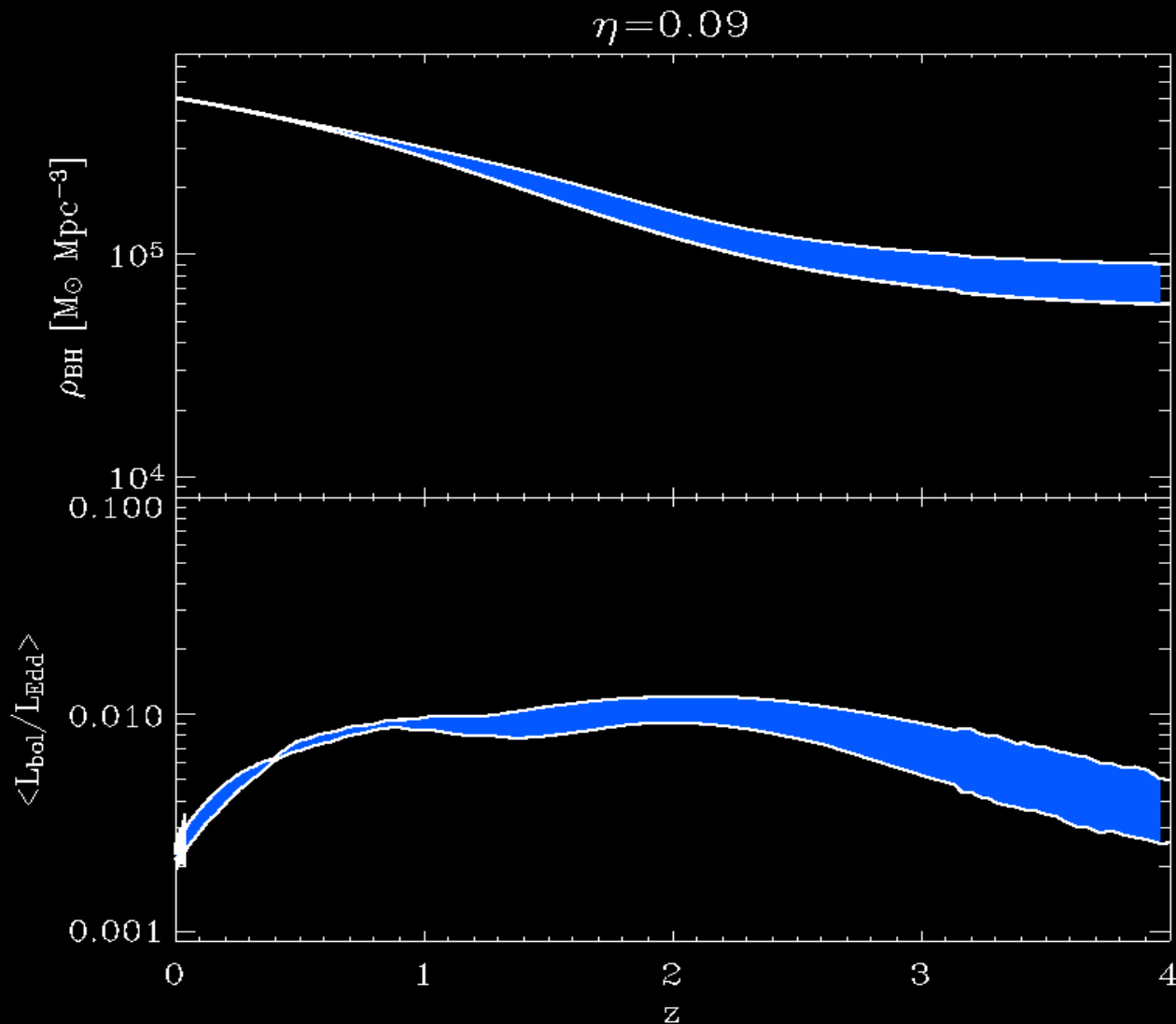


A 20% uncertainty on the total accreted mass from Compton Thick AGN translates in a **huge uncertainty on high- z density**

Open Questions: 2) efficiency and BH spin

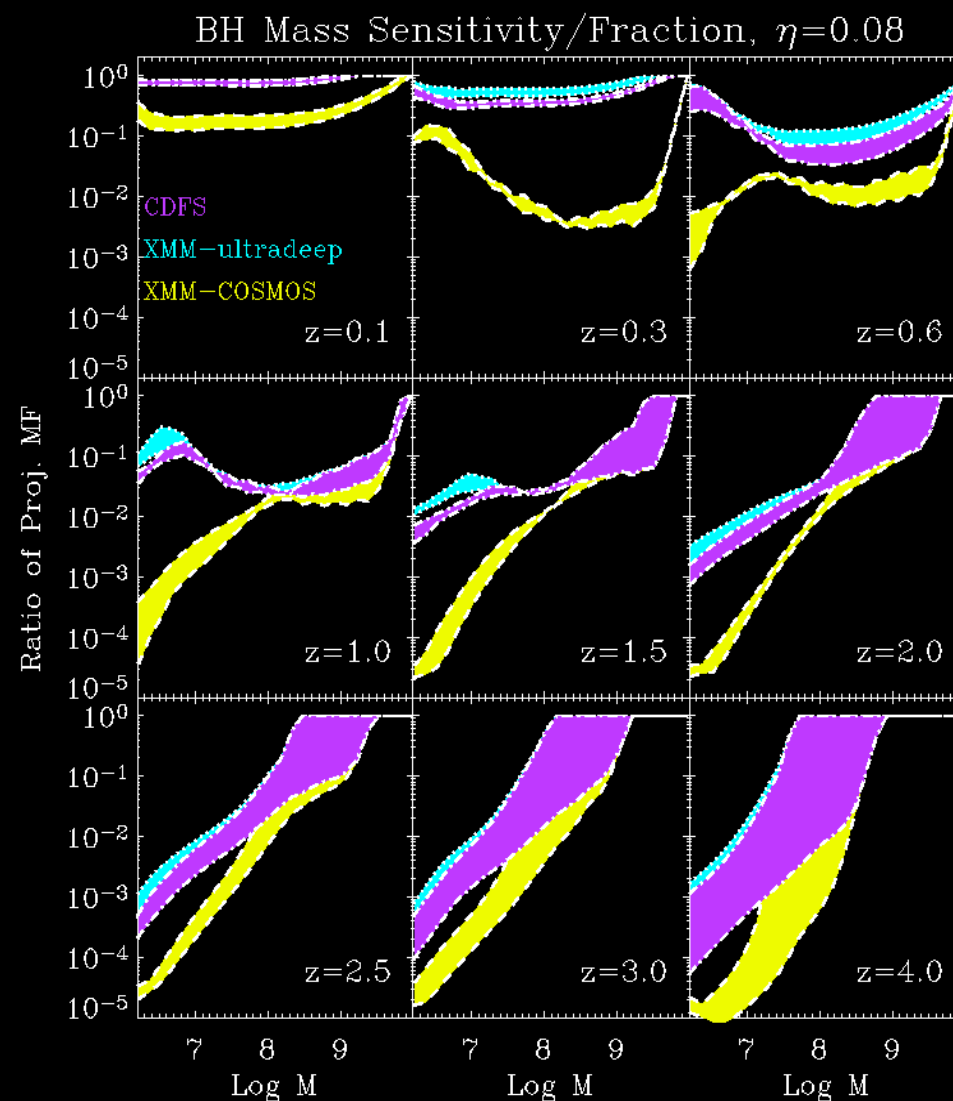
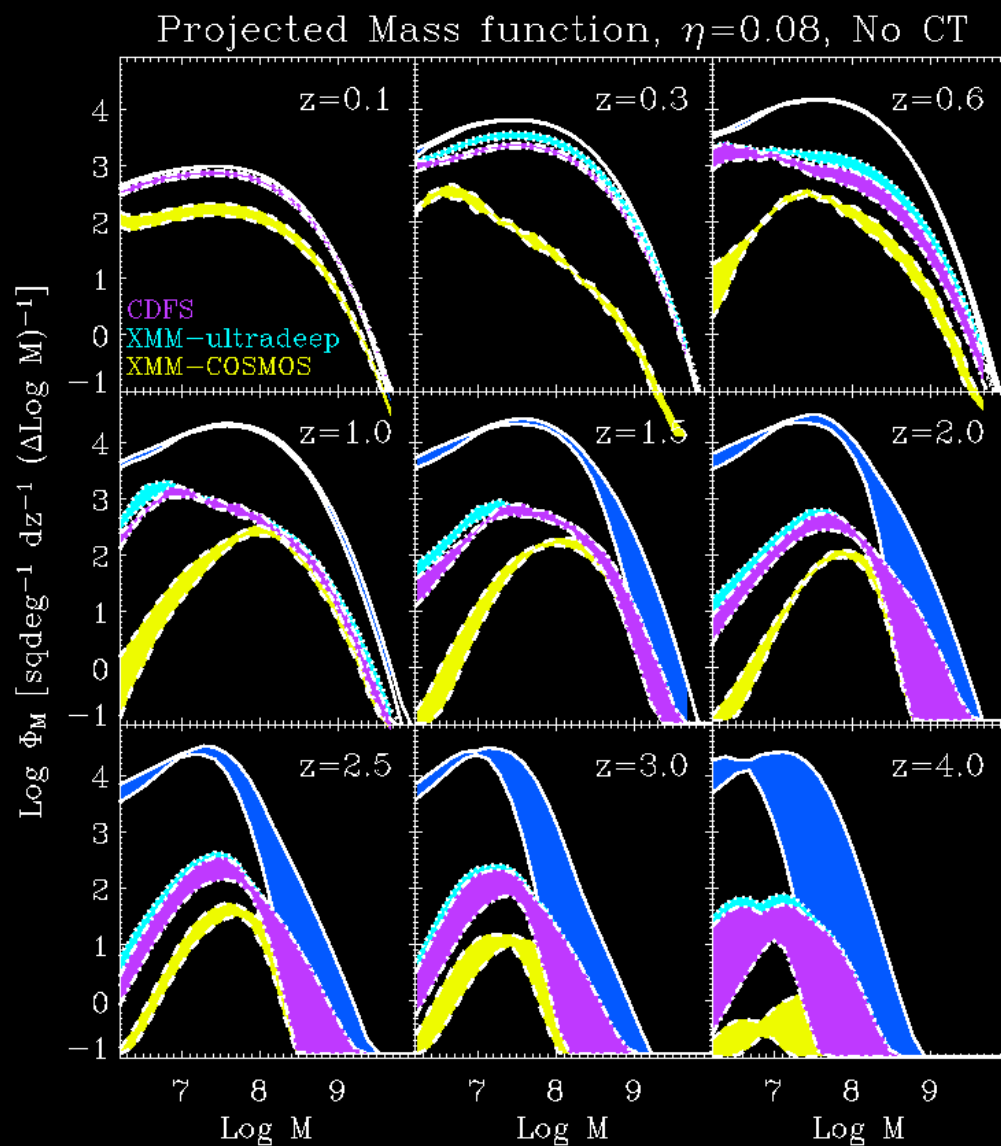


Open Questions: 2) efficiency and BH spin



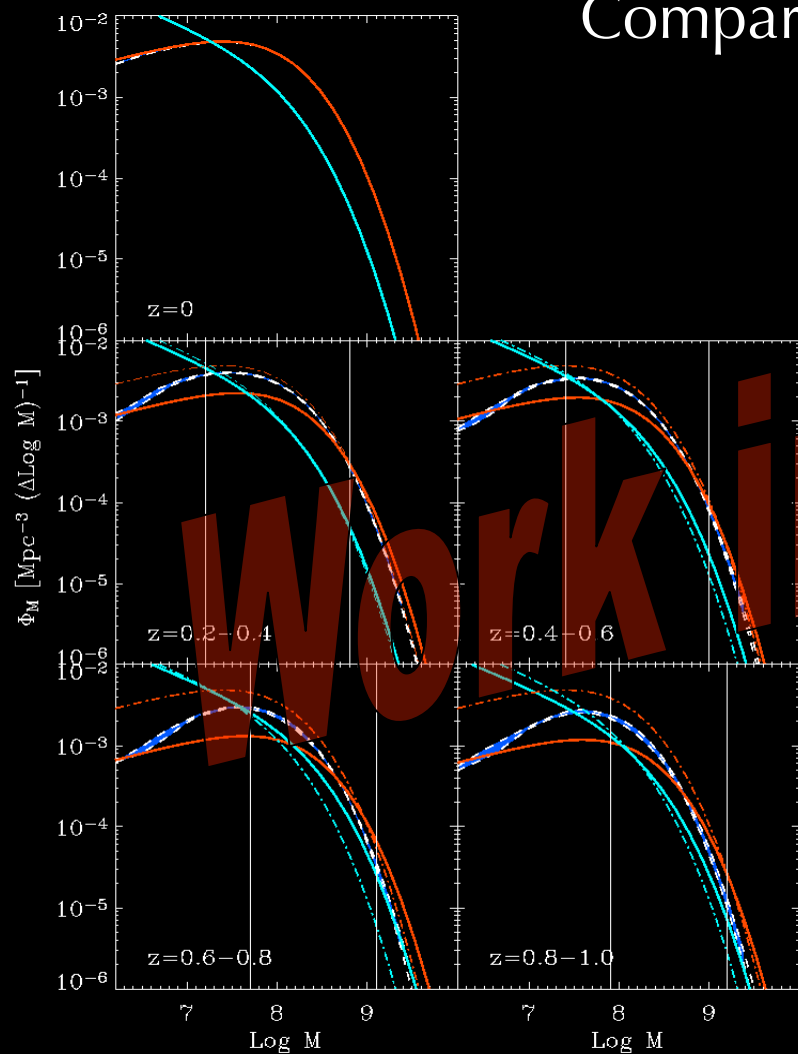
Independent constraints
on BH spin (thus η)
are badly needed:
Iron line spectroscopy?

Open Questions: 3) direct measures of BH MF

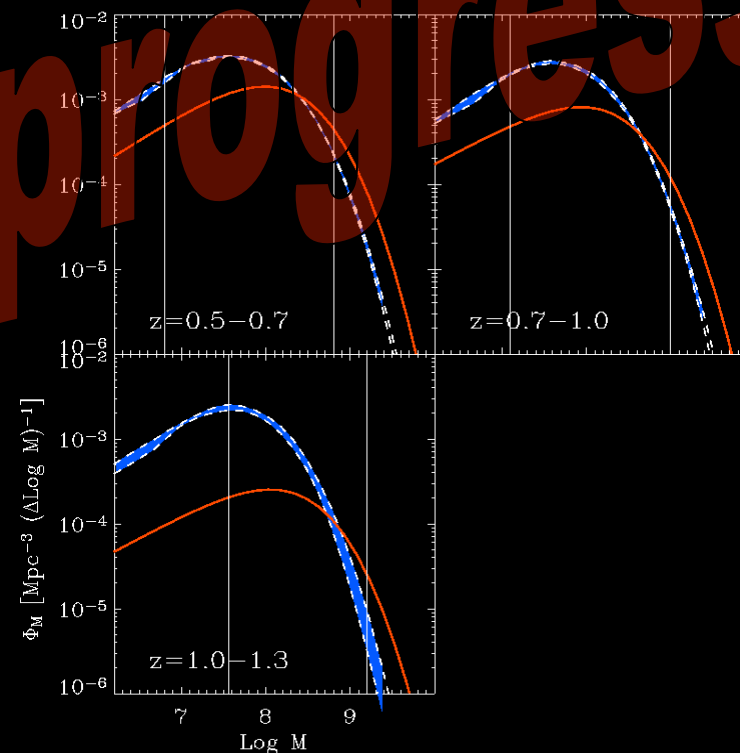


Open Questions: 4) evolution of scaling relation

Comparison of SMBH and galaxy mass functions



Borch et al. 2006 (COMBO 17)



Vergani et al. 2007 (VVDS)

Work in progress



Plenty to keep us busy!

The M87 jet

Hubble Heritage Project

<http://heritage.stsci.edu/2000/20/index.html>