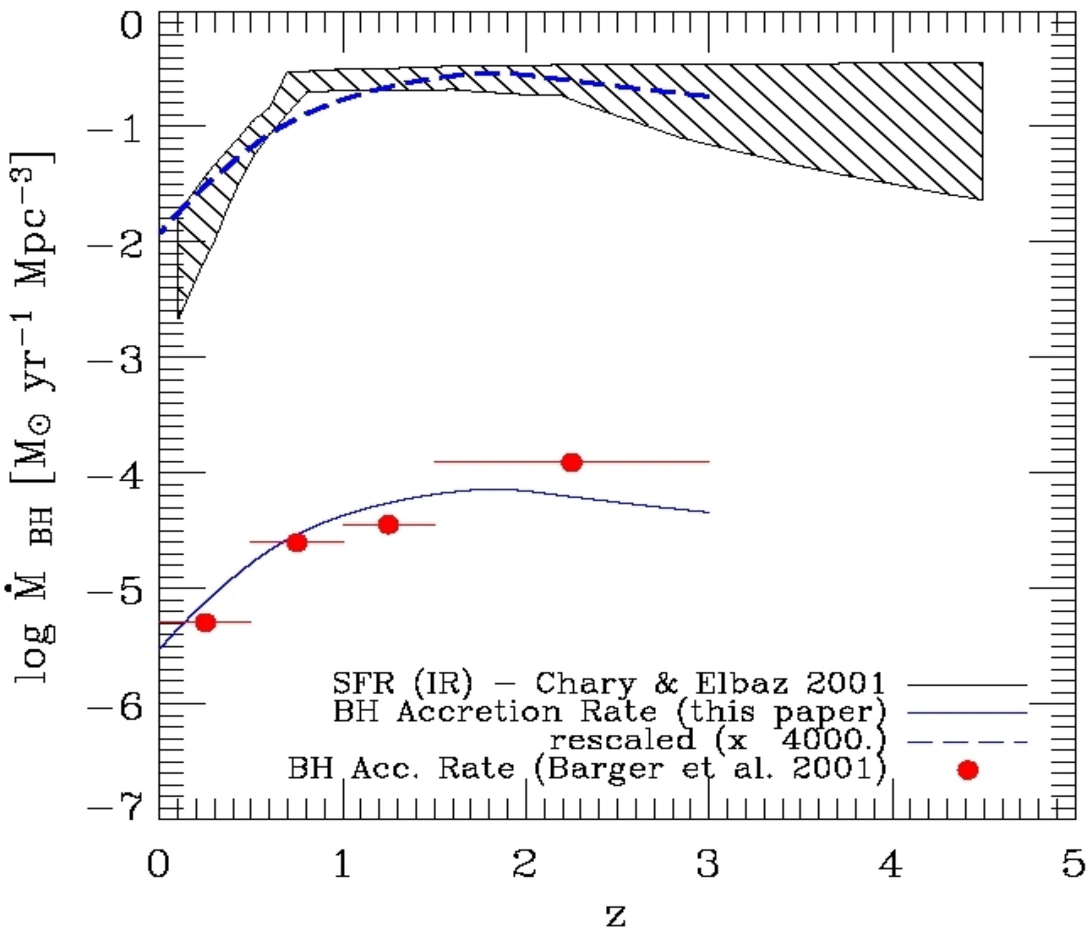
THE CO-EVOLUTION OF GALAXIES & BLACK HOLES

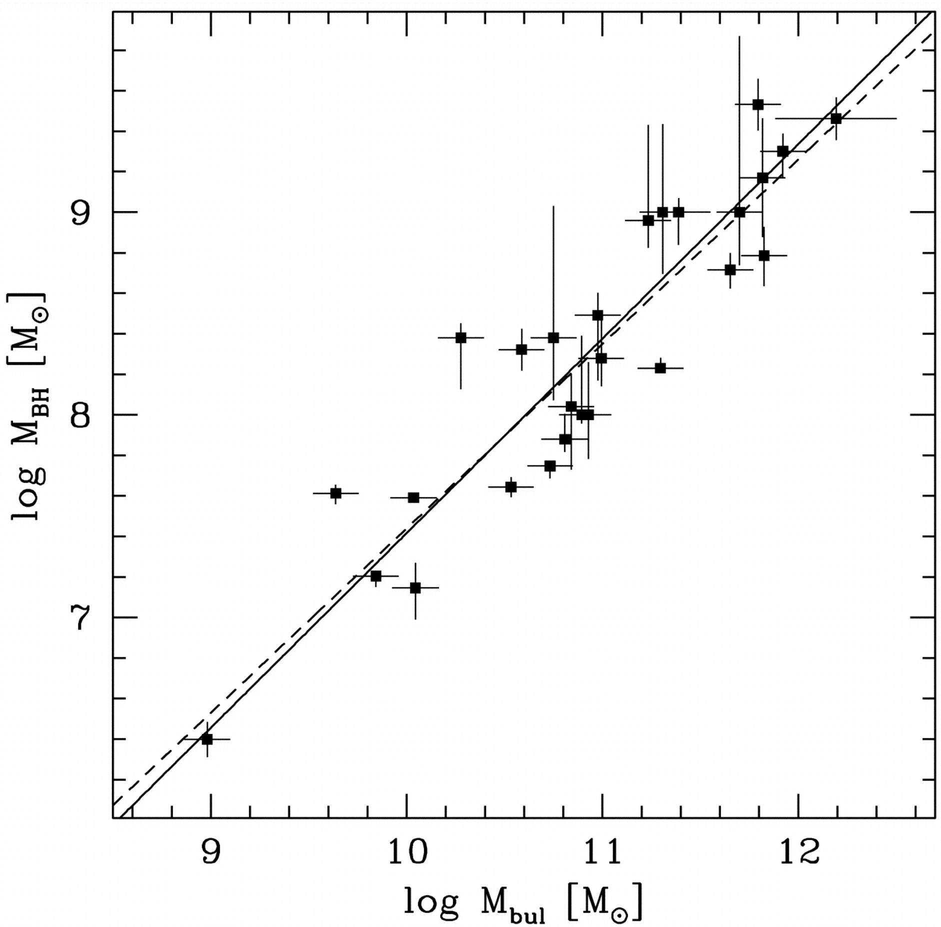
Clues in the Local Universe

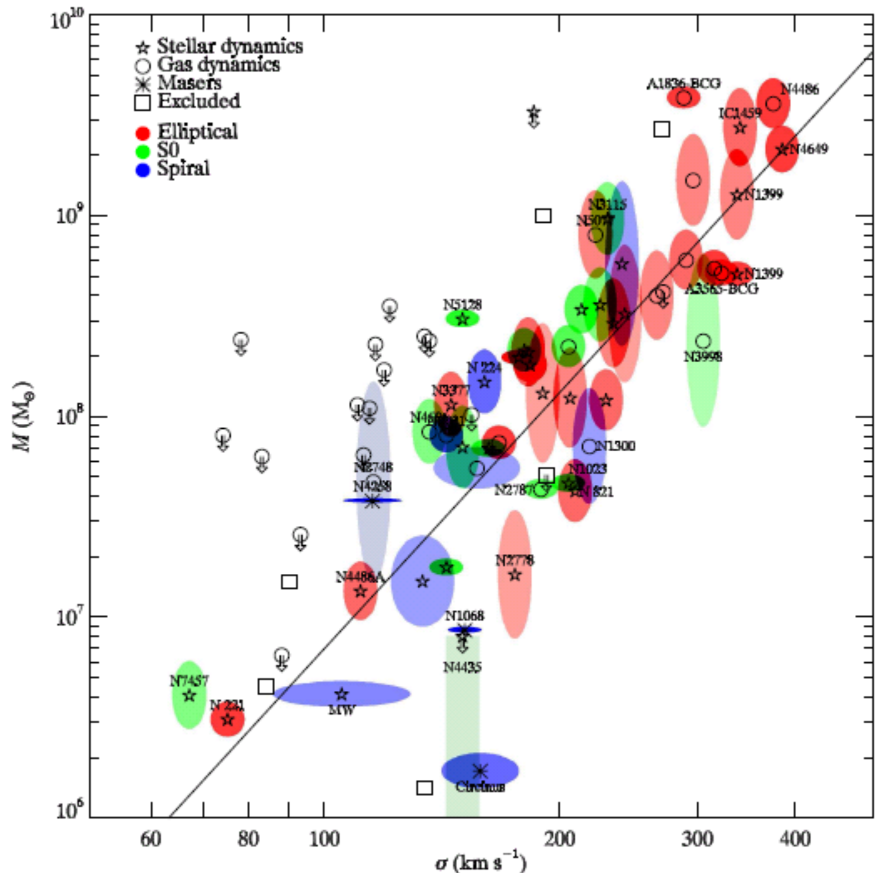
The Co-Evolution Across Cosmic Time



Marconi et al.

The "Fossil Record"

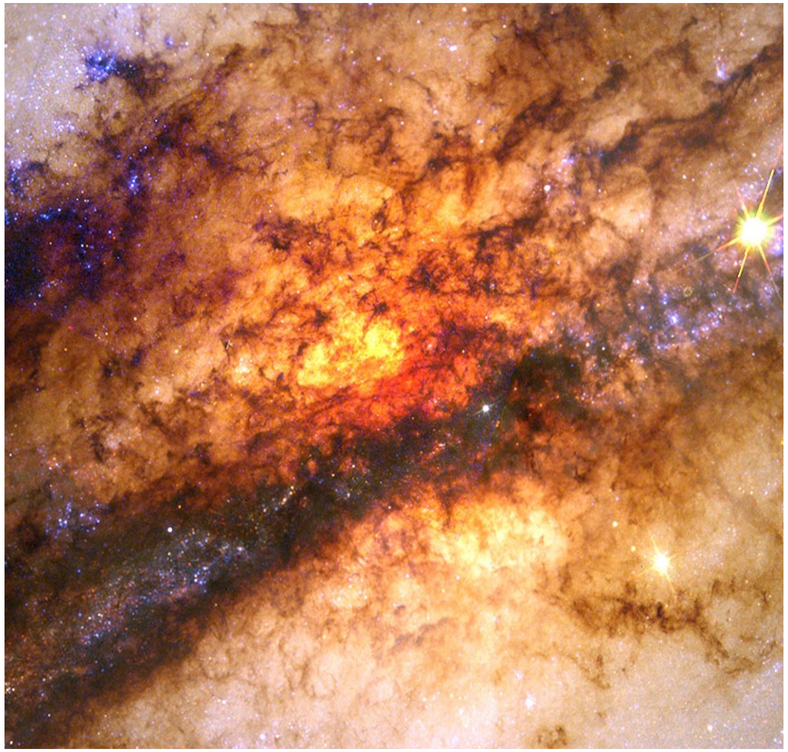


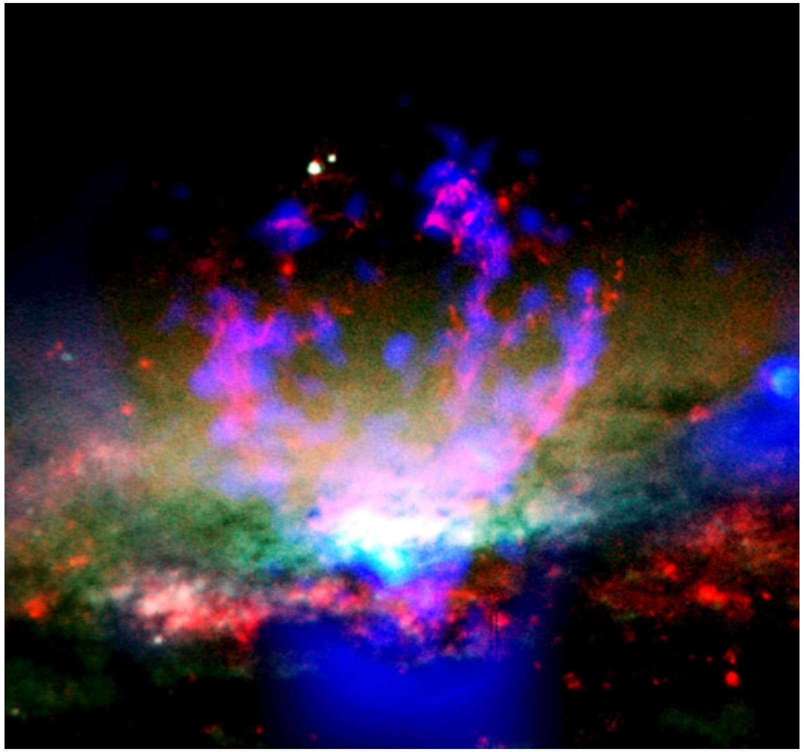


Marconi & Hunt

Gultekin et al.

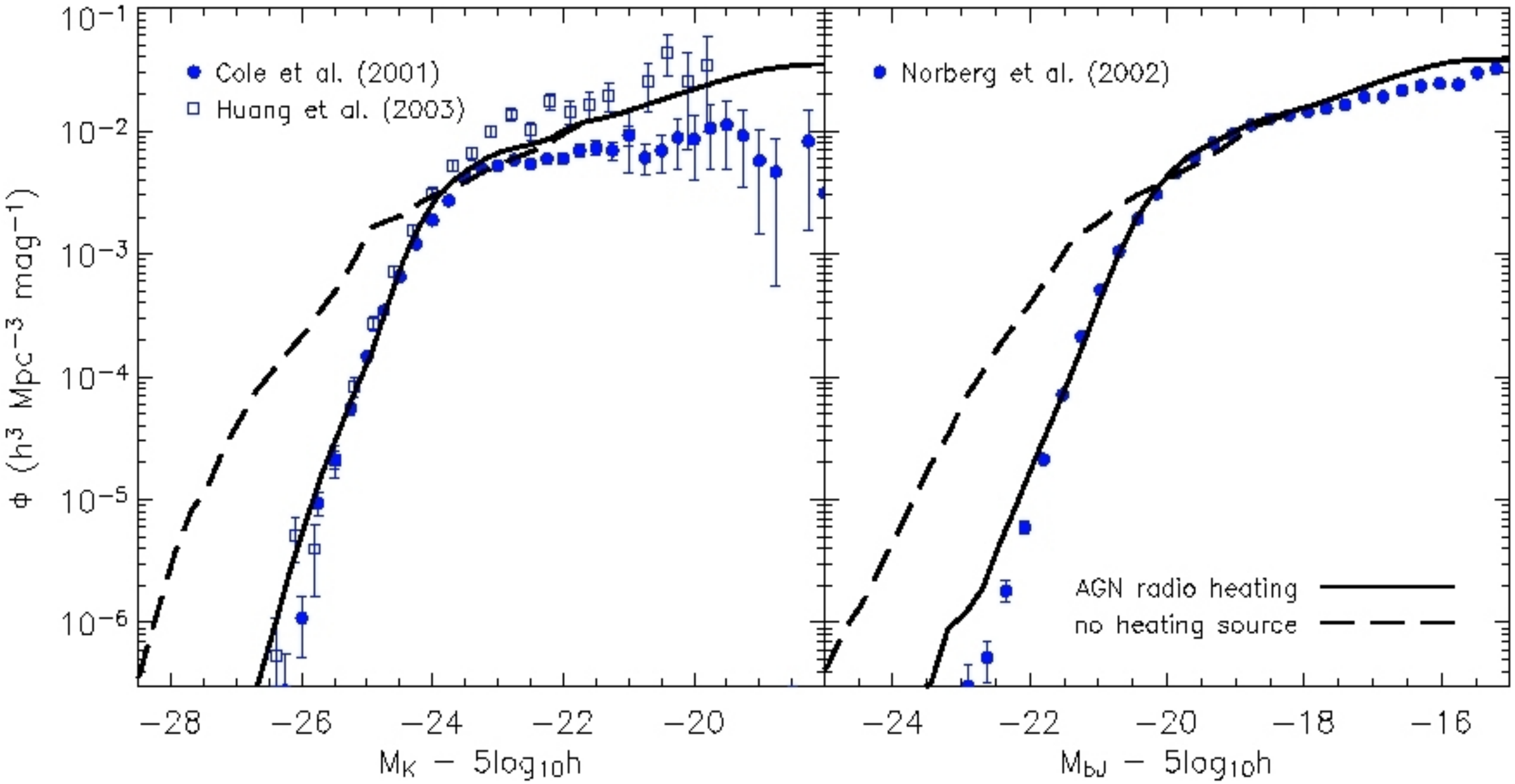
Two-way communication





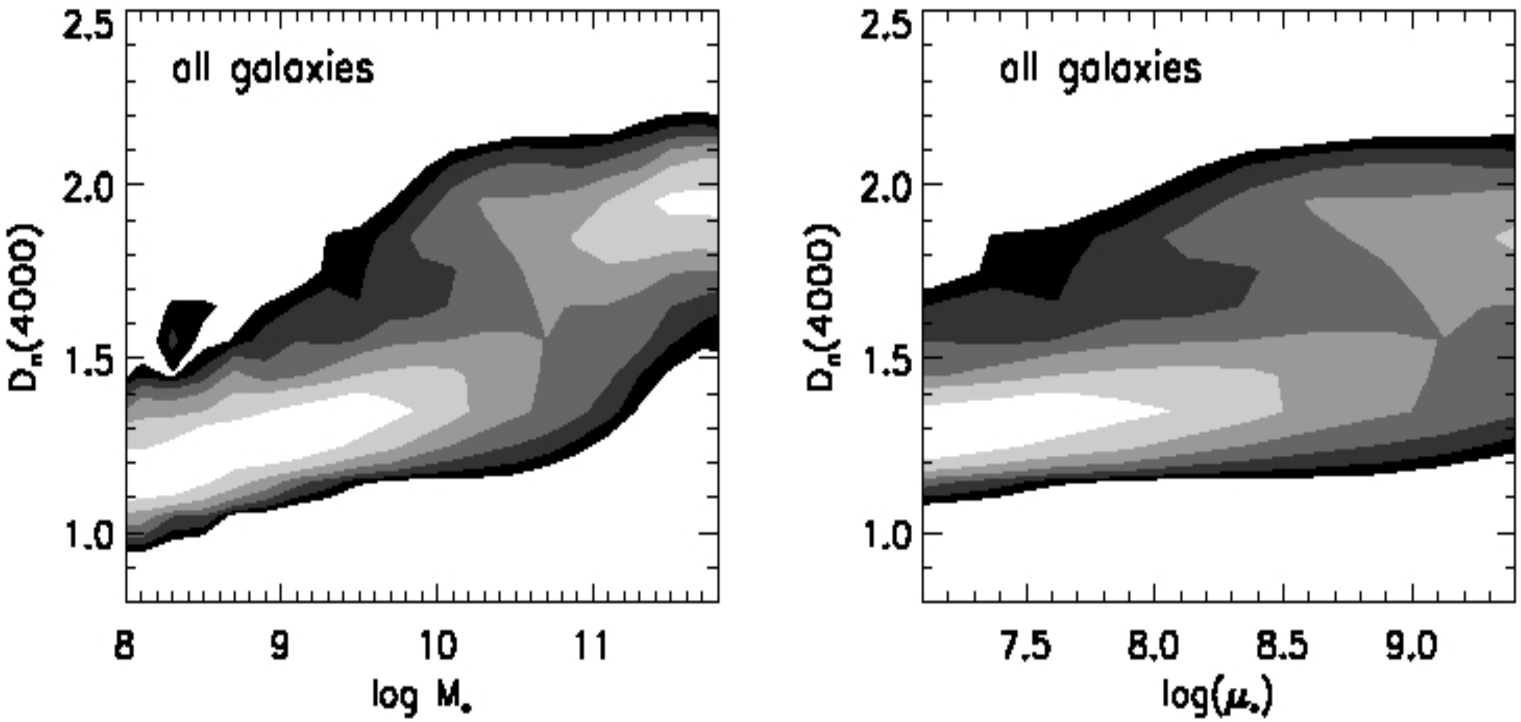
- How are supermassive black holes fed?
- How is their growth regulated? “local feedback”
- How do supermassive black holes affect their surroundings on galactic scales? “global feedback”
- How is this related to the host galaxy?

Global Feedback



- Cures “over-cooling” problem at high masses?
  (e.g. Croton et al.)

Global Feedback



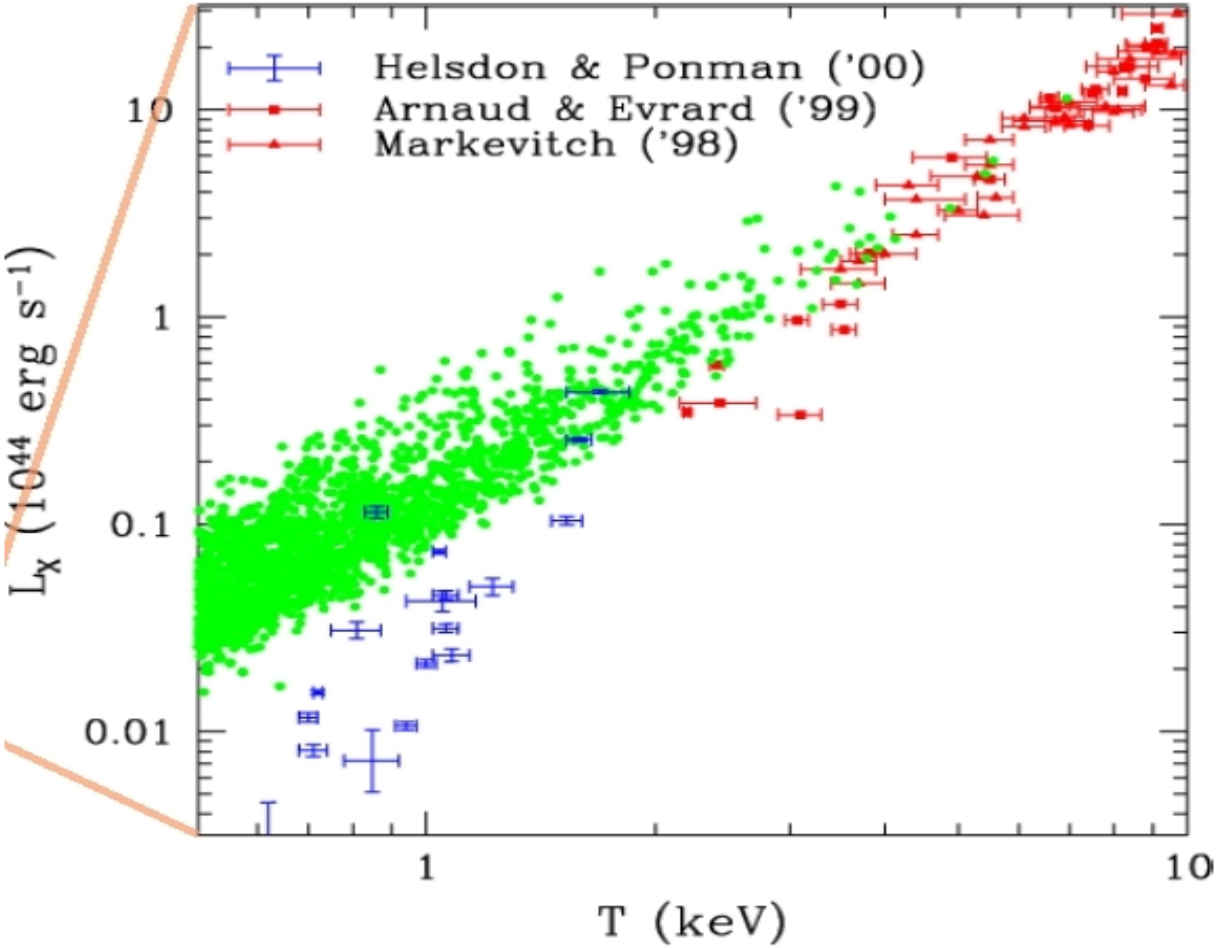
The bimodal galaxy population

How do galaxies move from “blue” to “red”?

What keeps massive/dense galaxies “dead”?

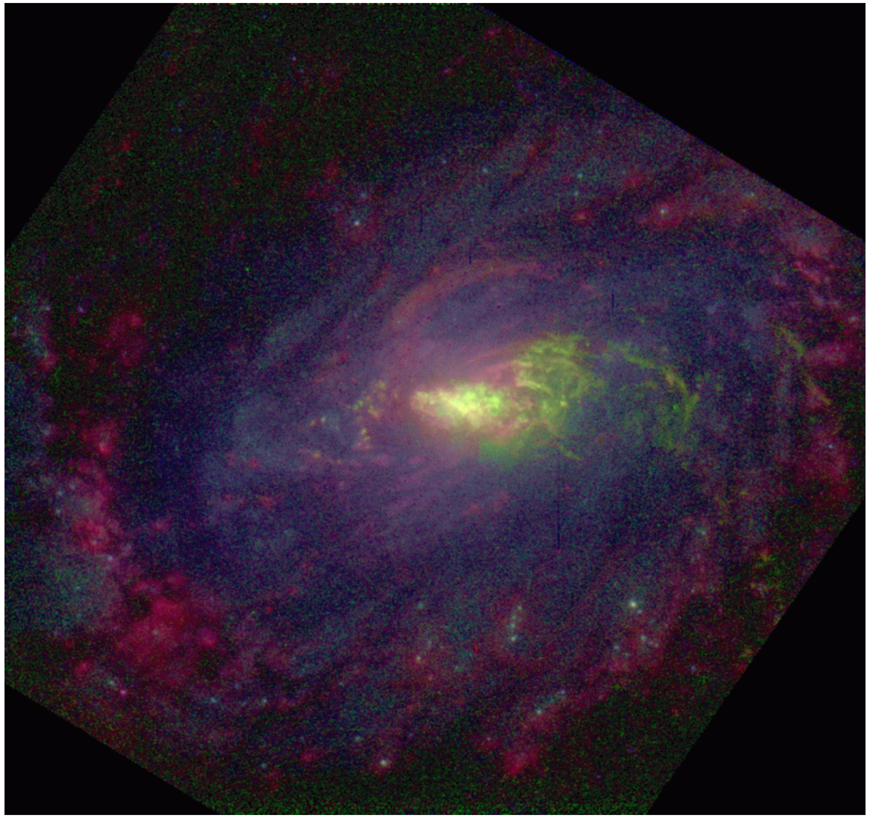
Global Feedback & the IGM

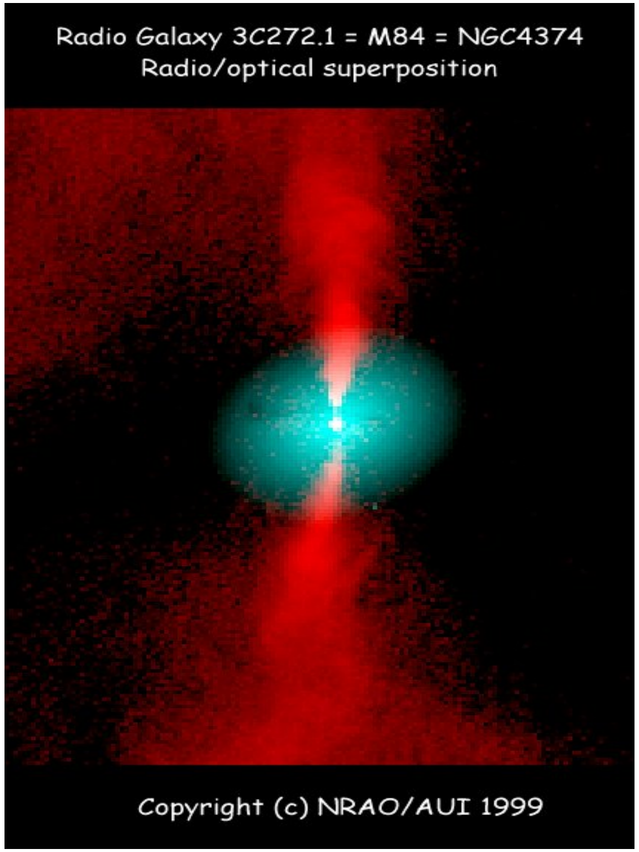
Borgani et al. (2003)



- Heating/raising the entropy of the IGM (I. McCarthy)
- Photoionizing the IGM (Lyman Alpha forest)

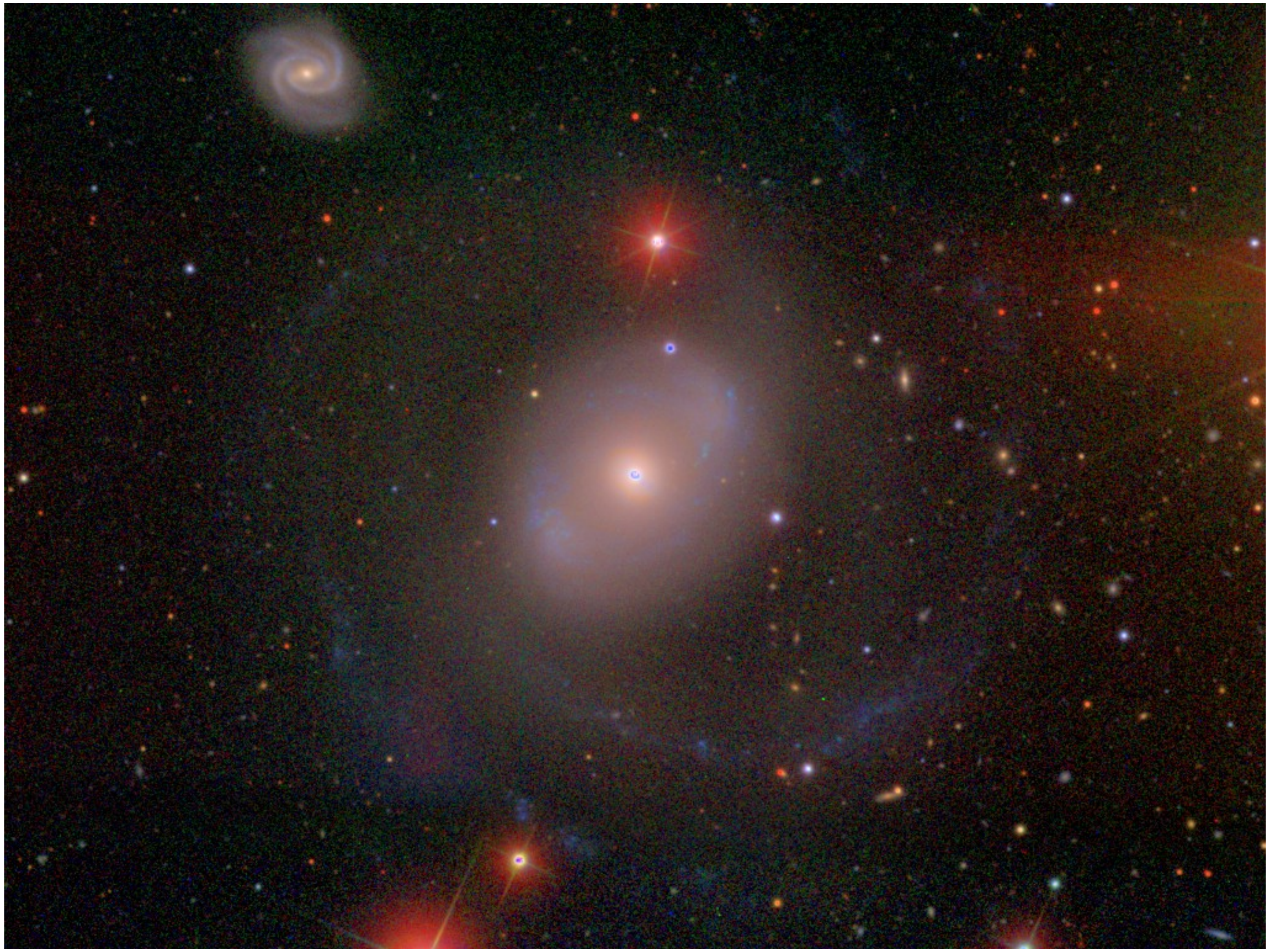
An AGN Primer



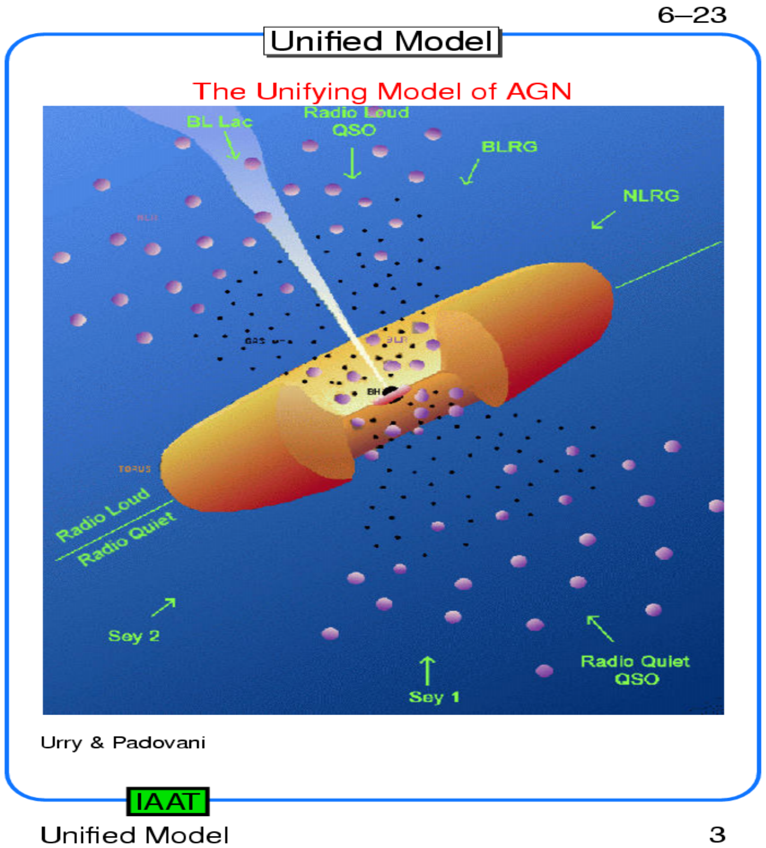


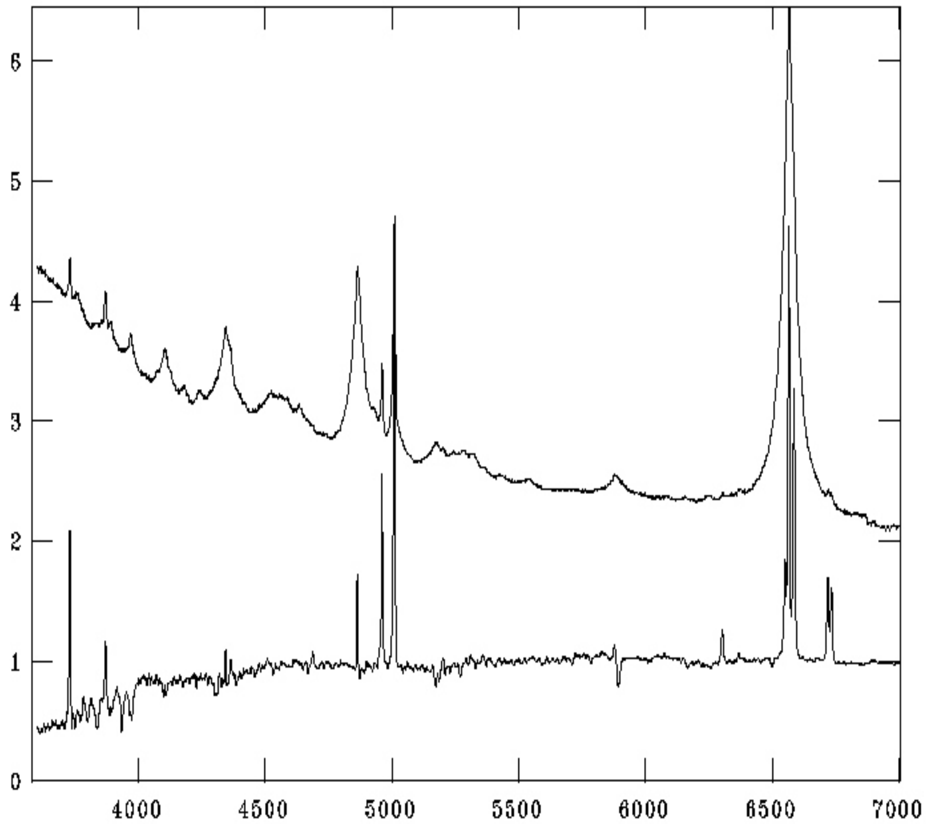
- Two primary independent modes in the local universe
- Seyfert galaxies: High accretion rate (>1% Edd)
  Radiated power >> jet power
- Radio galaxies: Low accretion rates & jet-dominated
  (Jet power > radiated power, which is <<1% Eddington)

Co-Evolution: Seyfert Galaxies



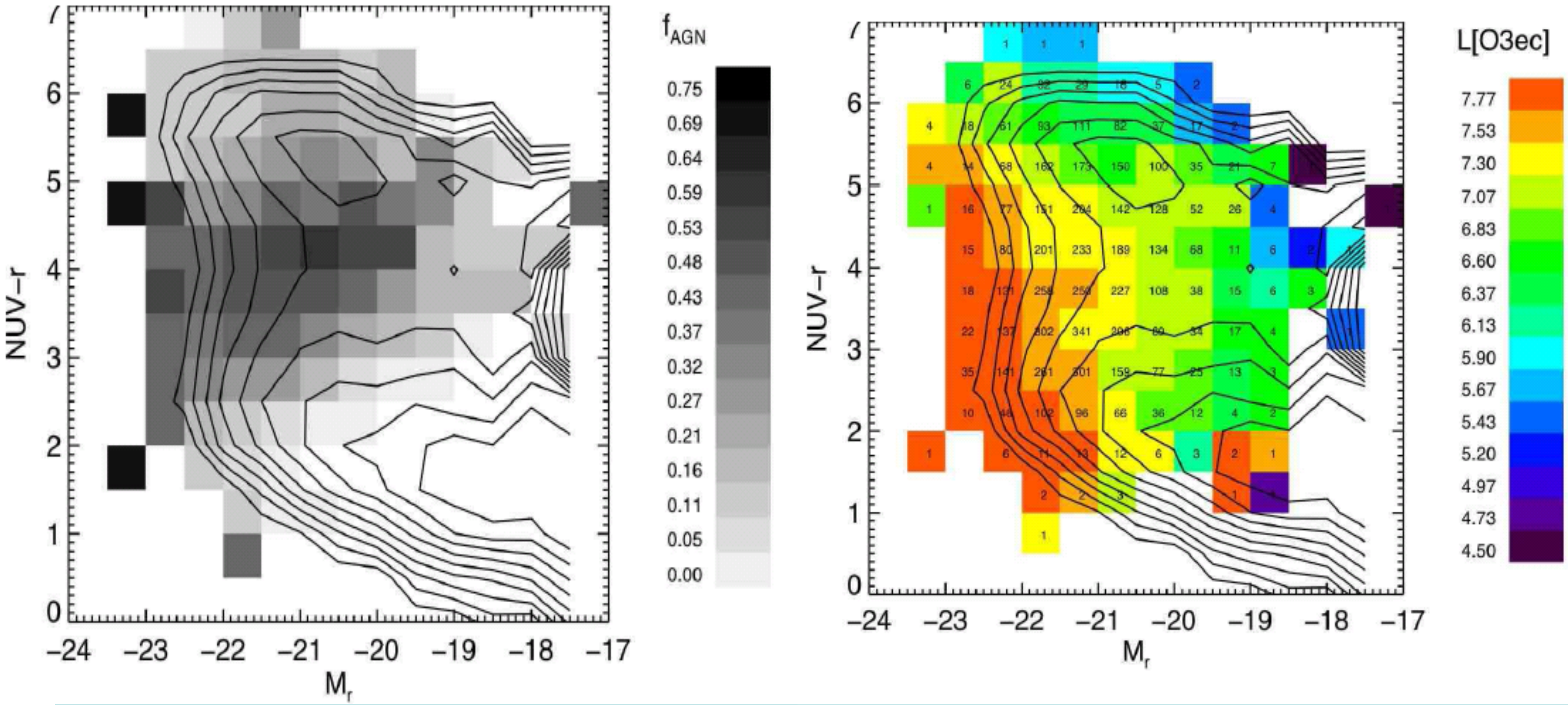
Obscured vs. "Naked" AGN





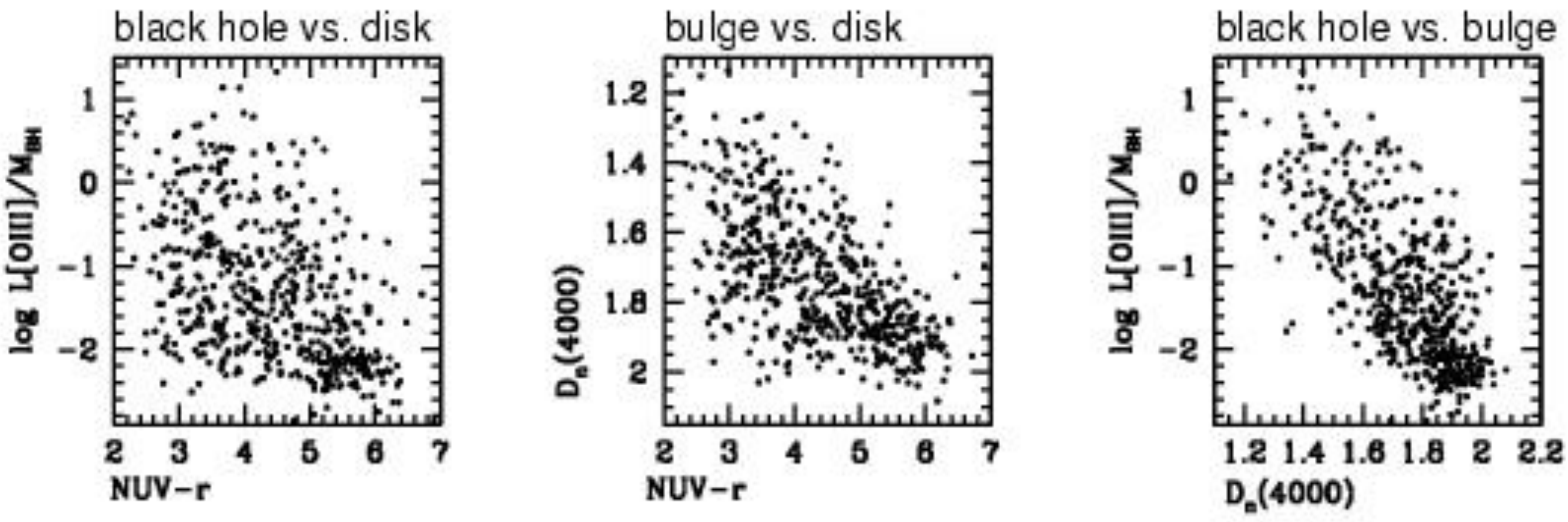
- Orientation: AGN obscured by dusty torus
- Can study the host galaxy without interference
- Use narrow high-ionization emission-lines and MIR from the torus to characterize the AGN

Global properties of hosts z ~ 0



- The fraction of galaxies with an AGN peaks in the “Green Valley” (transition from blue to red sequence)
- The brightest star-forming galaxies have the highest mean AGN luminosity (Martin et al.)

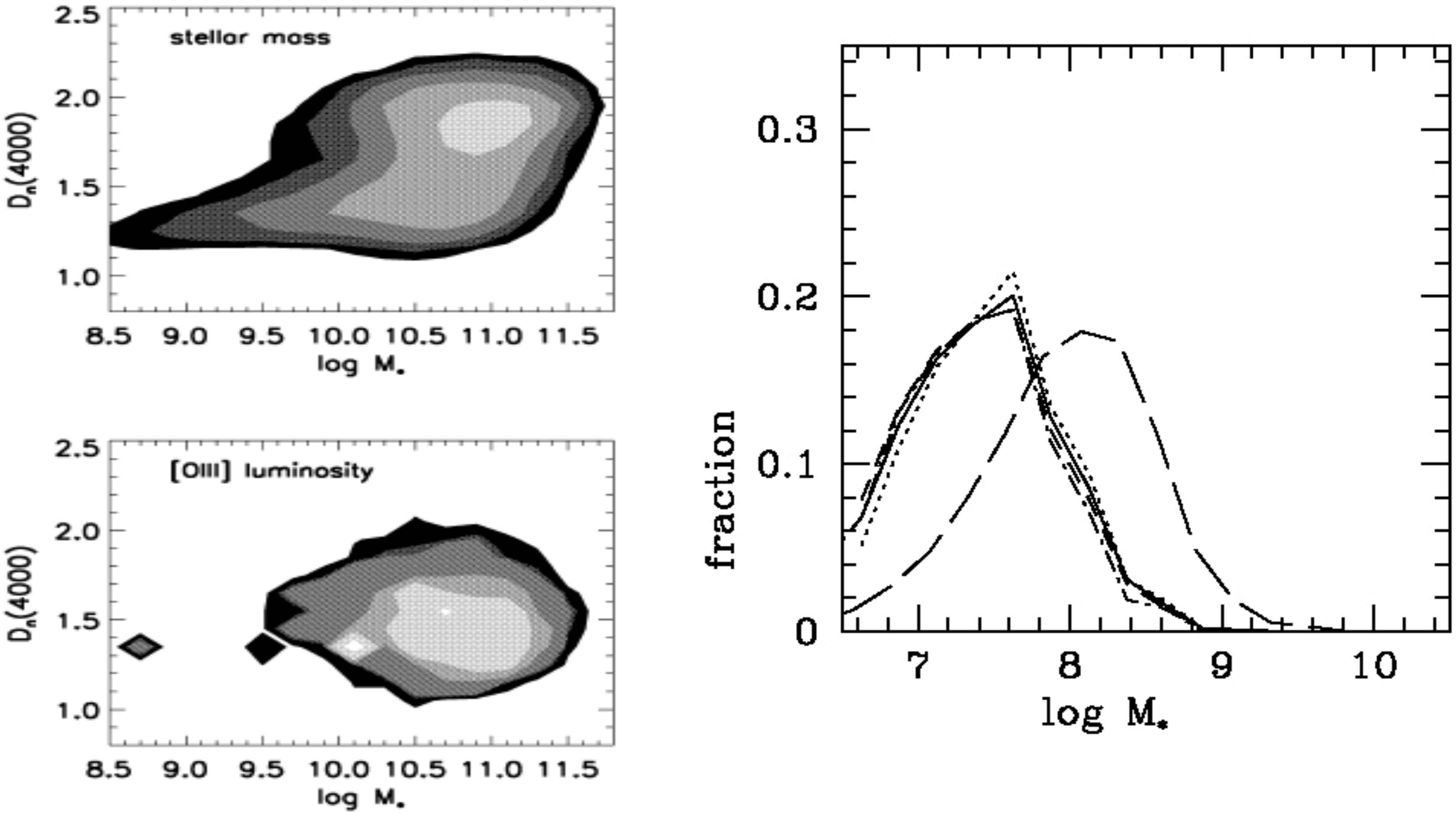
Disk vs. Bulge vs. Black Hole



- The strongest link is between the amount of star formation in the bulge & the growth rate of the black hole.
- A young disk is necessary…but not sufficient for the growth of the bulge and black hole
- Disk gas: the long-term reservoir for bulge & black hole

Kauffmann et al.

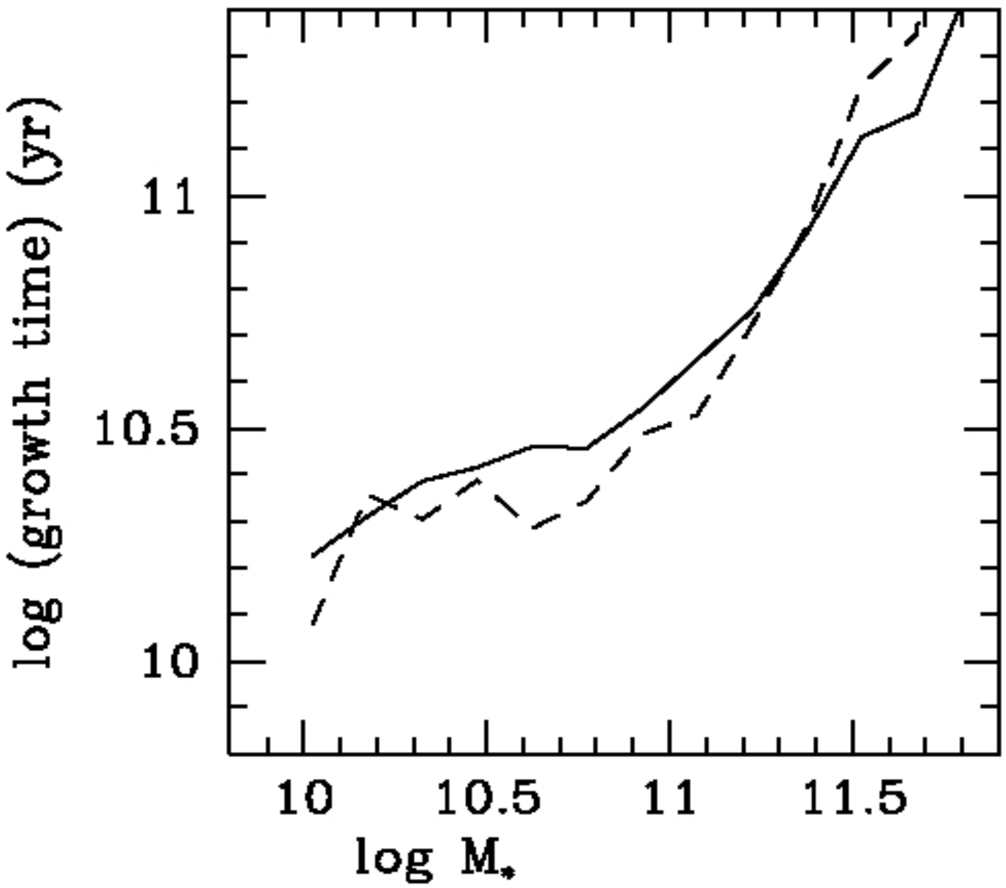
Where are BHs growing now?



>It's the lower mass black holes in the lower mass bulges

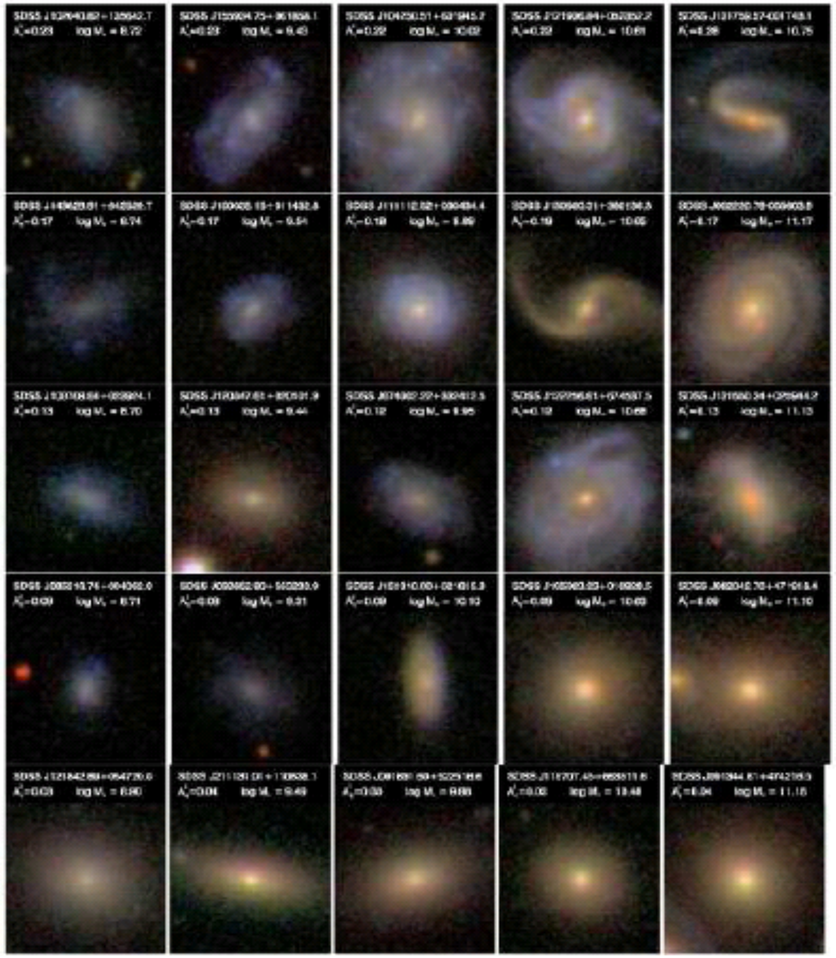
>In galaxies with bulges (BH) and an unusually young stellar population (copious fuel supply)

Coordinated down-sizing



- The mass-doubling timescales of the populations of black holes and bulges both increase in parallel with increasing mass

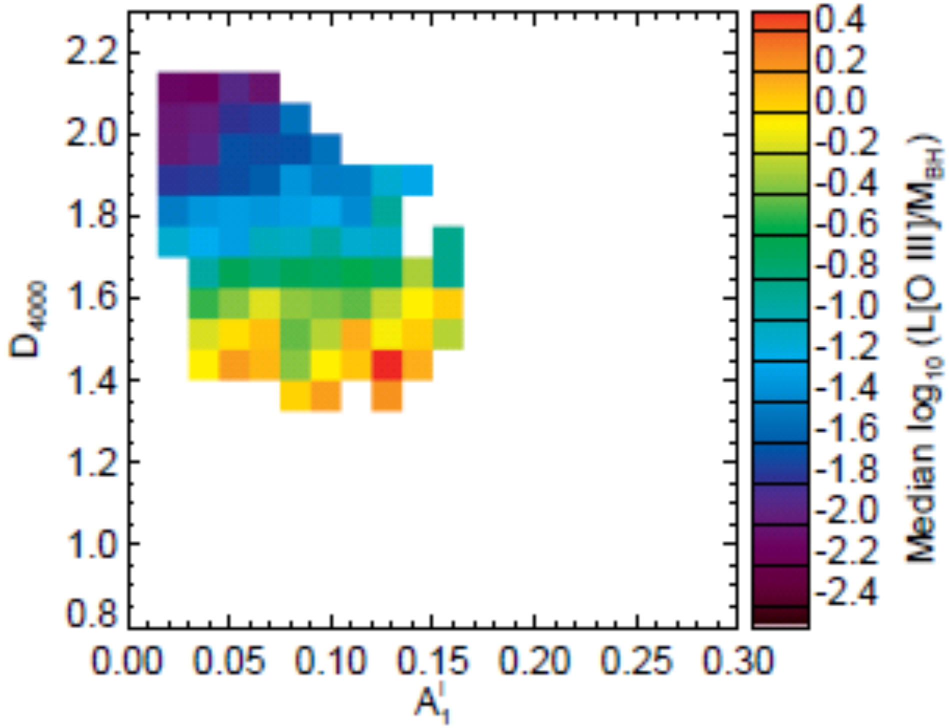
What is the fueling mechanism?

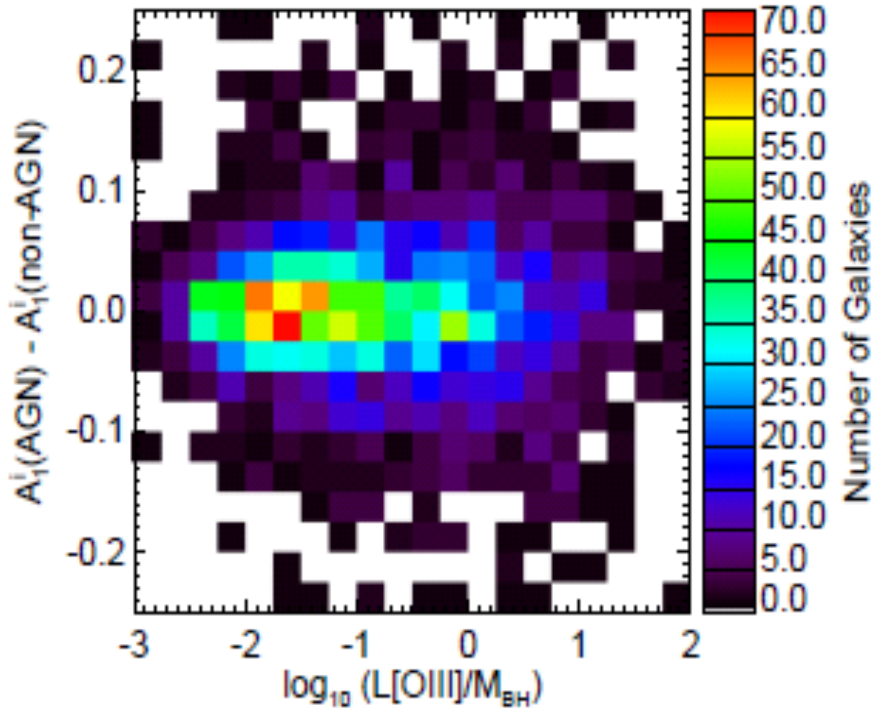


Reichard et al. (2009)

- Measure “lopsidedness” of galaxy
- Signpost of interactions & minor mergers

Lopsidedness vs. BH growth





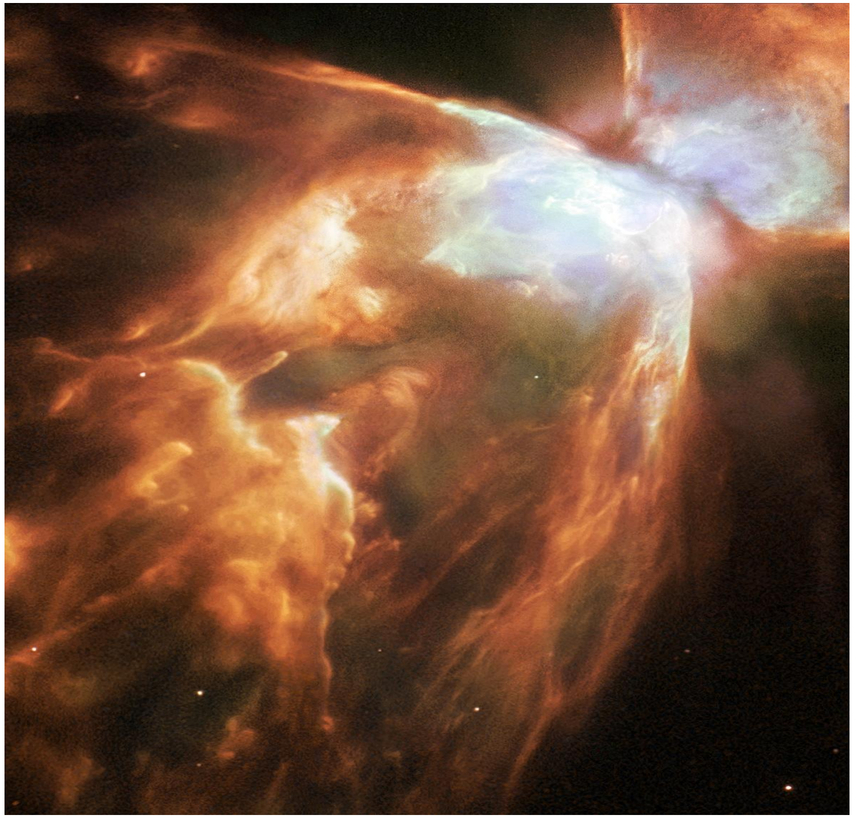
> See strong primary correlations between:

1) lopsidedness and star-formation in the bulge

2) star formation in the bulge and black hole growth

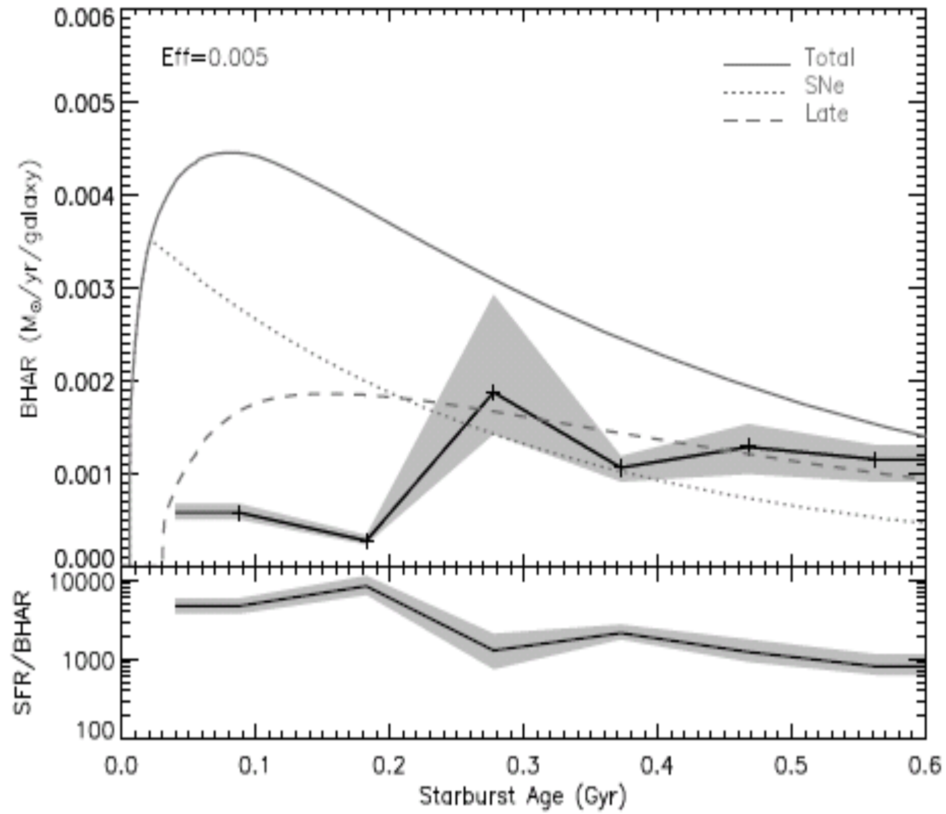
> No independent correlation between lopsidedness & black hole growth

Fueling & Feedback: the role of stars



- Star formation accompanies black hole growth
- Dying stars inject mass and energy into the bulge
- Fast ejecta (supernovae and O/WR winds) provide feedback
- Slow ejecta (AGB and red giants) could provide fuel

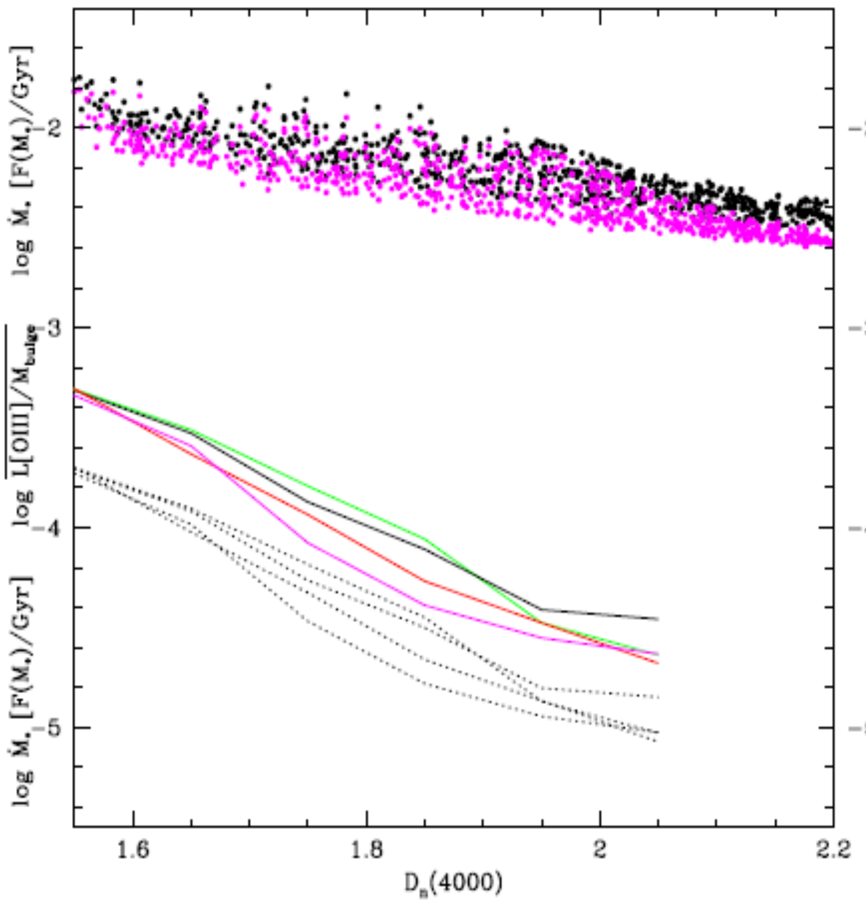
Test: Response to a Starburst



- Black hole growth is suppressed until the supernova rate drops
- Accretion rate then tracks mass loss from intermediate mass stars
- Roughly 0.5% accreted by black hole
- 1000:1 ratio of new stars to black hole mass growth over the event

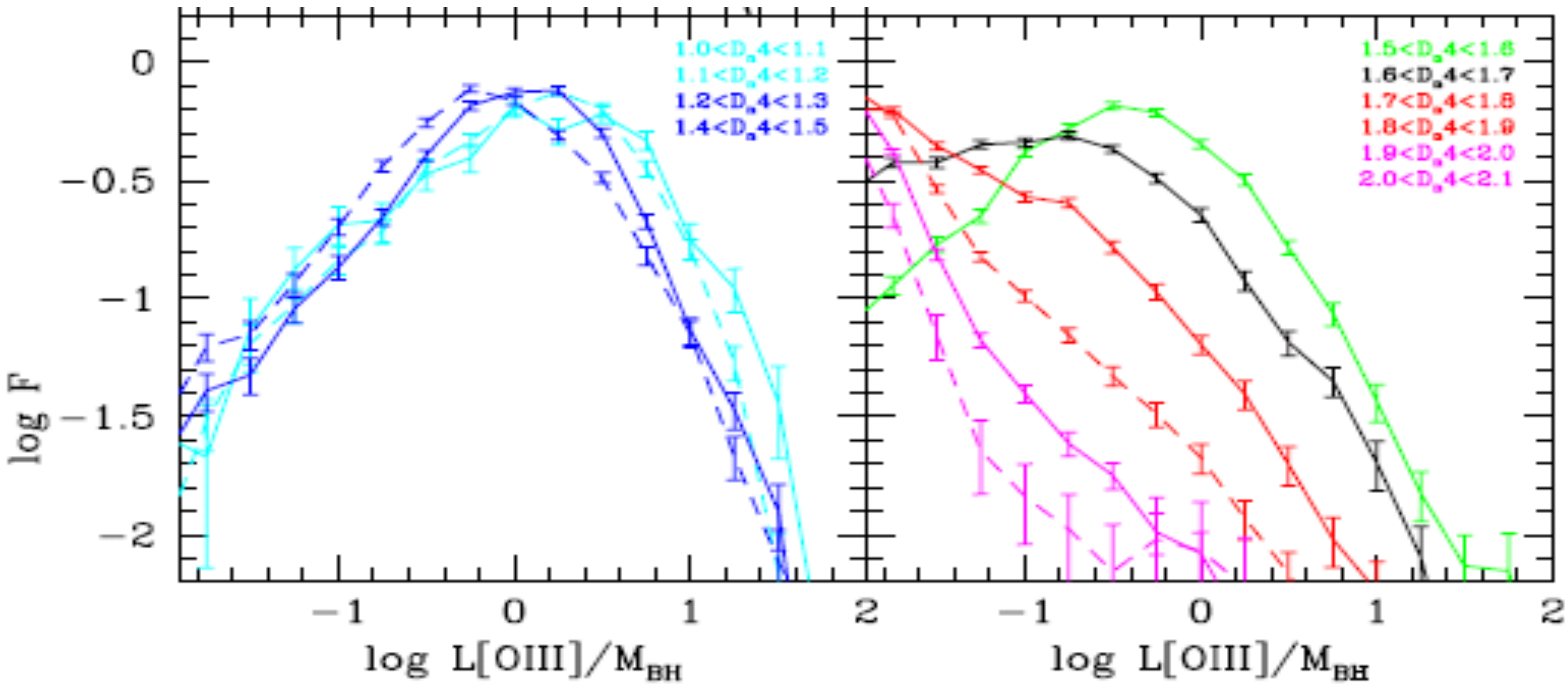
Wild et al (see also Davies et al; L. Trouille)

Similar results at later stages



- The age-dependence of the black hole growth rate for older systems is also consistent with the capture of about 0.5% of the mass lost by evolved stars in the bulge (GK & TH)

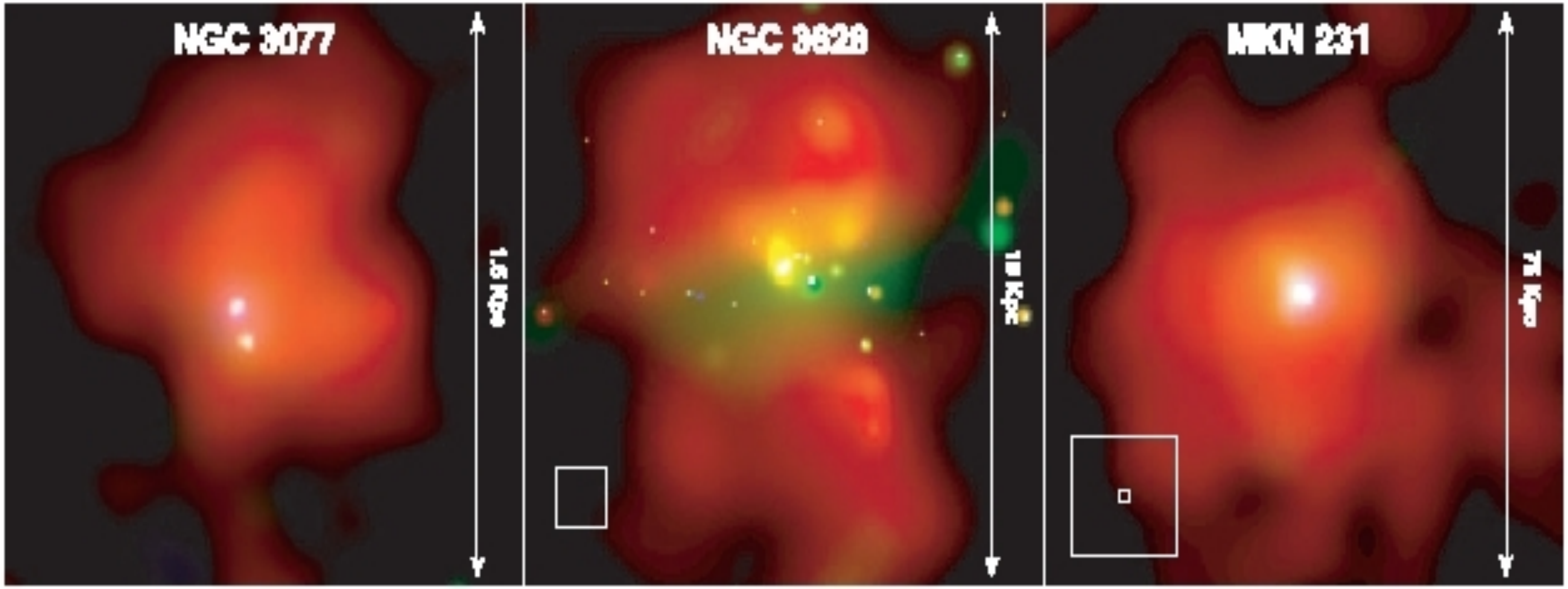
The BH growth-rate distribution



Universal log-normal shape for “living” bulges. SNe feedback causes growth rate to saturate?

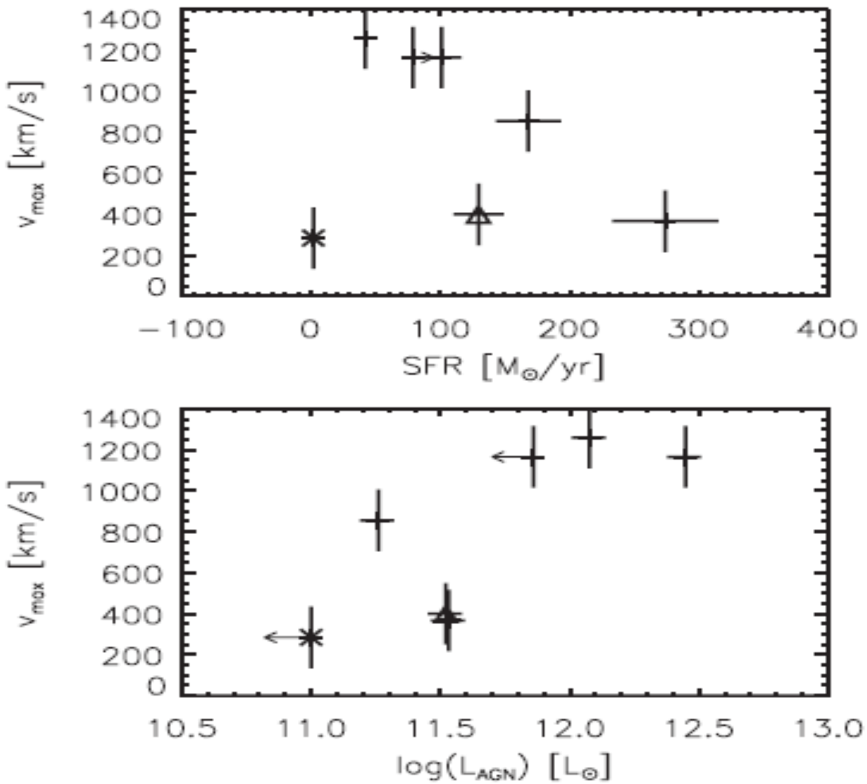
Age-dependent power-law for “dead” ones. Higher stellar mass loss rate leads to higher accretion rate

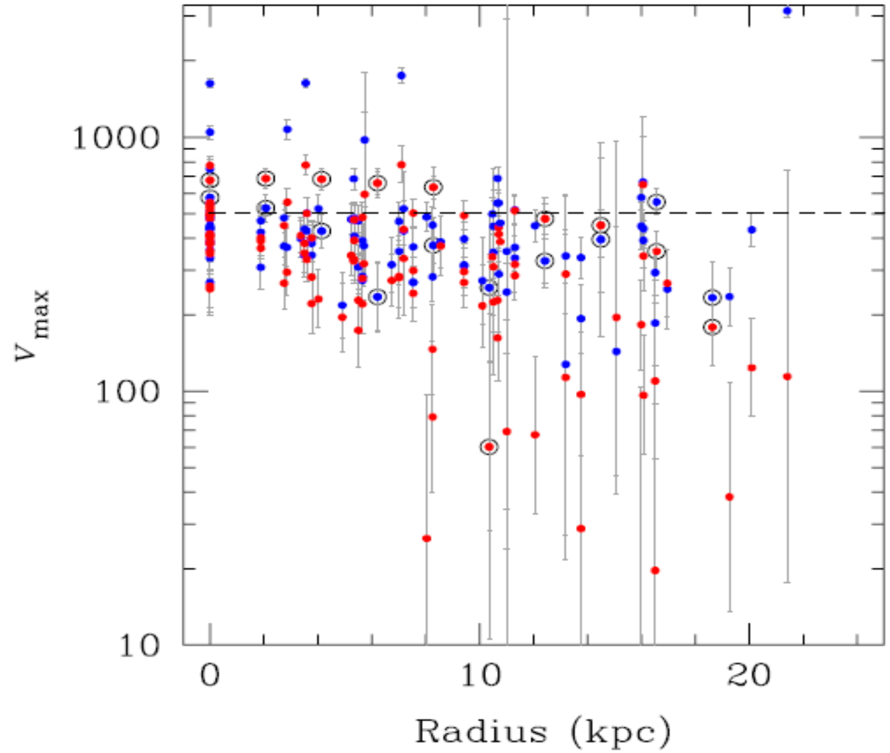
What about global feedback?



- Galaxy-scale winds are generic in starbursts (C. Martin & C. Steidel)
- The AGN/SF connection means this feedback is present even without the AGN’s contribution

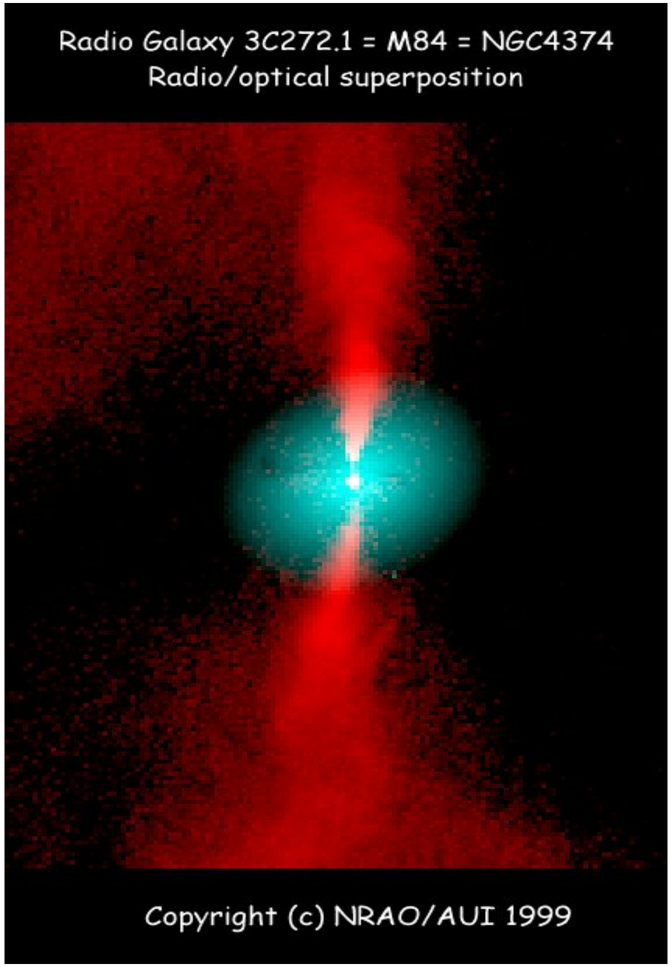
Global AGN Feedback

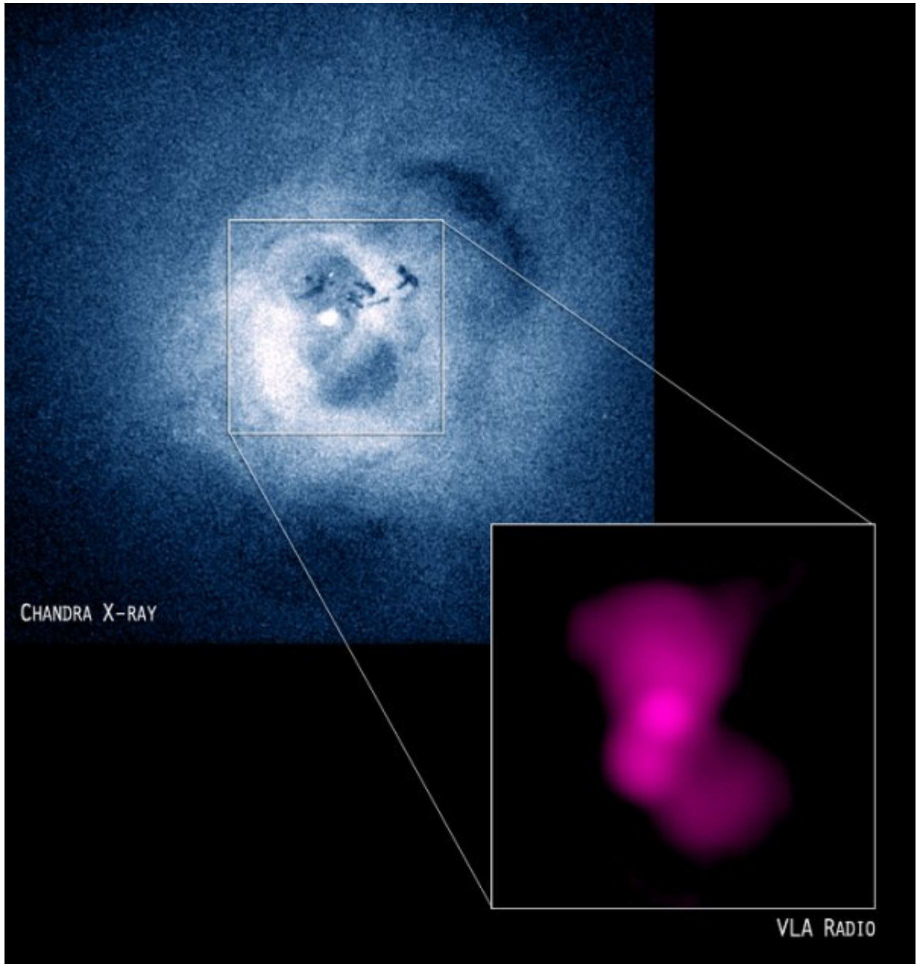




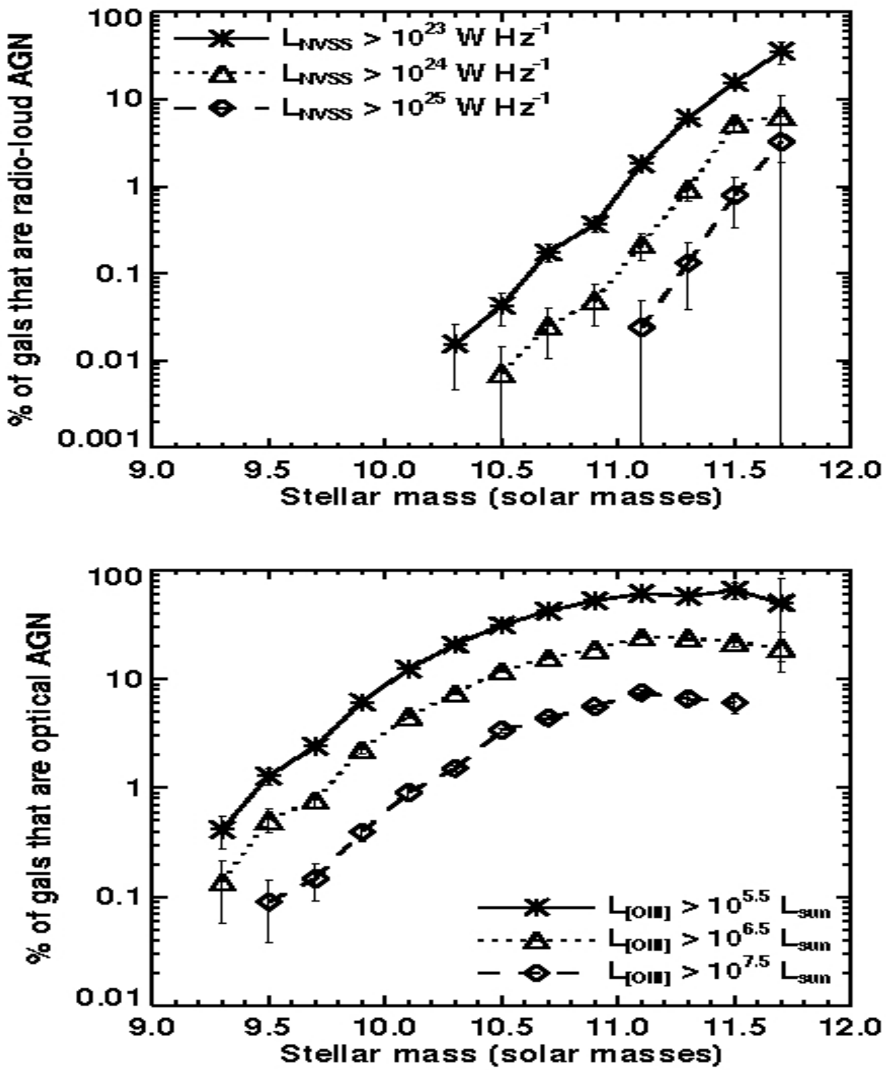
- High-velocity molecular outflows seen in ULIRGs with AGN (Sturm et al. 2011)
- Galaxy-scale disturbed ionized gas in Type 2 QSOs (Greene et al. 2011)

Co-Evolution: Radio Galaxies



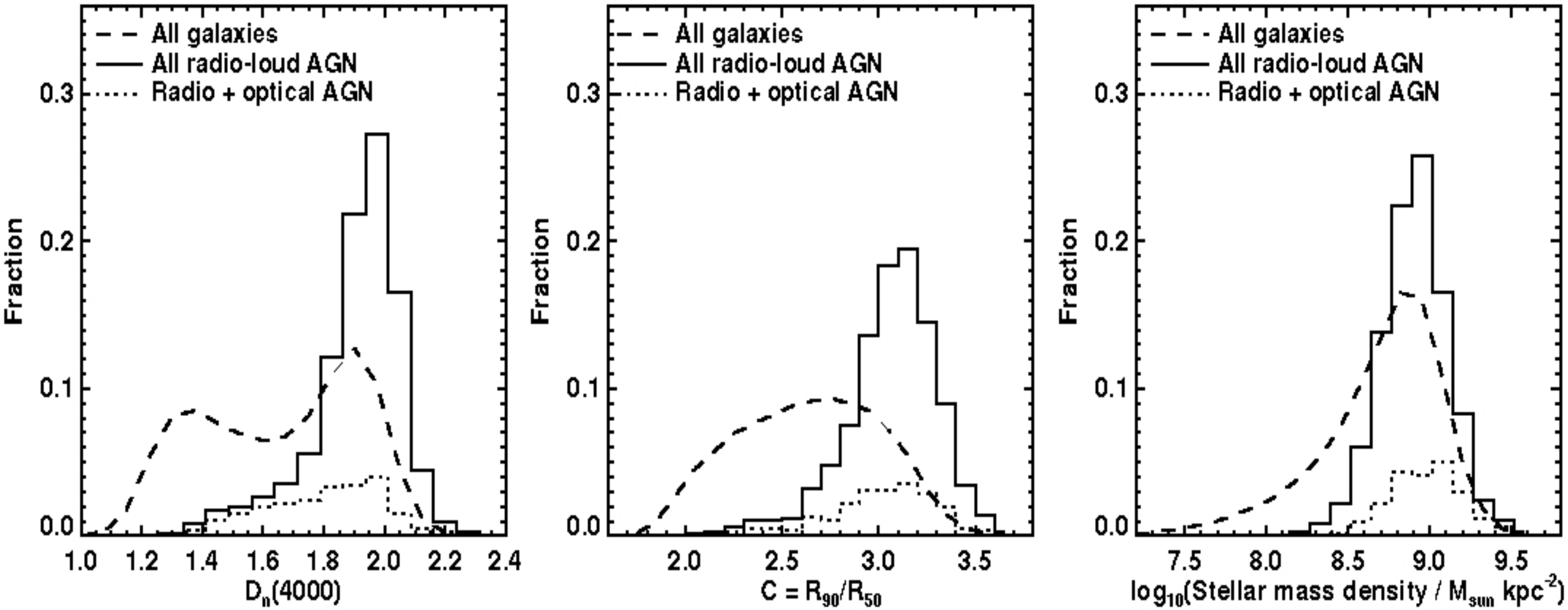


Masses



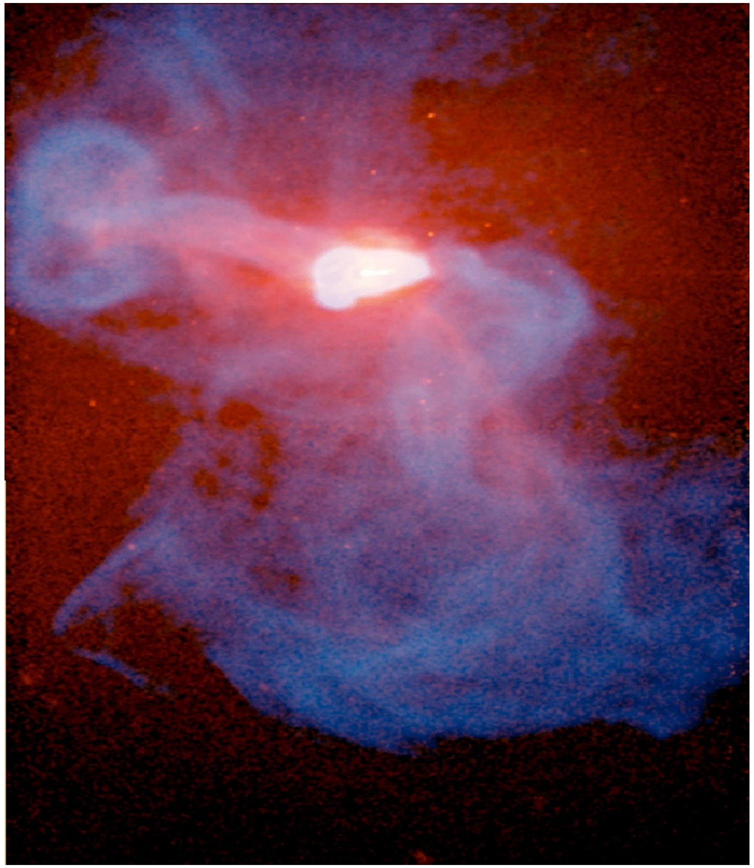
- Radio galaxies are the most massive galaxies
- Radio luminosity function strongly mass-dependent
- Best et al.

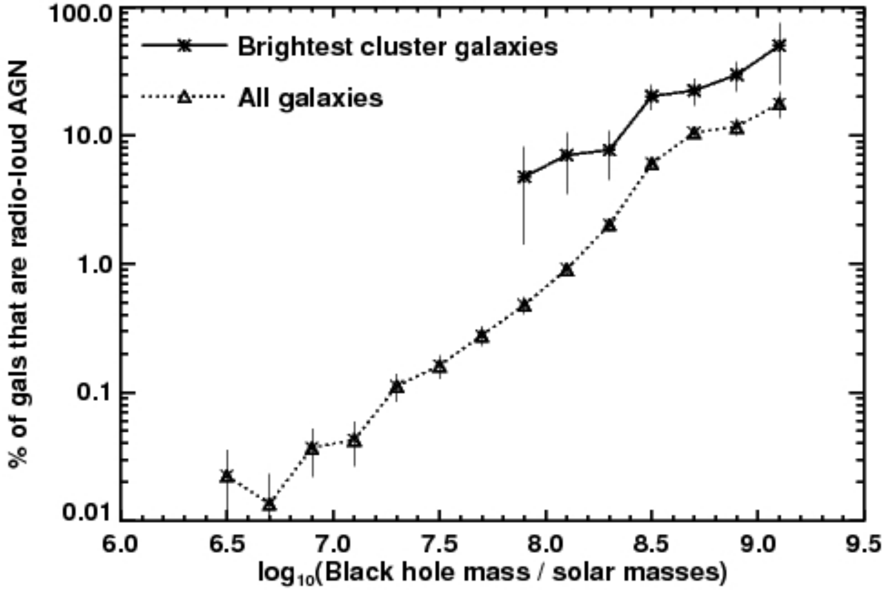
Structures and ages

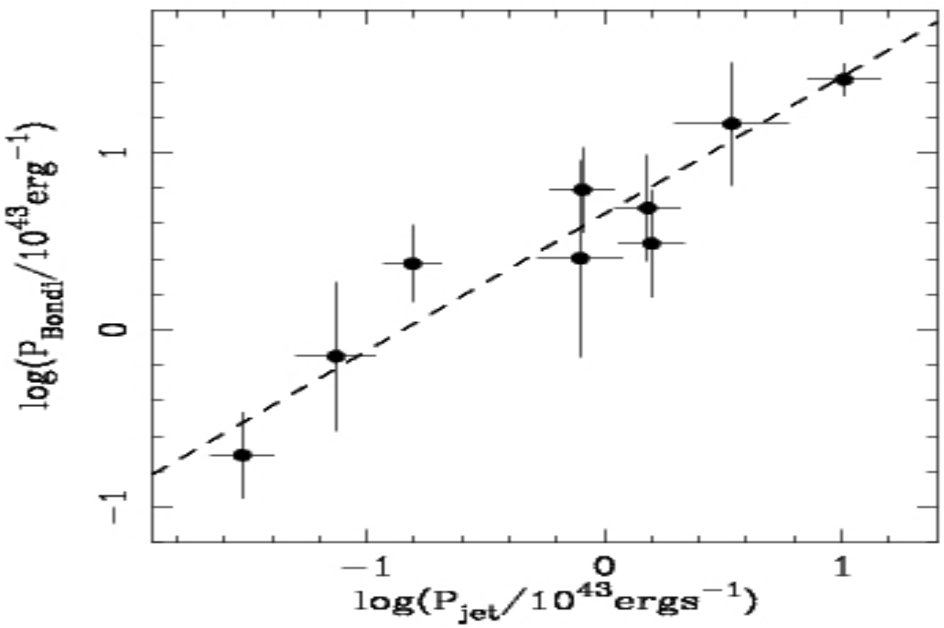


- Structural properties: giant elliptical galaxies
- Old stellar populations (normal)
- Very different from the Seyfert galaxies

Fueling by Cooling of Hot Gas

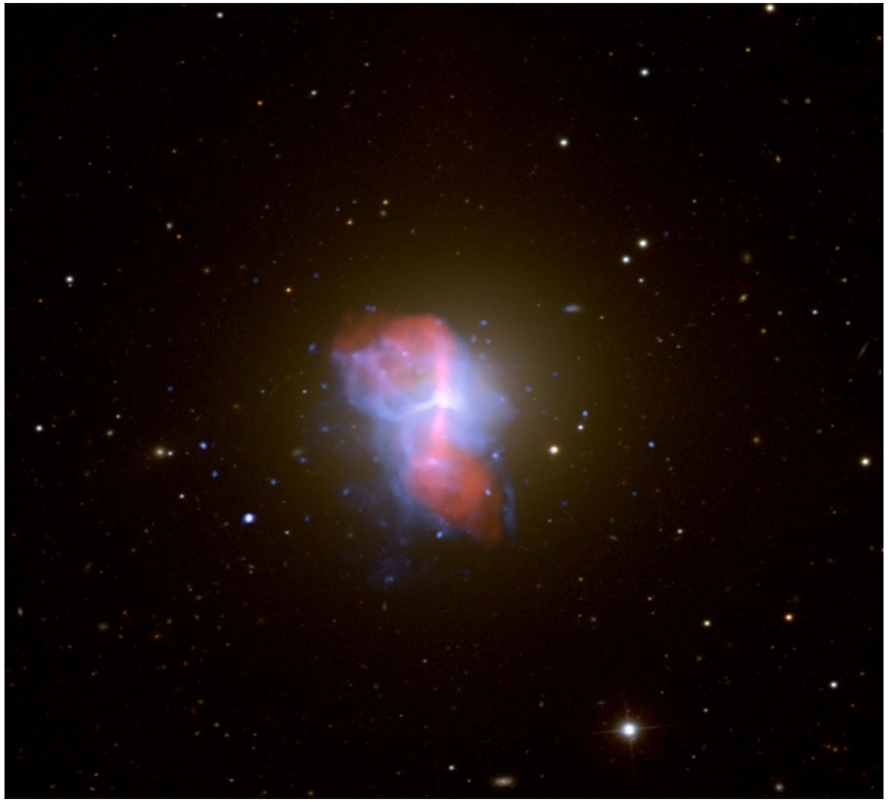
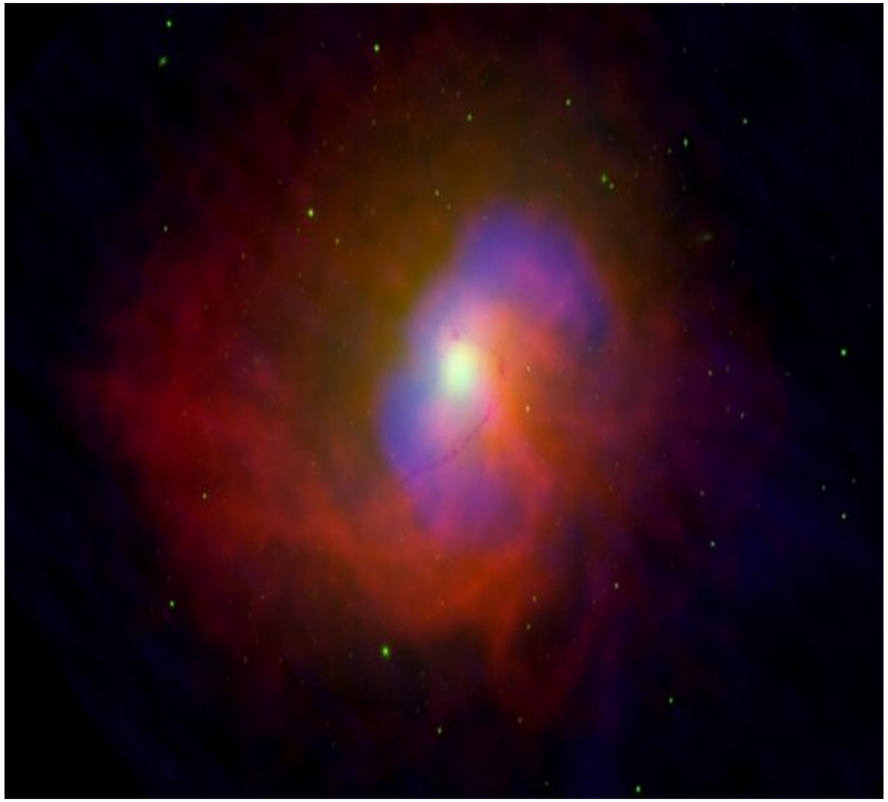






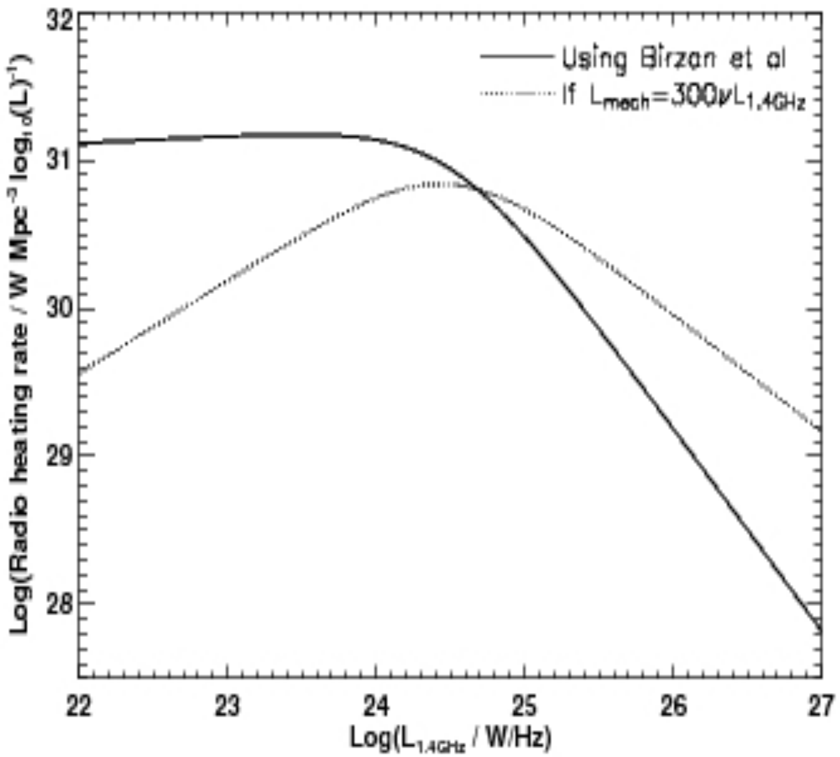
- Best et al.
- McNamara & Nulsen ARAA

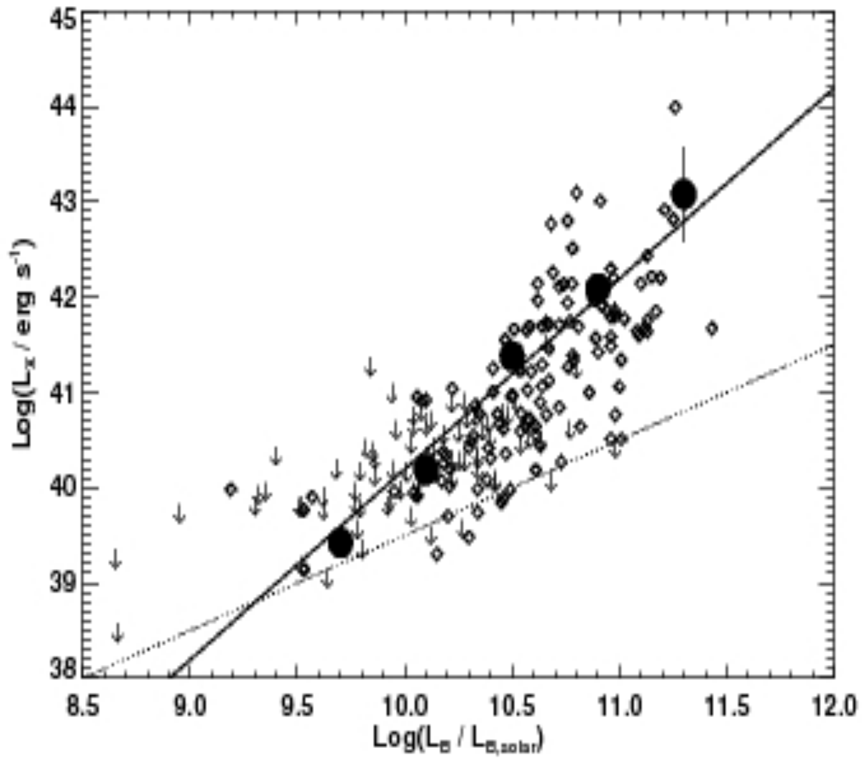
Feedback from radio sources

- Weak radio sources excavate cavities in the hot ISM of typical giant ellipticals
- Scaled-down versions of objects discussed by B. McNamara

Radio Feedback: Global Values





- Heating by radio sources sufficient to balance cooling in typical massive elliptical galaxies?

  (Best et al.)

- Detailed physics of coupling still unclear

Summary: The Living…

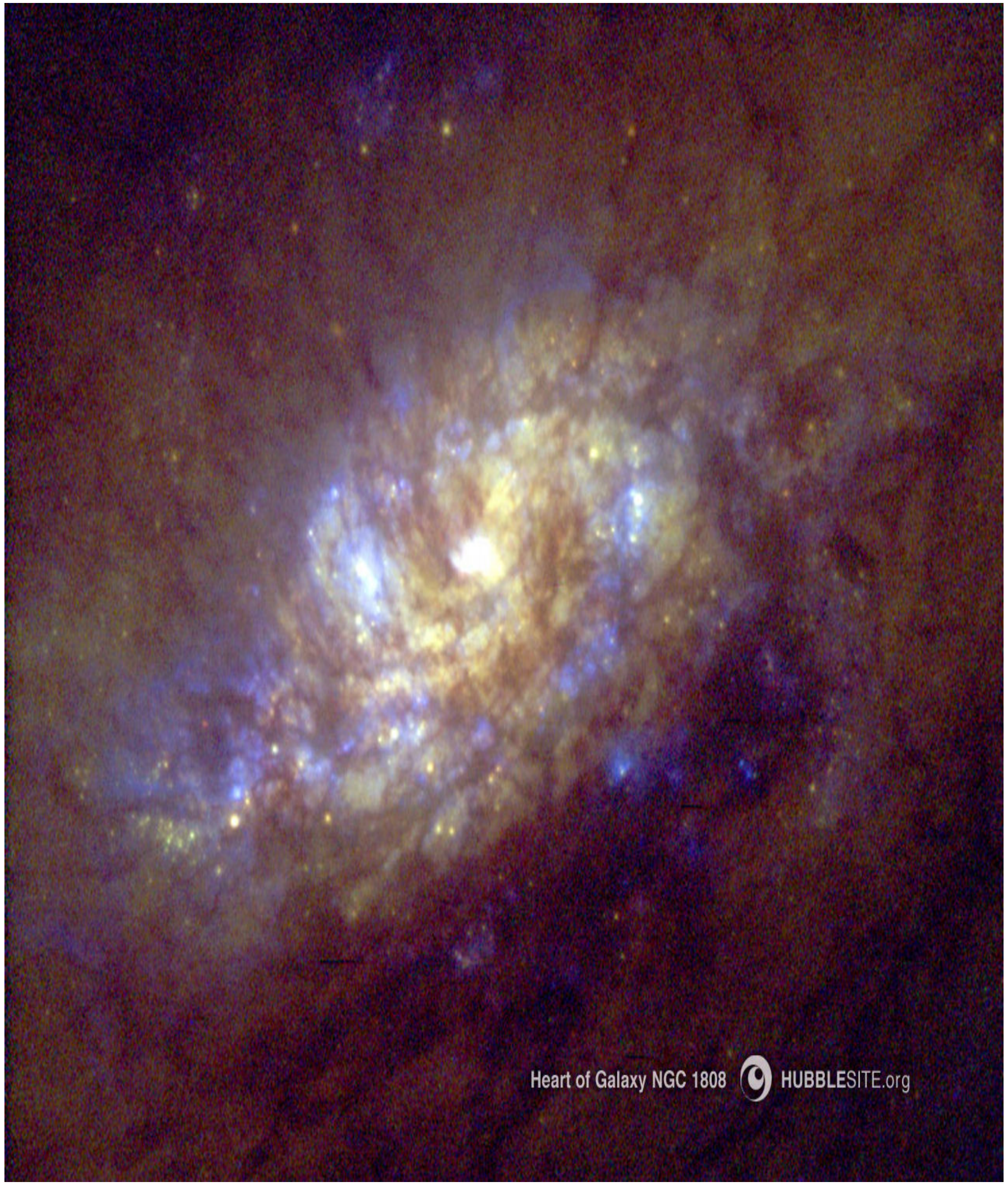
> AGN require a black hole (bulge) and cold gas in the bulge

> This combination now exists only in less massive bulges ("downsizing")

> Fueling: Intermediate mass stars

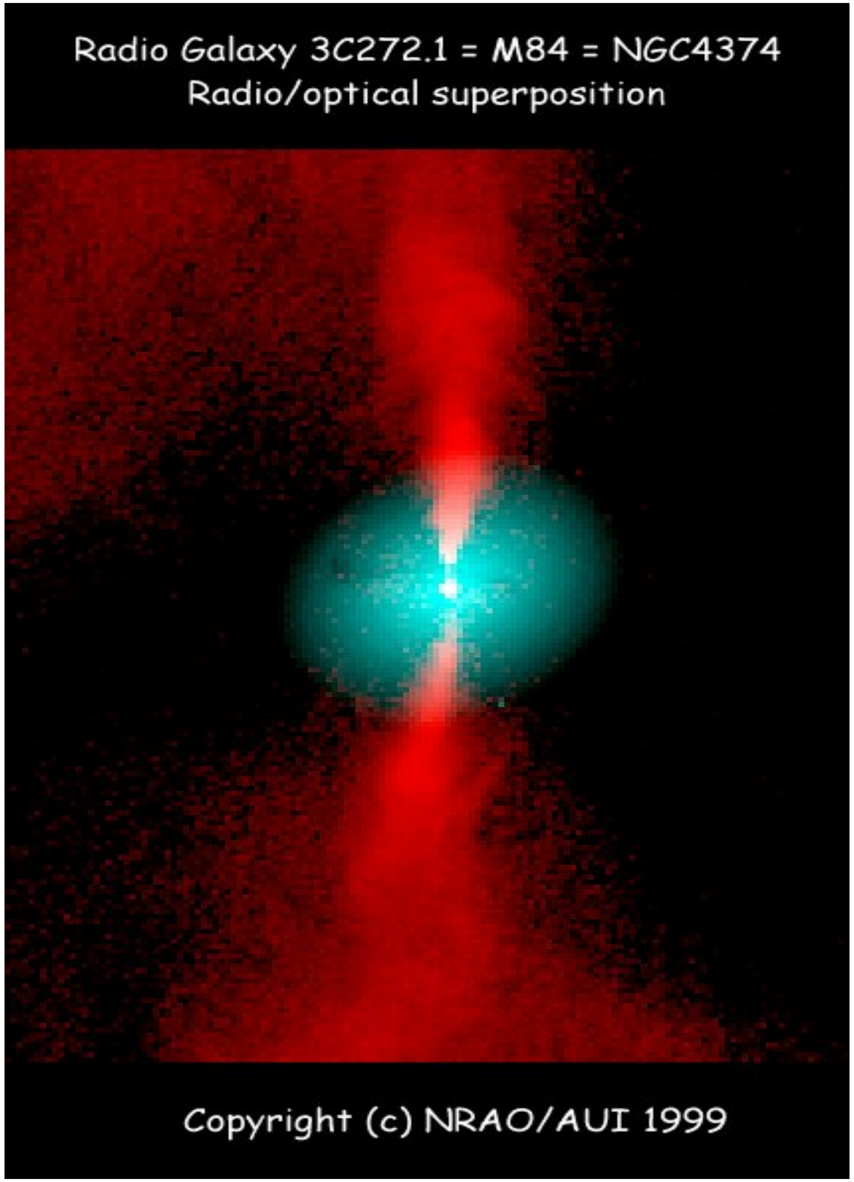
> Feedback from massive stars

> Global AGN feedback may be important at the highest luminosities



...and the Dead

- The most massive black holes (and their host galaxies) formed at redshifts ~ 2 to 3
- "Dead quasars" simmer as radio galaxies & low luminosity AGN
- Fueled by slow cooling of hot gas (evolved stars plus accretion flows)
- Radio source heating suppresses star formation
- Keeps galaxies red & dead, but not "transformative"

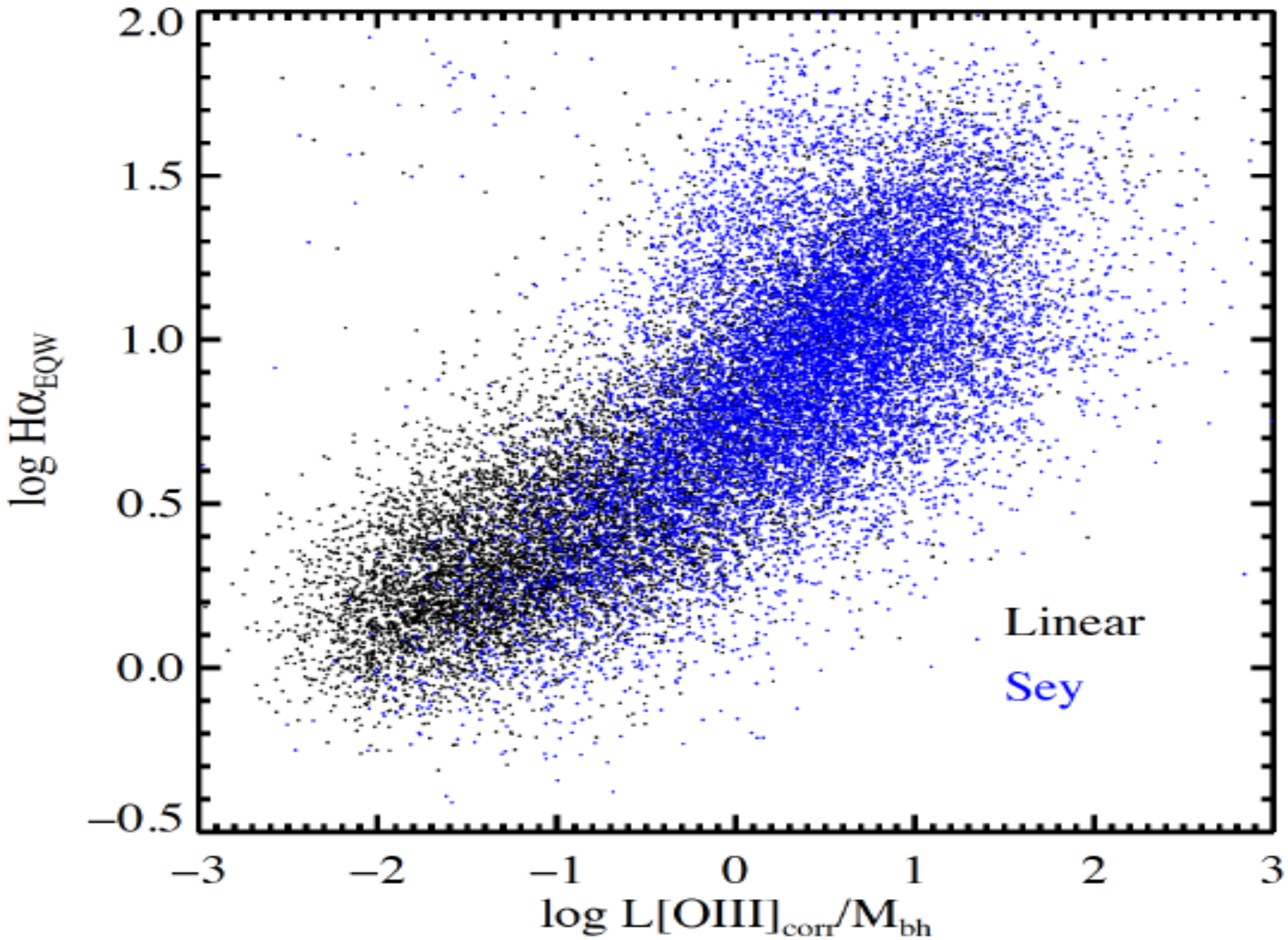


Points to provoke discussion

In the present-day universe:

- Mergers are not the direct driver of black hole growth
- Stellar mass loss in bulges is a major fuel source
- "Local" feedback from supernovae is important for regulation of black hole growth
- There is good evidence for "global" feedback that is generic in starbursts and radio-loud AGN but not yet for typical radio-quiet AGN

Are most LINERs AGN?



- Contamination by post-AGB stars possible below L/L_Edd ~ 0.001