Kinetic luminosity, jet production efficiency and feedback properties of growing black holes

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5GHz, VLA image of Cyg A by R. Perley

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)

XRB: low/hard state as jet-dominated RIAF

- Strong correlation between radio and X-ray emission in low/hard state (Gallo et al. 2003)
- Assume jet power L_{Kin}~ Accretion rate
- Independent of geometry and jet acceleration mechanisms, it can be shown that $L_R \sim M^{17/12} mdot^{17/12}$ for flat radio spectra from compact, self-absorbed synchrotron
- The observed radio-X-ray correlation ($L_R \sim L_X^{0.7}$) implies:
    - X-ray emission is radiatively inefficient ($L_X \sim Mdot^2$)
    - $L_{Kin} \sim L_R^{1.4}$

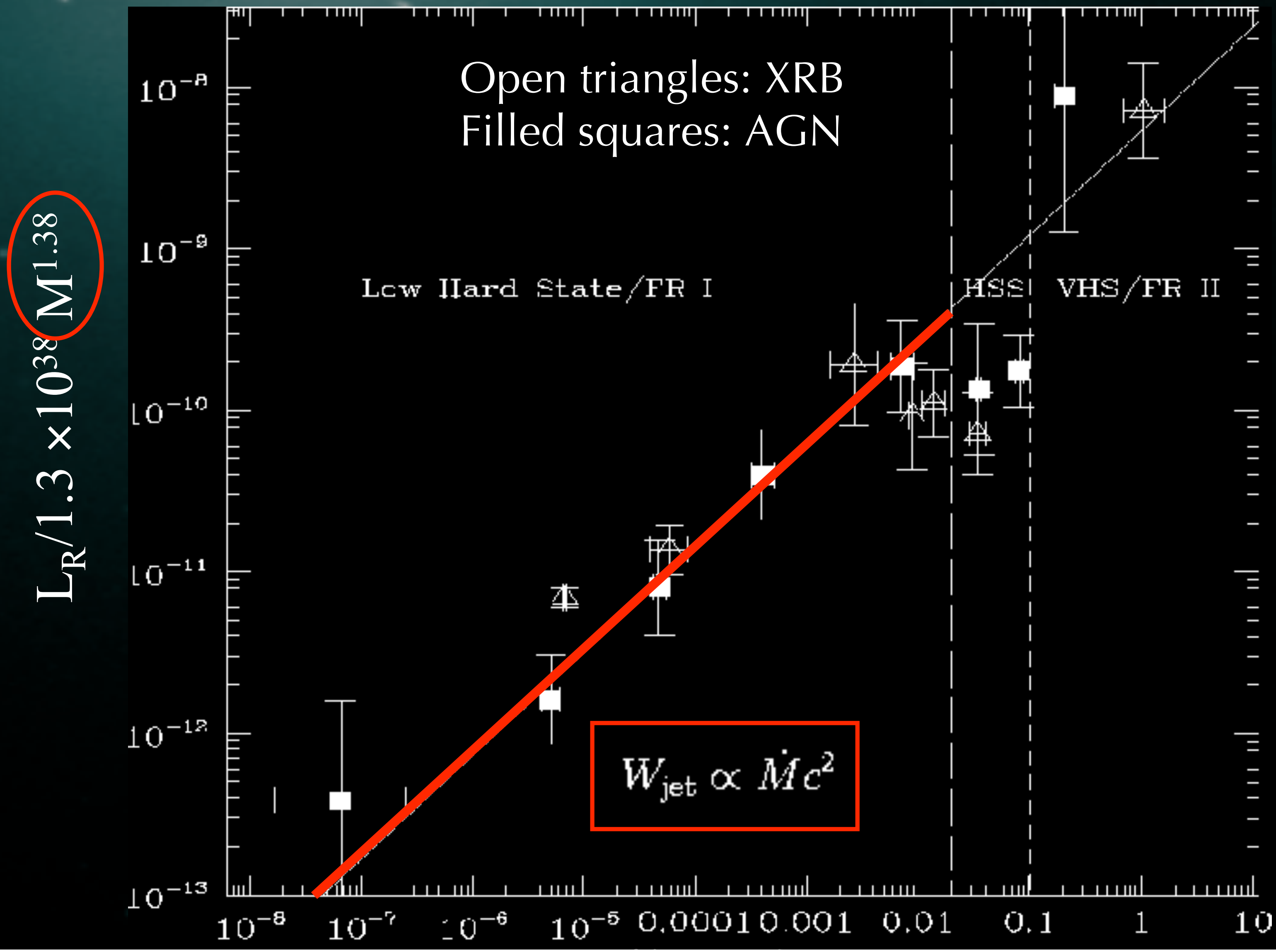
Falcke and Biermann '96; Heinz and Sunyaev 2003; Merloni et al 2003

What about radio galaxies and AGN?

- Verify the hypothesis that AGN at low luminosity release most of their power as Kinetic Energy and the Low-hard state scaling
- Need independent measures of L_{Kin} and L_R (and/or L_X, M_{BH})
  - Dynamical, from models of jet/lobe emission and evolution
    - Cyg A, M87, Perseus A, NGC 4636
  - Indirect, from estimates of PdV work done on surrounding gas (X-ray cavities) (Allen et al. 2006; Rafferty et al. 2006)

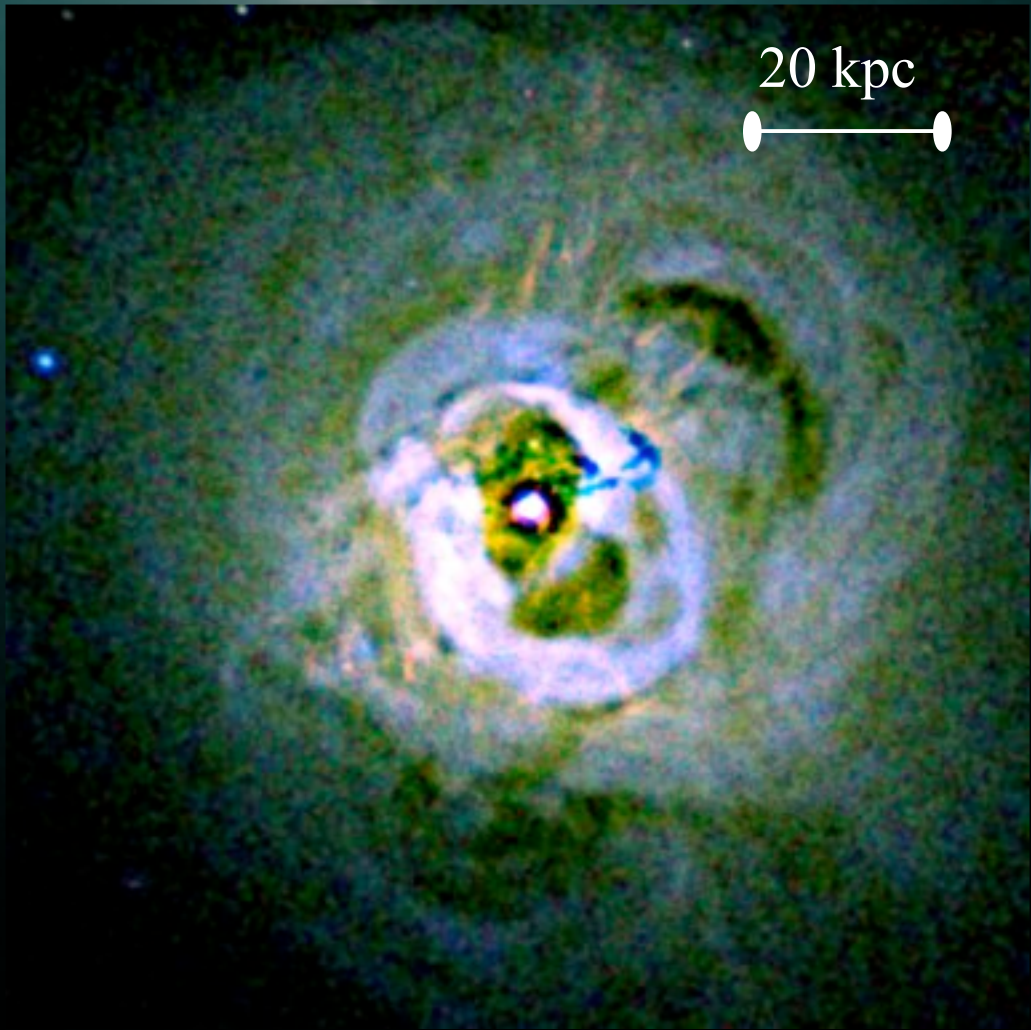
Radio cores scaling with M and mdot

A "fundamental plane" of active BHs [Merloni et al. 2003; Falcke et al. 2004]



Very little scatter if only flat-spectrum low-hard state sources are considered (Körding et al. 2006)

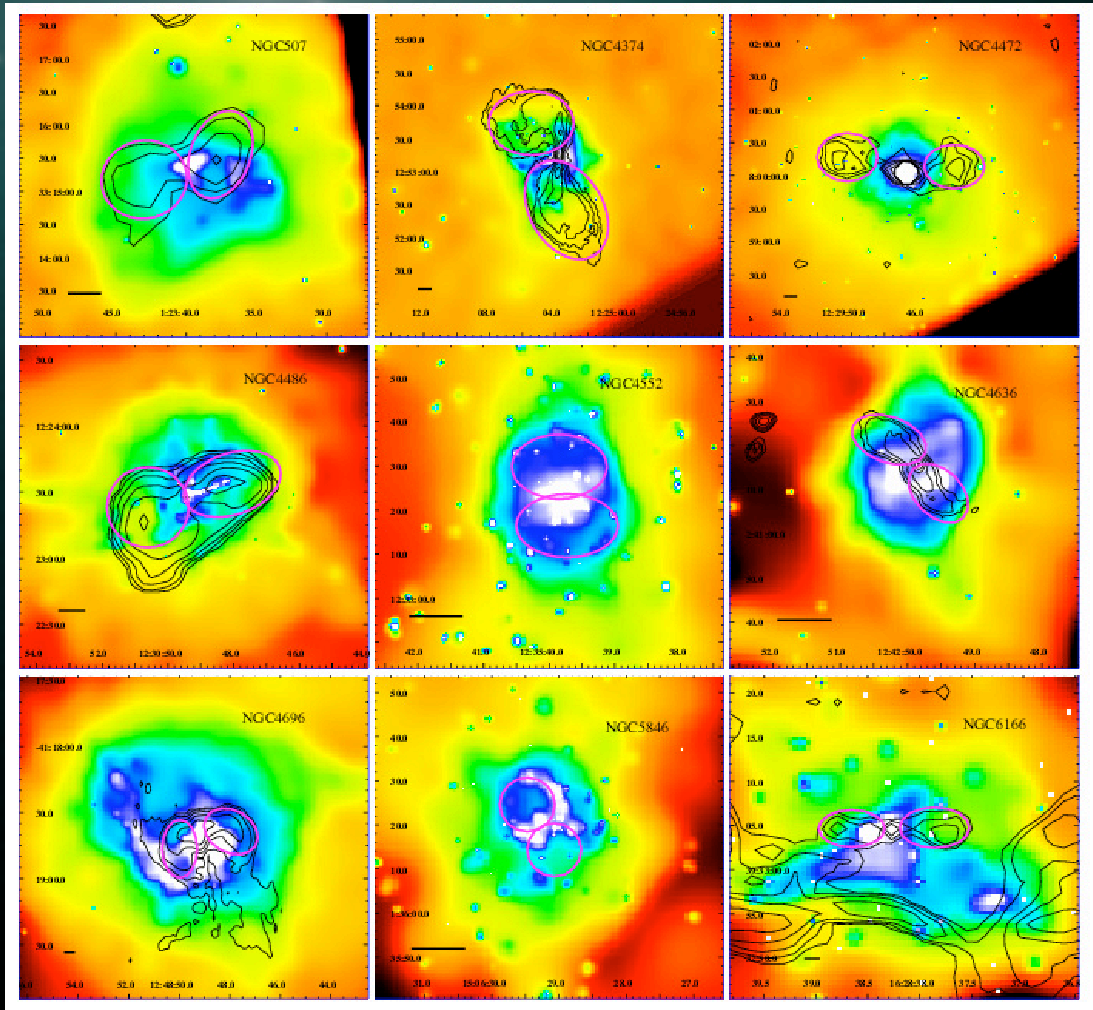
AGN feedback: evidence on cluster scale



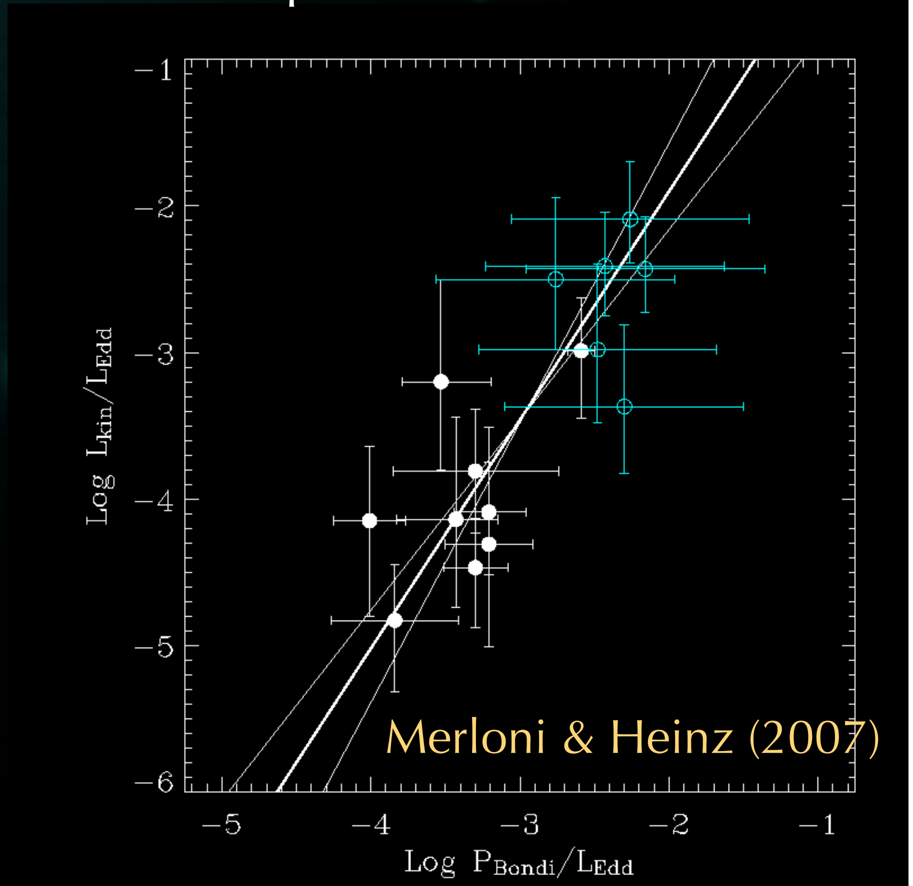
- 1 Msec observation of the core of the Perseus Cluster with the *Chandra* X-ray Observatory
- True color image made from 0.3-1.2 (red), 1.2-2 (green), 2-7 (blue) keV photons
- First direct evidence of ripples, sound waves and shocks in the hot, X-ray emitting intracluster gas
- Radio maps reveal close spatial coincidence between X-ray morphology and AGN-driven radio jets

Fabian et al. 2006

Estimating Jet power in nearby ellipticals

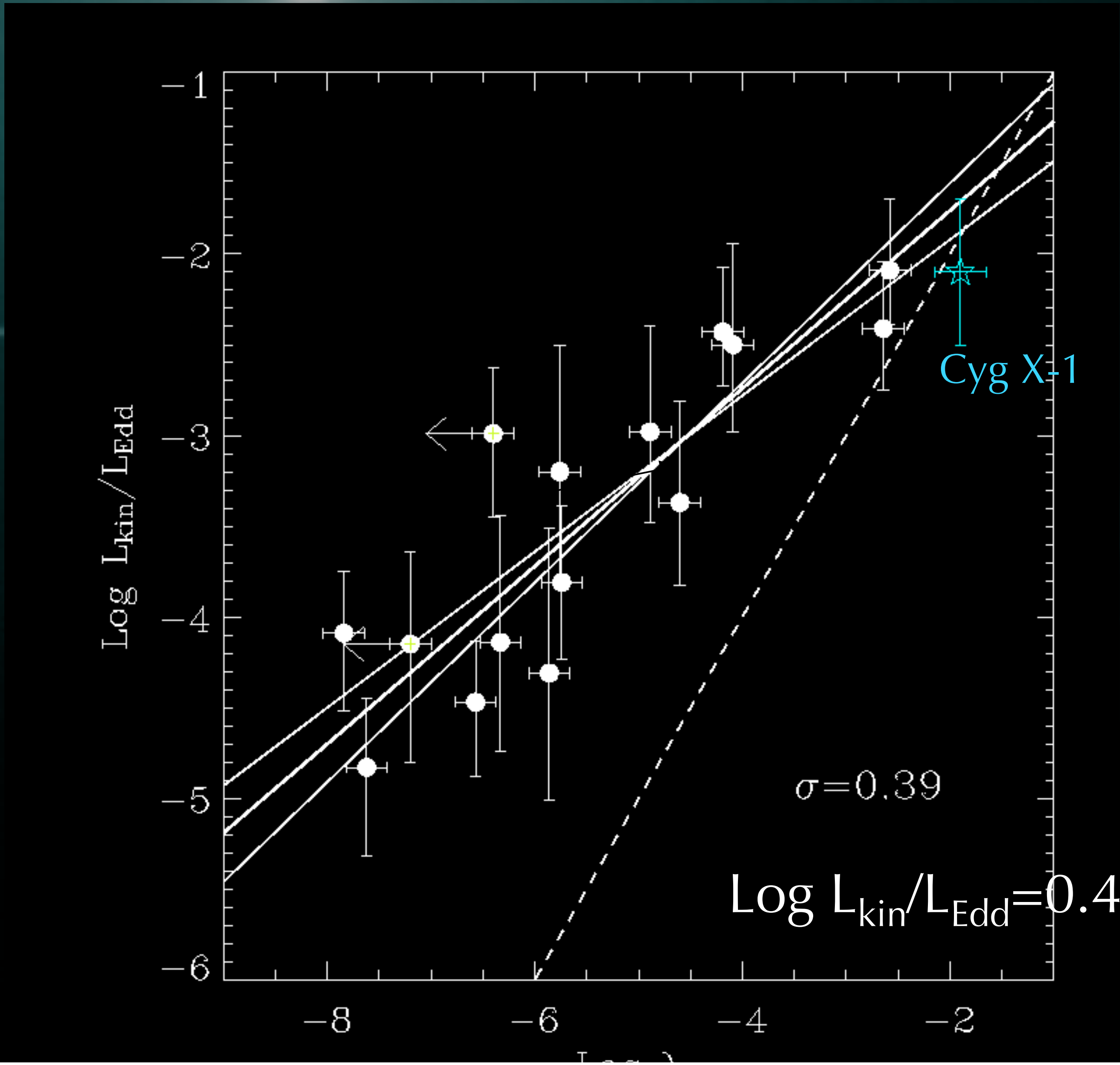


- Allen et al. (2006): correlation between Jet kinetic power and Bondi power



Chandra 0.5-8keV (colour), 1.5GHz VLA radio (contours), bubbles (magenta ellipses).
Allen et al. (2006), Birzan et al. (2004), Rafferty et al. (2006)

Low Power AGN are jet dominated

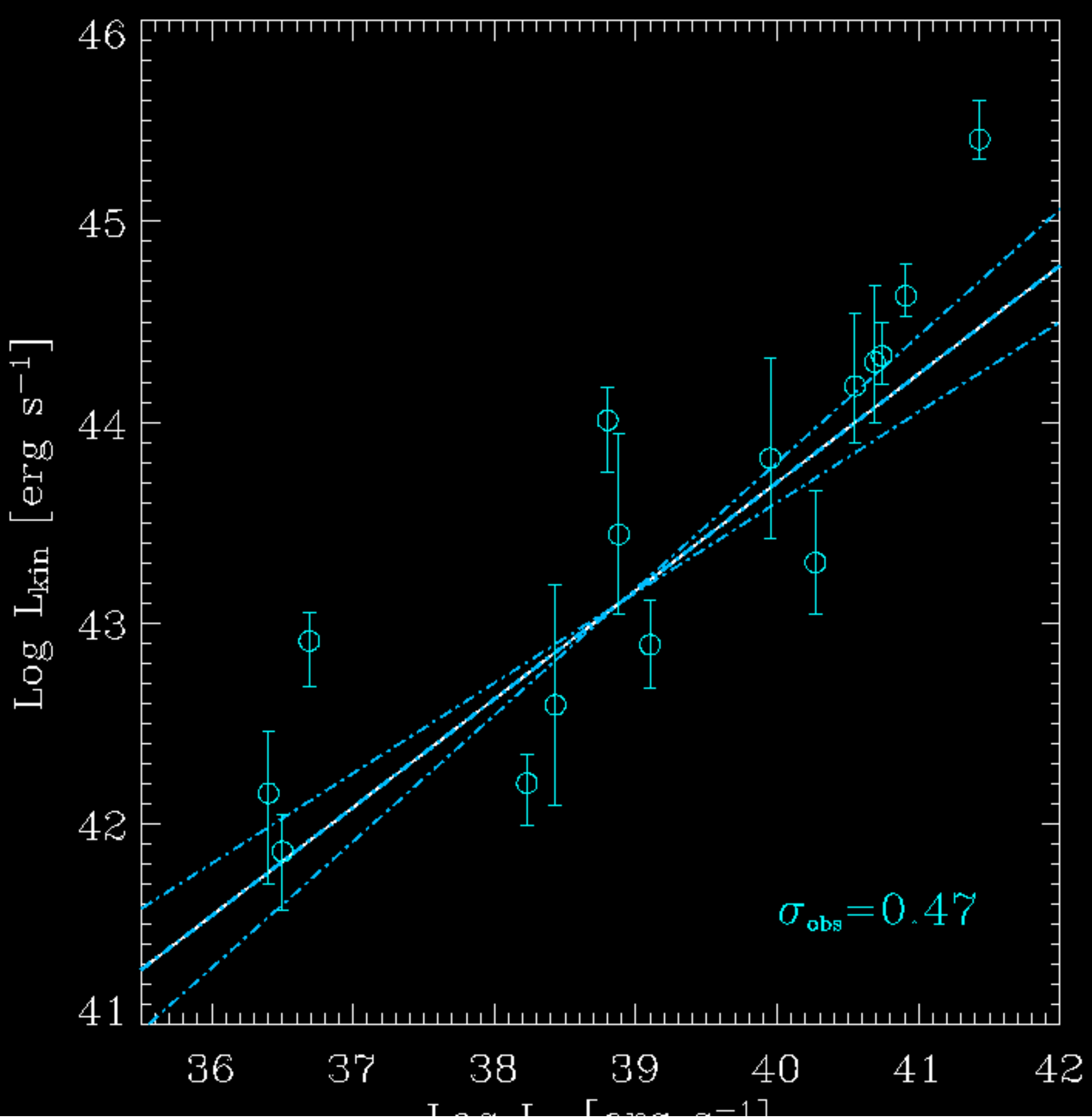


- By studying the nuclear properties of the AGN we can establish a link between jet power and accretion power
- The observed slope (0.50±0.045) is perfectly consistent with radiatively inefficient "jet dominated" models

$$\text{Log } L_{kin}/L_{Edd} = 0.49 \text{ Log } L_{bol}/L_{edd} - 0.78$$

Merloni and Heinz (2007)

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



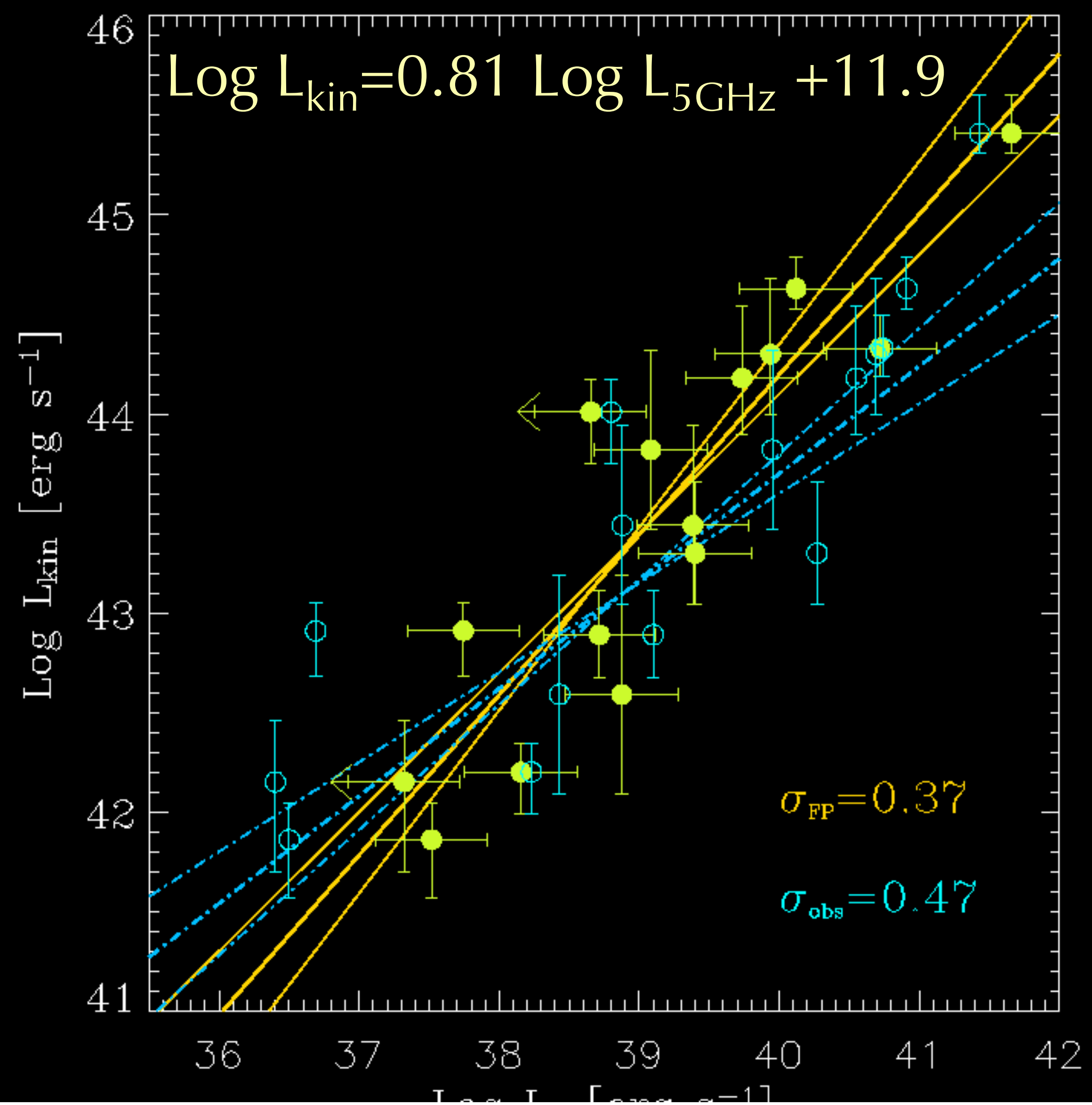
Slope=0.54

Observed L_R (beaming)

Birzan et al. (2004)

Best et al. (2006)

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



Slope=0.81

Slope=0.54

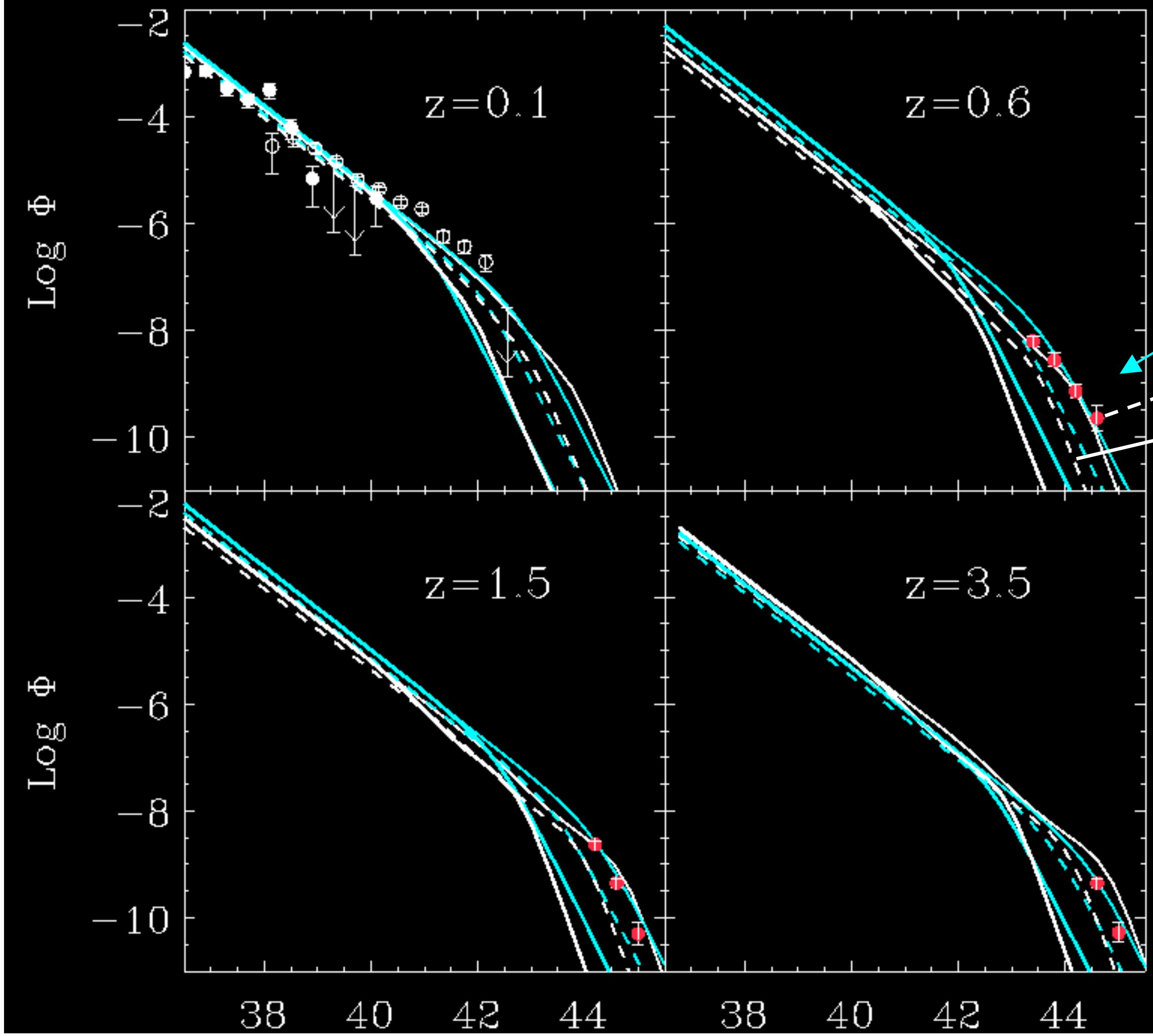
Observed L_R (beaming)
Derived from FP relation

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

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

Merloni and Heinz (2007)

Flat Spectrum radio LF: de-beaming



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

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

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

"Observed" FSRLFs

<Γ>=2

<Γ>=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)

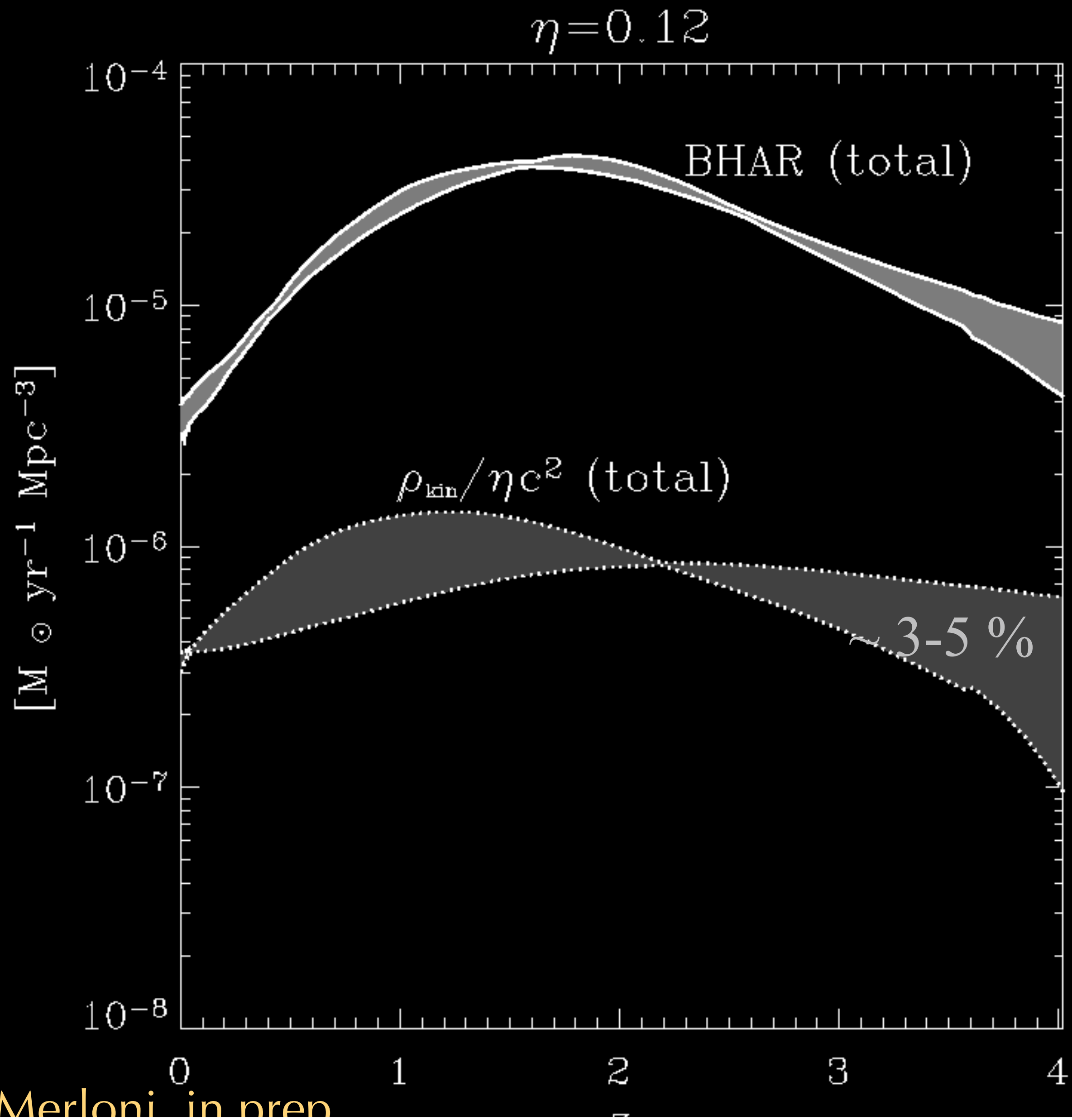
Beaming model from
Urry & Schaefer (1984)
Urry & Padovani(1991)

SMBH population synthesis model: accretion and jets

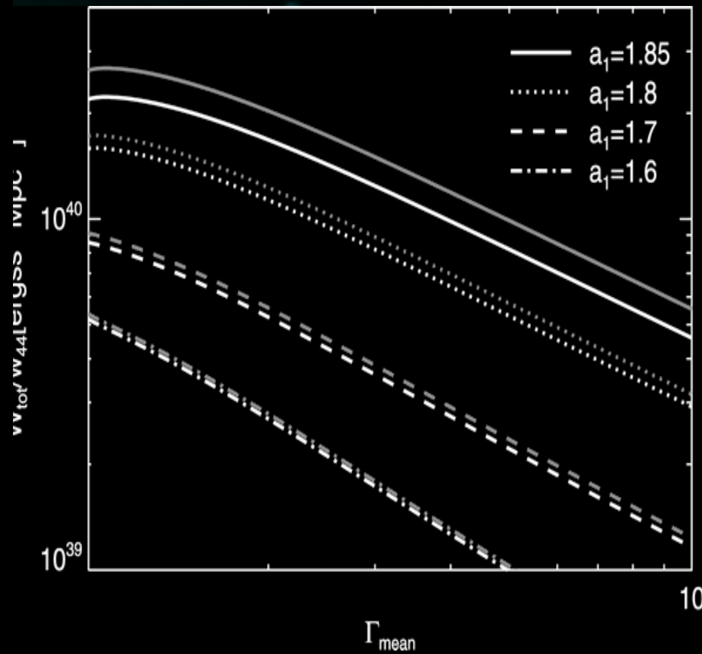
- Derive the intrinsic, un-beamed core radio luminosity function of AGN from the observed flat spectrum radio sources LF (Dunlop & Peacock 1990; De Zotti et al. 2005).
    - Assumes radio jets have all the same Gamma factor (or a distribution peaked around a single value)
- Use the L_R/L_{Kin} relation to estimate kinetic power (CAVEAT: extension to high power sources uncalibrated)
- Use the fundamental plane of active black holes to “couple” the evolving X-ray (accretion) and radio (kinetic power output) AGNLF (Merloni 2004)

(Merloni 2007; Heinz, Merloni & Schwab 2007)

Kinetic Energy output and SMBH growth



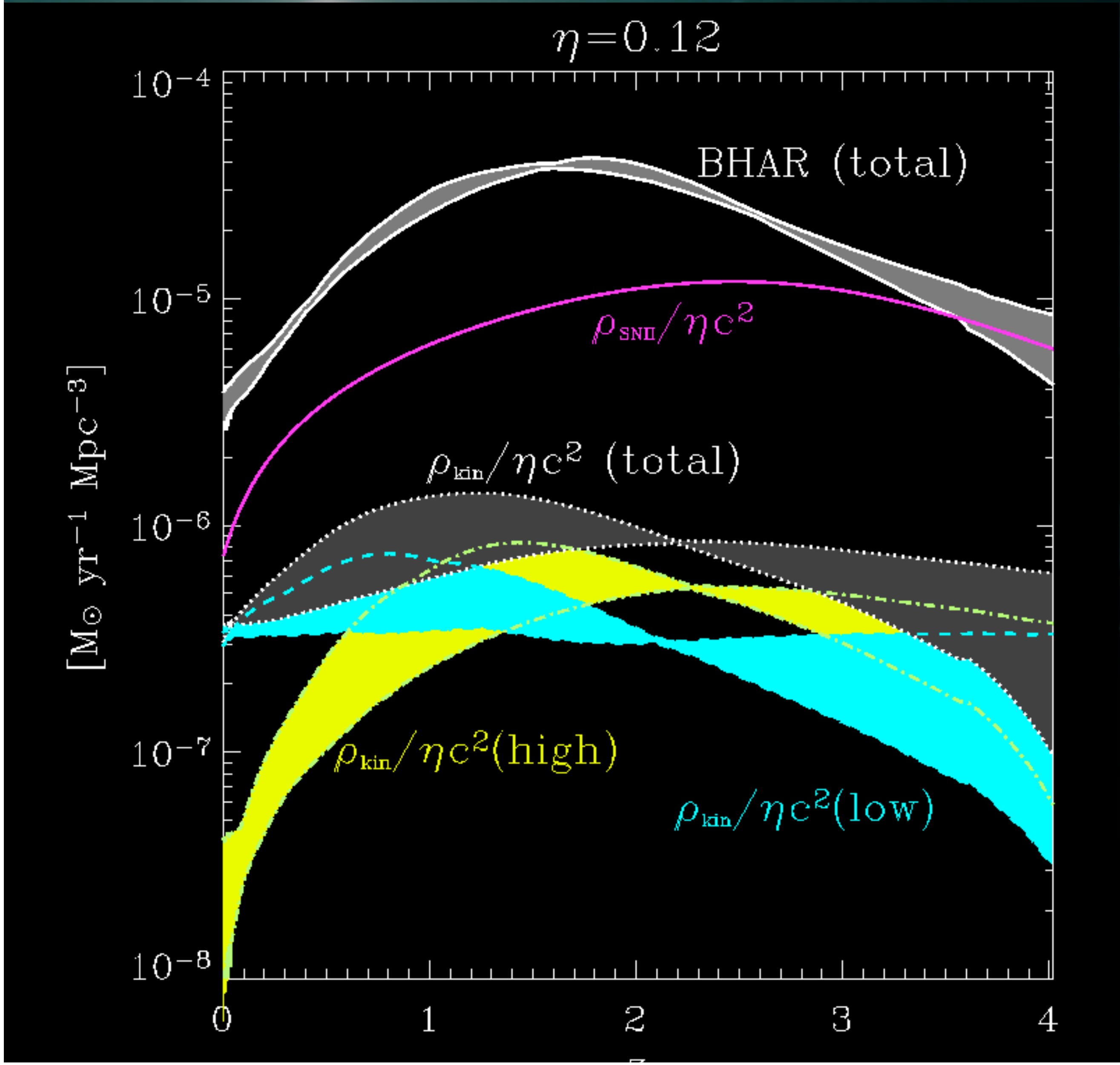
A consistency check for structure formation models



Dependence on Lorentz factor and faint-end slope of z=0 point Heinz et al. (2007)

Merloni, in prep

Kinetic Energy output and SMBH growth



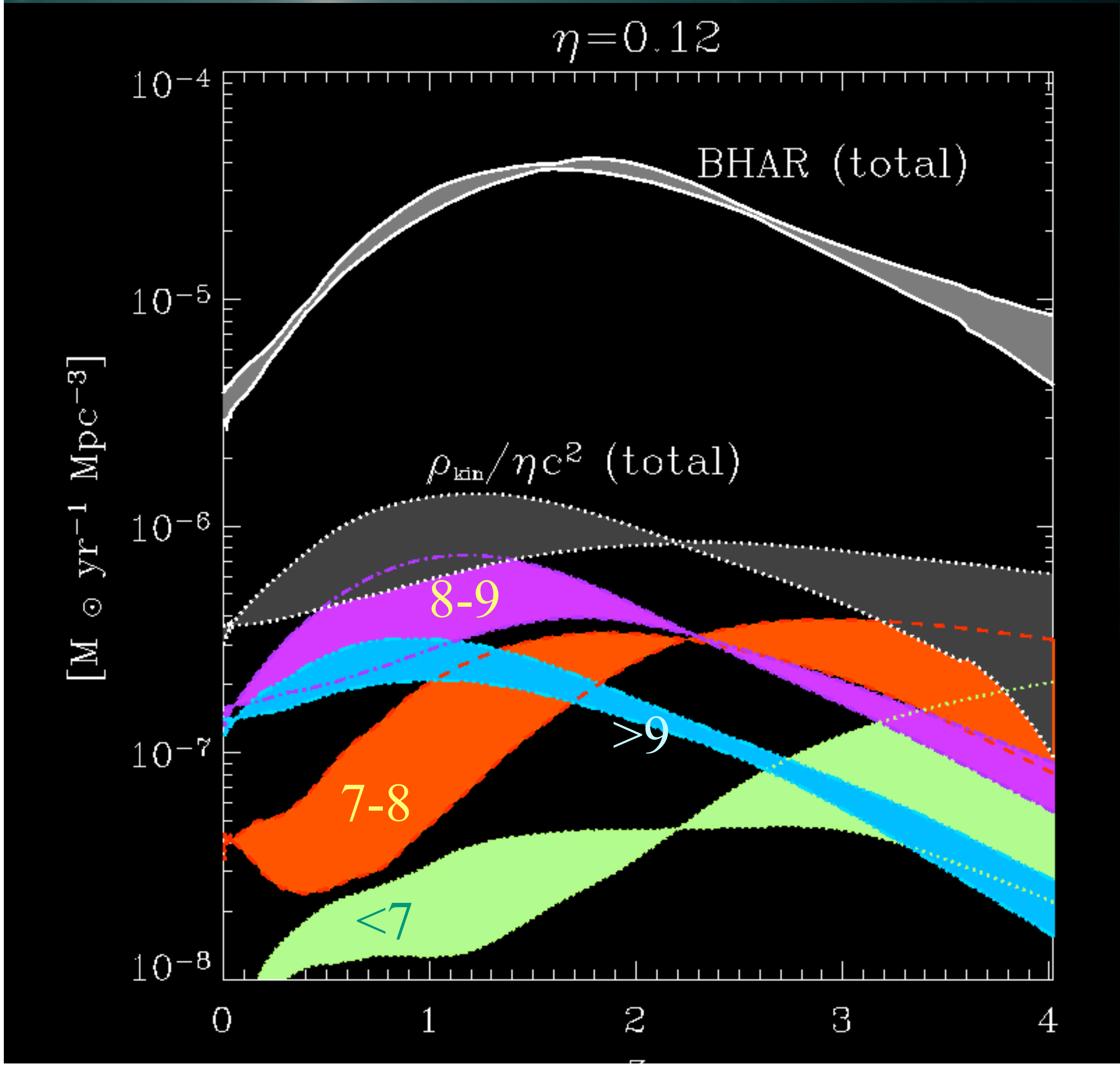
$\rho_{BH,X} \sim 2.1 \div 2.3 \times 10^5$

Compare: local stellar Luminosity density $\rho^* \sim 2x10^{41}$

Tentative split into accretion modes

Merloni, in prep.

Kinetic Energy output by SMBH mass



Tentative split into (log of) SMBH masses

Merloni, in prep.

Conclusions

- Constraints on the physics of accretion/jet production are crucial for our understanding of AGN feedback
- "Low-luminosity AGN" are most likely dominated by kinetic energy as a sink of energy
- Physically motivated scaling $L_{kin} \sim L_{core,5GHz}^{0.8}$
- We can put constraints on the redshift evolution of the mechanical energy output from growing black holes
- For an overall accretion efficiency of ~10%, the efficiency with which growing black holes convert mass into mechanical energy is 0.4-0.6%, sensitive to the low-end slope of the FSRLF locally and at high-z
- AGN enter the radio (accretion) mode at late times, and large black holes do it first (down-sizing?)

The M87 jet

Hubble Heritage Project

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