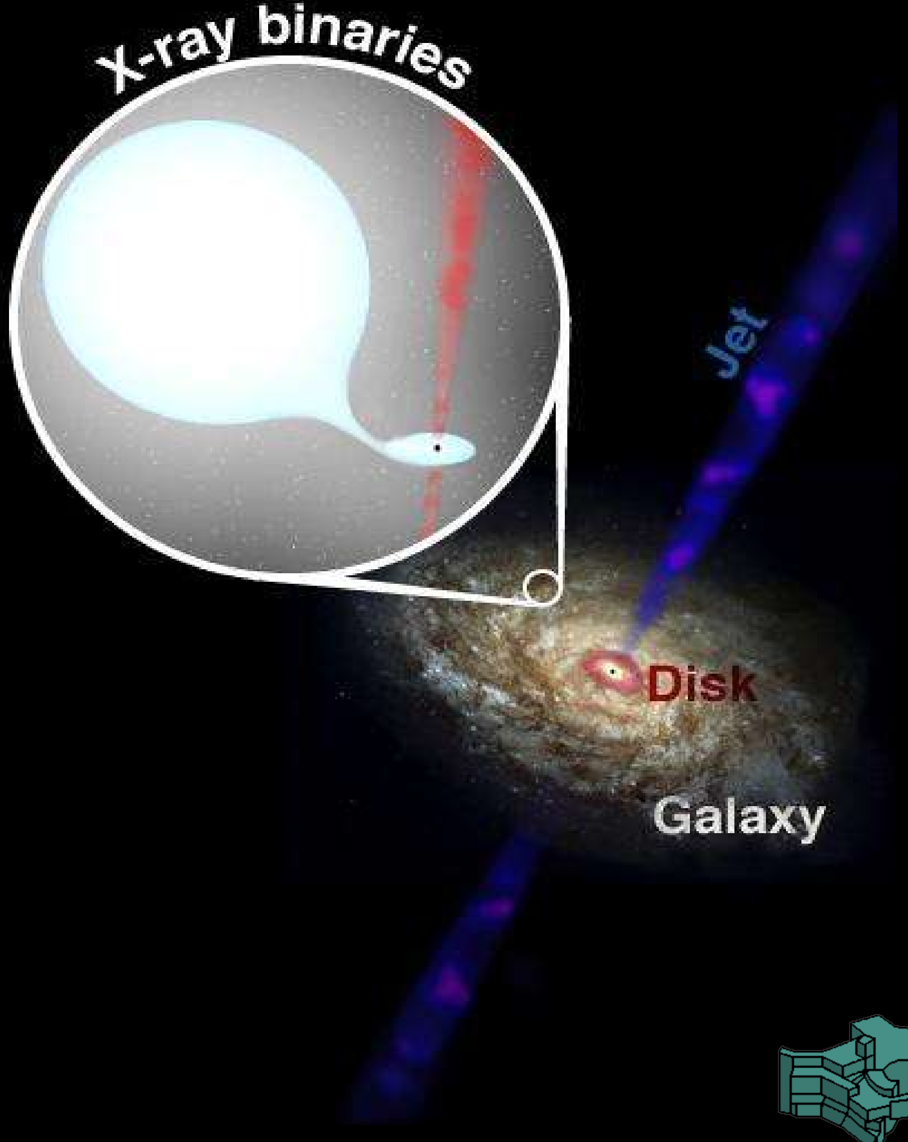
A grand unification:
the fundamental plane of active black holes and their cosmological growth



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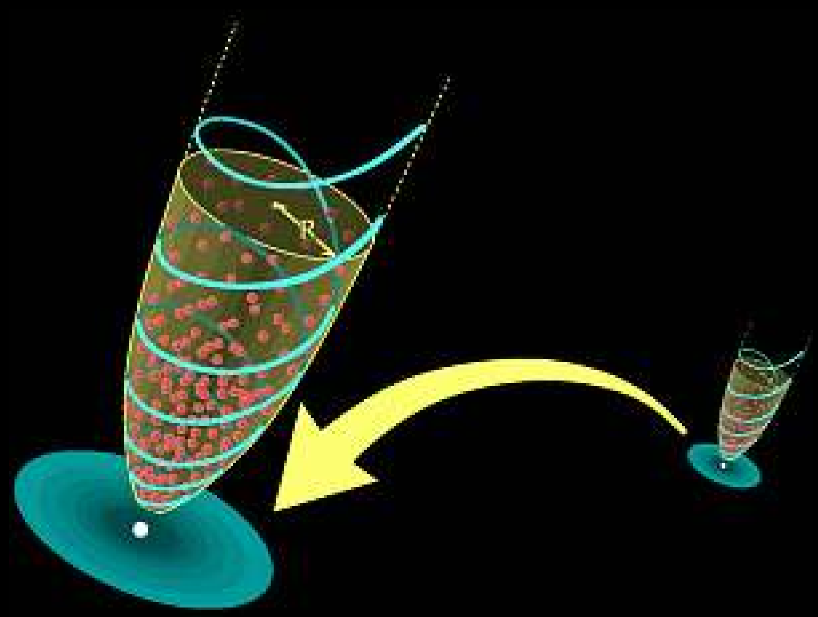
Isola d'Elba 5/2005

Pushing forward the unification scheme

- Unification by orientation: the inclination angle of the angular momentum vector wrt the line of sight determines the obscuration properties and the relativistic beaming from the jet
- Ubiquity of SMBH in nearby galaxies suggests unification by mass and accretion rates: quantitative scaling relations between black holes at different luminosity levels



Unification by mass and accretion rate: scale invariance paradigm

- Accretion theory provides (since 1973) analytical solutions (Shakura-Sunyaev discs, Slim discs, ADAFs, etc.) that can be rescaled by changing mass and accretion rate
- Jet formation occurs in the innermost accretion disc region (see e.g. M87) and is also mainly governed by the same parameters
- The structure and dynamics of the disc-jet system is invariant under change of mass and/or Eddington scaled accretion rate (= $L_{bol}/\eta\, L_{Edd}$); unless a global accretion mode change takes place.

Properties of scale invariant jets
[Heinz & Sunyaev 2003]

- Any quantity f needed to calculate synchrotron emission from the jet can be decomposed

$$f(\mathbf{R}, M, \dot{m}, a) = \phi_f(M, \dot{m}, a) \cdot \psi_f(\mathbf{R}/R_g, a)$$

Normalization (set by boundary conditions at the jet base => accretion)

Structure function (set by jet geometry and structure)

- Unknowns are: normalization of the magnetic field strength ϕ_B, jet cross section ϕ_A, normalization of the electron power-law distribution ϕ_C.

Properties of scale invariant jets
[Heinz & Sunyaev 2003]

- The radio luminosity at a given frequency, then scales with mass and accretion rate independently on the structure functions (ψ), and therefore on the jet model
- The scaling depends on the radio spectral index $\alpha = \partial \log L_\nu / \partial \log \nu$ on the electron distribution power-law index p and on the normalization functions (ϕ), and therefore on accretion physics

$$\frac{\partial \ln(L_\nu)}{\partial \ln(M)} = \frac{2p+13+2\alpha}{p+4} + \frac{\partial \ln(\phi_B)}{\partial \ln(M)}\left(\frac{2p+3+\alpha p+2\alpha}{p+4}\right) + \frac{\partial \ln(\phi_C)}{\partial \ln(M)}\left(\frac{5+2\alpha}{p+4}\right) \equiv \xi_M$$

$$\frac{\partial \ln(L_\nu)}{\partial \ln(\dot{m})} = \frac{\partial \ln(\phi_B)}{\partial \ln(\dot{m})}\left(\frac{2p+3+\alpha(p+2)}{p+4}\right) + \frac{\partial \ln(\phi_C)}{\partial \ln(\dot{m})}\left(\frac{5+2\alpha}{p+4}\right) \equiv \xi_{\dot{m}}$$

Correlation coefficients (theoretical)

The sample

- We build a sample with the largest possible dynamical range in both mass and accretion rate (we consider GBH and SMBH as members of the same class)
- We consider compact synchrotron emission in the radio band as proxy for jet activity and hard X-rays to probe accretion states (minimize effect of absorption and extinction)
- The sample consists of active BH with estimated mass (making use of primary, secondary and tertiary indicators), 5 GHz core radio luminosity and hard (2-10 keV) X-ray luminosity
- We have excluded all Blazars/BL Lac
- The importance of high spatial resolution (*HST=mass + Chandra=accretion + VLA/VLBI=radio cores)*

The sample

- The sample includes 99 active galactic nuclei and 50 simultaneous radio-X-ray observations of 8 different galactic black holes, mainly in the low/hard state

  14 Quasars (14 reverberation mapping)

  19 Seyfert 1 (15 reverberation mapping + 4 M-σ)

  7 NLSy1 (4 reverberation mapping + 3 M-[OIII])

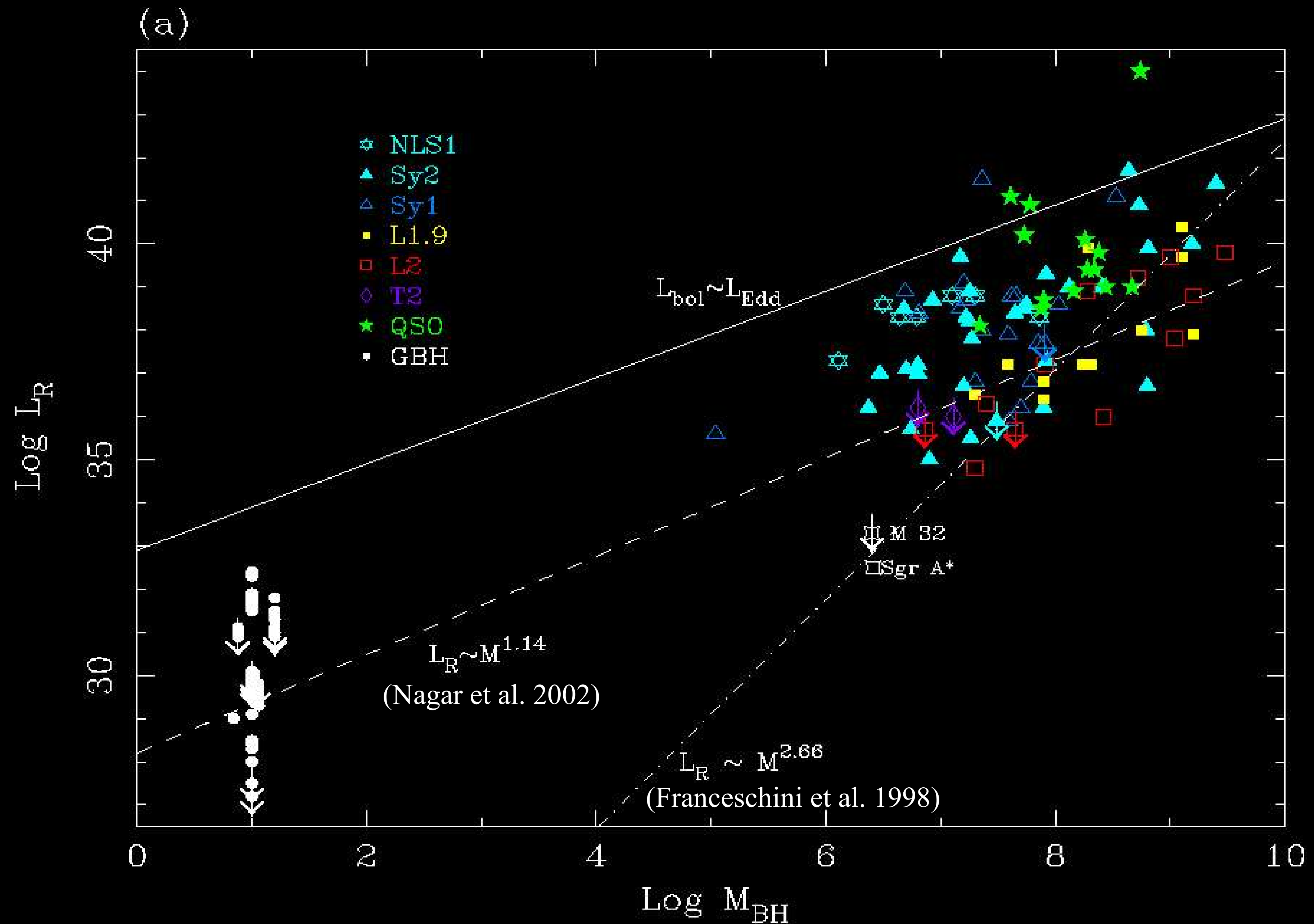
  32 Seyfert 2 (2 gas kinematics + 30 M-σ)

  23 LINERS (4 stellar kinematics + 4 gas kinematics + 15 M-σ)

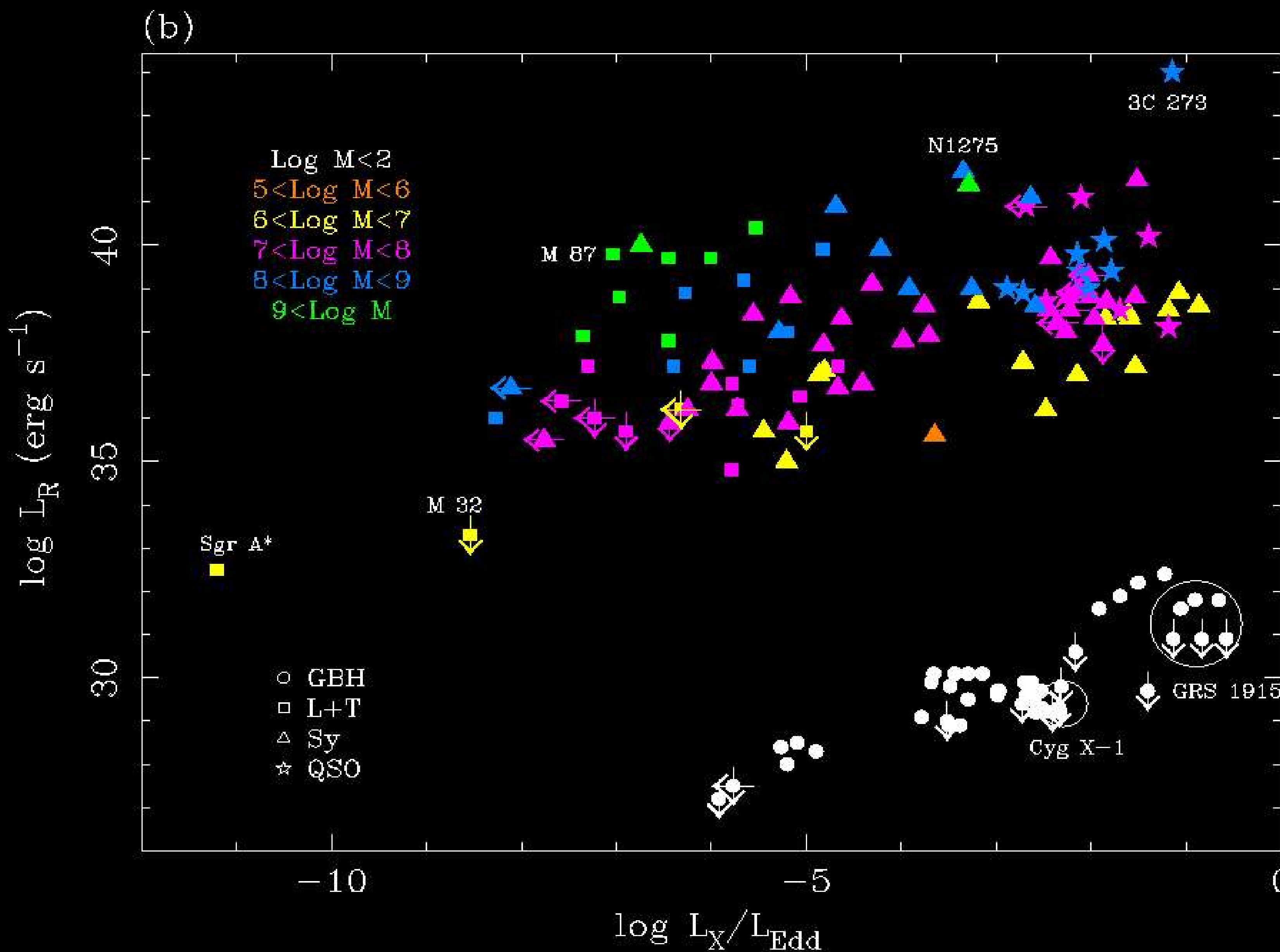
  2 'Transition' objects (2 M-σ)

  Sgr A* & M32 (2 stellar kinematics)

Core radio luminosity vs. BH mass

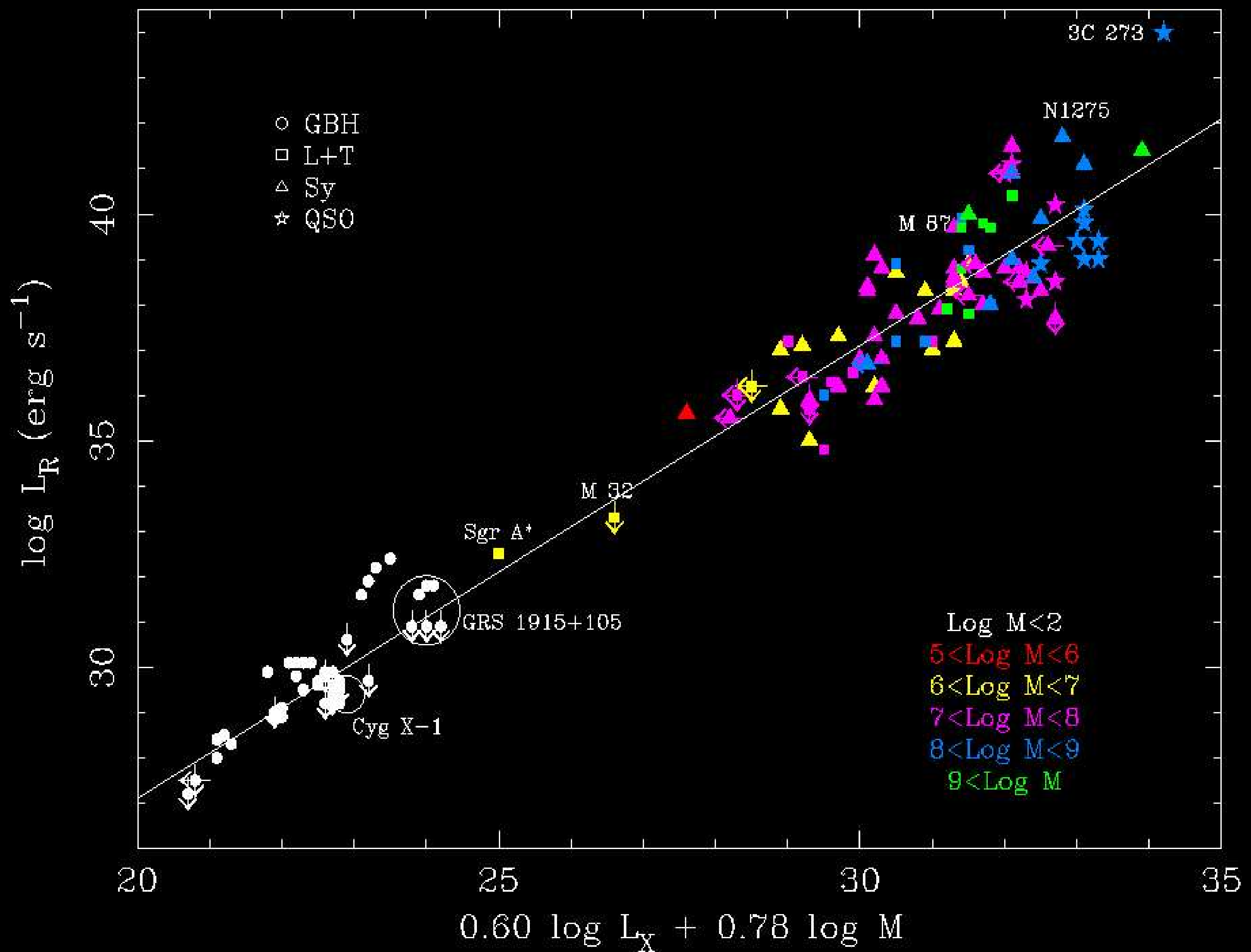


Core radio luminosity vs. Eddington ratio



The fundamental plane of accreting BH

$$\log L_R = (0.60^{+0.11}_{-0.11}) \log L_X + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.05}_{-4.07}$$



Observed correlation coefficients vs. theory: testing accretion modes

- Need the link between the observed correlation coefficients (ξ_{RM}=0.78; ξ_{RX}=0.60) and the theoretical ones
- Let us define: $\log L_{\rm X} = \log M + q \log \dot{m} + K_2$
- Then, the properties of scale invariant jets imply:

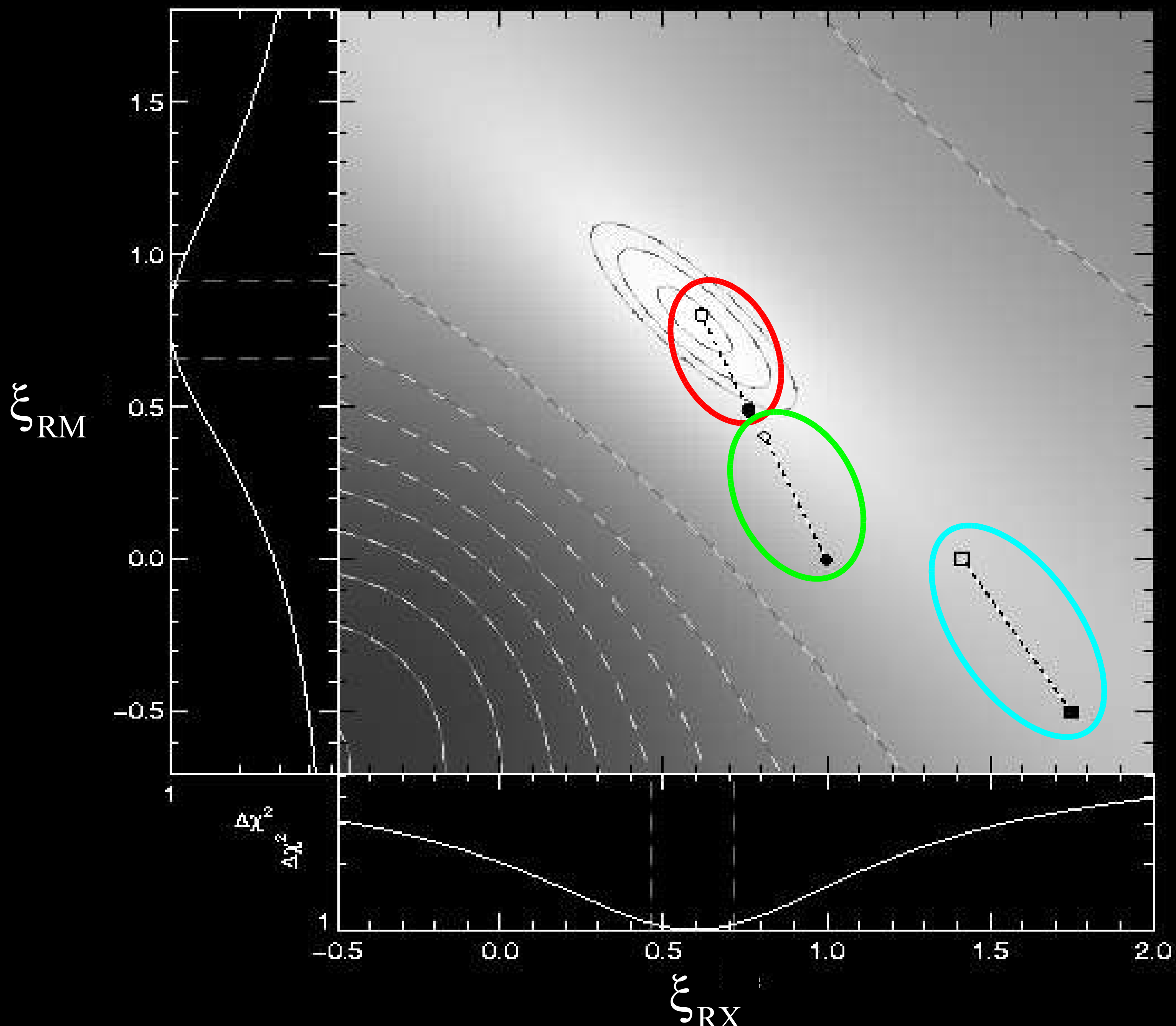
$$\begin{aligned}
\xi_{\rm R\mathit{M}} &= \frac{2p+13+2\alpha_{\rm R}}{p+4} + \frac{\partial \ln \phi_B}{\partial \ln M}\left(\frac{2p+13+\alpha_{\rm R}p+6\alpha_{\rm R}}{p+4}\right) \\
&- \frac{\partial \ln \phi_B}{\partial \ln \dot{m}}\left(\frac{2p+13+\alpha_{\rm R}p+6\alpha_{\rm R}}{q(p+4)}\right) \\
\xi_{\rm RX} &= \frac{\partial \ln \phi_B}{\partial \ln \dot{m}}\left(\frac{2p+13+\alpha_{\rm R}p+6\alpha_{\rm R}}{q(p+4)}\right).
\end{aligned}$$

q=2 => rad. inefficient

q=1 => rad. efficient

- (We have assumed that the pressure of relativistic particles is a fixed fraction of the total pressure at injection, implying $\phi_C \propto \phi_B^2$

The correlation coefficients



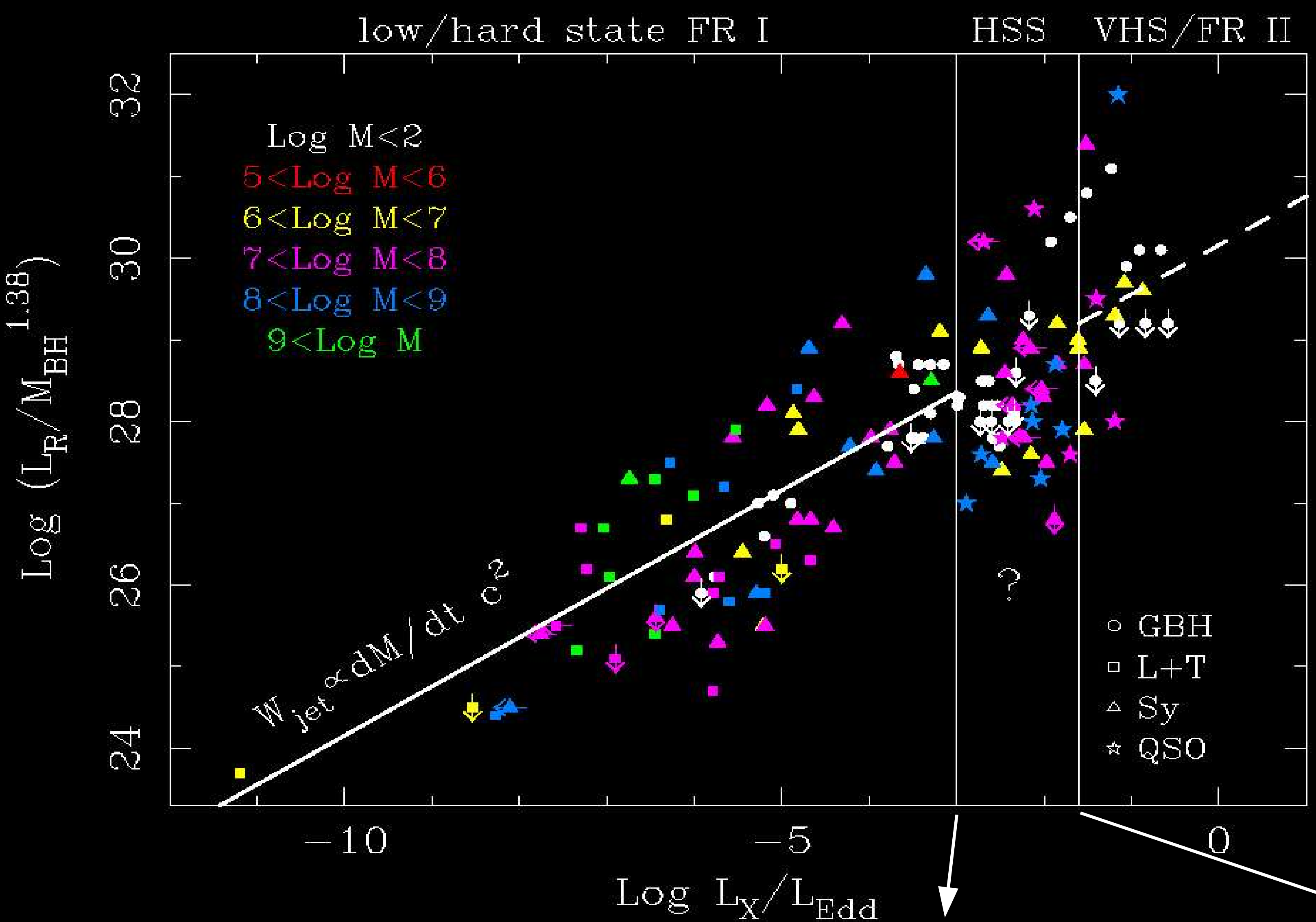
Radiatively inefficient model
p=2, -1<α<0

Jet model
p=2, -1<α<0

Thin disc model
p=2, -1<α<0

What drives the correlation?

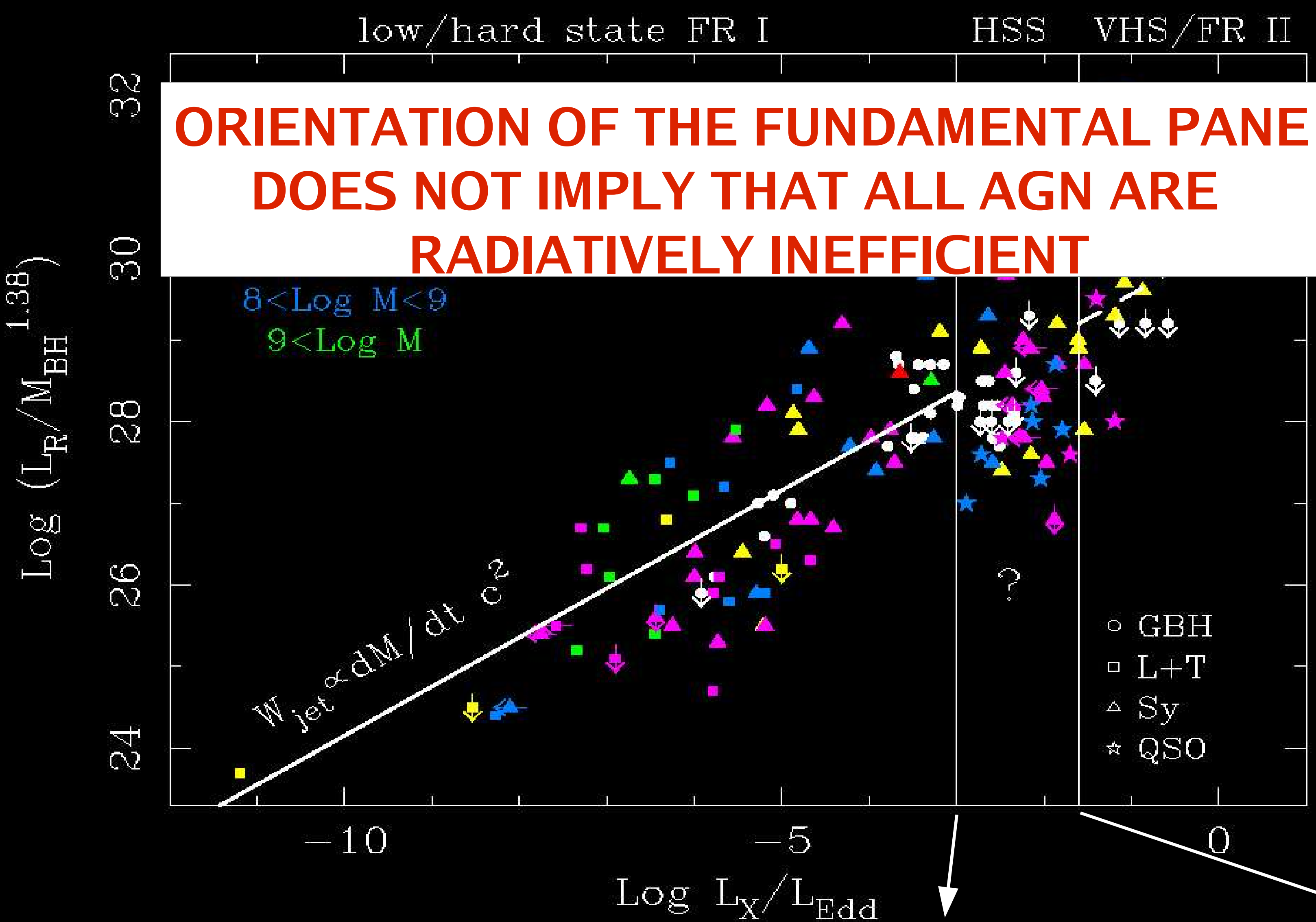
- Bends, fractures, bifurcations: seeing accretion mode changes



Expected range of critical accretion rates

What drives the correlation?

- Bends, fractures, bifurcations: seeing accretion mode changes



ORIENTATION OF THE FUNDAMENTAL PANE DOES NOT IMPLY THAT ALL AGN ARE RADIATIVELY INEFFICIENT

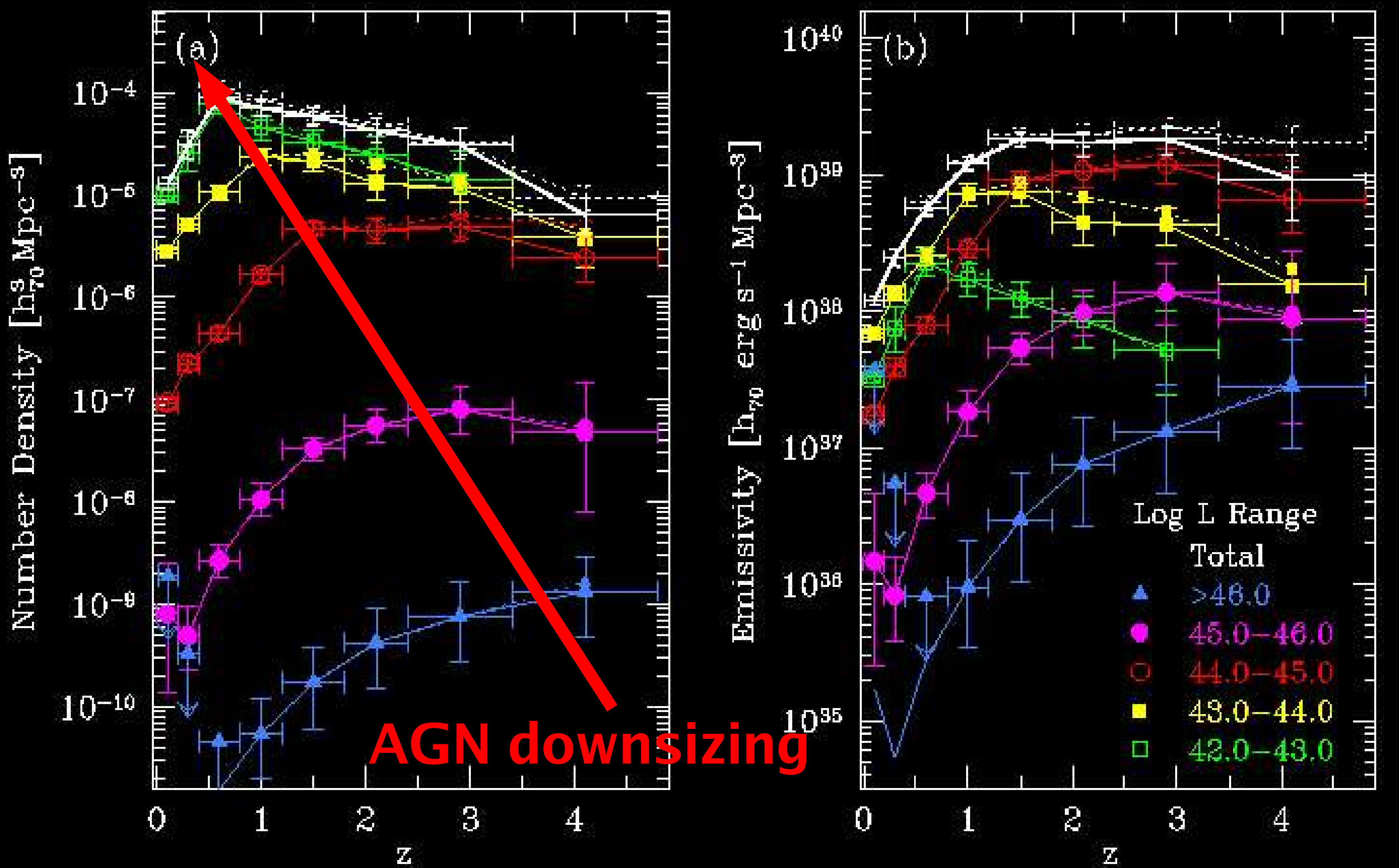
Expected range of critical accretion rates

Conclusions (I)

- The scale invariance *ansatz* for the disc-jet coupling captures the main physical properties of these systems
- X-ray emission from black holes accreting at less than a few per cent of the Eddington rate:
  - is consistent with radiatively inefficient models only
- In low accretion rate sources, the total jet power is proportional to the total accretion rate (jet dominated sources?)
- The fundamental plane relationship can be used a baseline to detect accretion mode changes

Merloni, Heinz, Di Matteo, 2003, MNRAS, 345, 1057

The history of SMBH activity: more clues from deep X-ray surveys



(Hasinger et al. 2005)

(see also Cowie et al. 2003; Fiore et al.2003 Ueda et al. 2003; Barger et al. 2004)

Redshift evolution of black hole mass function: a new approach

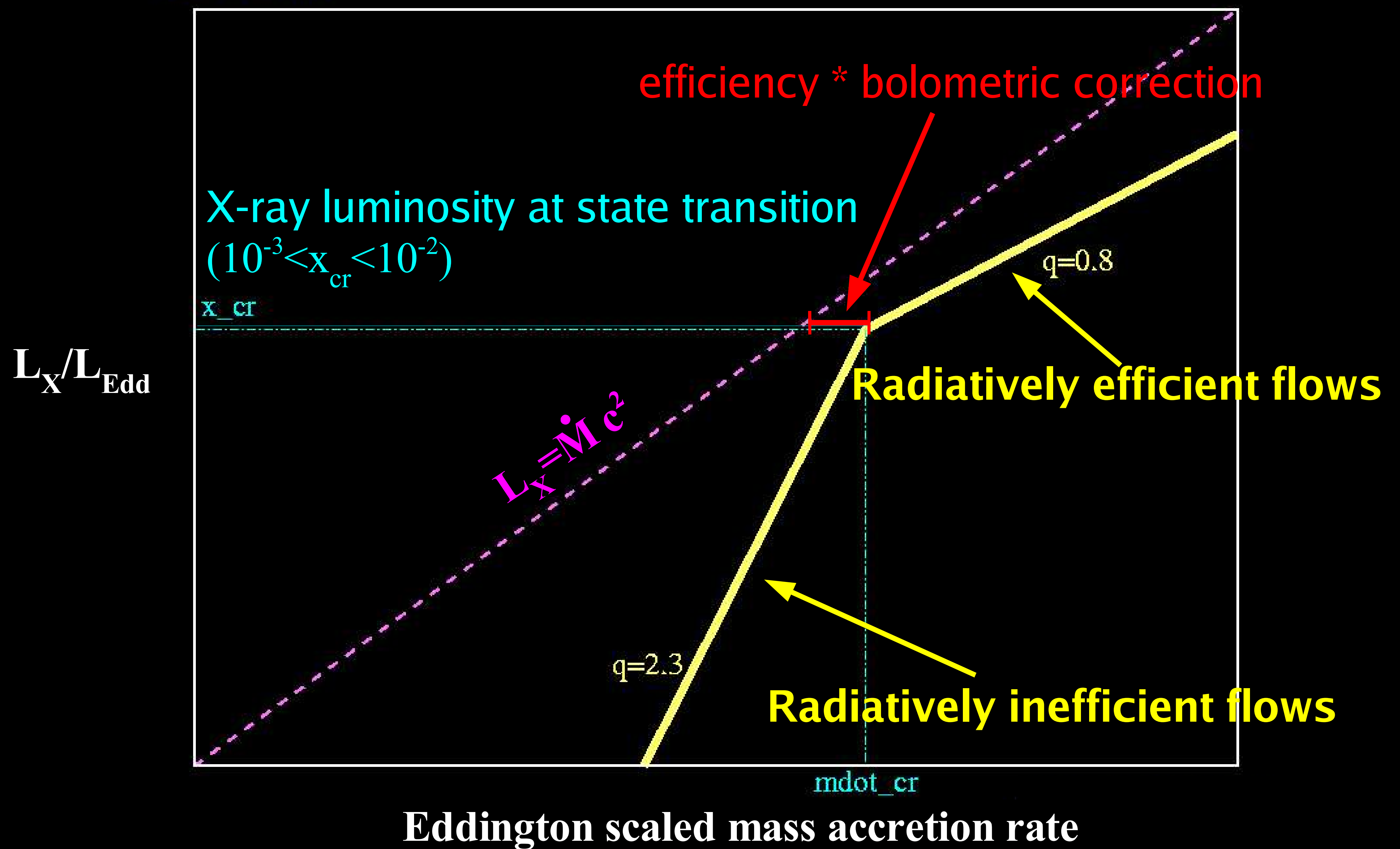
(Merloni 2004)

- Simultaneous Radio and X-ray observations of active BH cores can be used to estimate both black hole mass and accretion rate through the fundamental plane of active black holes

$$\log L_{\rm R} = 0.60^{+0.11}_{-0.10} \log L_{\rm X} + 0.78^{+0.11}_{-0.09} \log M + 7.33^{+4.05}_{-4.07}$$

- From the local BHMF and the AGN Radio and X-ray luminosity functions we can derive the local accretion rate function.
- Then, the local black hole mass function can be used as a secure boundary condition

The model parameters: the Lx-mdot relation



Using the fundamental plane of BH activity to unveil the history of accretion

- We integrate backwards in time the continuity equation, provided a redshift evolution of both XLF and RLF of AGN (and neglecting mergers)
- It is possible then to find (using a modified Lucy-Richardson algorithm) an approximated conditional X-ray and Radio AGN LF fulfilling:

$$\phi_R(\log L_R)\, d\log L_R = \int \psi_C(\log L_X, \log L_R)\, d\log L_X;$$

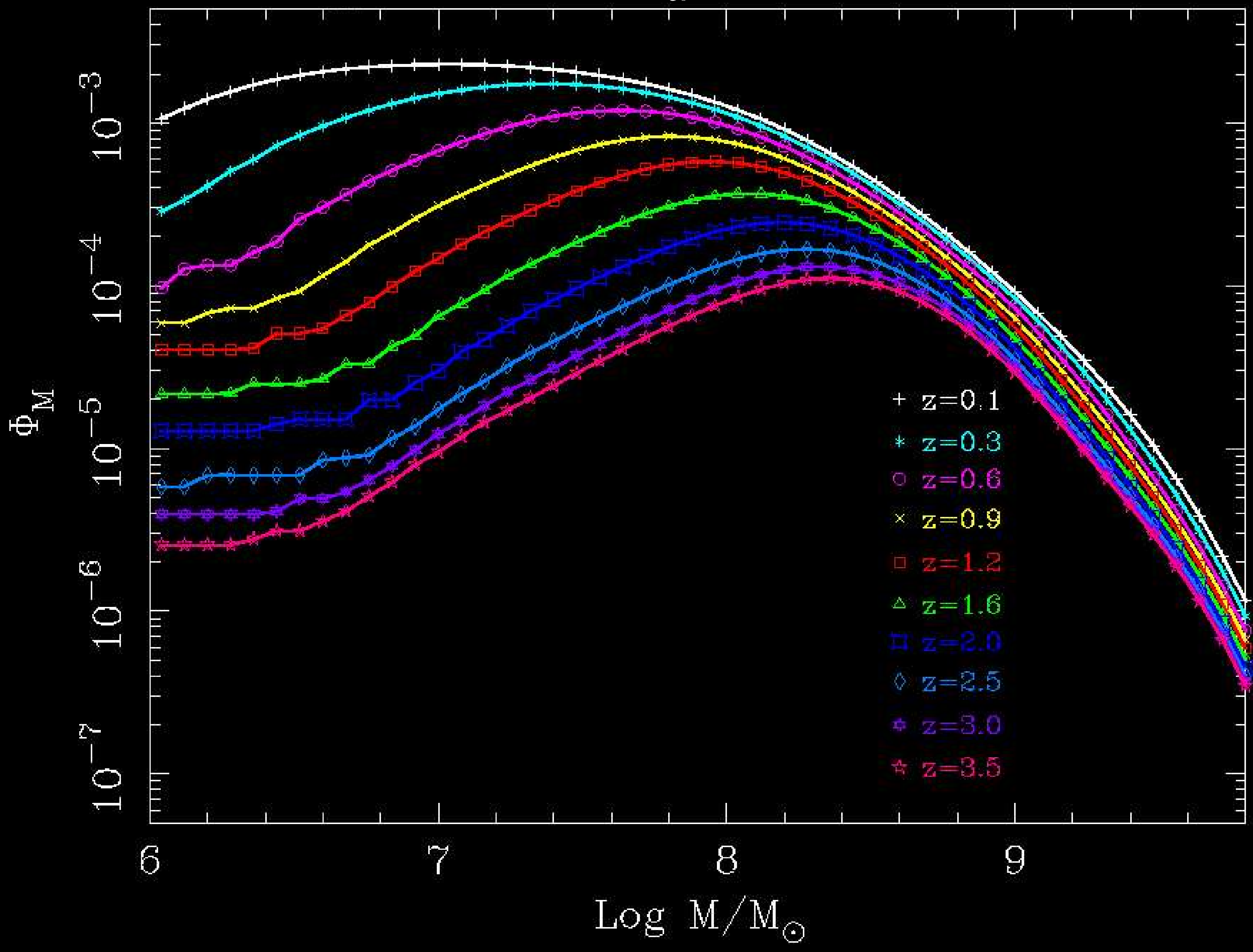
$$\phi_X(\log L_X)\, d\log L_X = \int \psi_C(\log L_X, \log L_R)\, d\log L_R$$

$$\phi_M(\log M)\, d\log M = \iint_{\log M < g < \log M + d\log M} \psi_C(\log L_R, \log L_X)\, d\log L_X\, d\log L_R$$

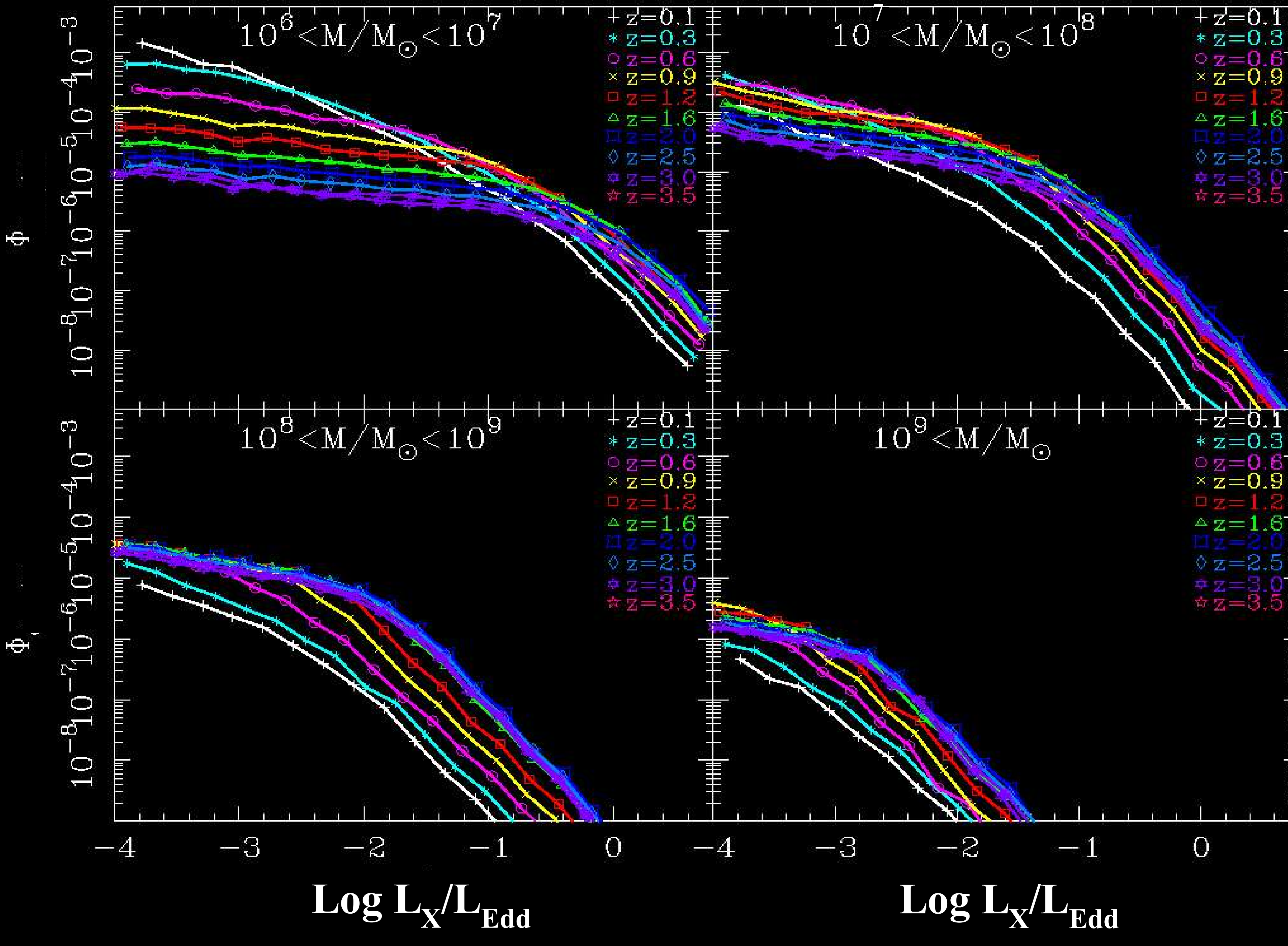
$$\log M \simeq 1.28(\log L_{\rm R} - 0.60 \log L_{\rm X}) - 9.34 \pm 1.06 \equiv g(\log L_{\rm R}, \log L_{\rm X}).$$

Mass function evolution

(η=0.1, x_{cr}=10^{-3})

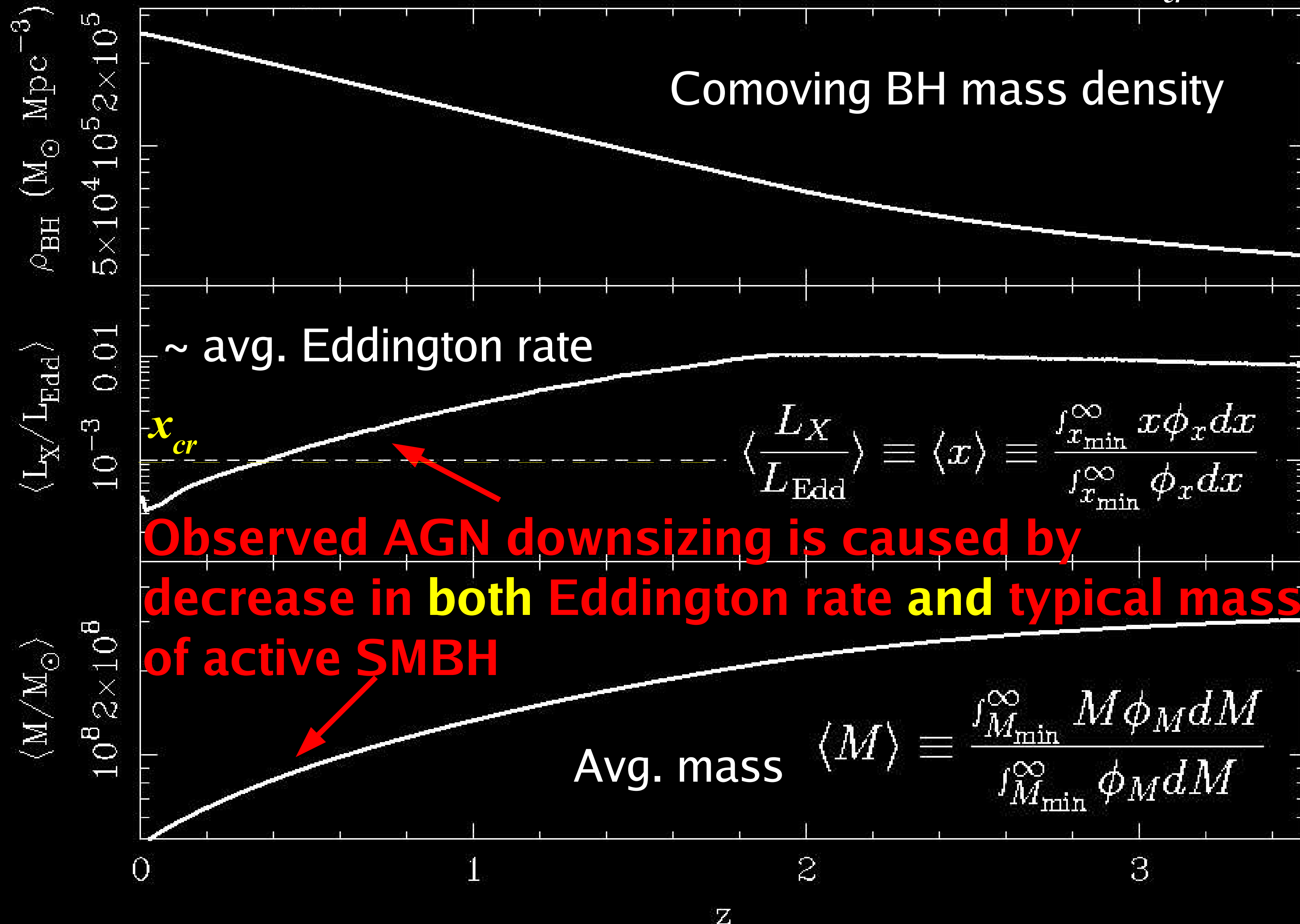


Accretion rate function evolution

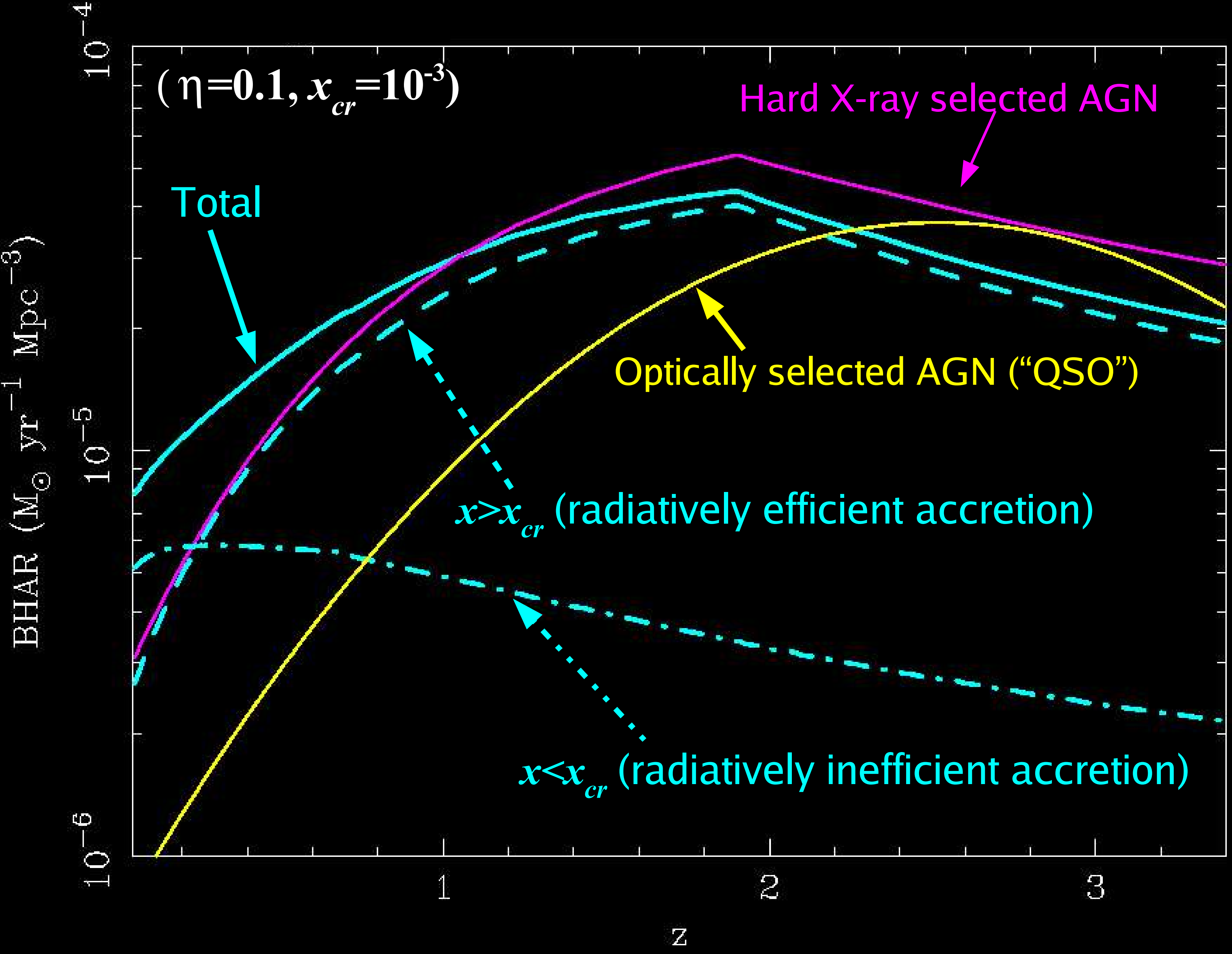


The SMBH anti-hierarchical evolution

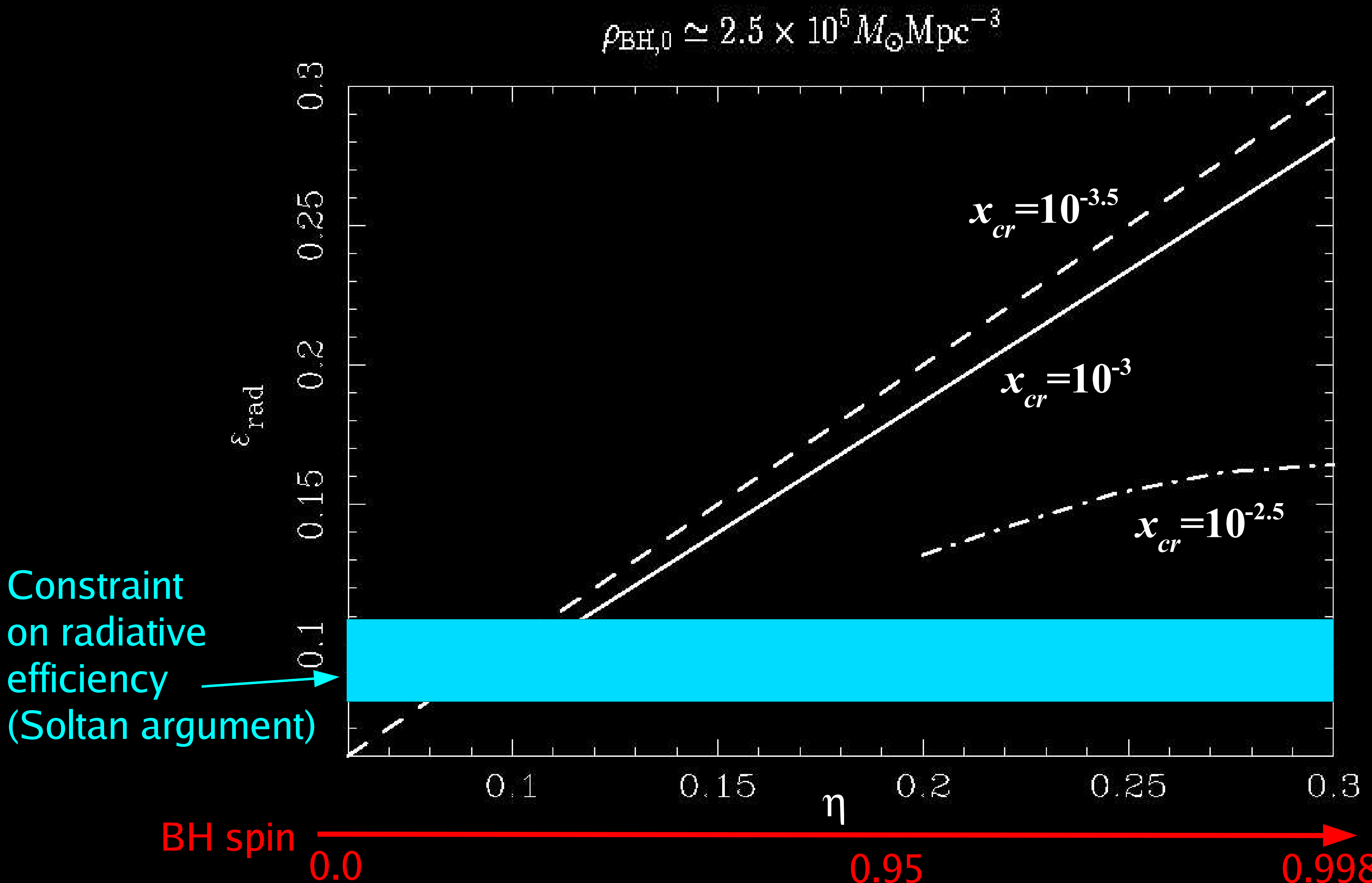
(η=0.1, x_{cr}=10^{-3})



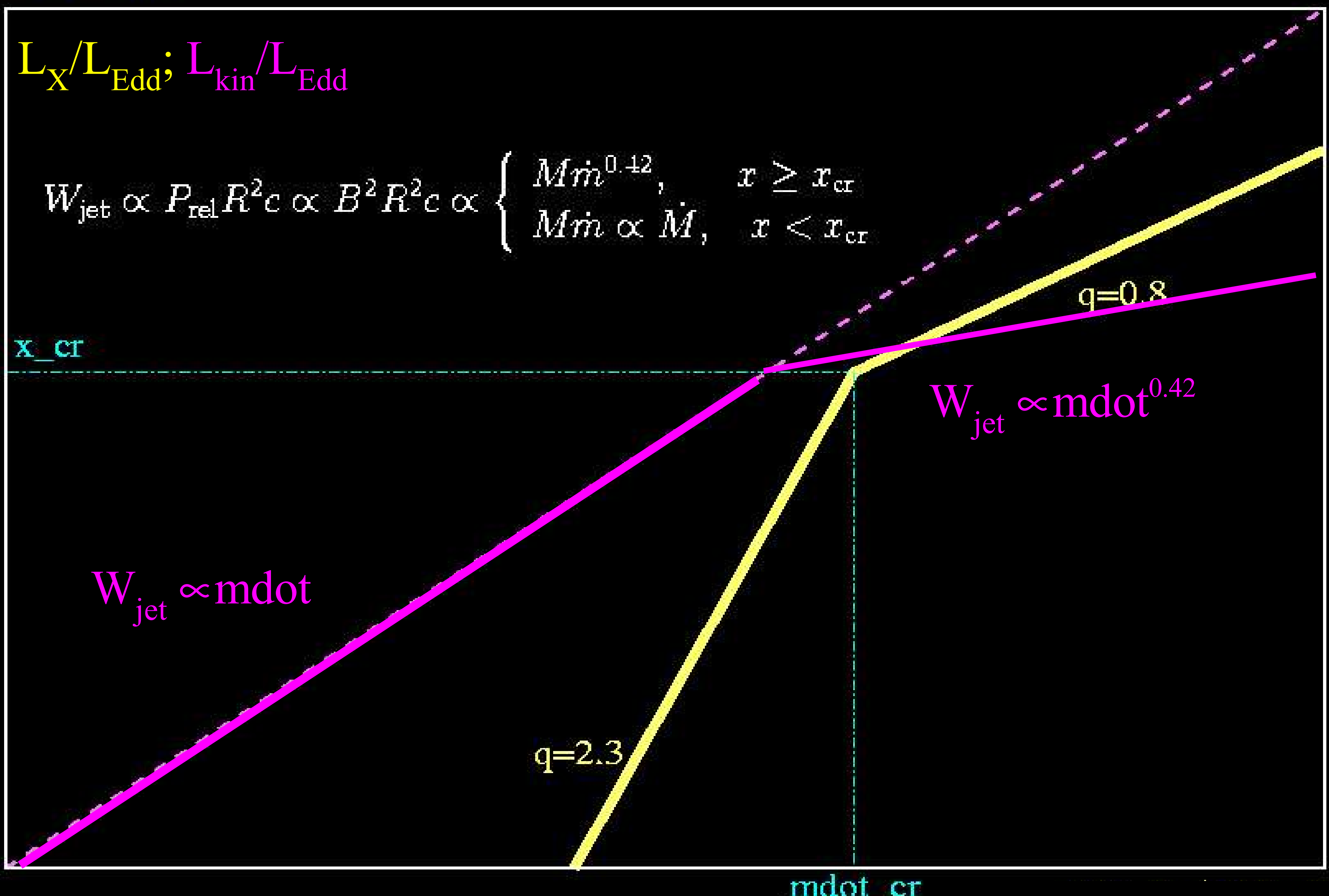
BHAR density evolution



Constraints on efficiency

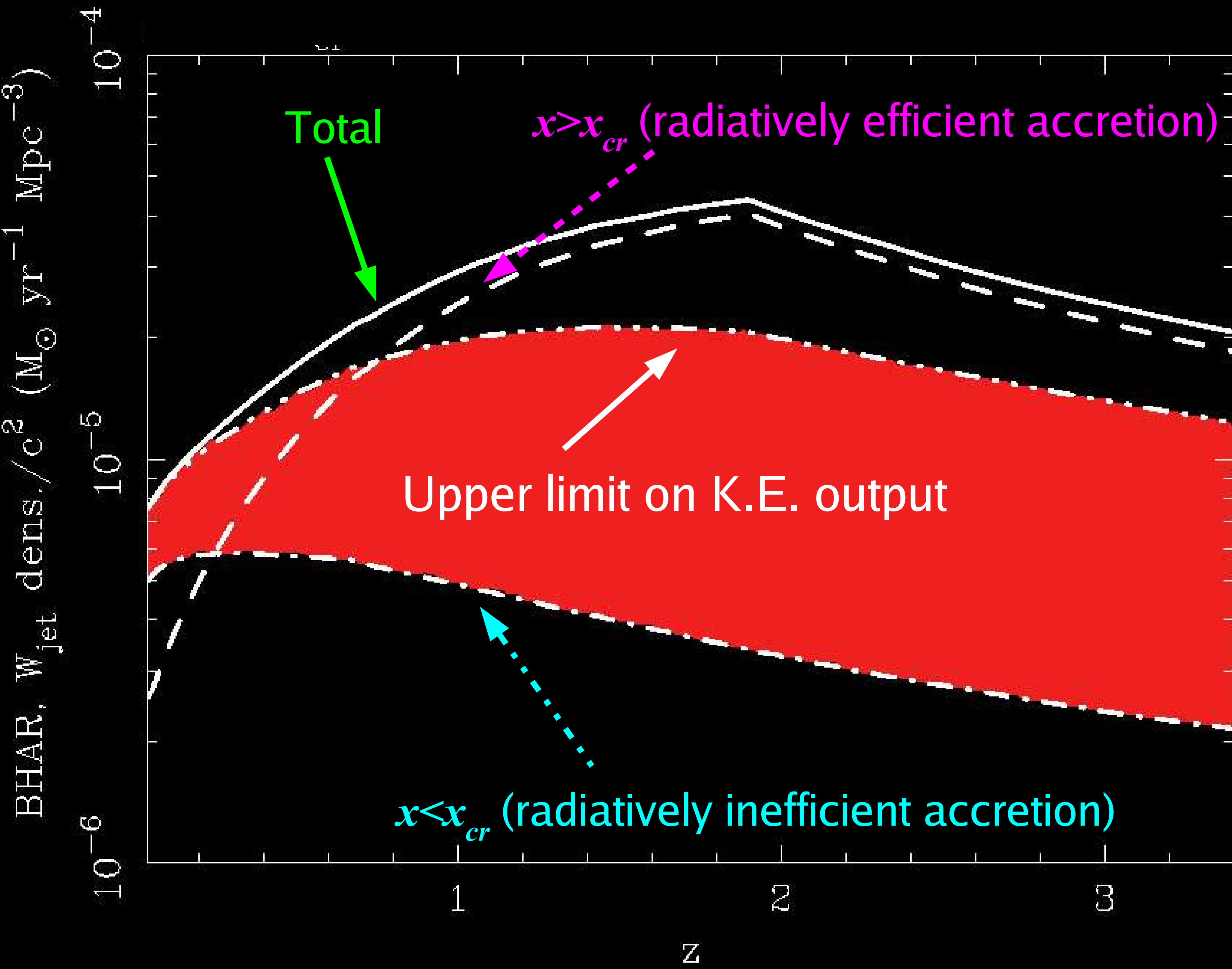


Kinetic Energy output

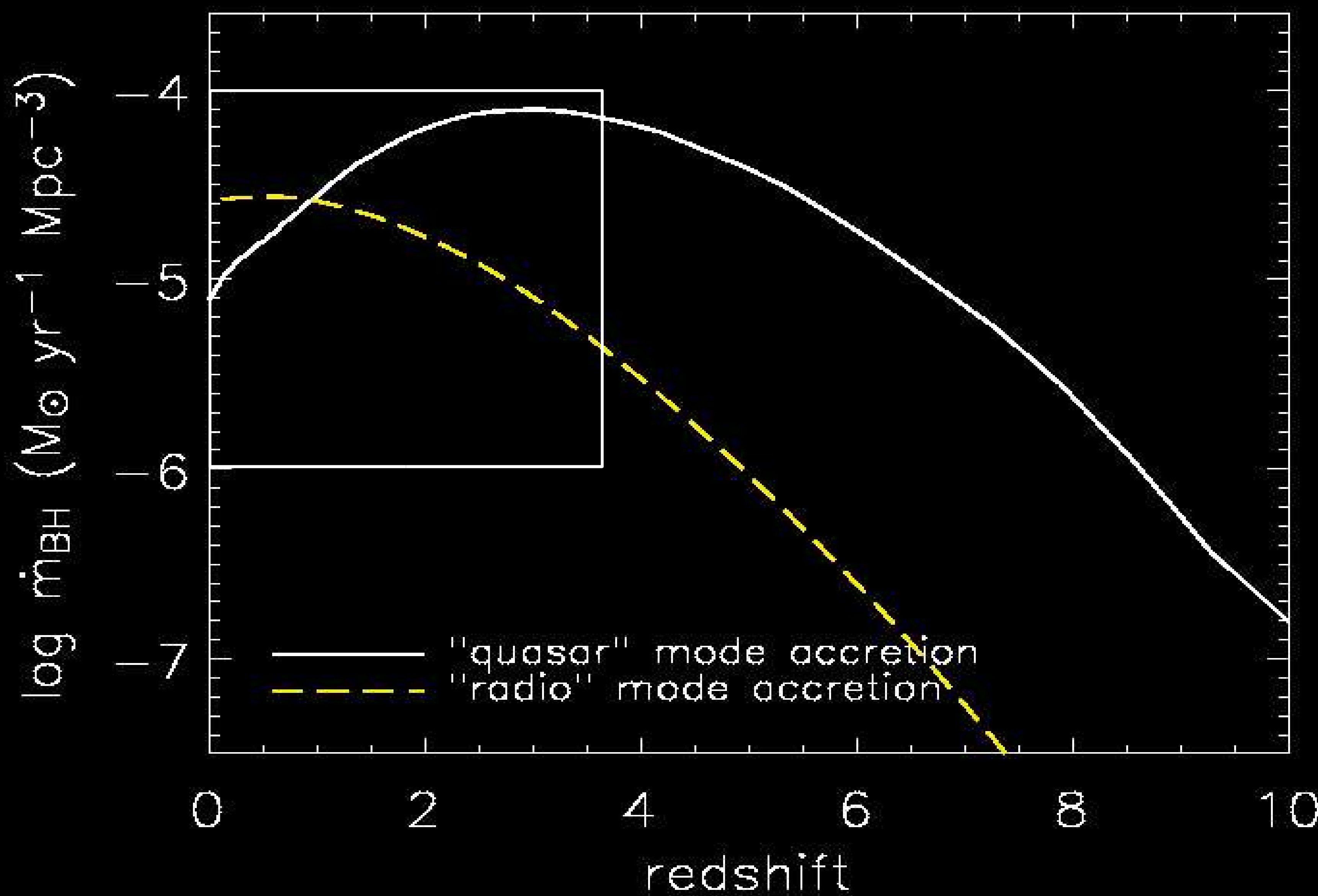


Eddington scaled mass accretion rate

Kinetic Energy output and feedback history



Kinetic Energy output and feedback history



(Croton et al. 2005)

Conclusions (II)

- The redshift evolution (from z=0 up to z=3.5) of SMBH mass function can be determined from the joint evolution of X-ray and Radio AGN luminosity functions using the mass-L_X-L_R relationship given by the fundamental plane of black hole activity
- SMBH down-size: most massive object were formed earlier and stopped growing earlier ("anti-hierarchical evolution")
- Galaxies down-size (Cowie 1996): the highest mass galaxies stop forming stars at the earliest times
- The largest black holes are the first to enter the radiatively inefficient accretion regime, probably dominated energetically by kinetic energy output
- The feedback from low luminosity AGN jets starts dominating high mass objects first and then objects of progressively lower mass