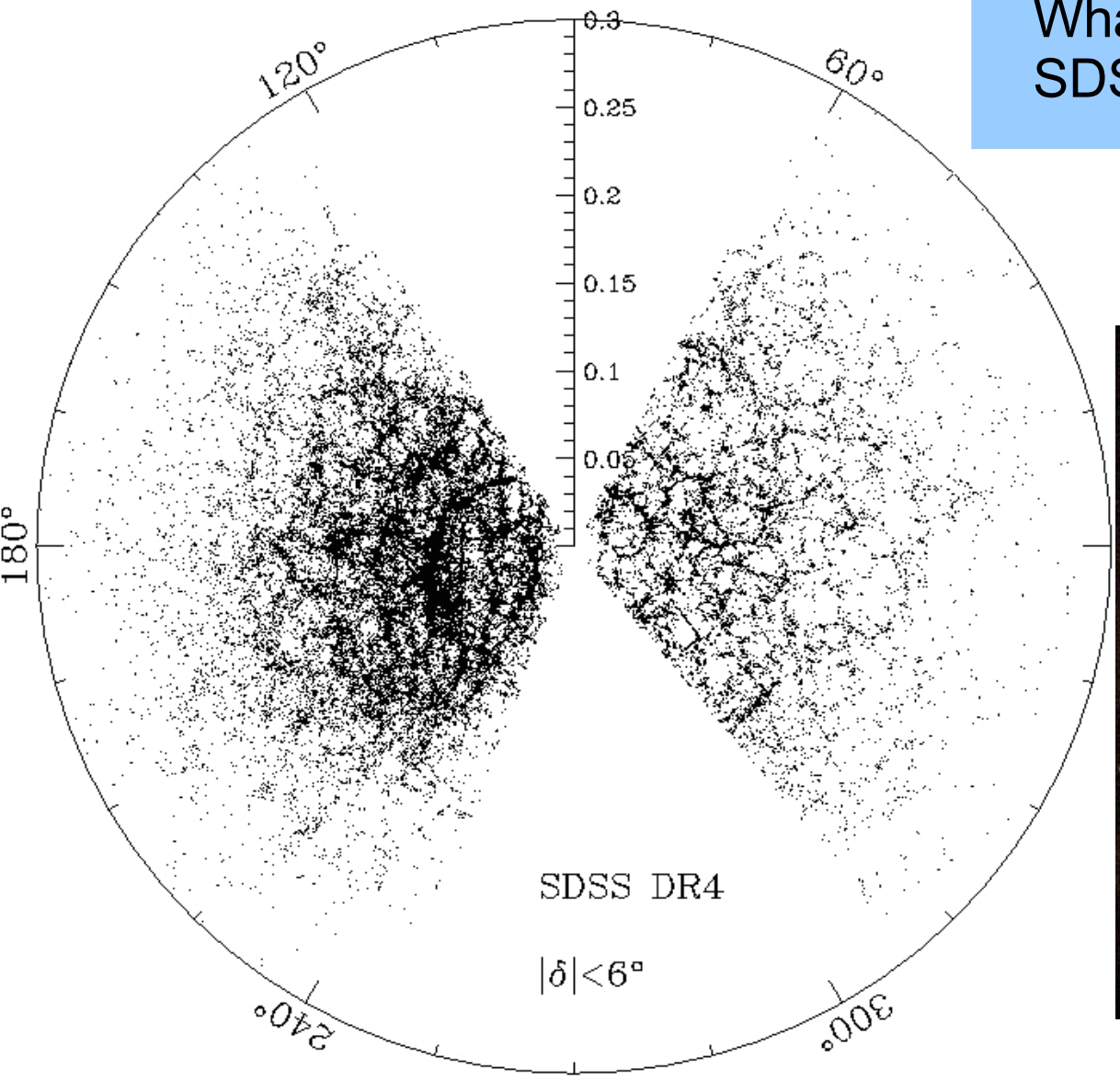
The Co-evolution of Galaxies and their Supermassive Black Holes

What have we learned from the SDSS?



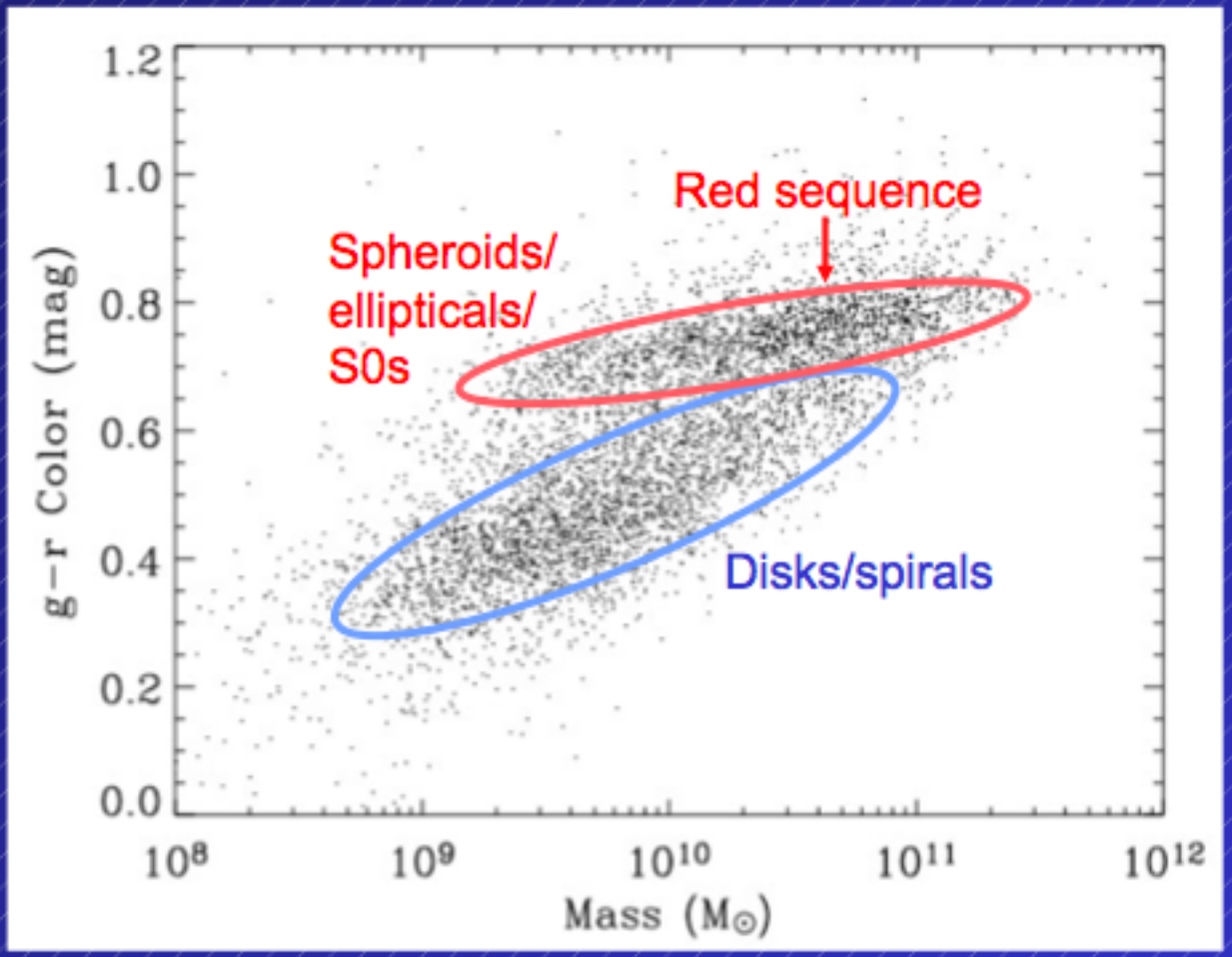
Color bimodality seen in Sloan galaxies

"Red-and dead" ellipticals/S0s populate the red sequence

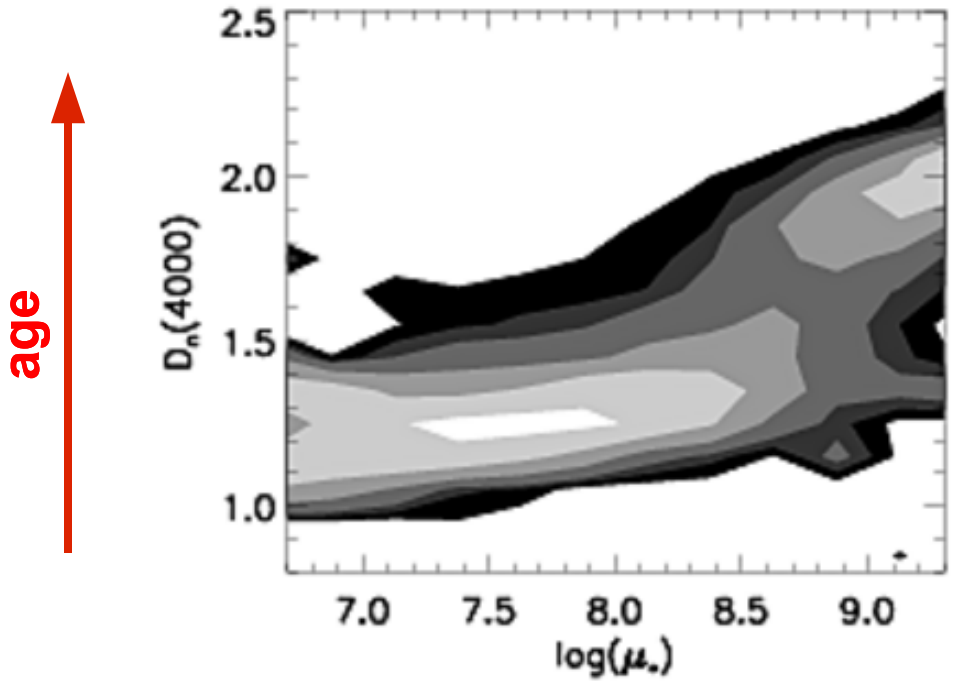
Star-forming blue, disky galaxies populate the "blue cloud"

Red

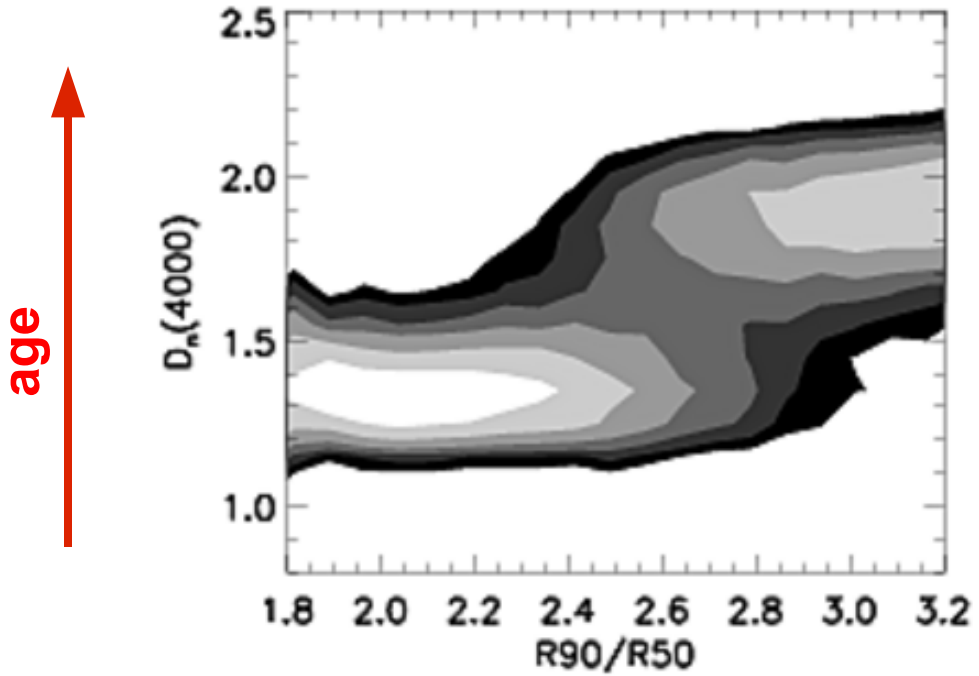
Blue



Color vs. stellar mass for Sloan Digital Sky Survey galaxies



As a function of surface mass density



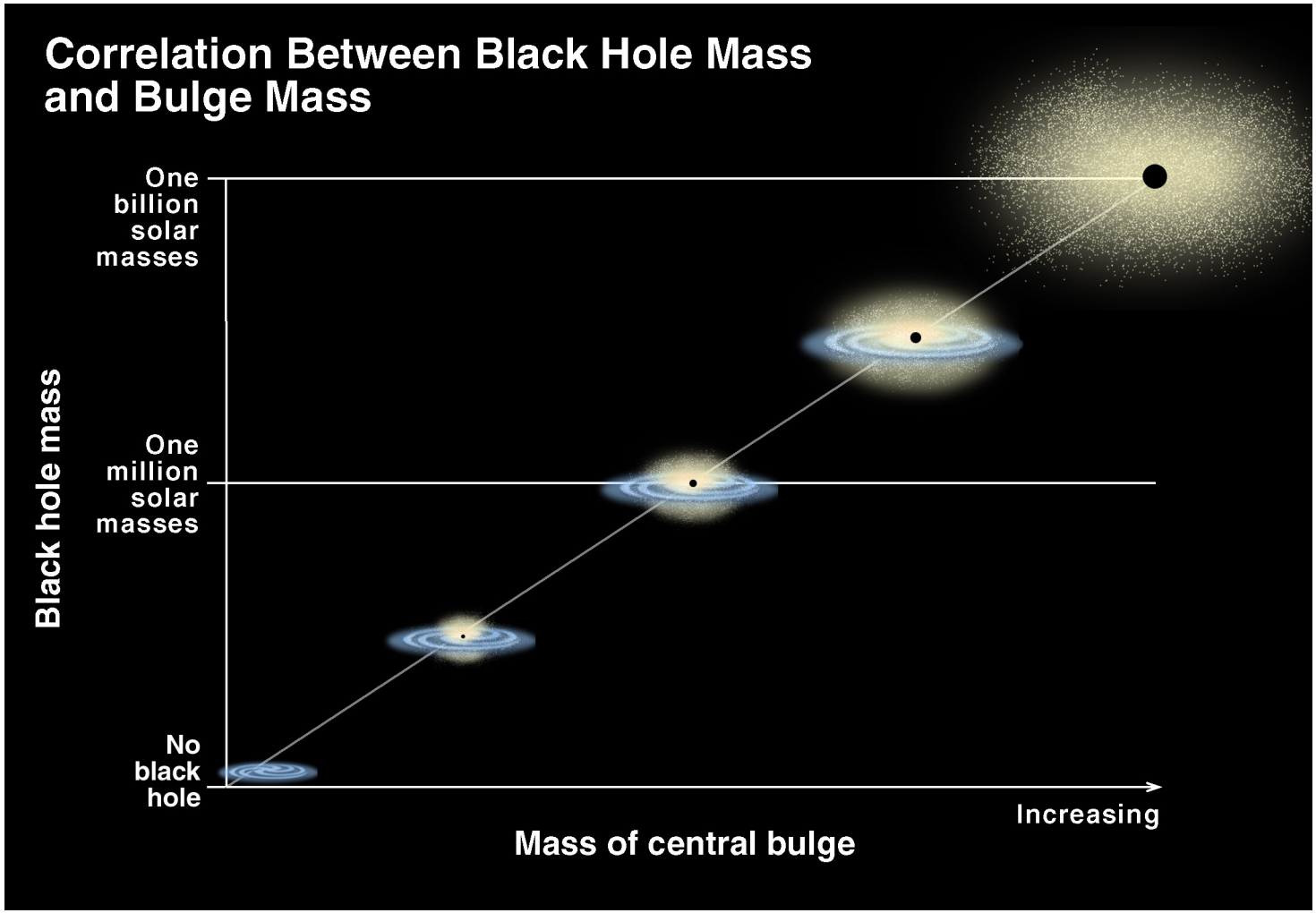
As a function of concentration

Kauffmann et al 2003

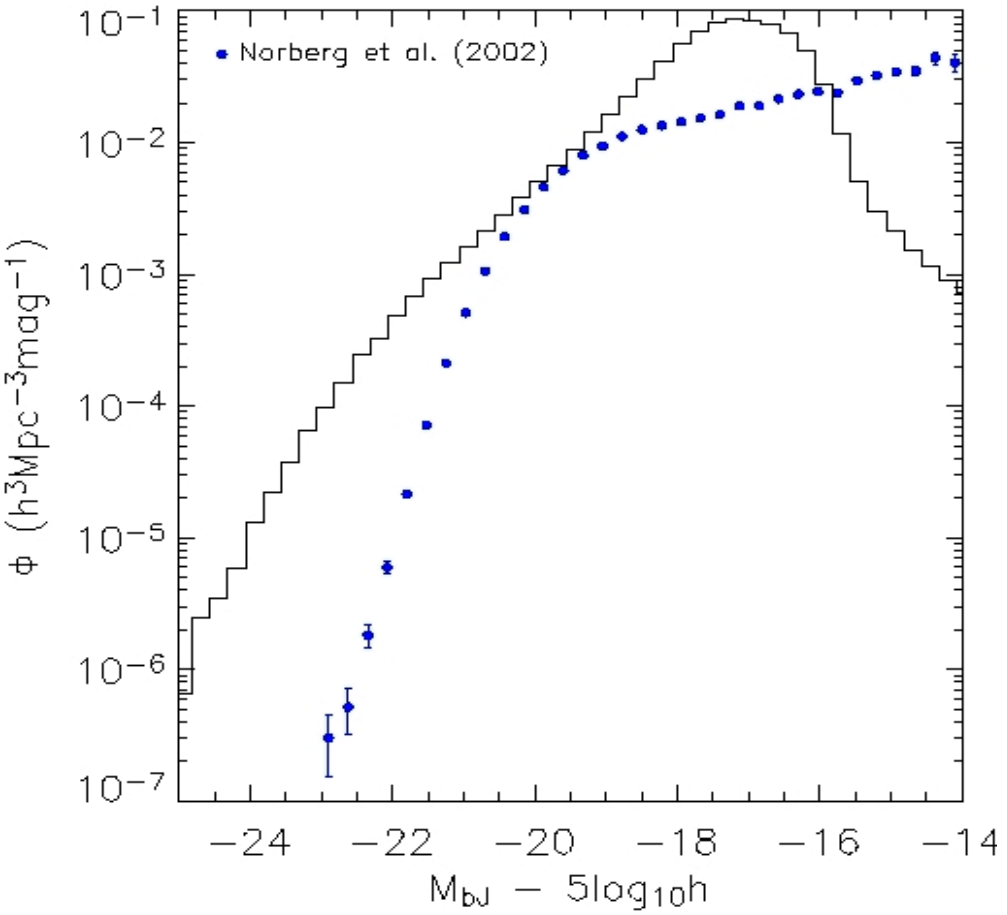
Revolution in in our understanding of galaxy formation:

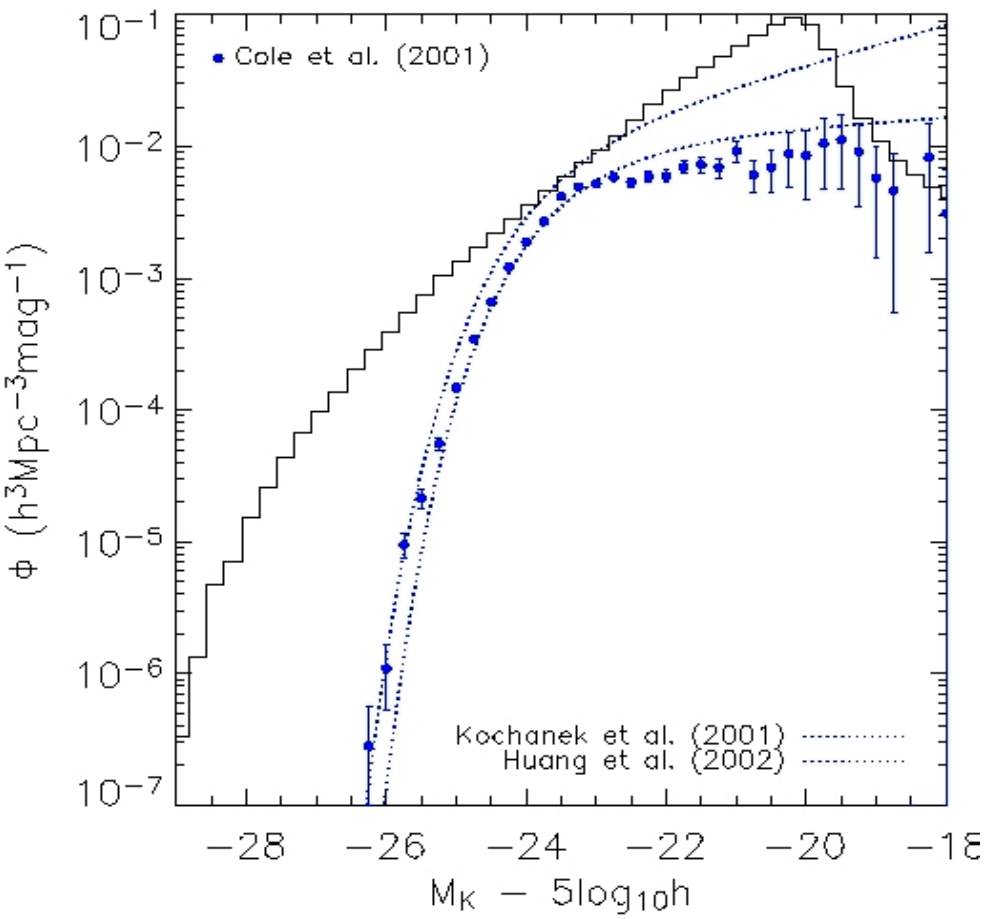
1) All galaxy bulges contain supermassive black holes
2) The mass of the black hole is tightly correlated with the mass of the bulge.

Does the black hole regulate the growth of the galaxy?



Effect of feedback on the Luminosity Function

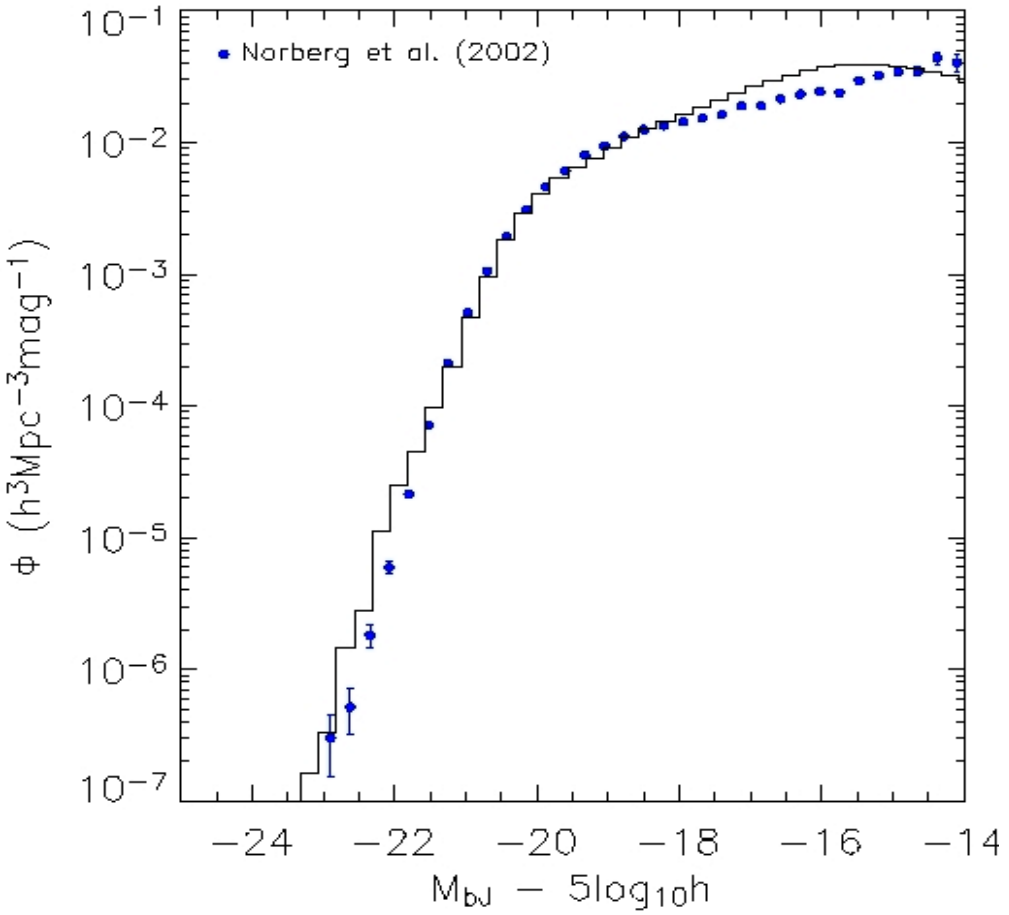


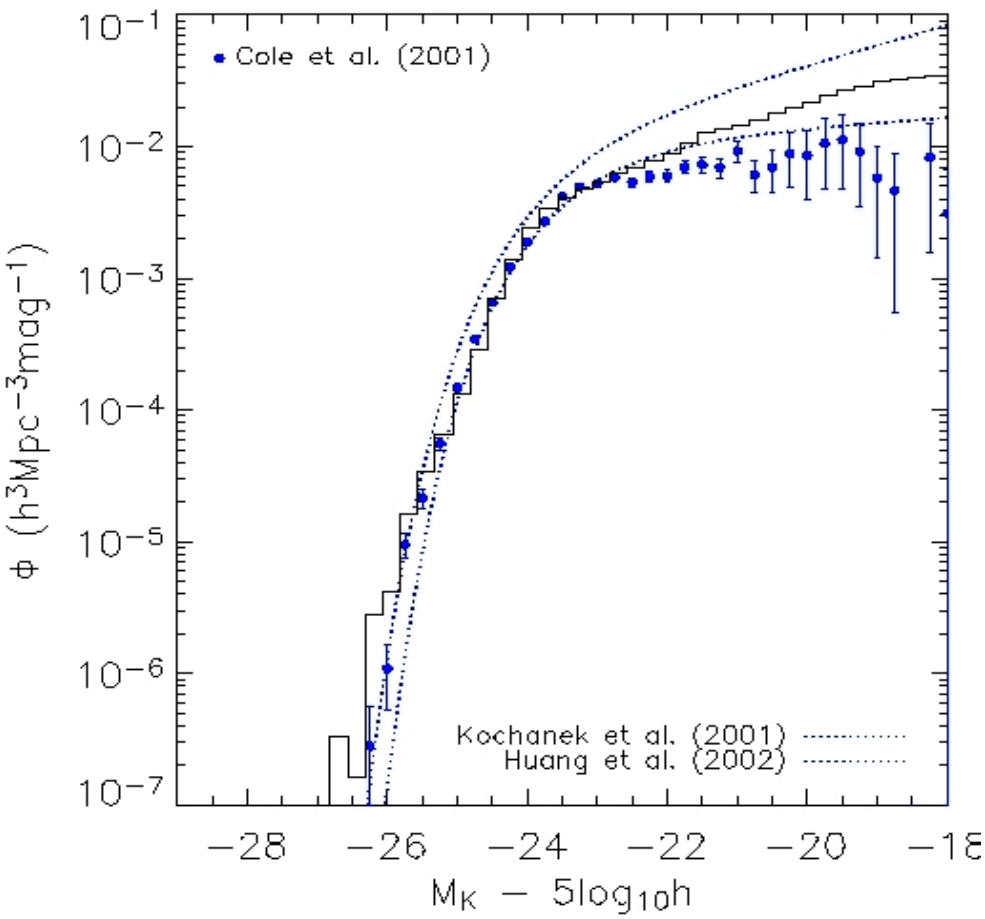


Model with no feedback

Croton et al 2006

Effect of feedback on the Luminosity Function

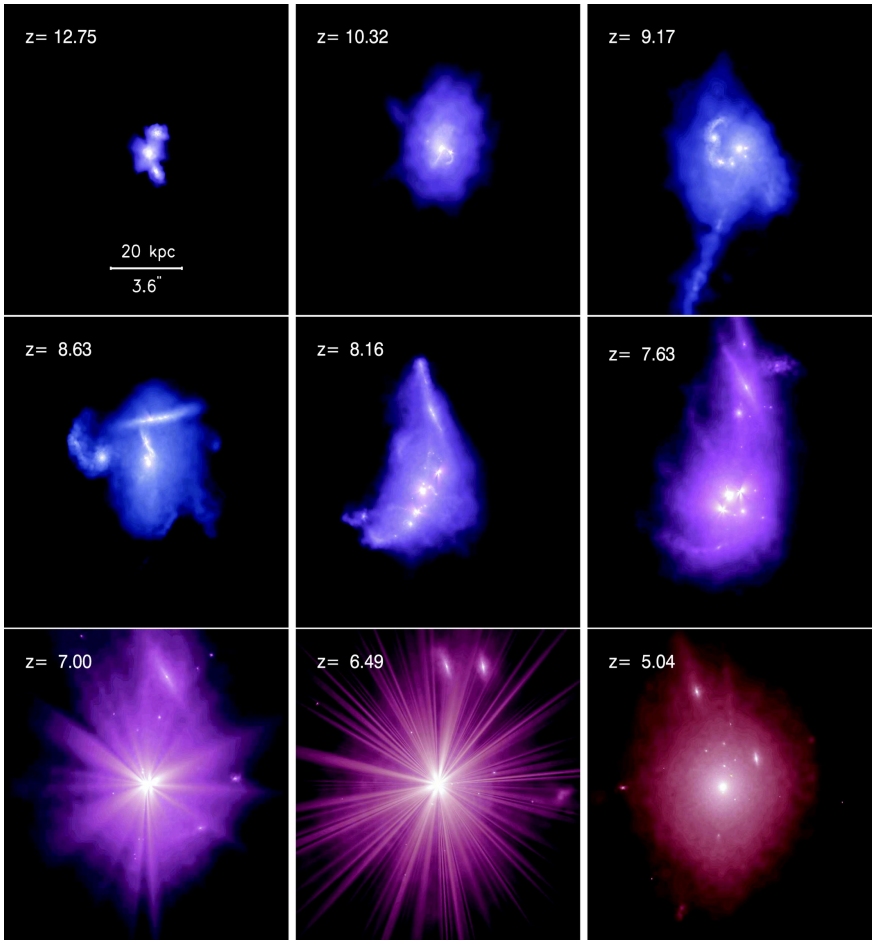




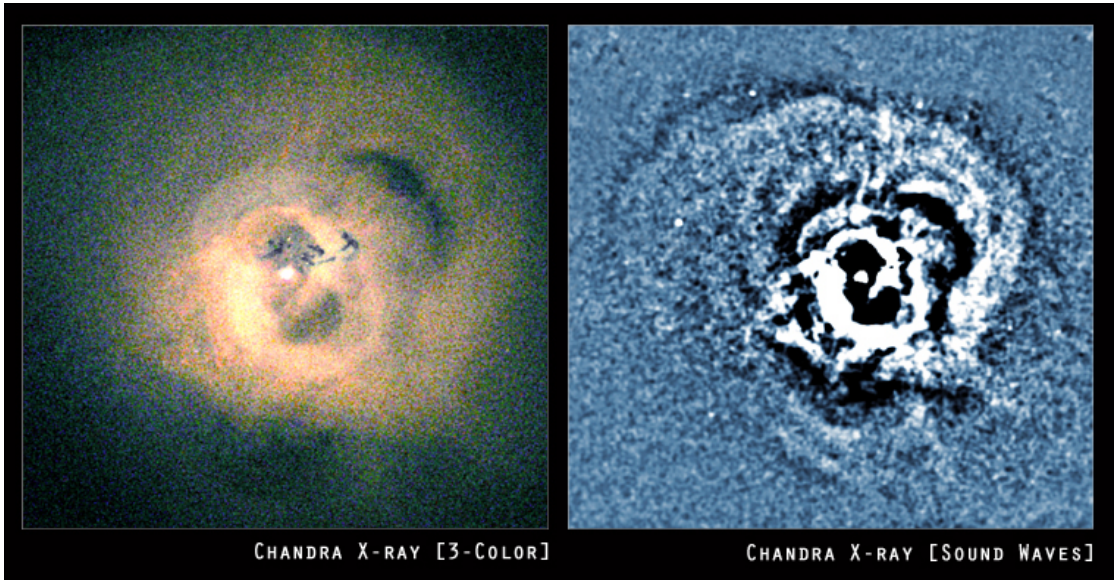
Full model with SN and radio AGN feedback

What is the nature of the feedback?

Di Matteo, Springel, Hernquist , Hopkins

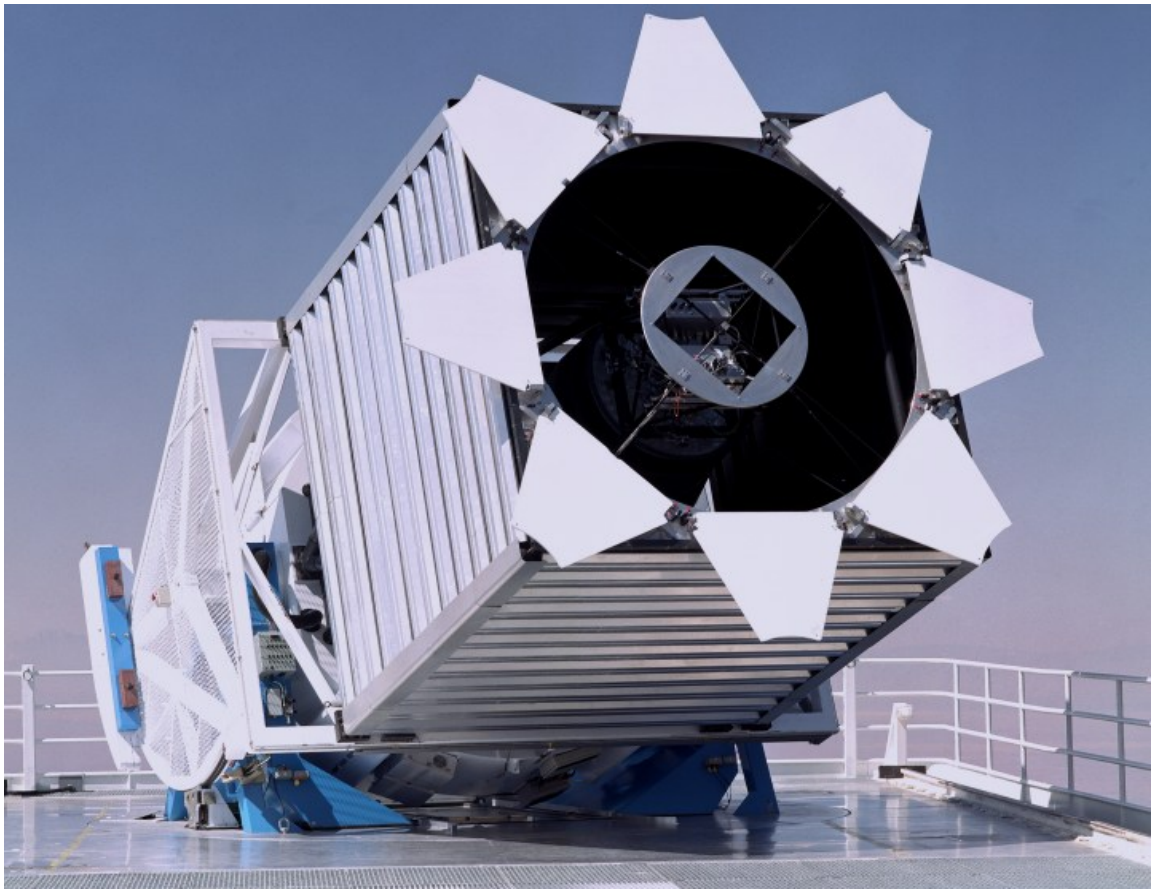


Croton, Bower etc

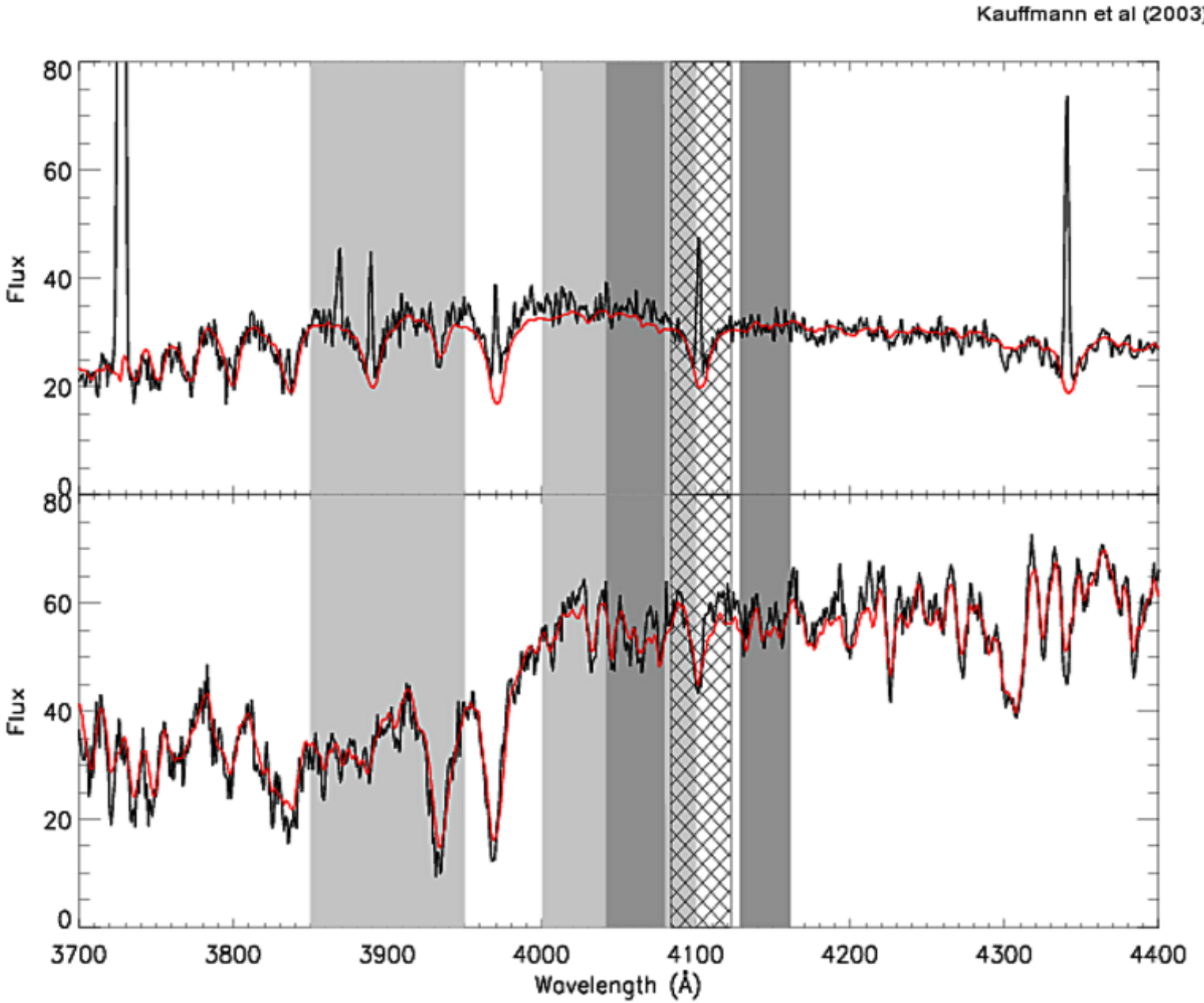


Sloan Digital Sky Survey

http://www.sdss.org/

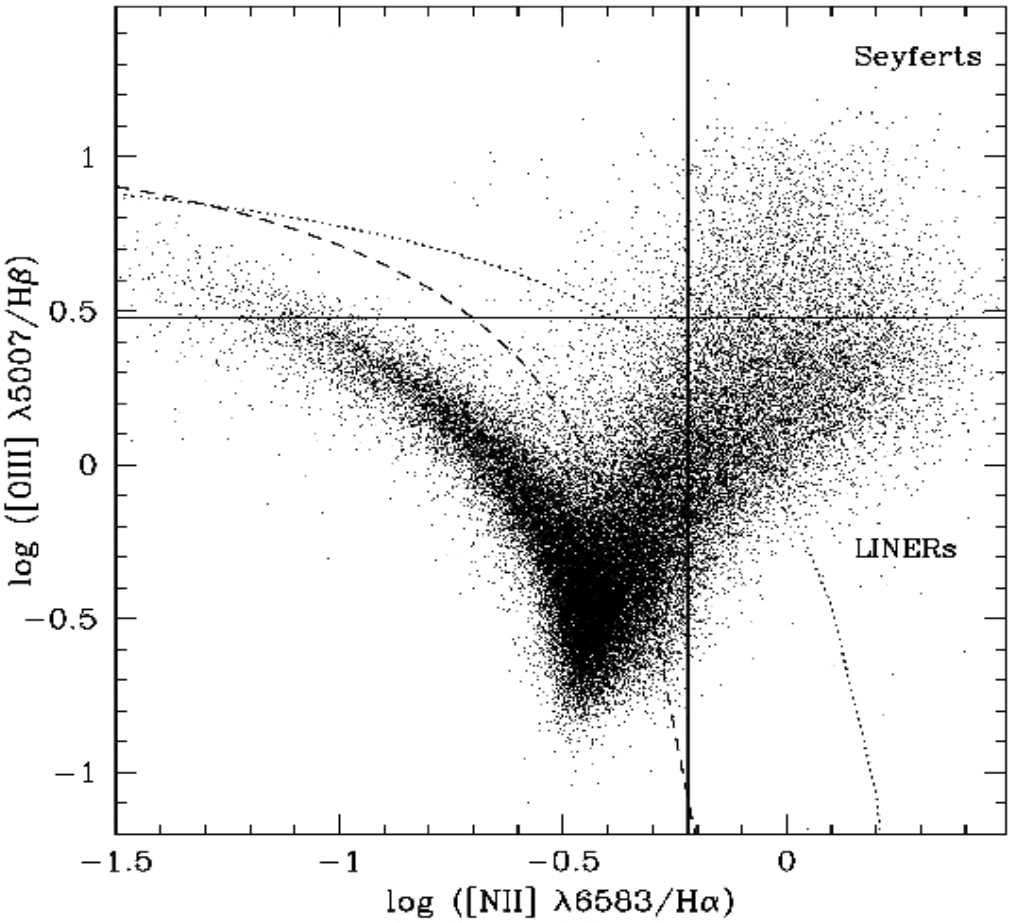


Emission lines and measurs of stellar age and recent SFH from absorption features



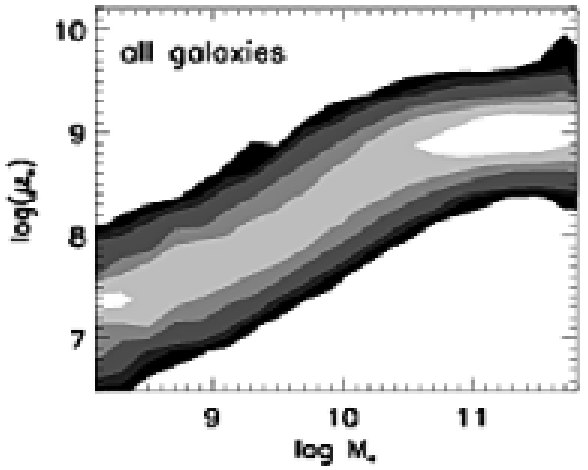
Surveys of Type II AGN at Low Redshifts from SDSS

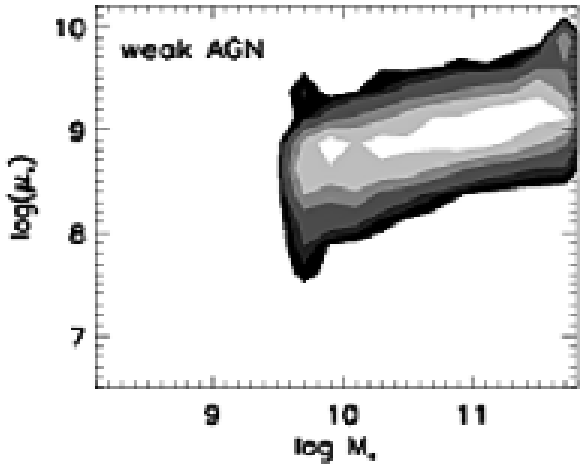
(for detailed analysis of host galaxy properties)

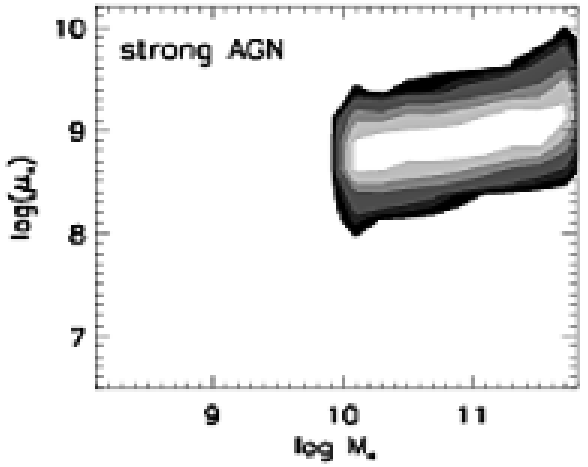


Kauffmann et al 2003

80,000 out of 400,000 galaxies are classified as AGN





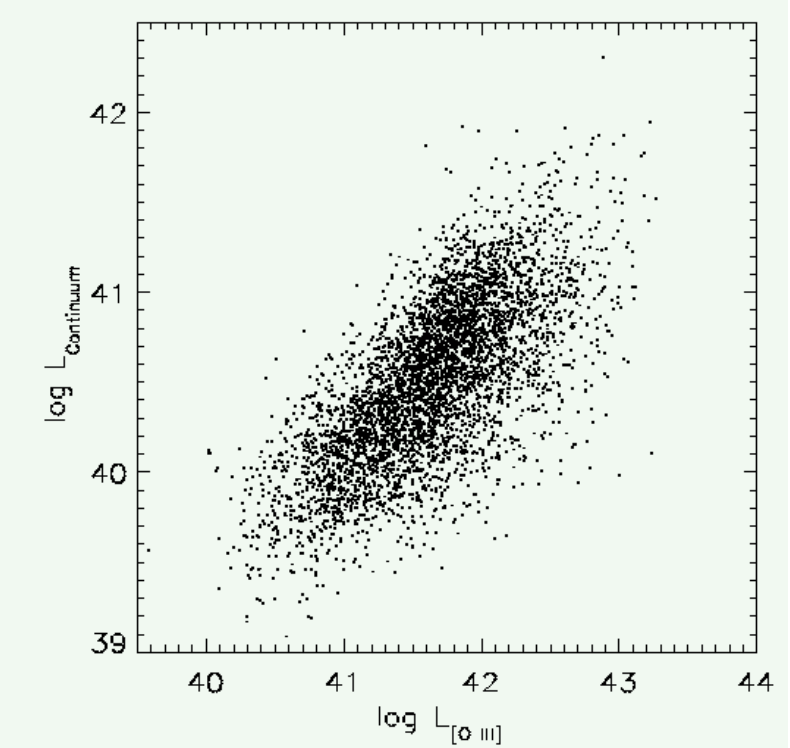


The Stellar Masses and Structural Properties of AGN Hosts

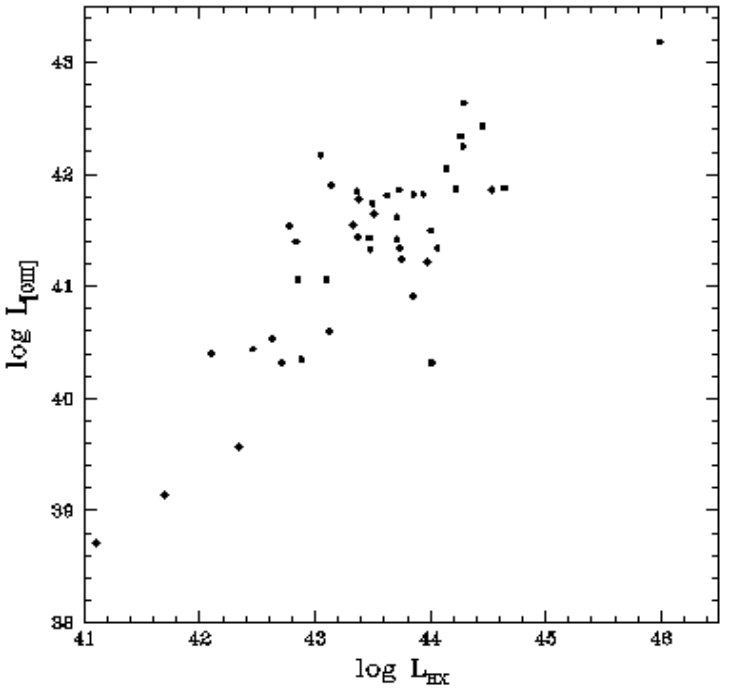
Main Conclusion:
all AGN live in the same region of parameter space as massive, early-type galaxies

Accretion

The [OIII] Line Luminosity as a Black Hole Accretion rate Indicator

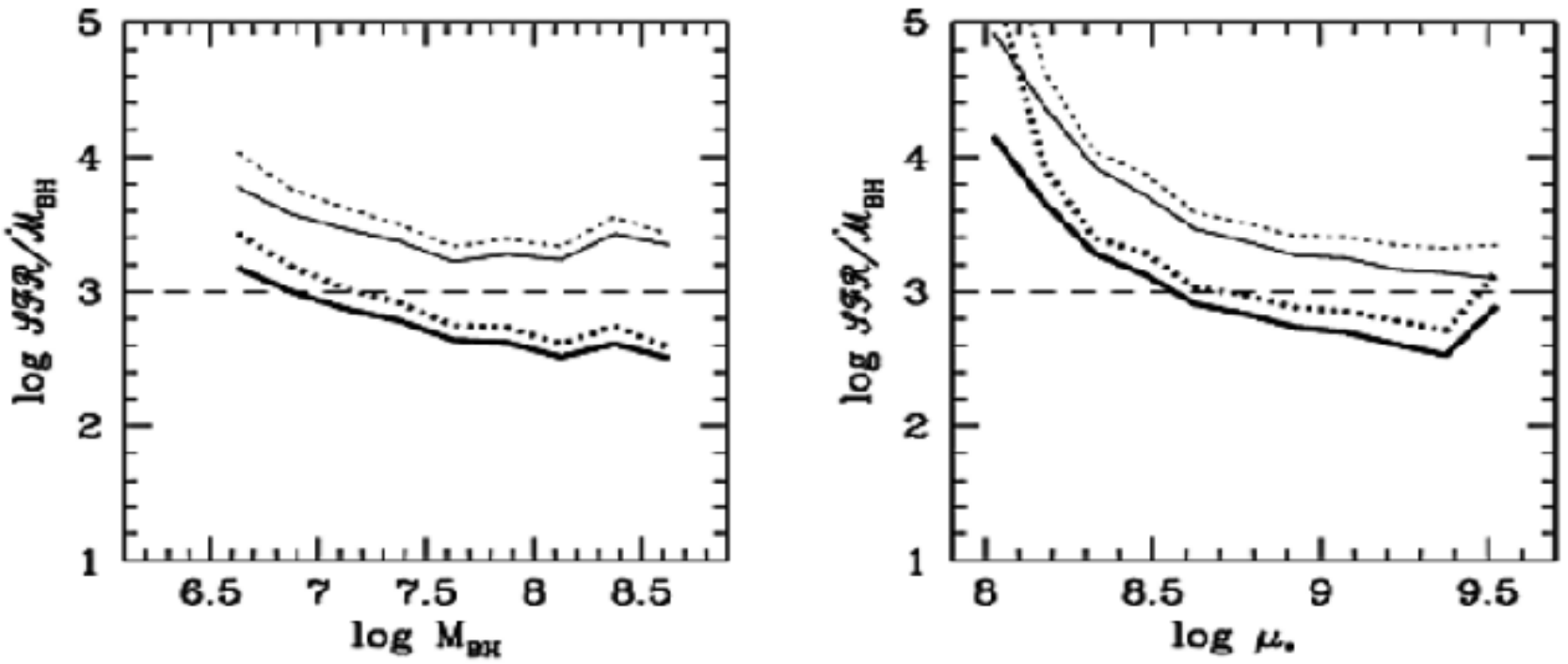


Correlation of [OIII] luminosity with continuum luminosity for Type 1 AGN (Zakamska et al 2003)



Correlation of [OIII] luminosity with hard x-ray luminosity (Heckman et al 2005)

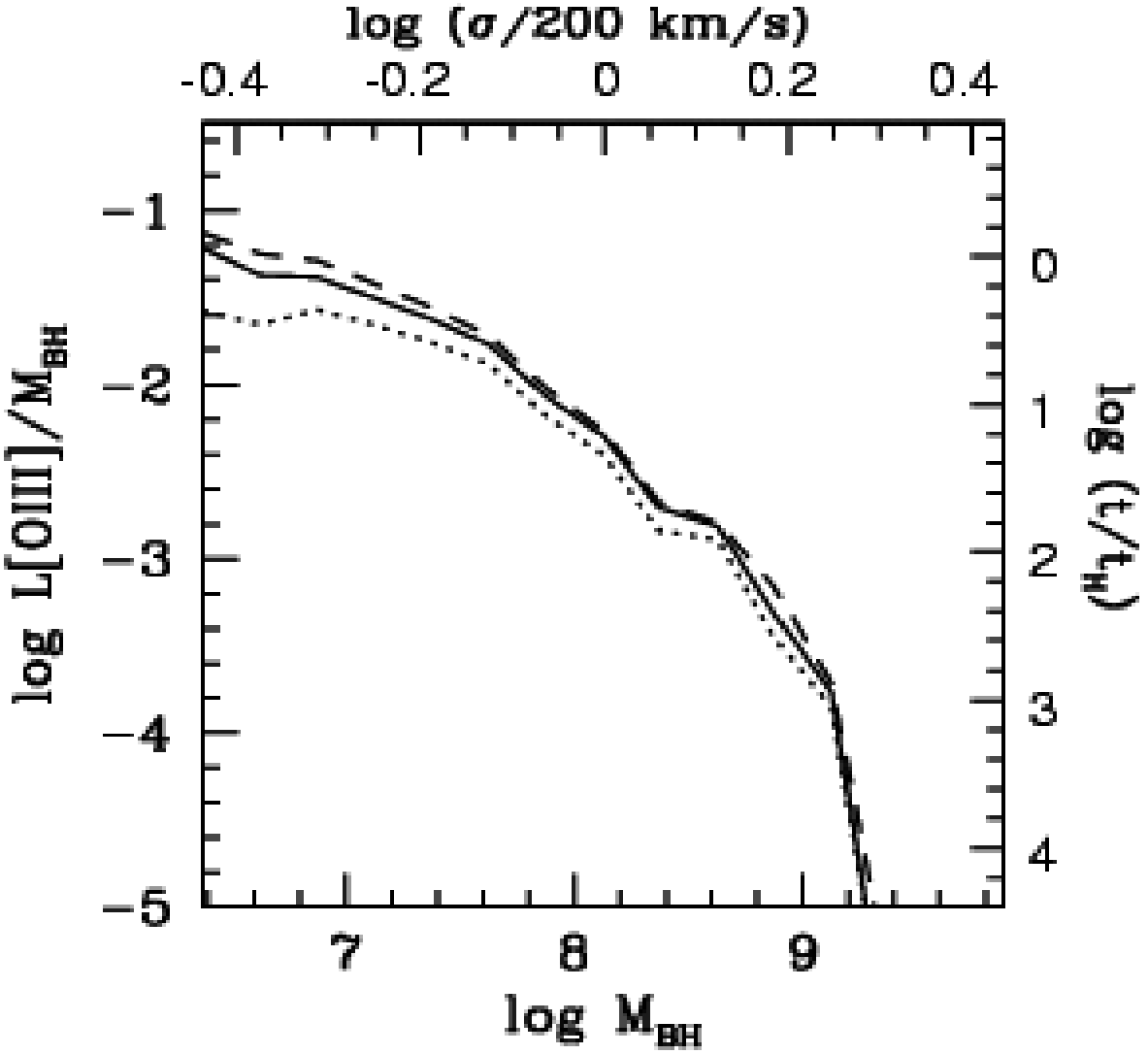
BULGES AND BLACK HOLES ARE "CO-EVOLVING" AT THE PRESENT DAY



The average ratio between the star formation rate in the bulge and the accretion rate onto the black hole is 1000 – remarkably close to the ratio of bulge mass to black hole mass.

Heckman et al 2004

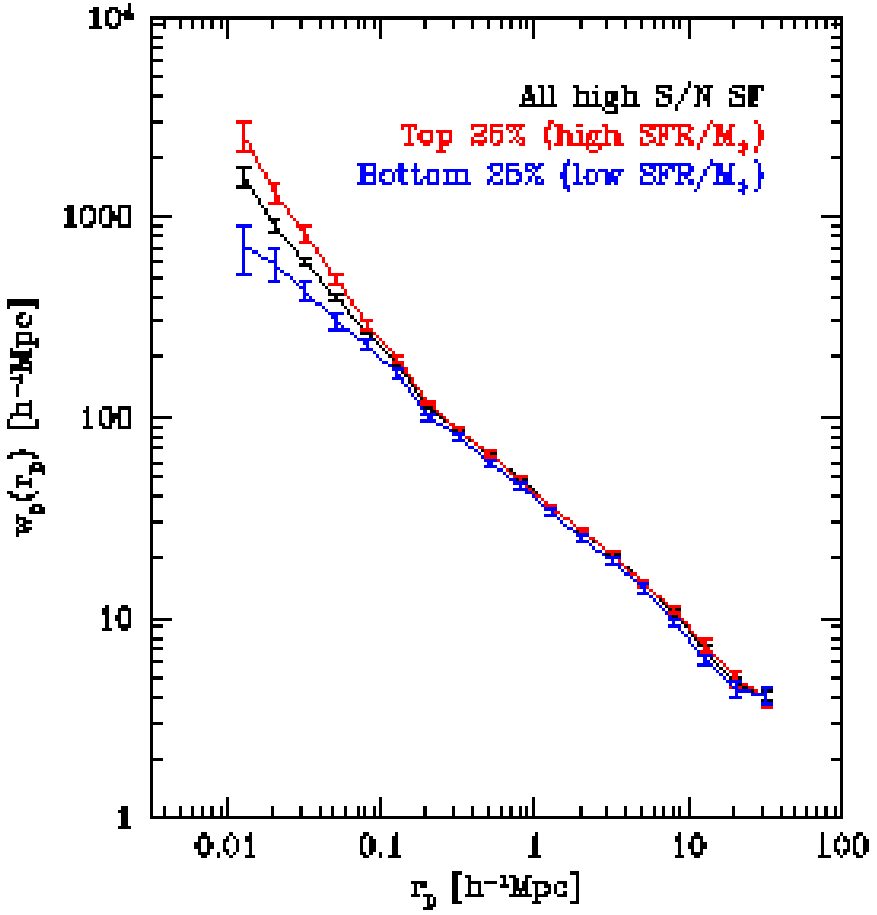
Most of the accretion today is occurring onto low mass black holes (consistent with down-sizing) **.**

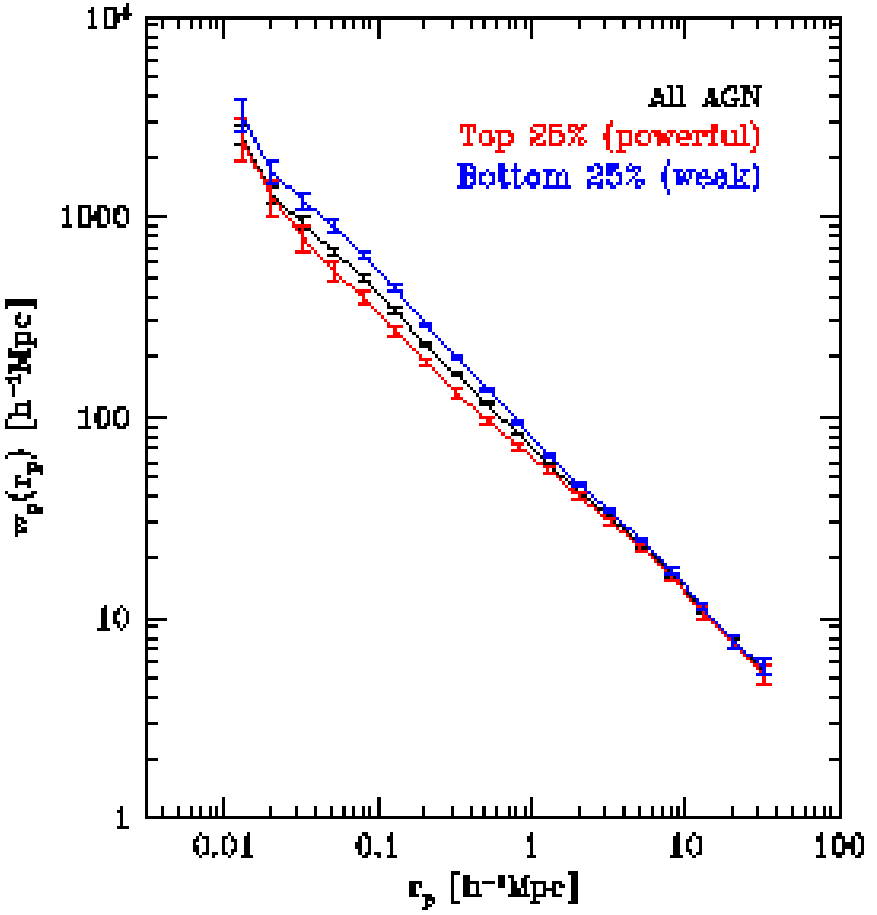


Heckman et al 2004

BUT ARE MERGERS THE DRIVER OF OPTICAL AGN ACTIVITY?

Strongly star-forming galaxies exhibit an excess of close neighbours, but strong ([OIII]-luminous) AGN do not

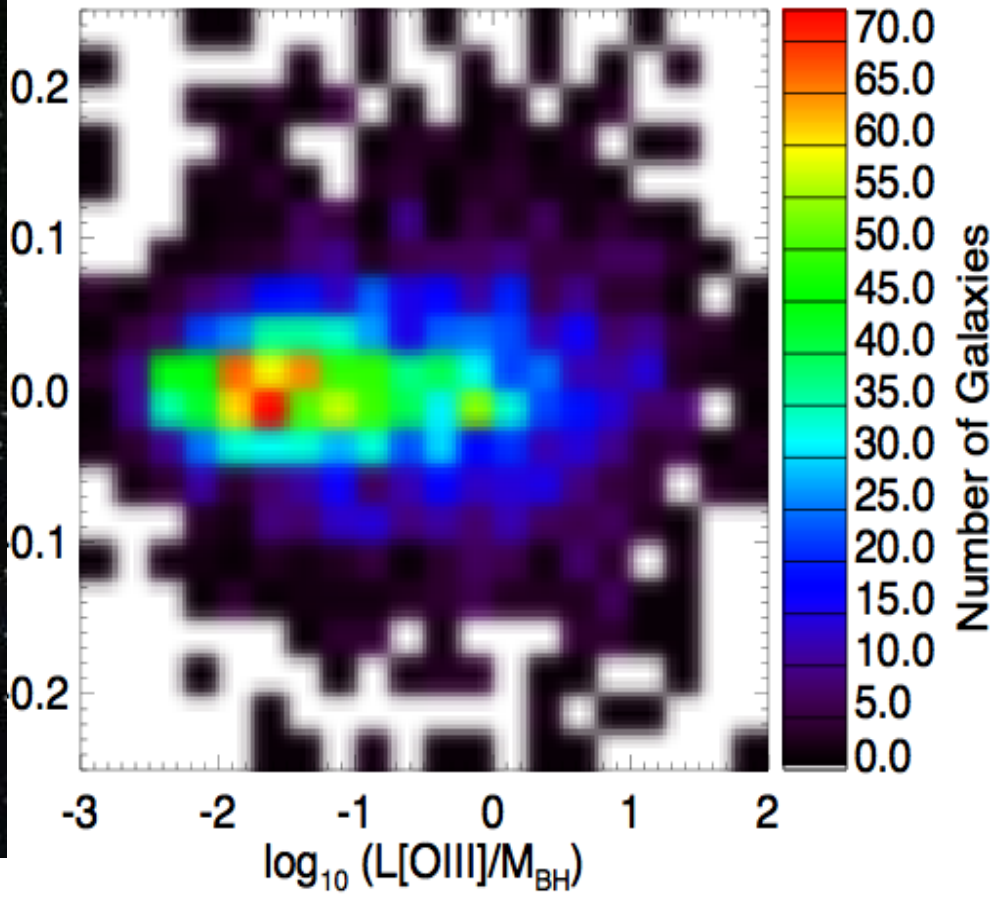




Li et al 2007

There is also no evidence of any connection of AGN activity with lopsidedness

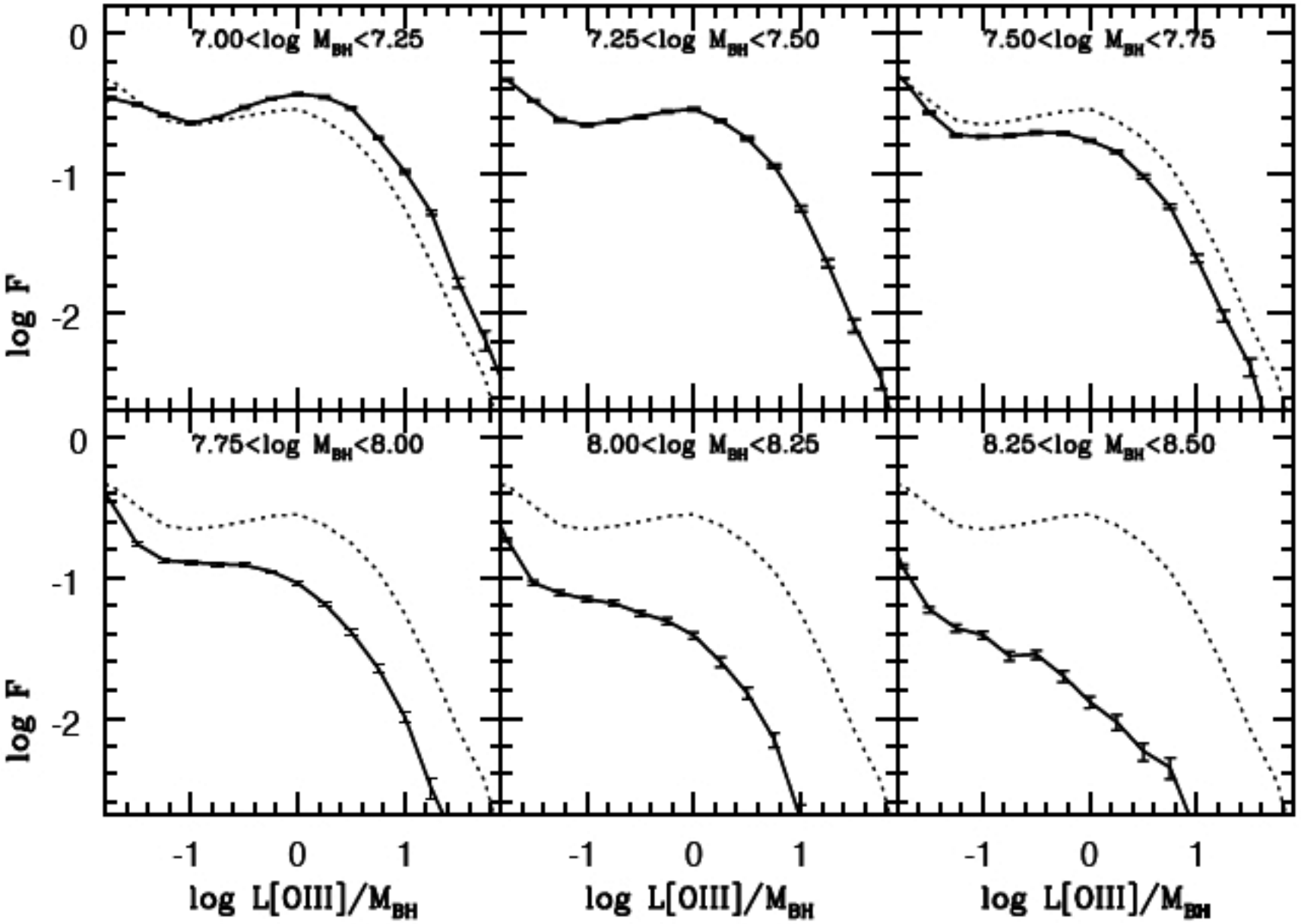
Reichard et al 2009

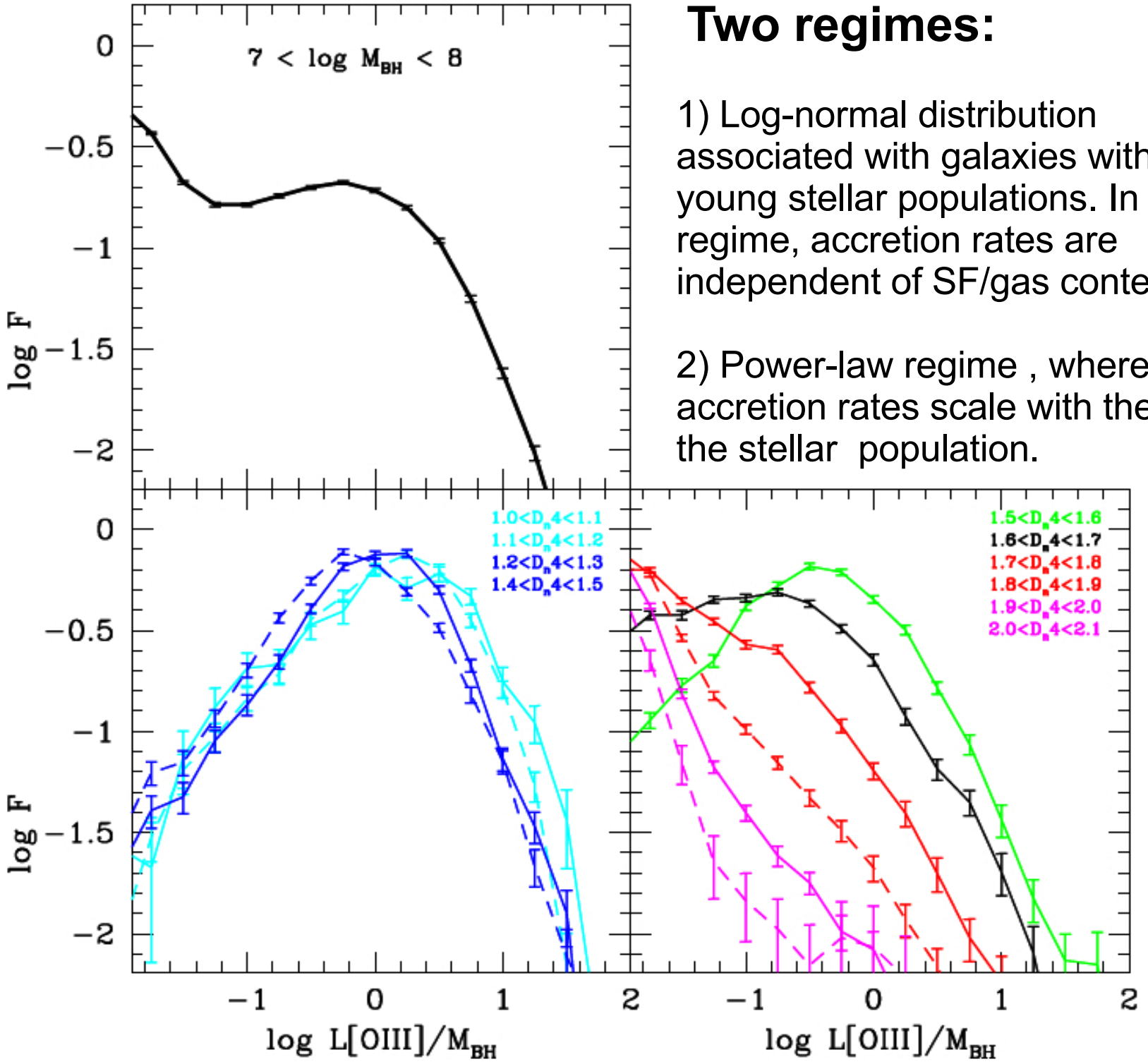


No empirical evidence that there is a causal link between AGN activity and mergers – similar results are now being found at z~2 (the peak of the epoch of black hole growth).

Distribution Functions of Black Hole Accretion Rates for Black Holes of Different Masses

Kauffmann & Heckman 2009

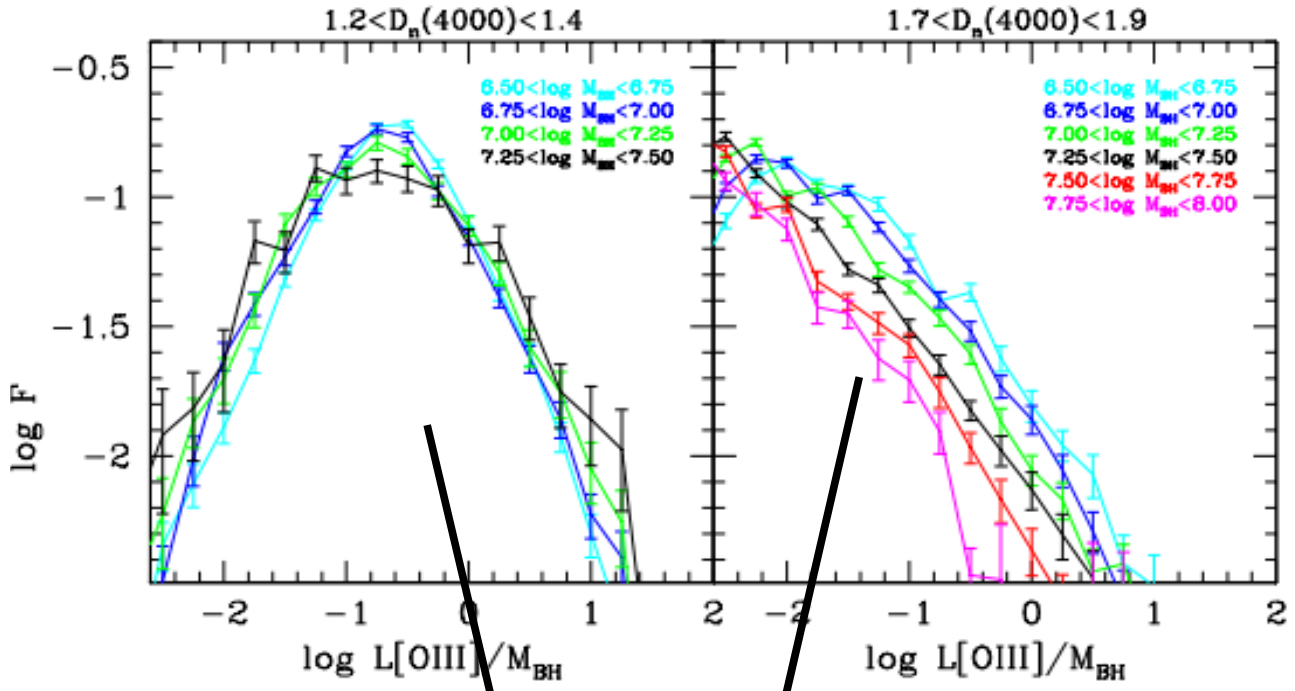




Two regimes:

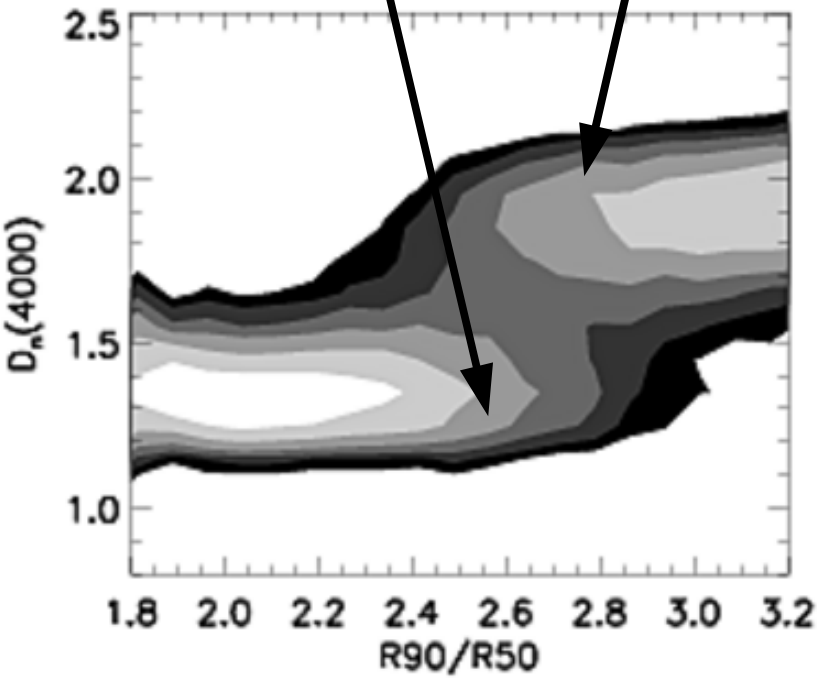
1) Log-normal distribution associated with galaxies with gas an young stellar populations. In this regime, accretion rates are independent of SF/gas content.

2) Power-law regime , where accretion rates scale with the age of the stellar population.



Kauffmann & Heckman 2009

age



The transition between the “lognormal” and the “power-law” regimes occurs at the same value of D4000 where the bimodality in galaxy properties are seen

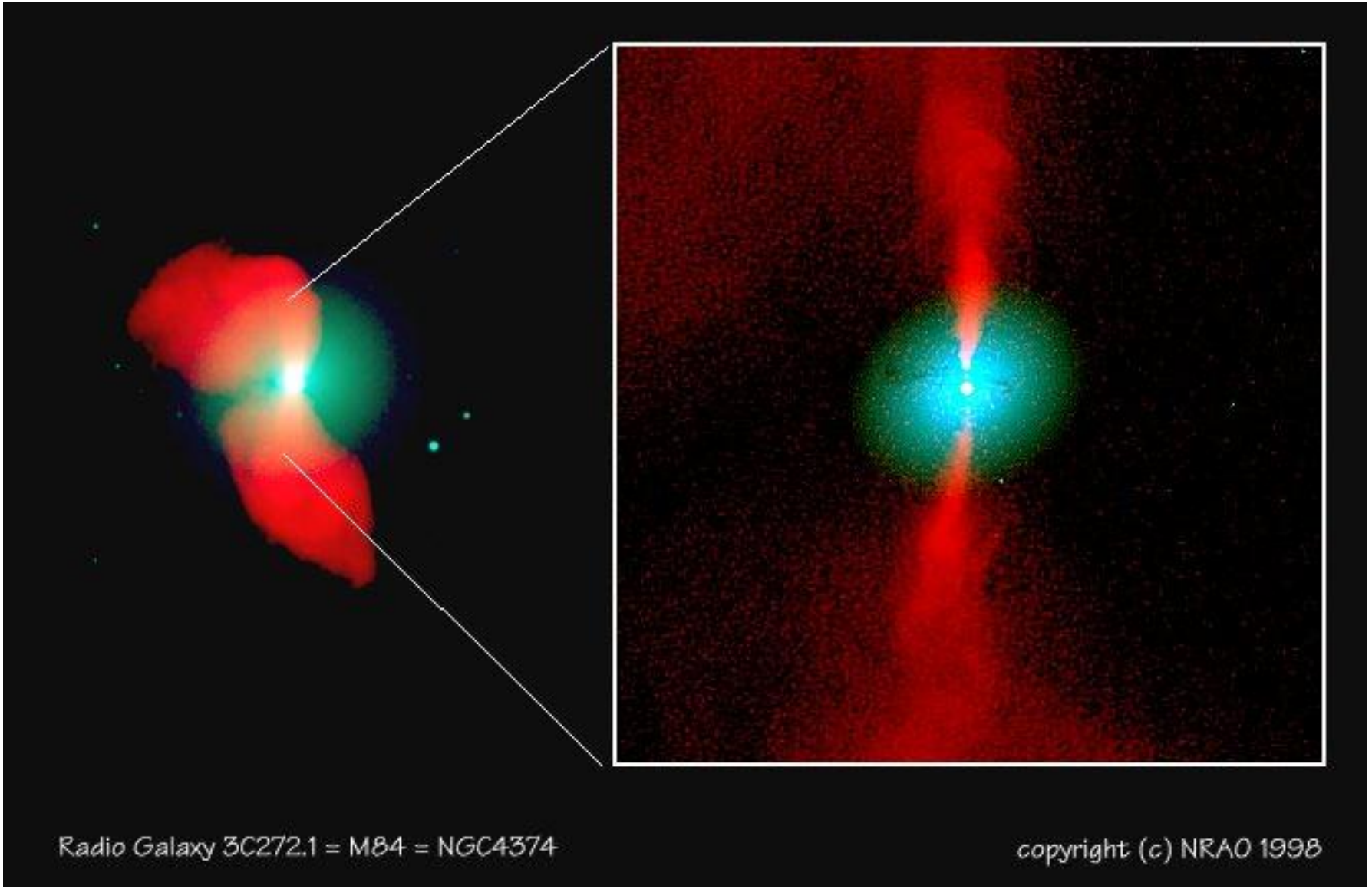
FEAST

When the gas supply is plentiful, the black hole regulates its own growth.

FAMINE

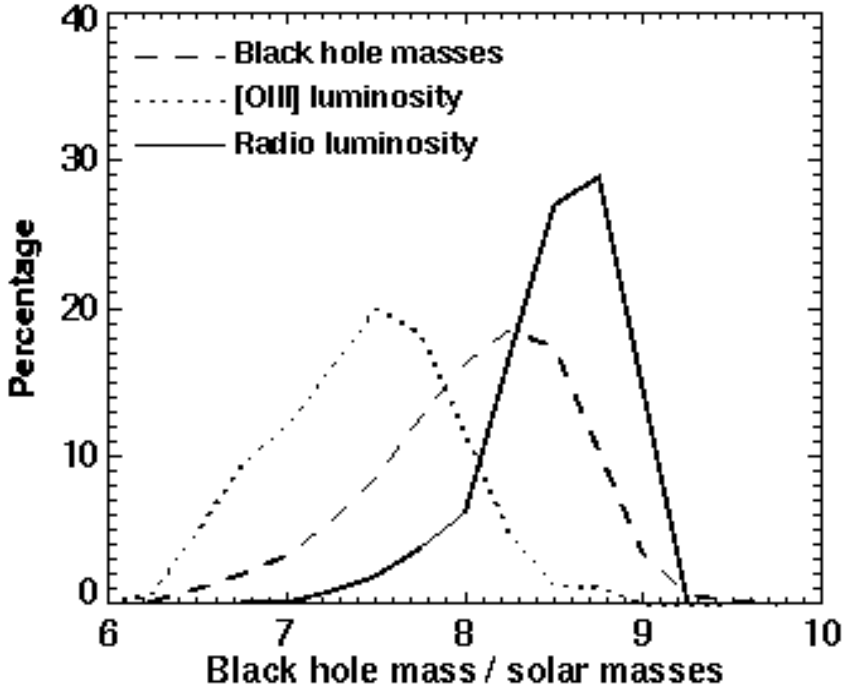
When there is little or no gas, the growth rate of the black hole is regulated by the fuel supply. In Kauffmann & Heckman (2009), we proposed that mass loss from stars could be the source (around 0.1 percent would have to reach the black hole).

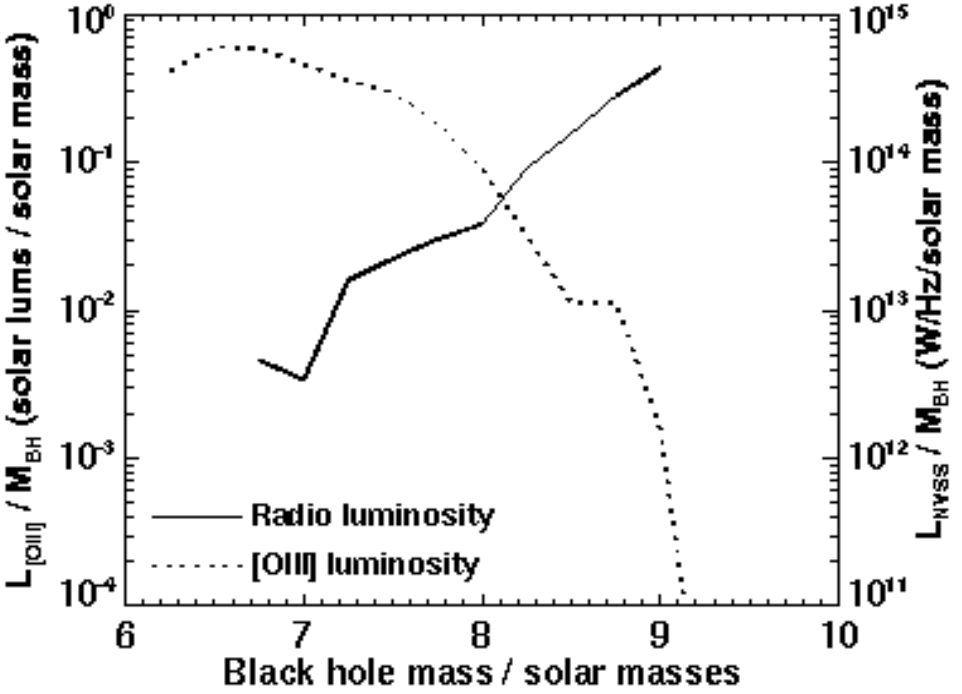
What about radio-loud AGN?



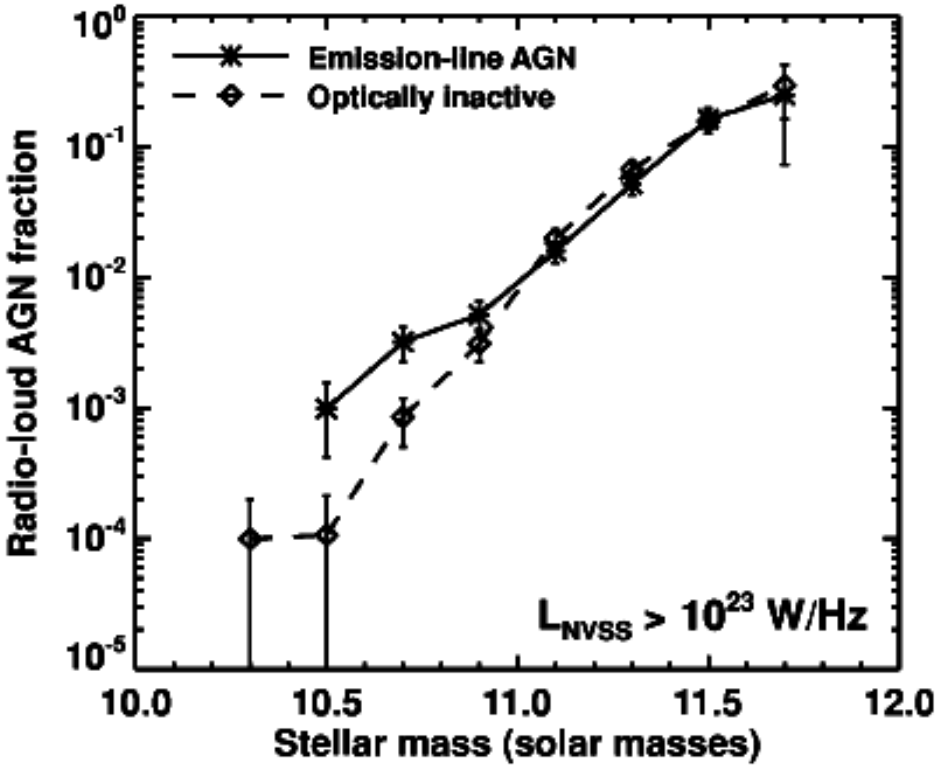
Radio galaxies are strongly biased towards high mass galaxies that contain massive black holes.

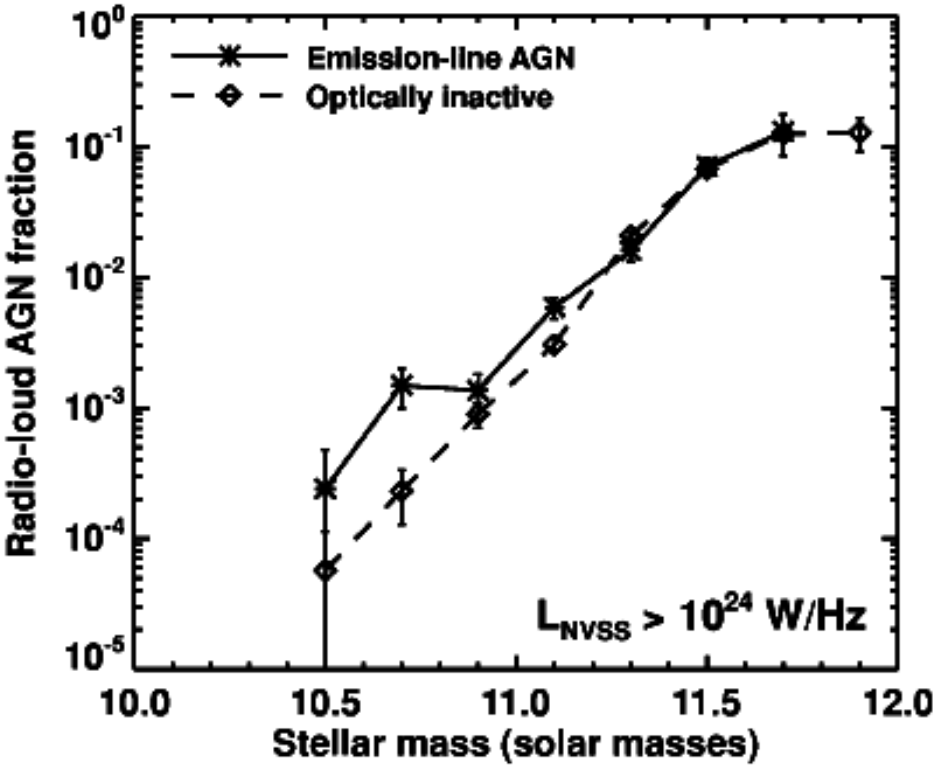
Best et al 2005



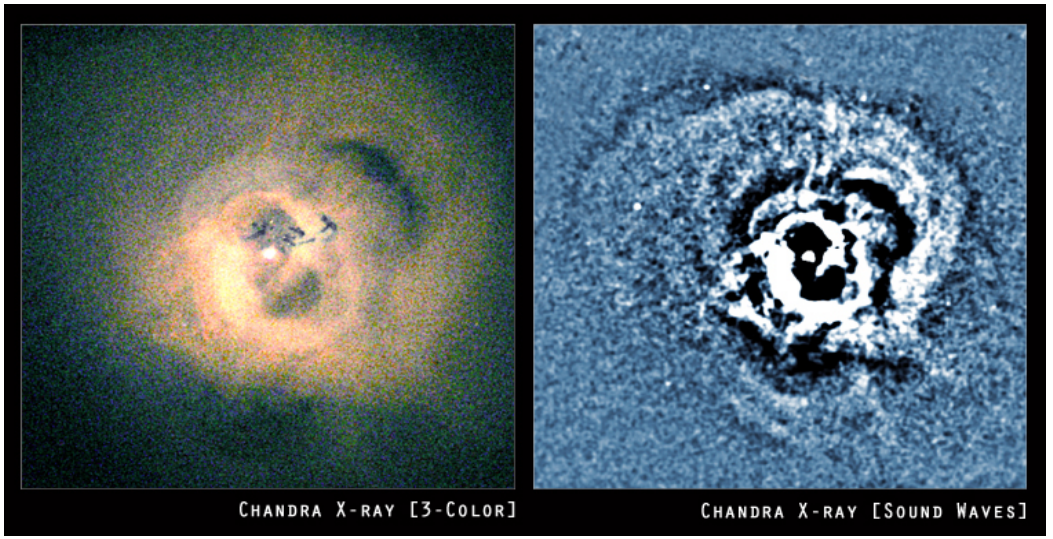


Probability of Radio-loud AGN Activity is independent of optical AGN activity

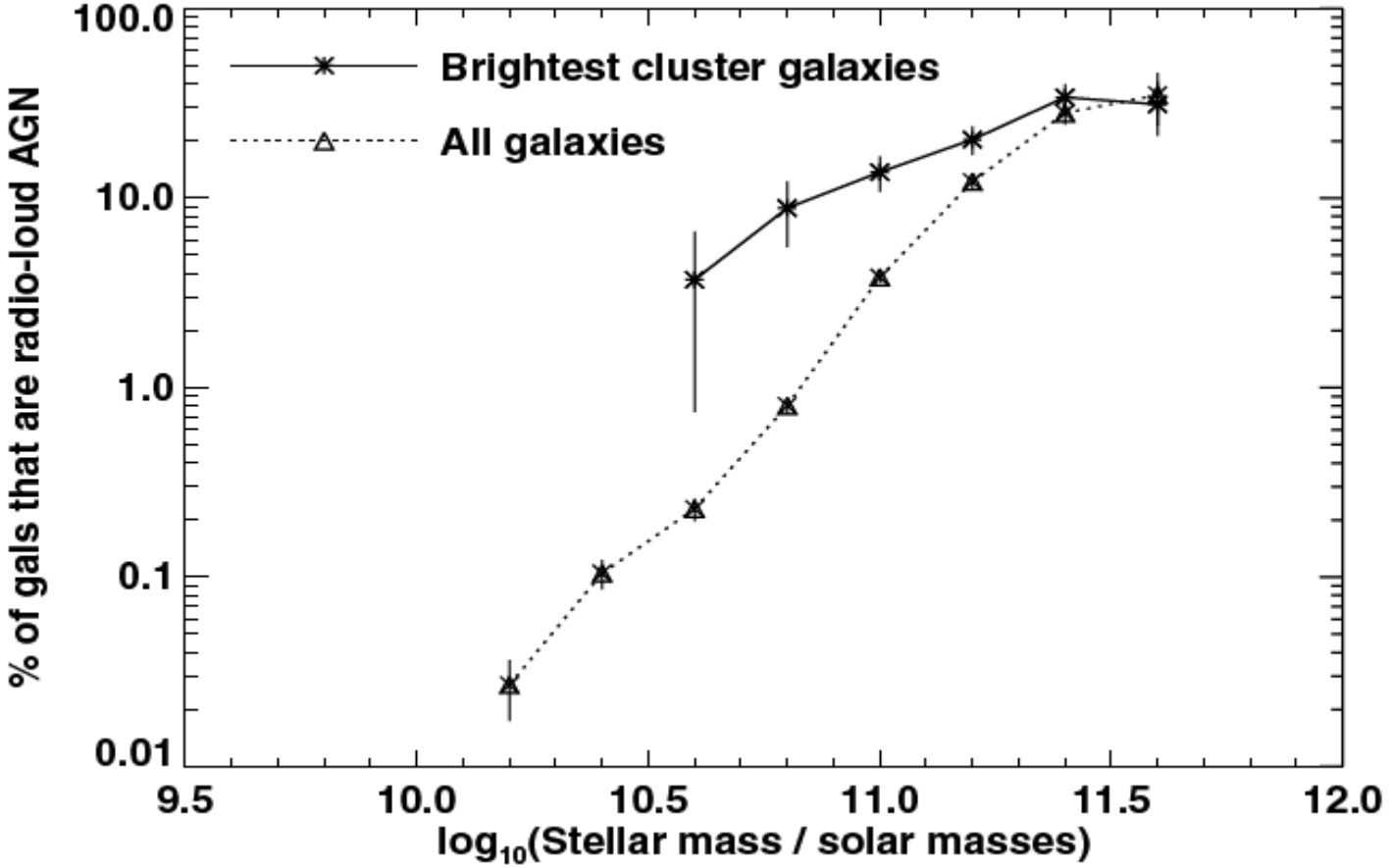




Best et al 2005

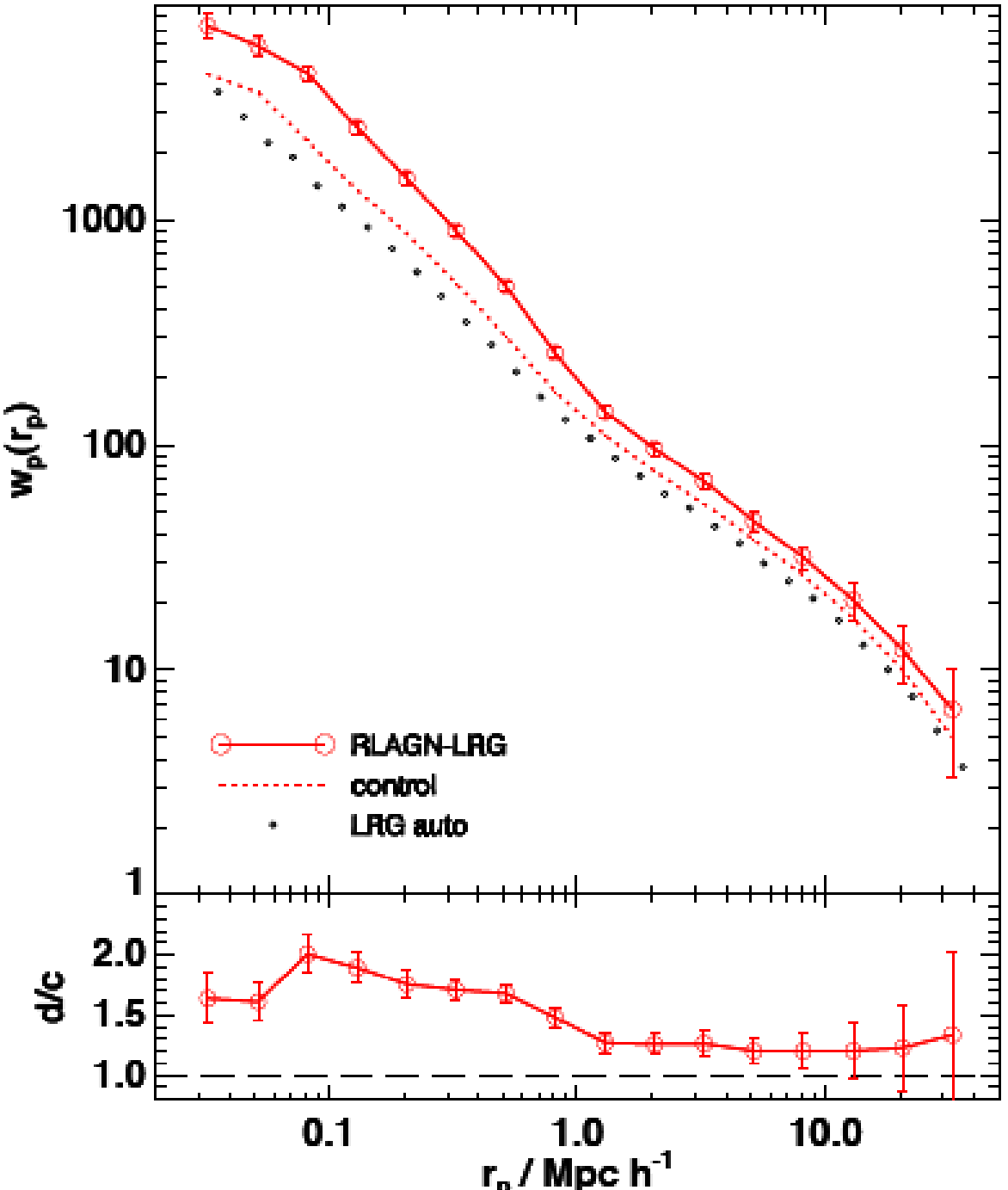


At fixed stellar mass, radio AGN activity is enhanced in galaxies that sit at the **centers** of groups and clusters.

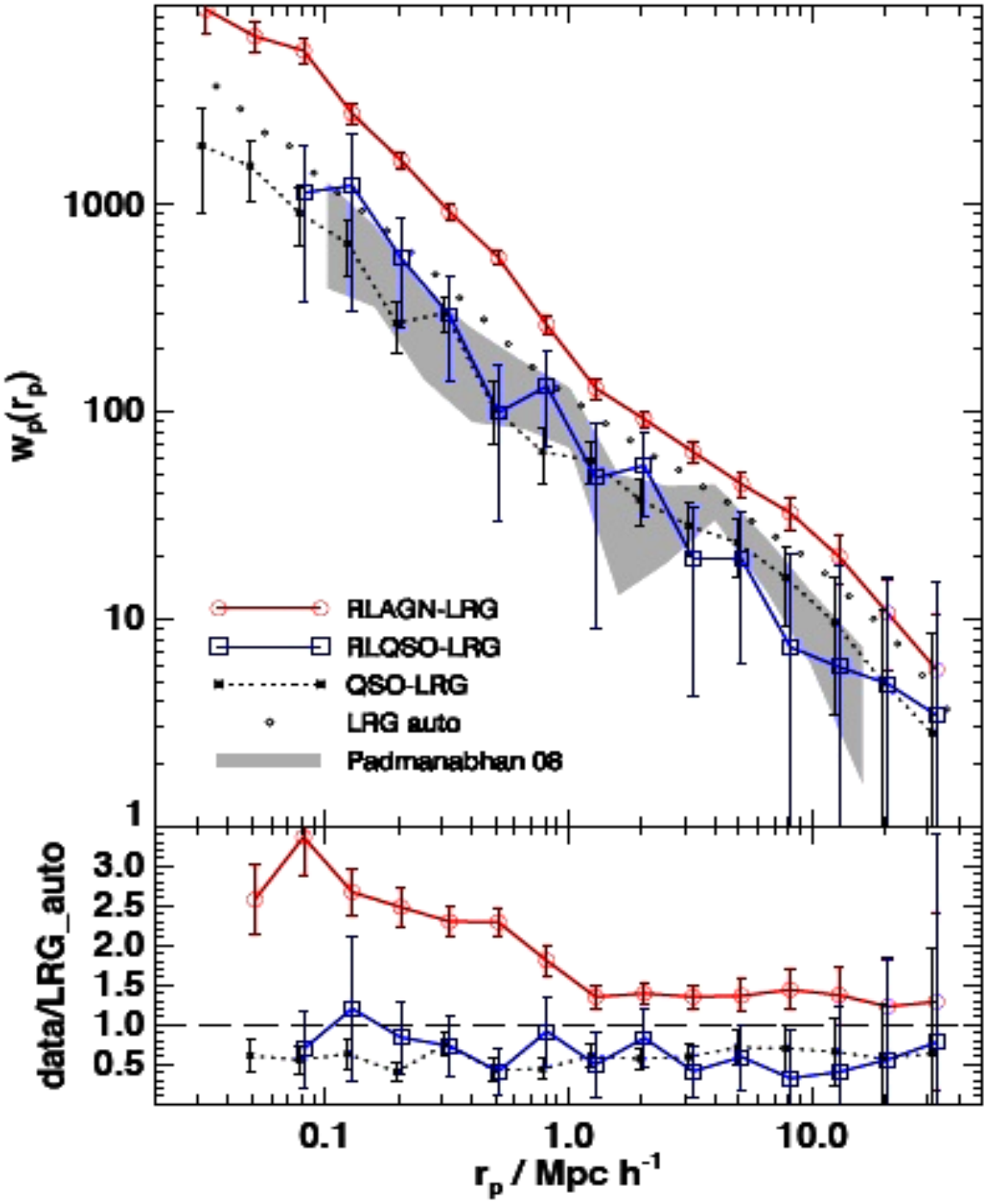


Best et al 2007

Cross-correlation function of radio AGN compared to "control" galaxies of the same stellar mass



Donoso et al 2010



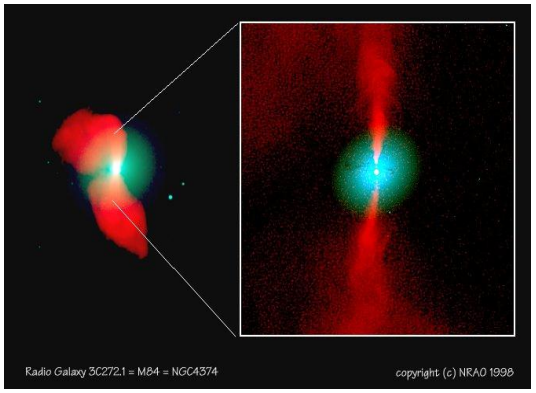
However, radio-loud QUASARS cluster like radio-quiet quasars, and do not cluster like radio-loud galaxies.

Donoso et al 2010

CONCLUSIONS FROM STUDYING HOST GALAXIES

Present-day Optical (emission-line) AGN activity

1) lower mass black holes are most active
2) the activity is NOT triggered by mergers
3) the activity level is “universal” for galaxies with gas, and scales with mean stellar age for the passive population.

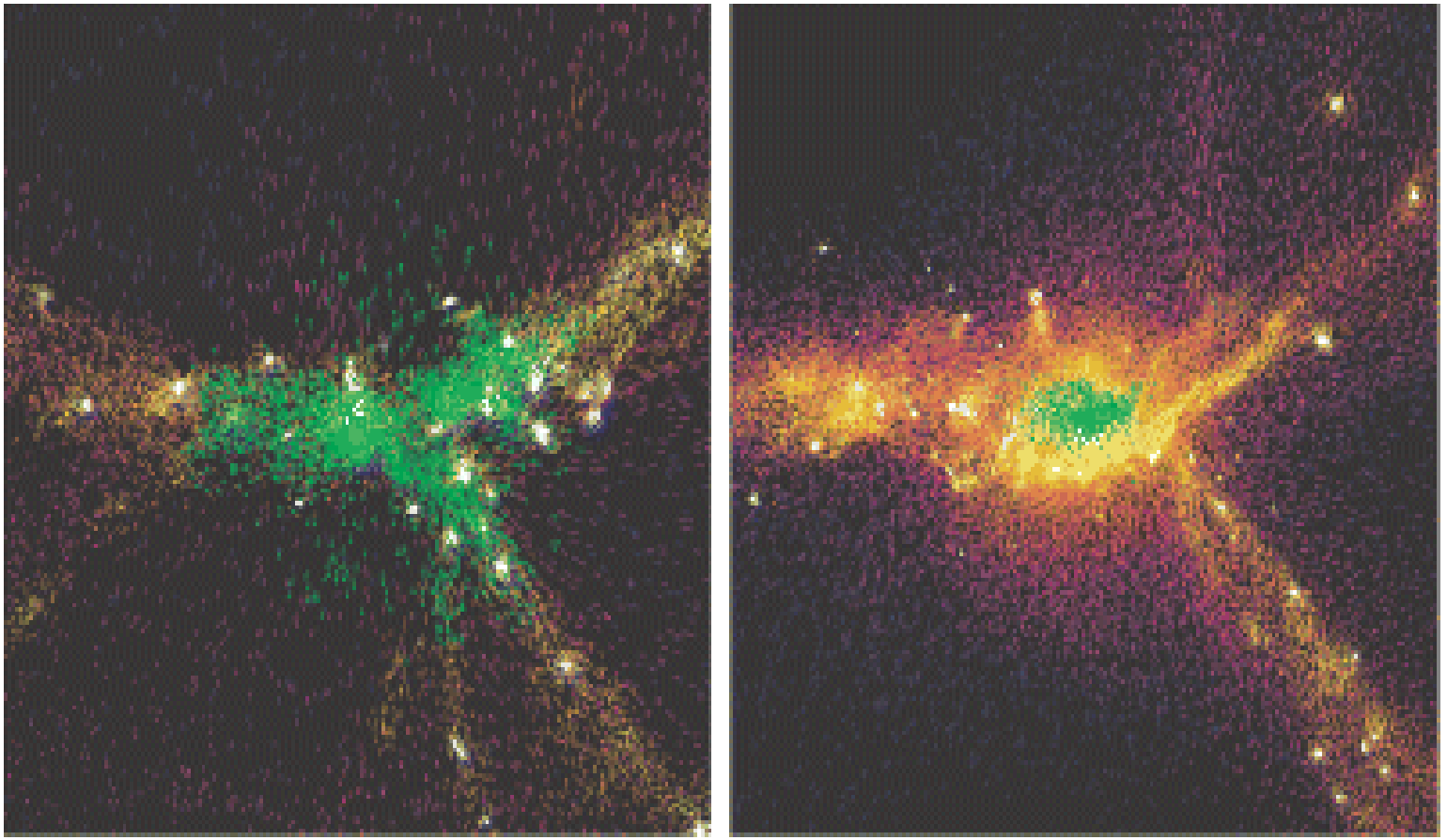


Present-day Optical Radio-AGN activity is linked to:

1) high mass black holes
2) galaxies in the centers of groups and clusters
3) is an independent phenomenon to the optical AGN one

COLD ACCRETION ALONG FILAMENTS

GAS COOLS QUASI-STATICALLY



Halos less than 10^12 M_solar

OPTICAL AGN

Halos greater than 10^12 M_solar

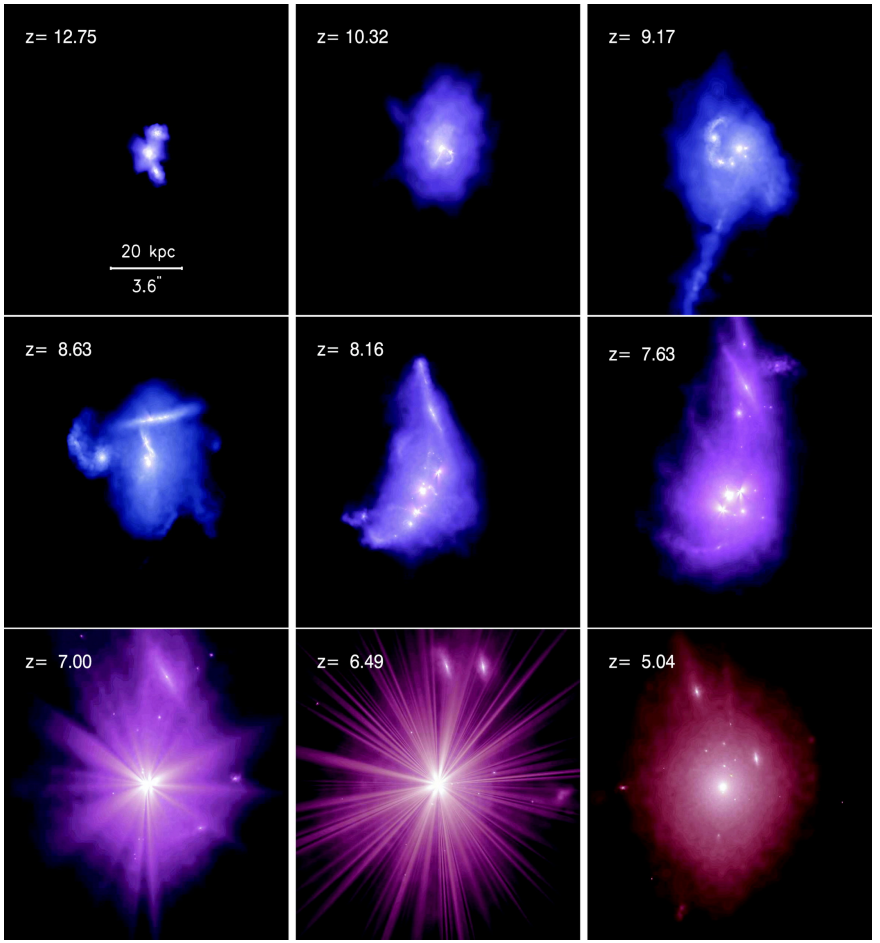
RADIO AGN

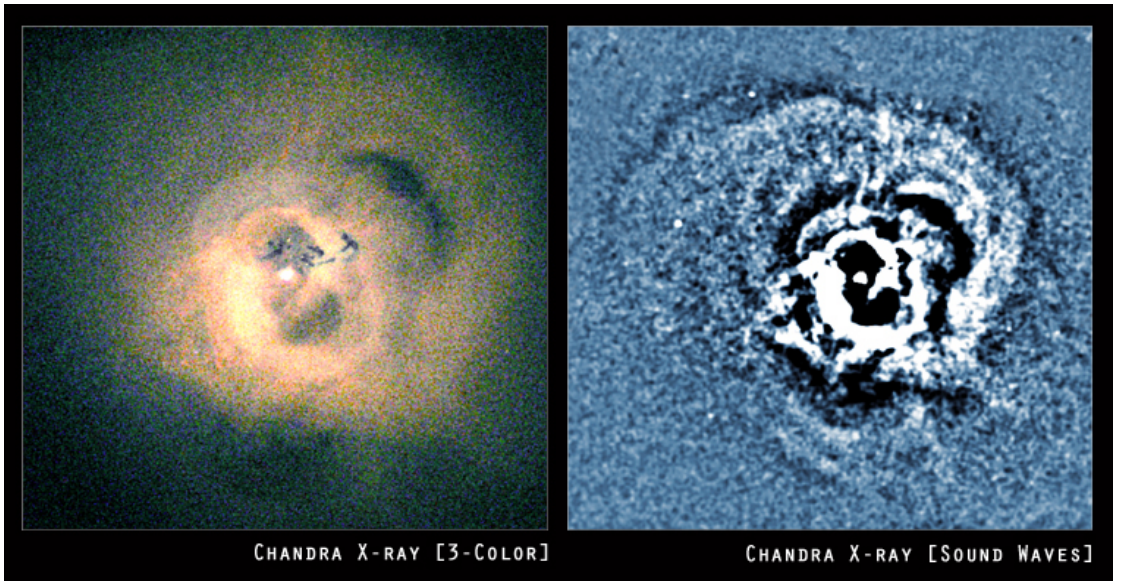
But what are the radio-loud quasars? Do the two modes co-exist at higher redshifts?

CHALLENGE FOR THE FUTURE:

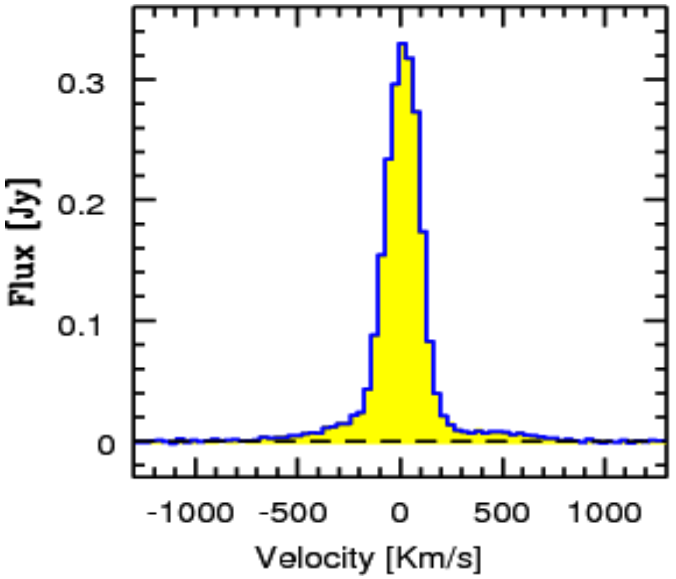
TO CLOSE THE LOOP, IT IS NECESSARY TO UNDERSTAND THE IMPACT OF AGN ON THE SURROUNDING GAS :

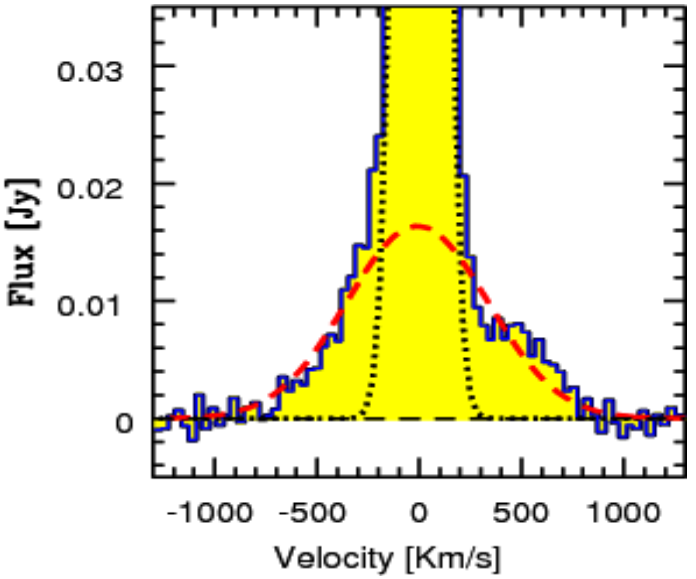
Feedback

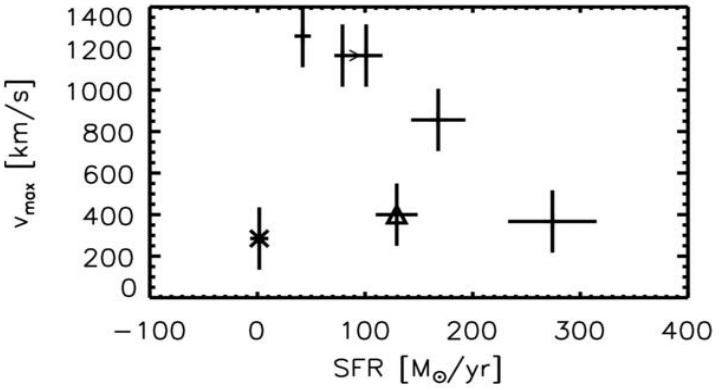


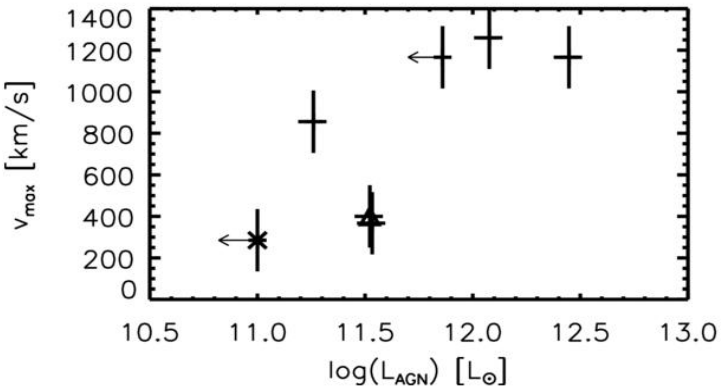


Clearly relevant at low redshifts









Some developing observational evidence that there are outflows in the molecular gas component of galaxies with active nuclei (Feruglia et al 2010)

The maximum outflow velocities are large (implying that gas may escape the galaxy). Tentative evidence for a correlation with black hoe accretion rate rather than star formation rate (Sturm et al 2011)