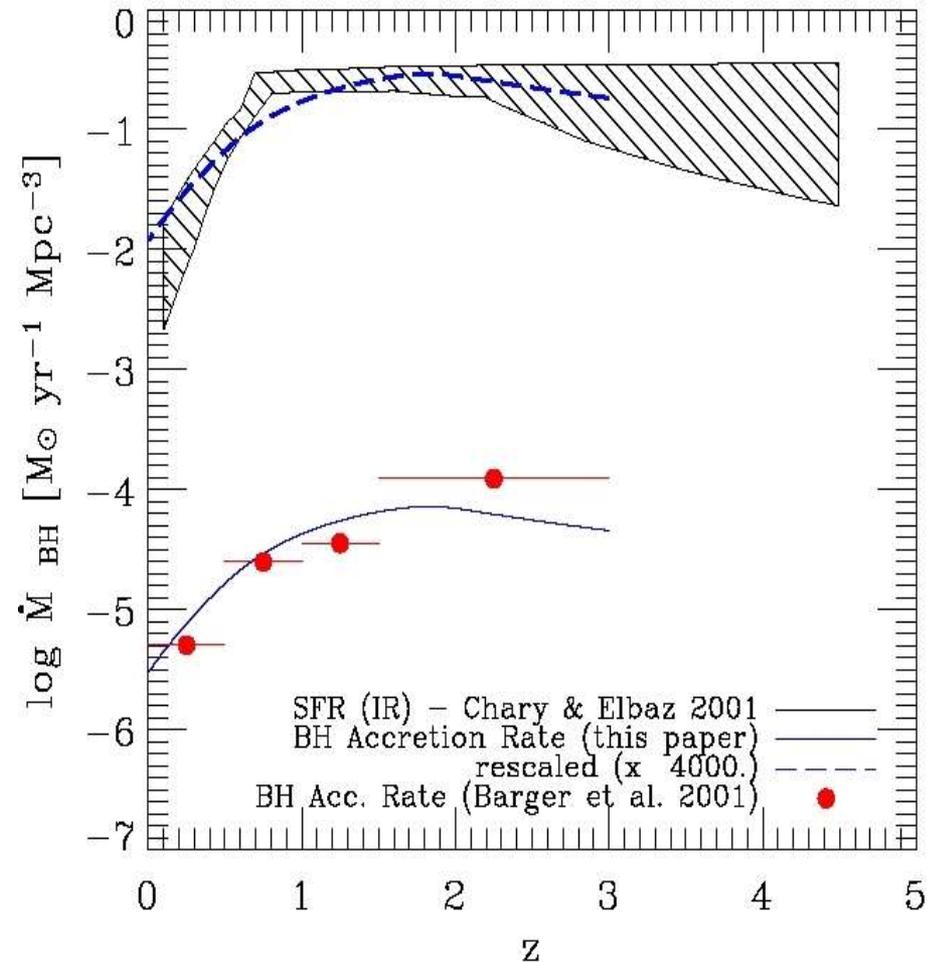
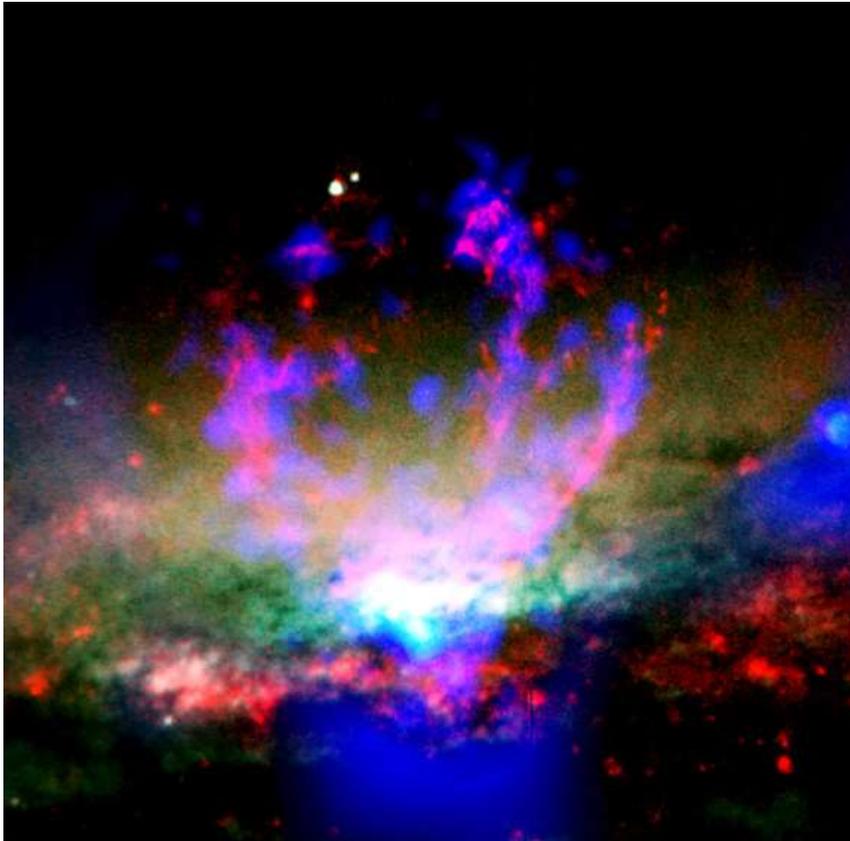


# The Co-Evolution of Black Holes & Bulges: **A Local Perspective**



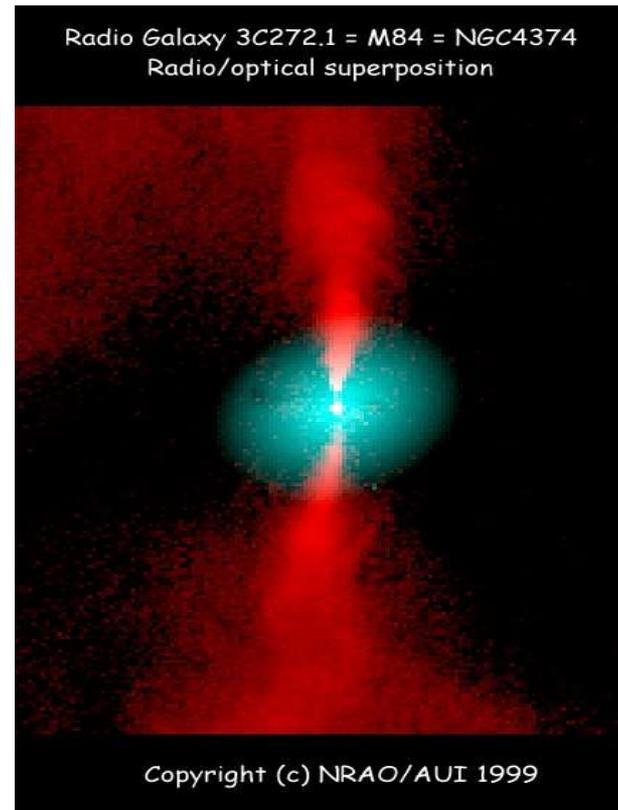
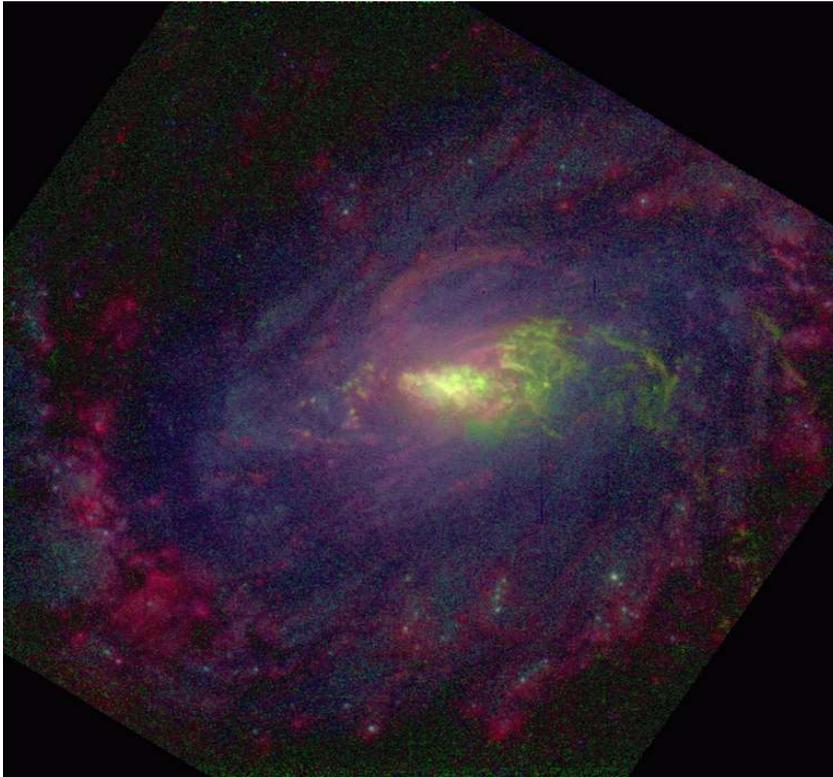
# COLLABORATORS

- G. Kauffmann – MPA (Garching)
- P. Best – ROE (Edinburgh)
- J. Brinchmann – CAUP (Portugal)
- S. Charlot – IAP (Paris)
- C. Kaiser – Southampton
- T. Reichard - JHU
- C. Tremonti - Arizona
- A. von der Linden – MPA
- S. White – MPA
- V. Wild – MPA
- The SDSS & GALEX Teams

# Motivating Questions

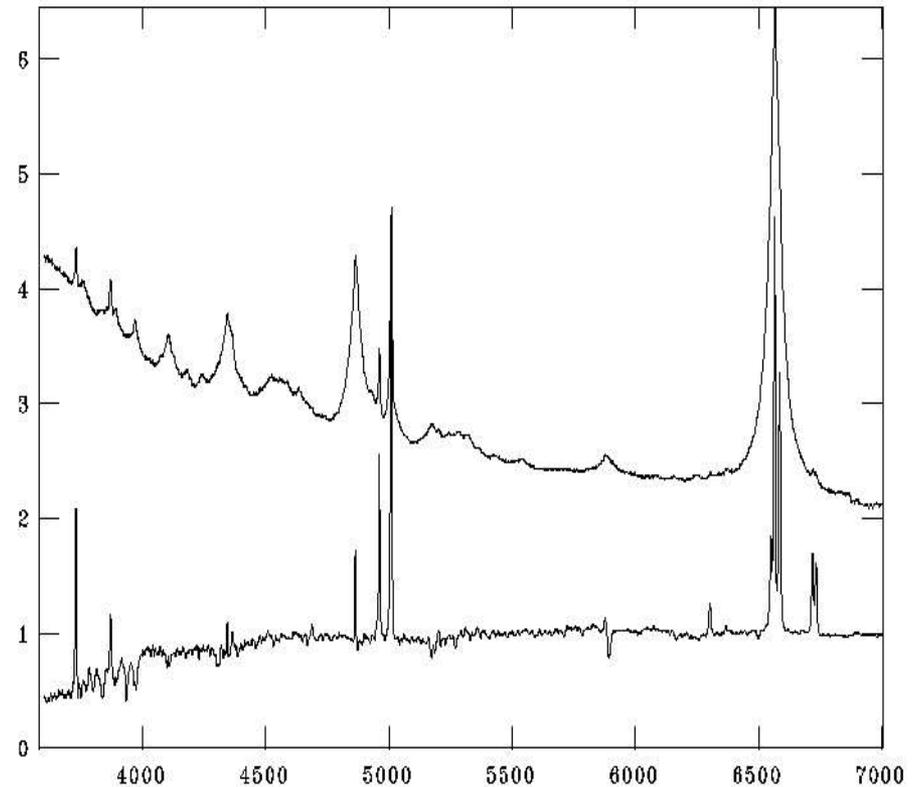
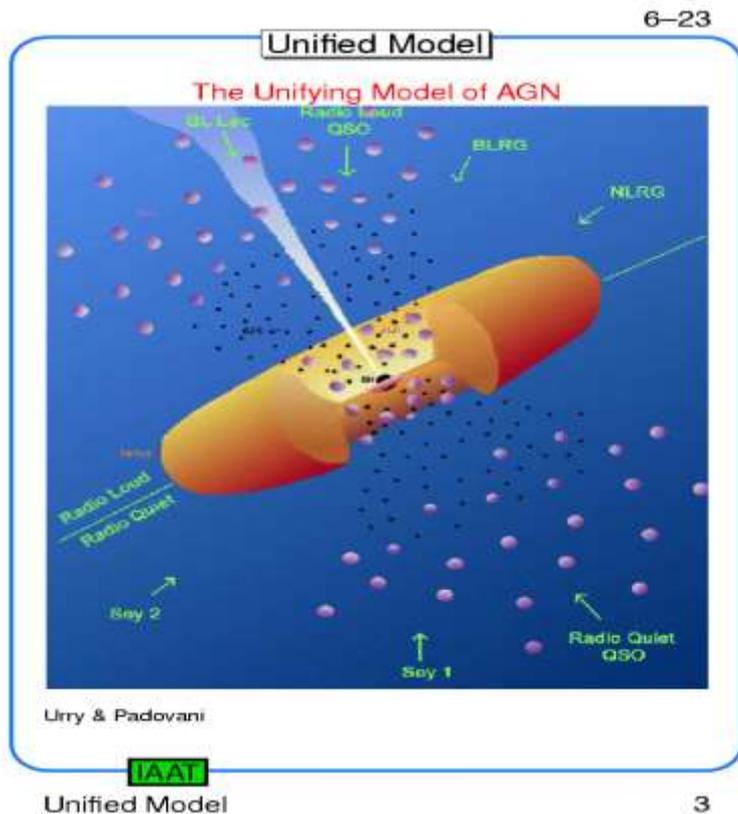
- By what processes are the formation of stars and the growth of black holes linked in galactic bulges?
- What form does feedback from AGN take, and what is its effect on galaxy formation?
- Can we see these processes operating in the local universe (where they can be studied in detail)?

# An AGN Primer



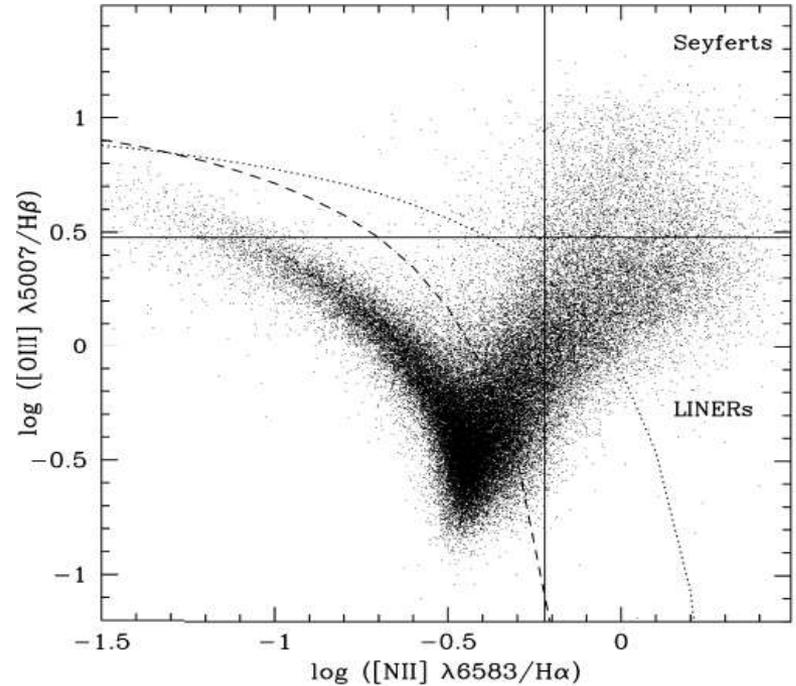
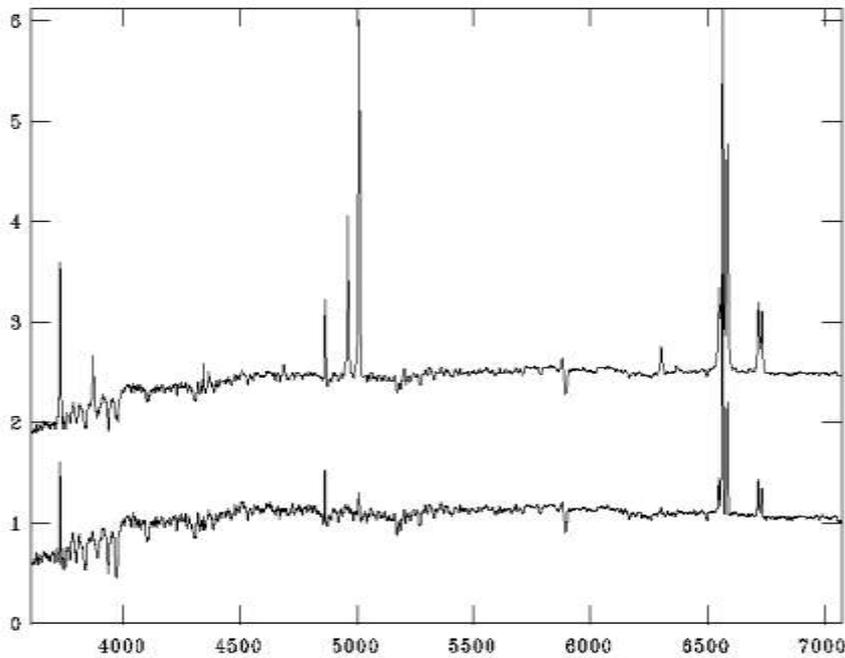
- Two primary **independent modes** in the local universe
- **Emission-Line AGN** (high accretion rates/efficiency)
- **Radio galaxies** (low accretion rates/low efficiency)

# The Standard “Unified” Model



- View “central engine” directly in Type 1 AGN
- Central engine occulted in Type 2 AGN
- Powerful jets in Radio Galaxies

# Emission-Line AGN

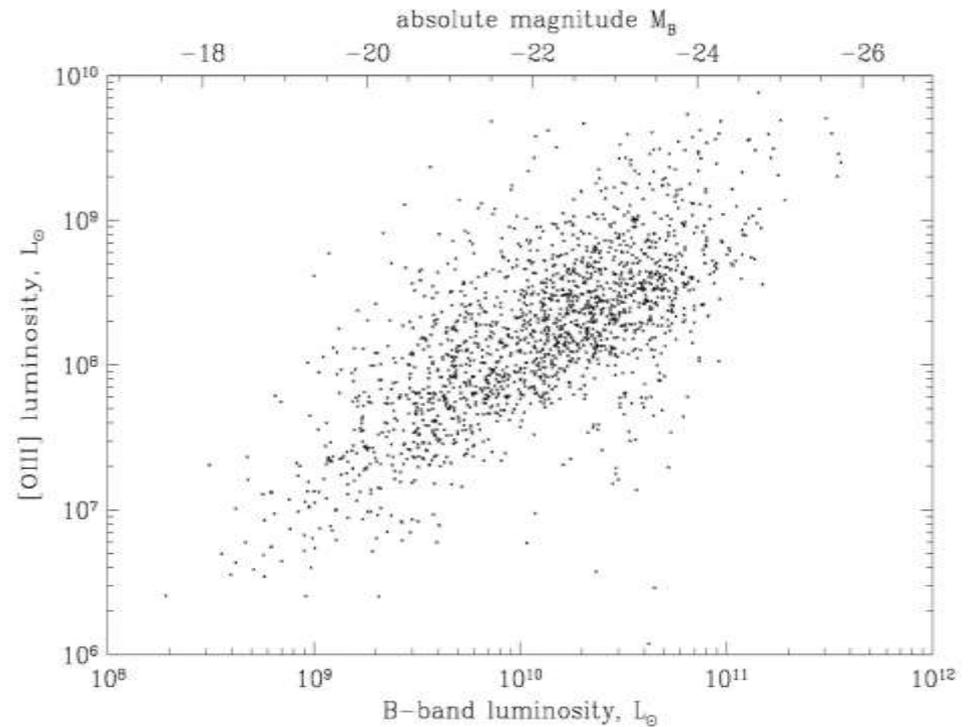
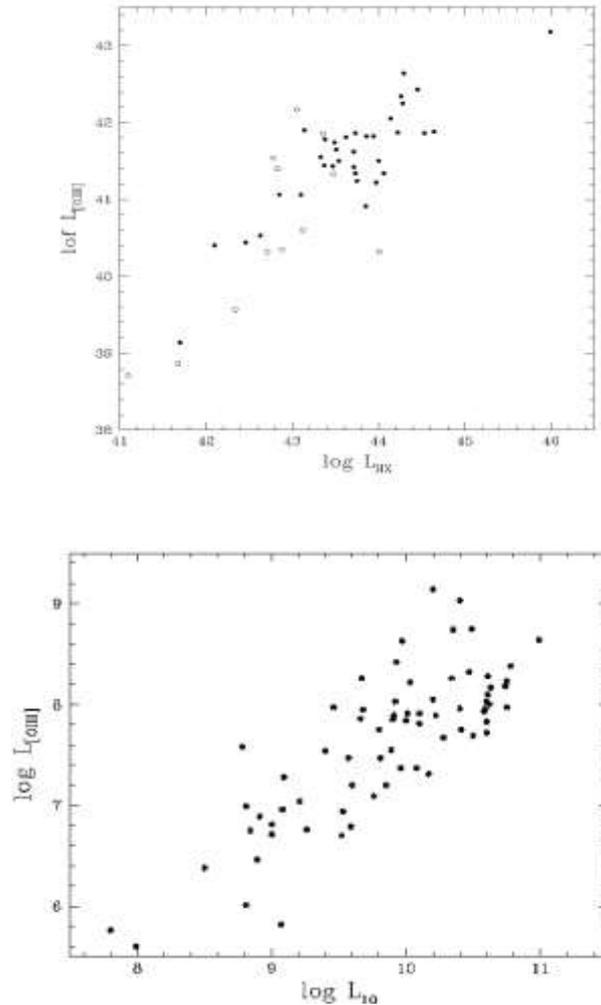


Classification AGN vs. SF: emission-line ratios

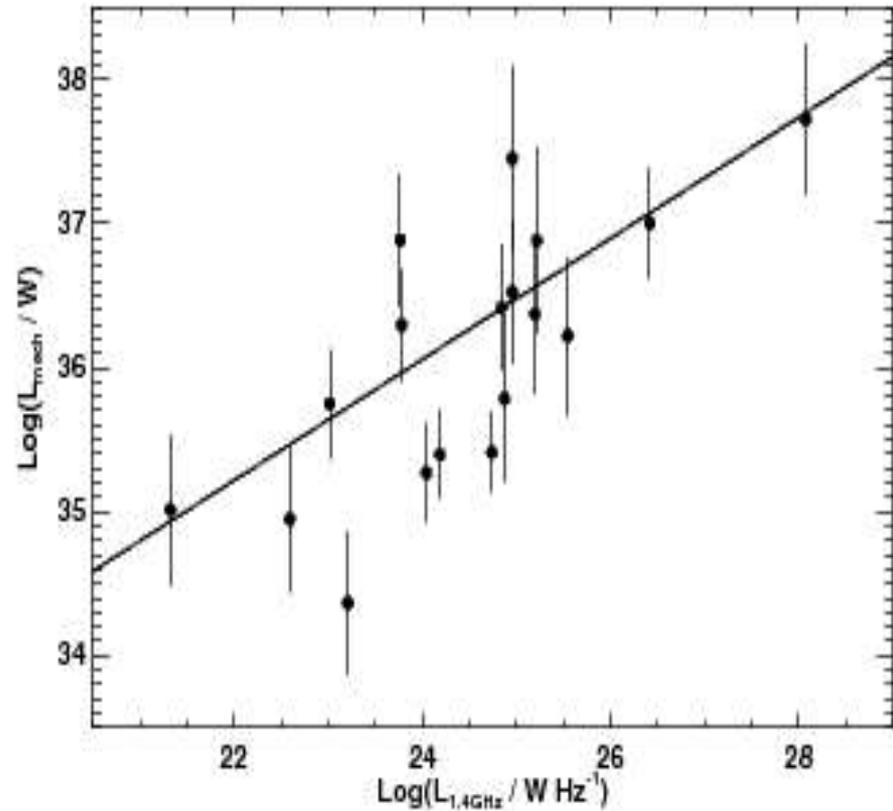
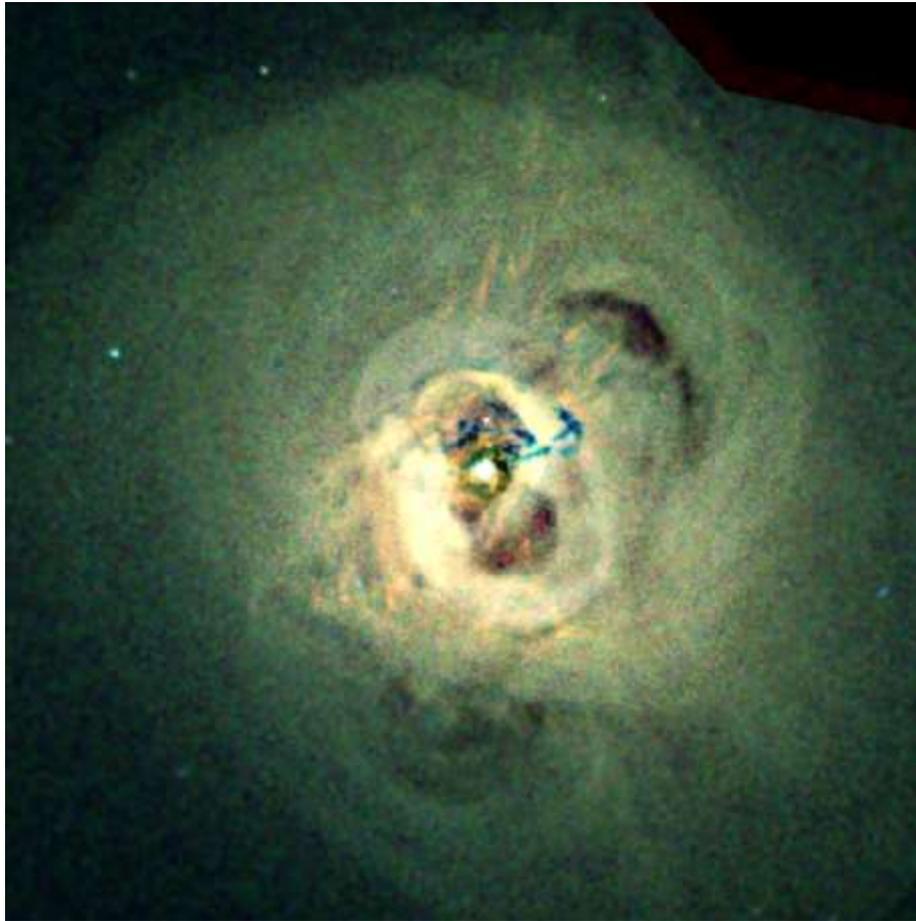
$[\text{OIII}]\lambda 5007$  as AGN tracer

Strongest AGN line and minimal contribution from SF

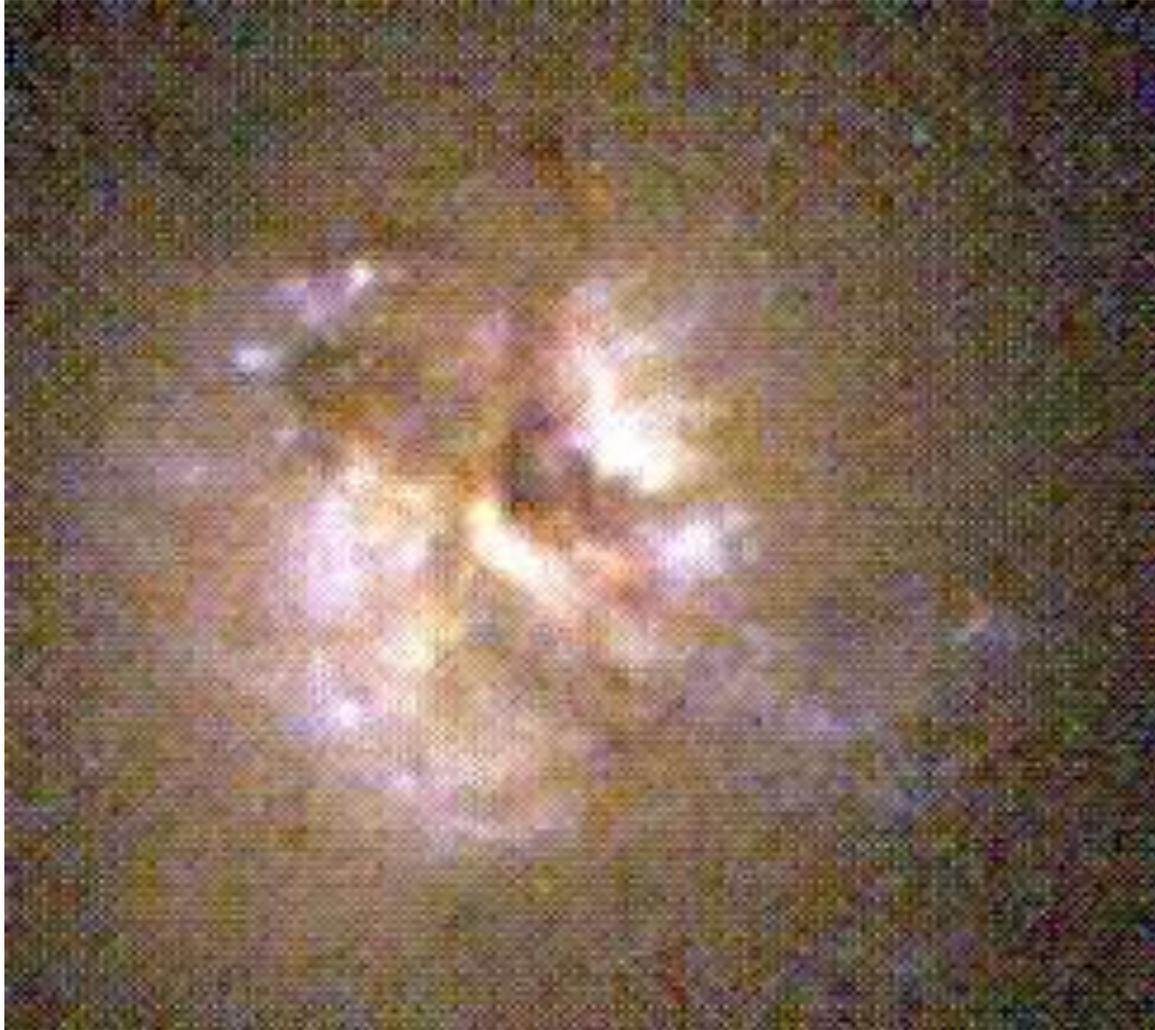
# The [OIII] Lines as a proxy for the bolometric luminosity (BC $\sim 3000$ )



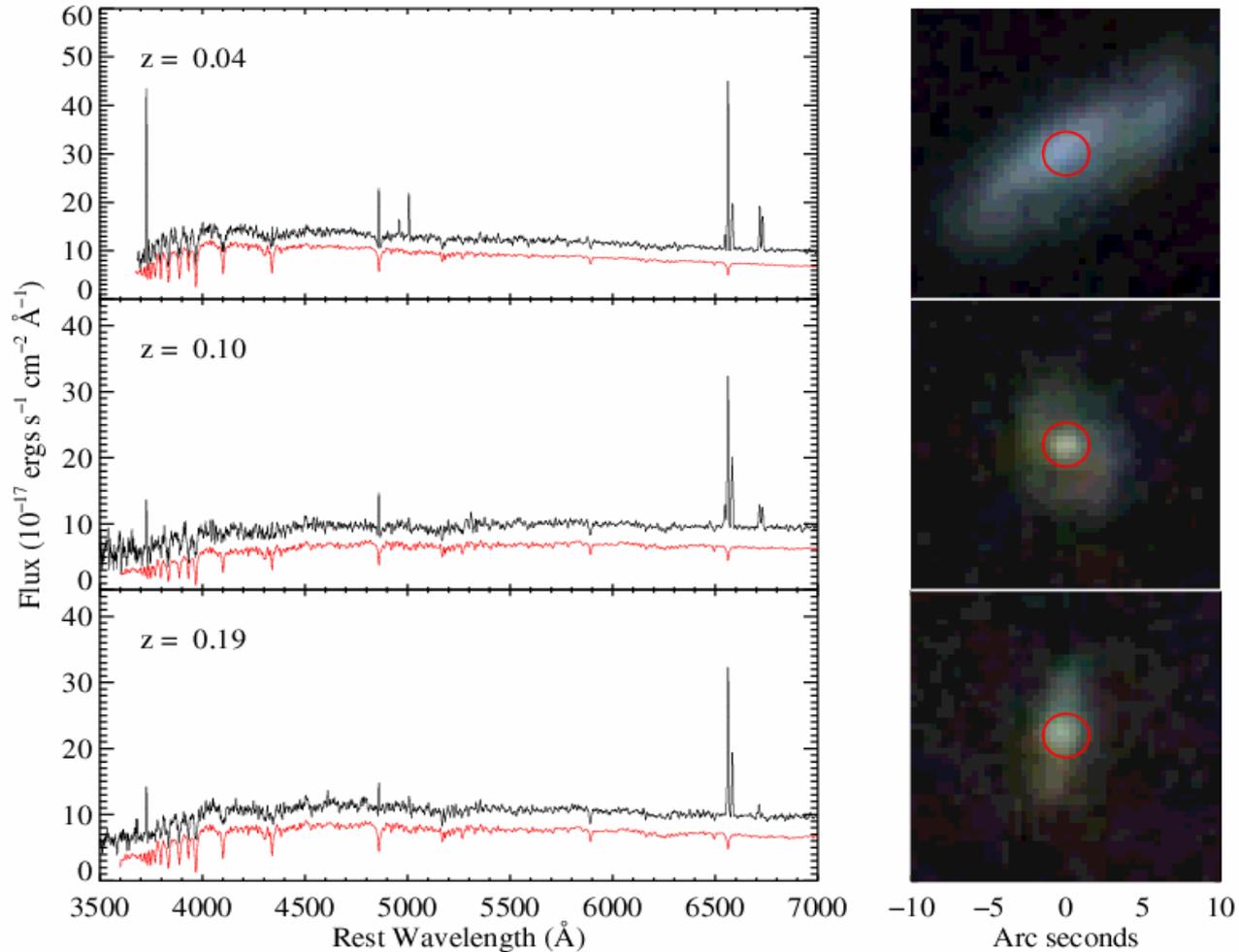
# Radio Jets: Energetics based on cavities inflated in the hot ICM



# Part I: The Link Between Star Formation & Black Hole Growth



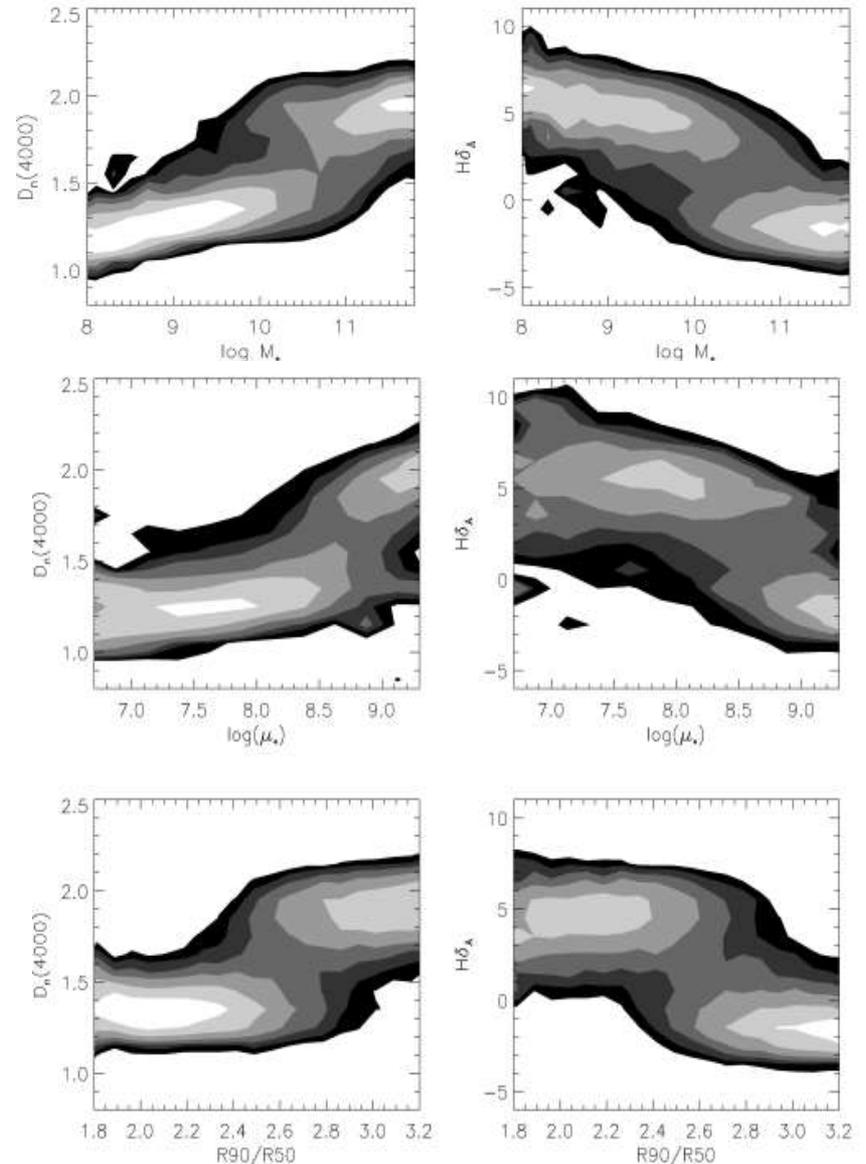
# SDSS SPECTRA: The Bulge



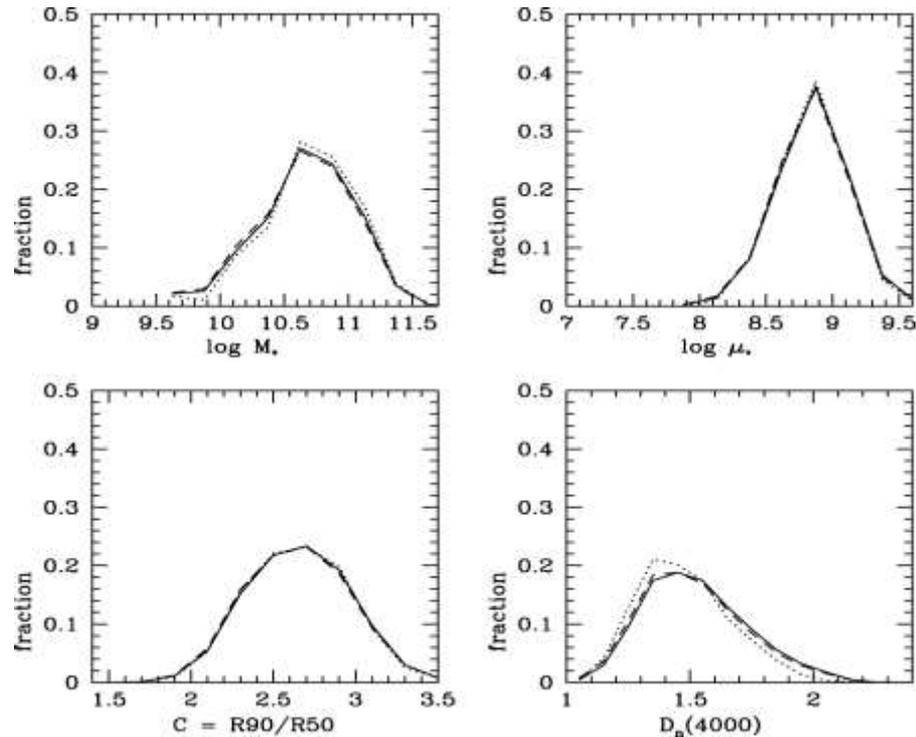
# THE BIMODAL SDSS GALAXY POPULATION

Characteristic scales for transition from old to young:

- $M_* \sim 3 \times 10^{10} M_\odot$
- Low mass galaxies are young, high mass galaxies are old
- $\mu_* \sim 3 \times 10^8 M_\odot/kpc^2$
- Low density galaxies are young, high density galaxies are old
- $C \sim 2.6$
- Low-concentration (late-type) galaxies are young  
High-concentration (early-type) galaxies are old
- **Black Holes: the domain of massive, dense, high-concentration galaxies (big bulges)**

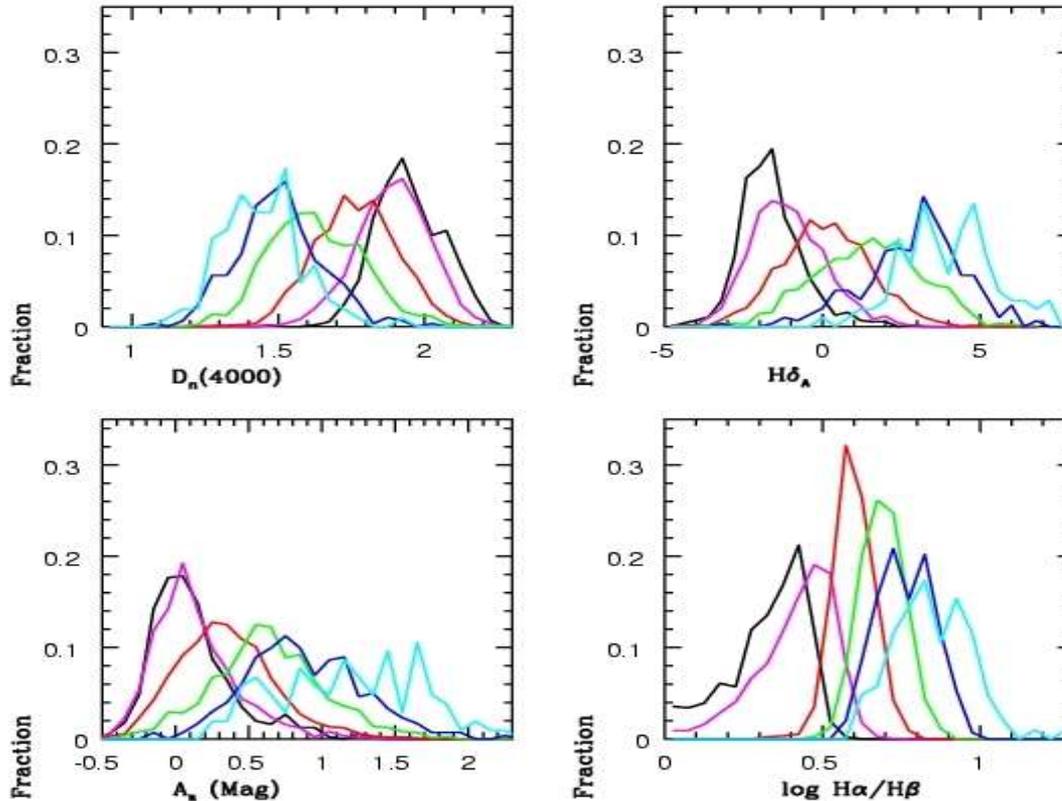


# Where do emission-line AGN live?



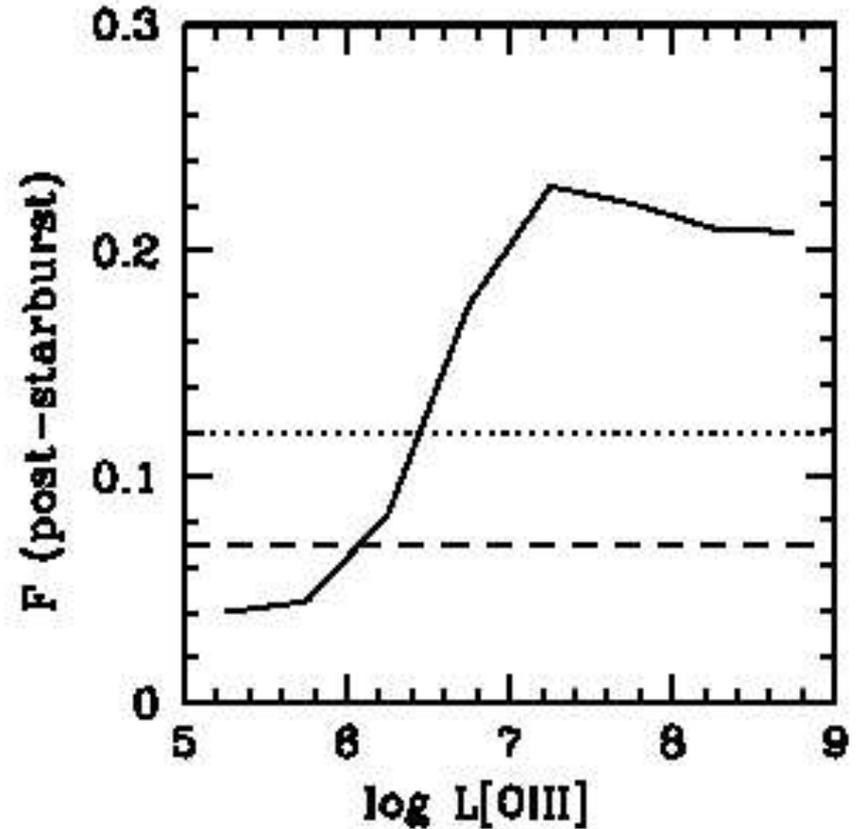
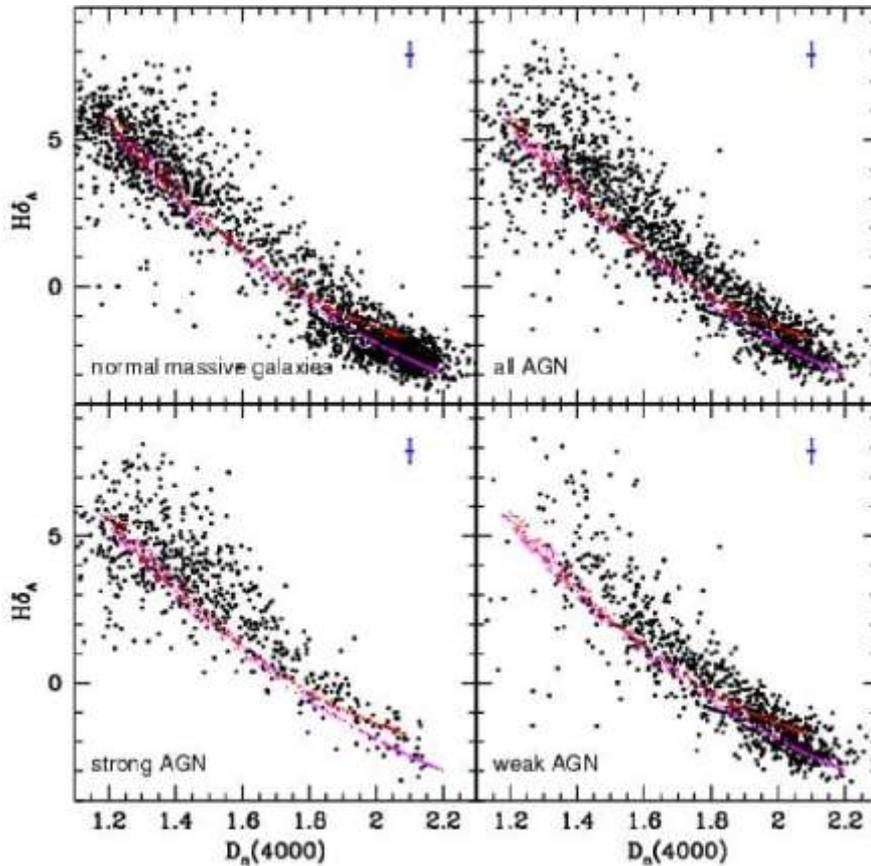
- The production of [OIII] emission by AGN is dominated by “hybrid” galaxies
- Near the boundaries between the bimodal population
- Structures/masses of early-type galaxies
- Bulges: young stellar population

# Luminosity Dependence



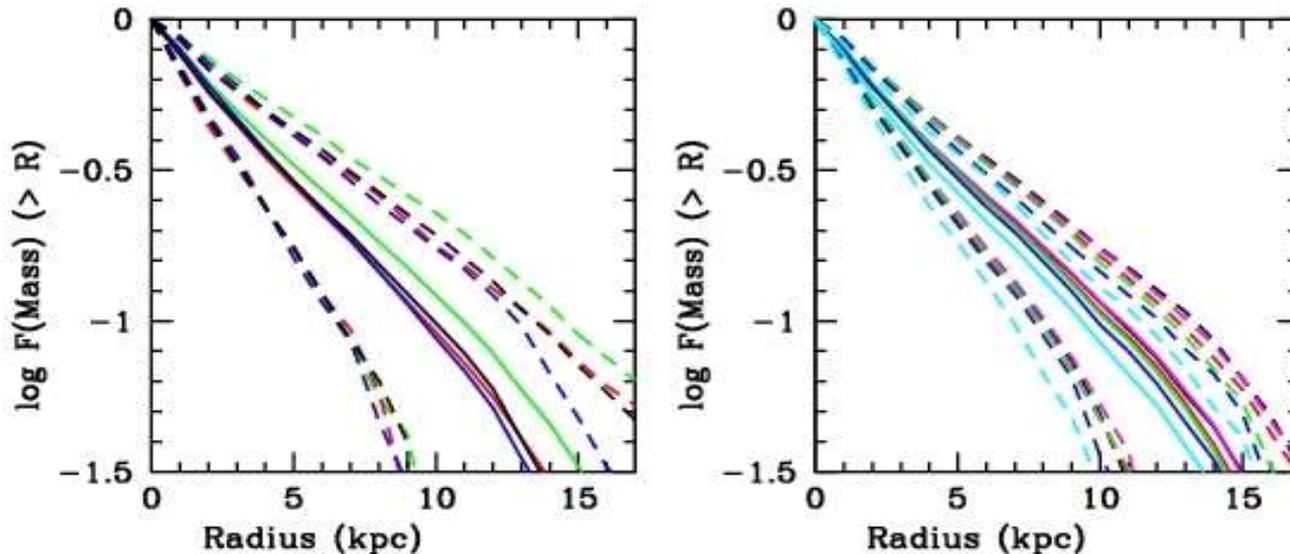
- As the AGN luminosity increases the stellar population in the bulge becomes younger
- And the amount of dust/cold-gas increases

# Luminosity Dependence



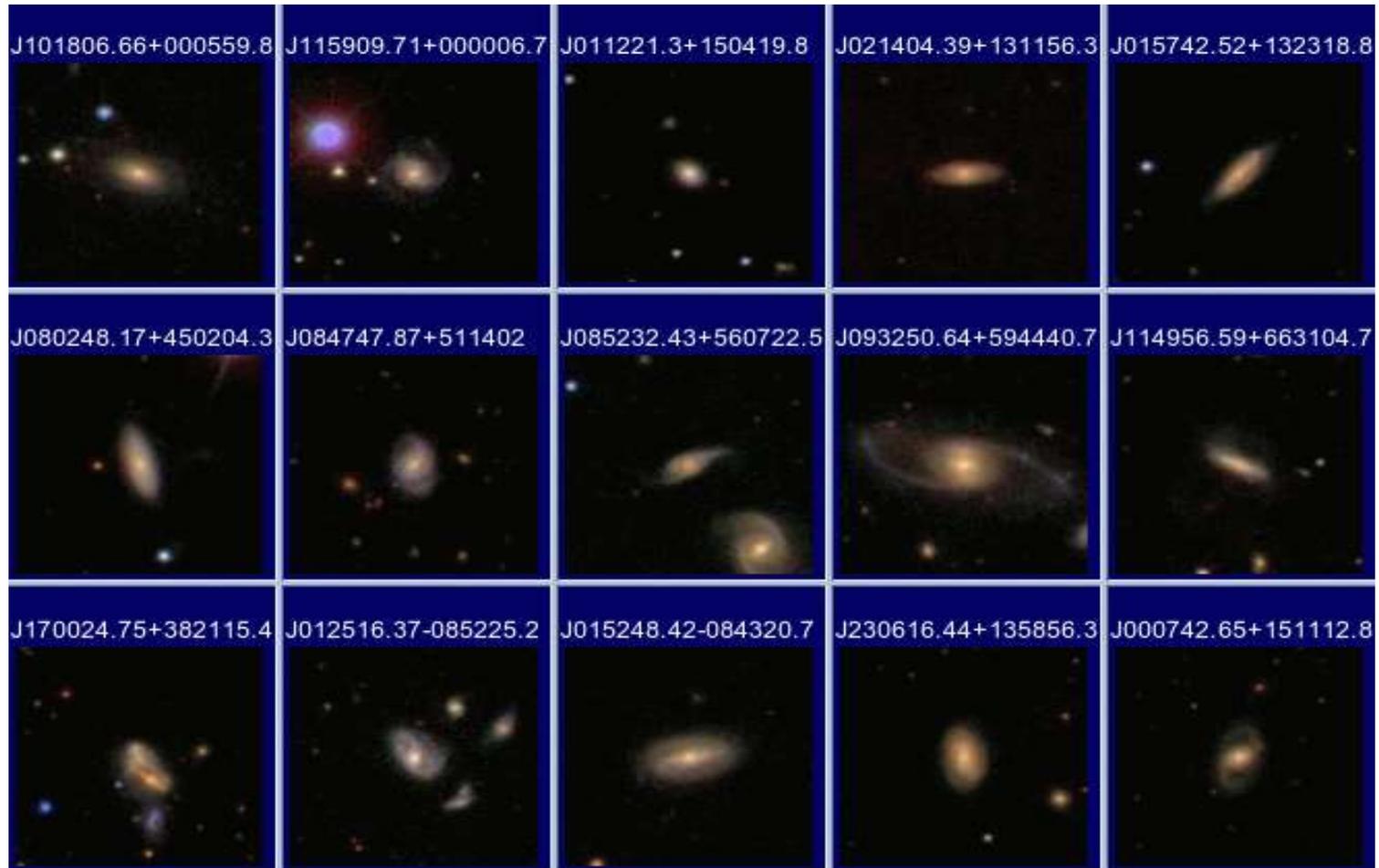
- At higher AGN luminosities, the fraction that are post-starbursts is higher

# Stellar Mass Profiles



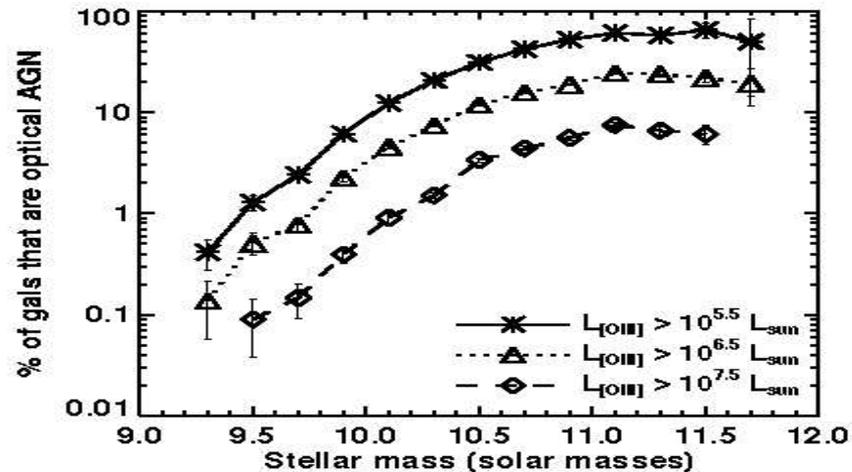
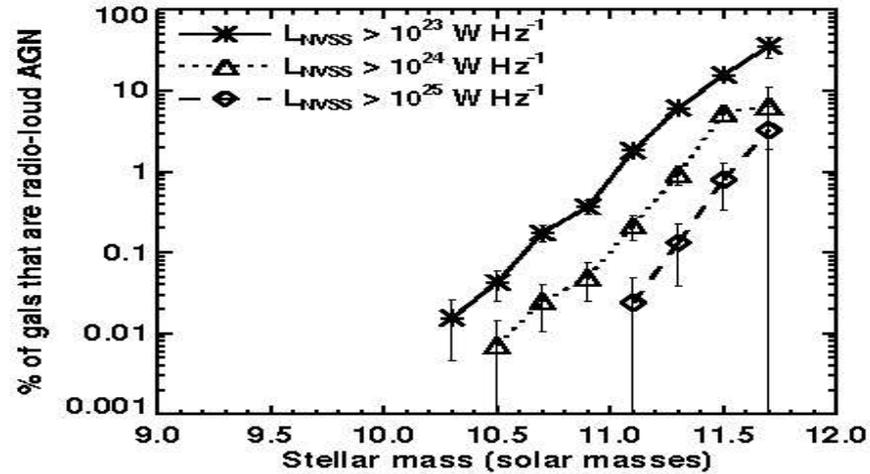
- Galaxies with rapidly growing black holes and bulges have very similar stellar mass profiles to red/dead galaxies with same velocity dispersion
- The trigger does not involve a major “event”

# Morphology

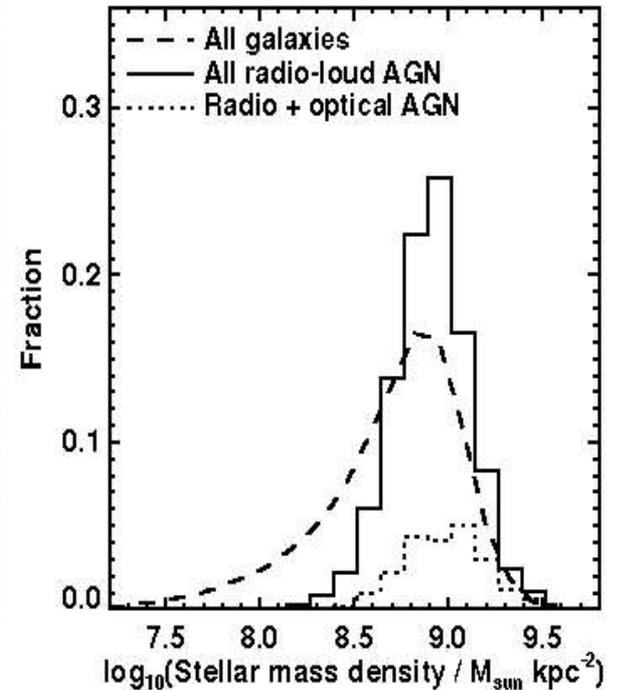
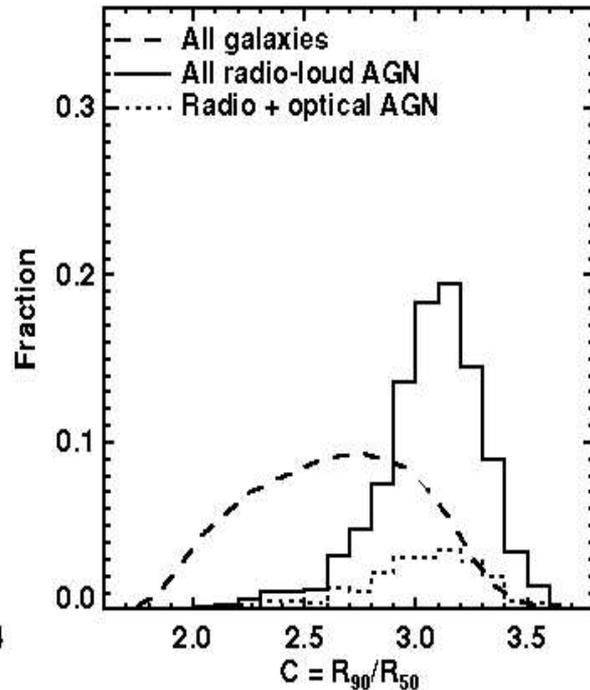
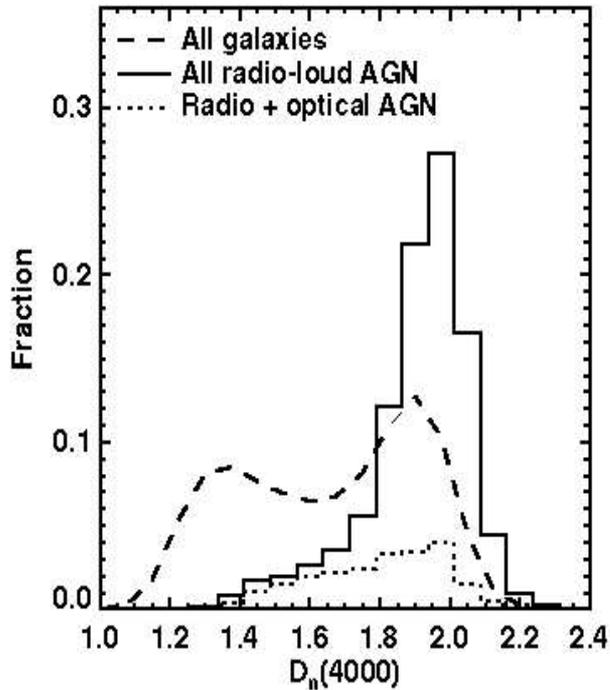


- Usually ~normal early-type disk galaxies

# How about radio galaxies?



- They are the most massive galaxies

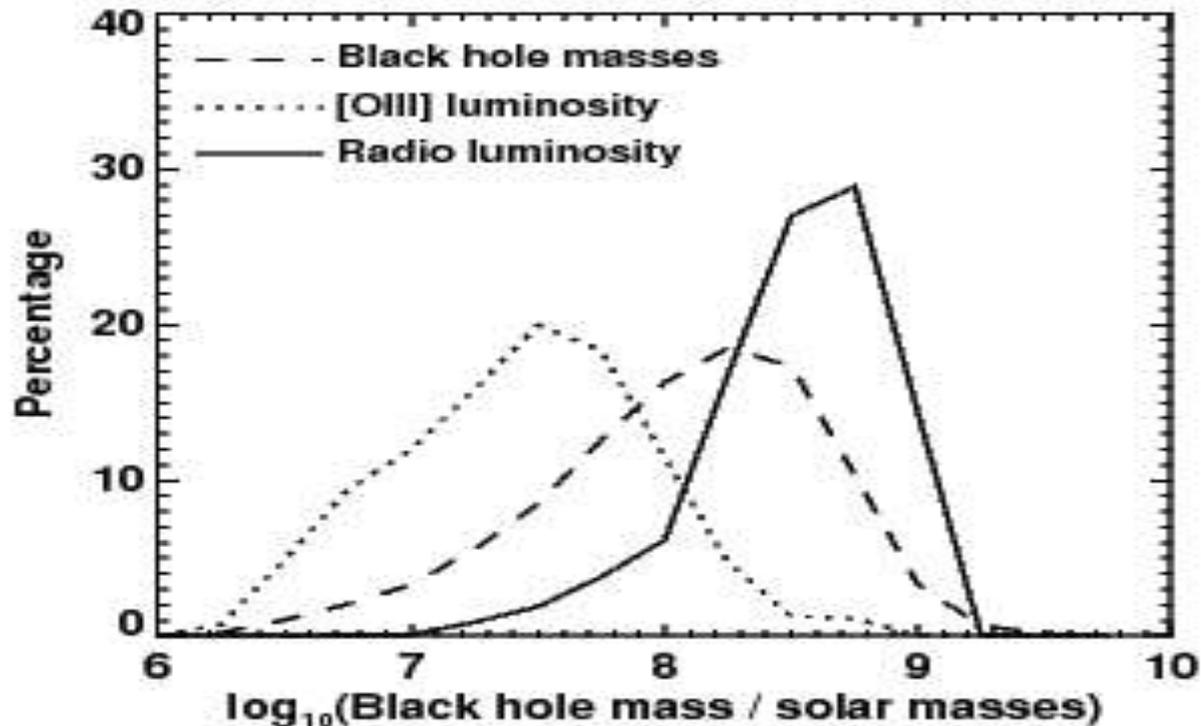


- Structural properties: giant elliptical galaxies
- Old stellar populations (normal)
- **Very different from emission-line AGN**

# BLACK HOLE DEMOGRAPHY

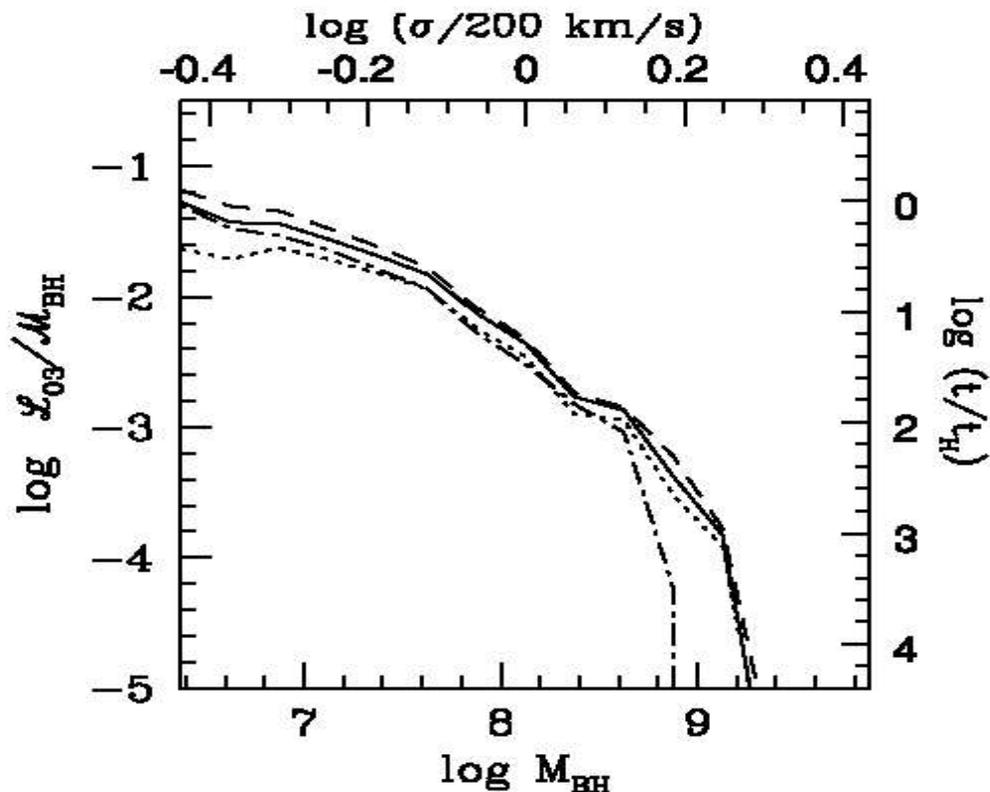
- Estimate black hole masses using the stellar velocity dispersion (AGN hosts are bulge-dominated)
- Estimate the accretion rate using the bolometric luminosity derived from [OIII]
- Accretion rate associated with radio galaxies can be neglected to first order
- Perform volume averages over SDSS

# WHICH BLACK HOLES ARE GROWING?



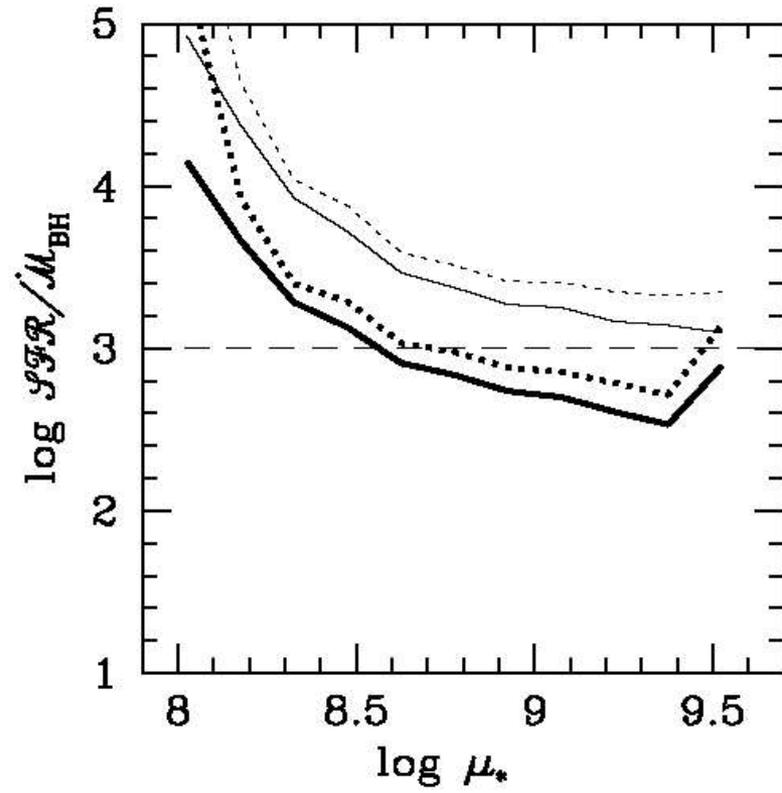
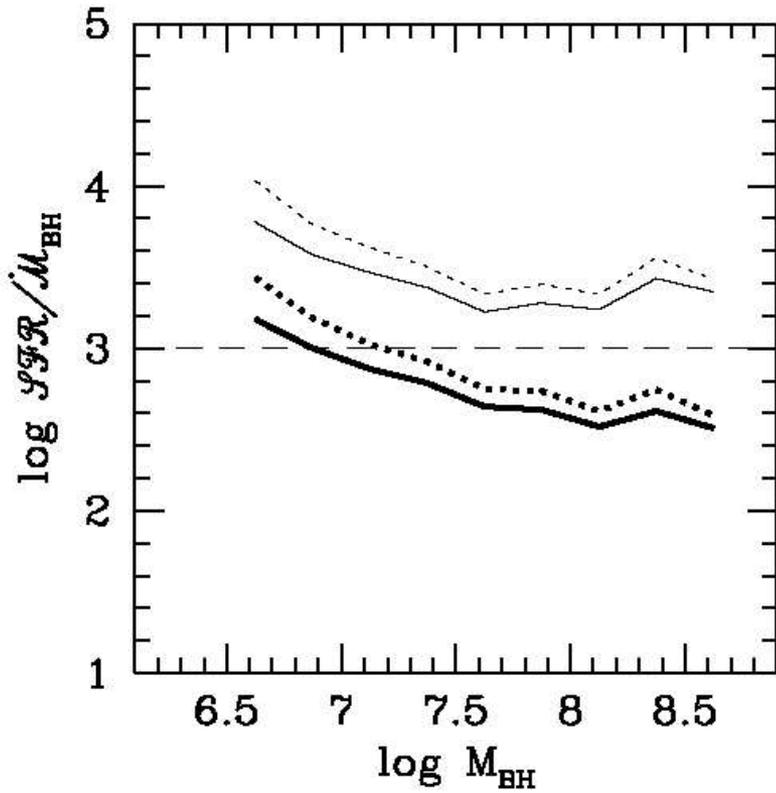
- Mass resides in the more massive black holes
- Growth dominated by less massive ones
- Radio sources are the most massive ones

# MASS-DOUBLING TIMES



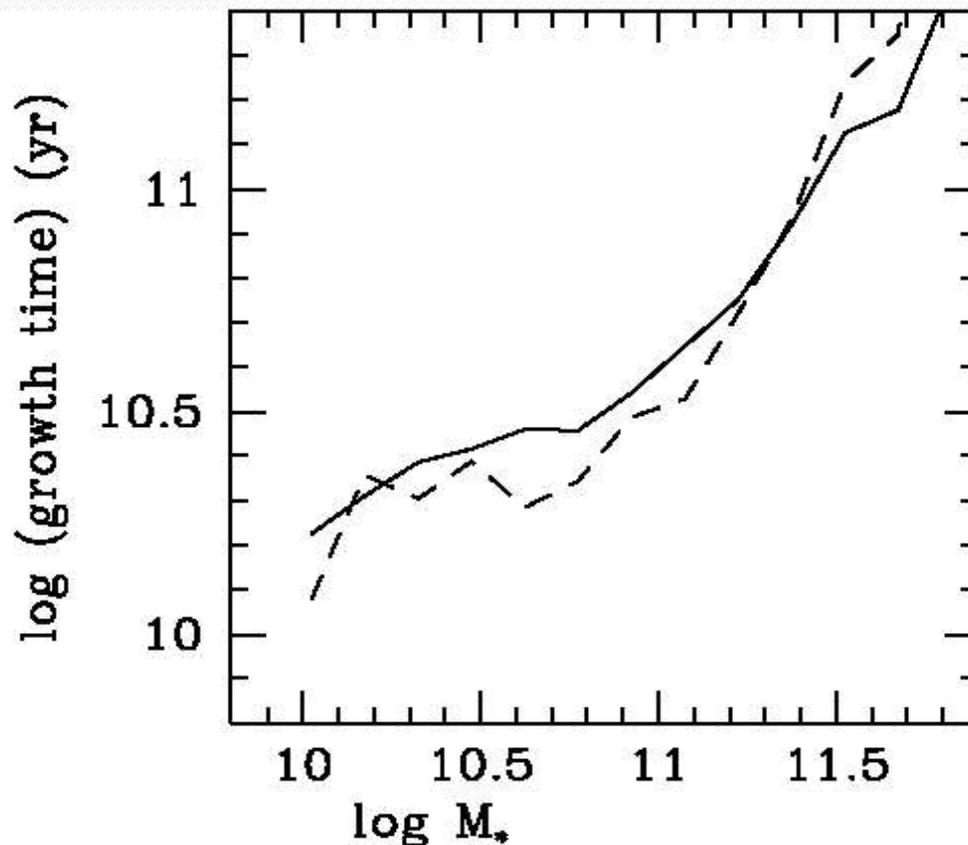
- Only  $\sim$  Hubble Time for lower mass black holes
- Orders-of-magnitude longer for the most massive black holes (“dead quasars”)

# BLACK HOLES & BULGES



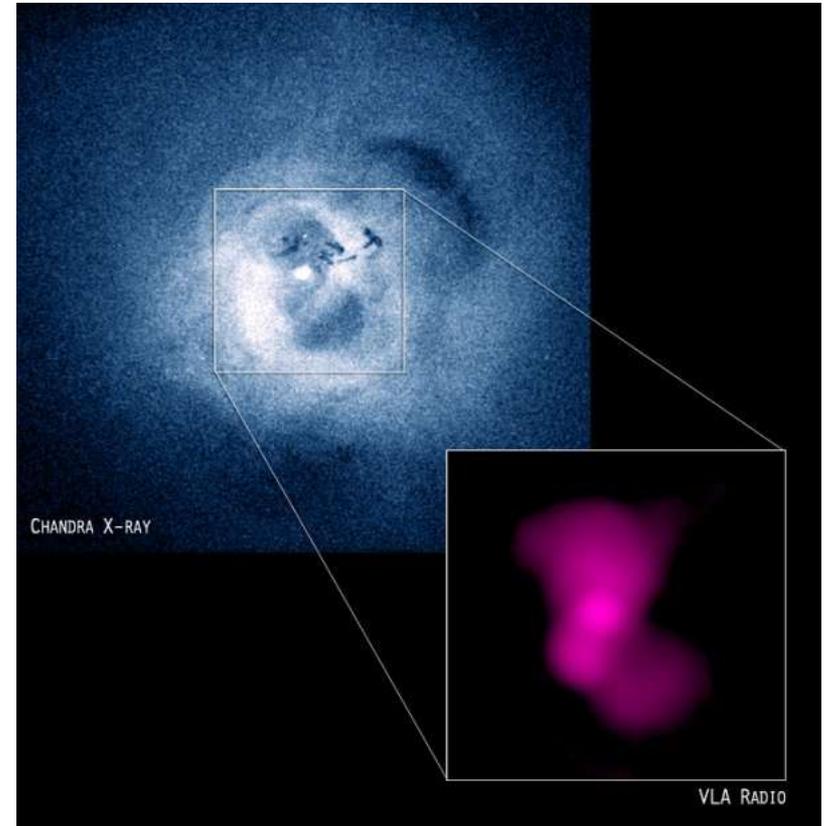
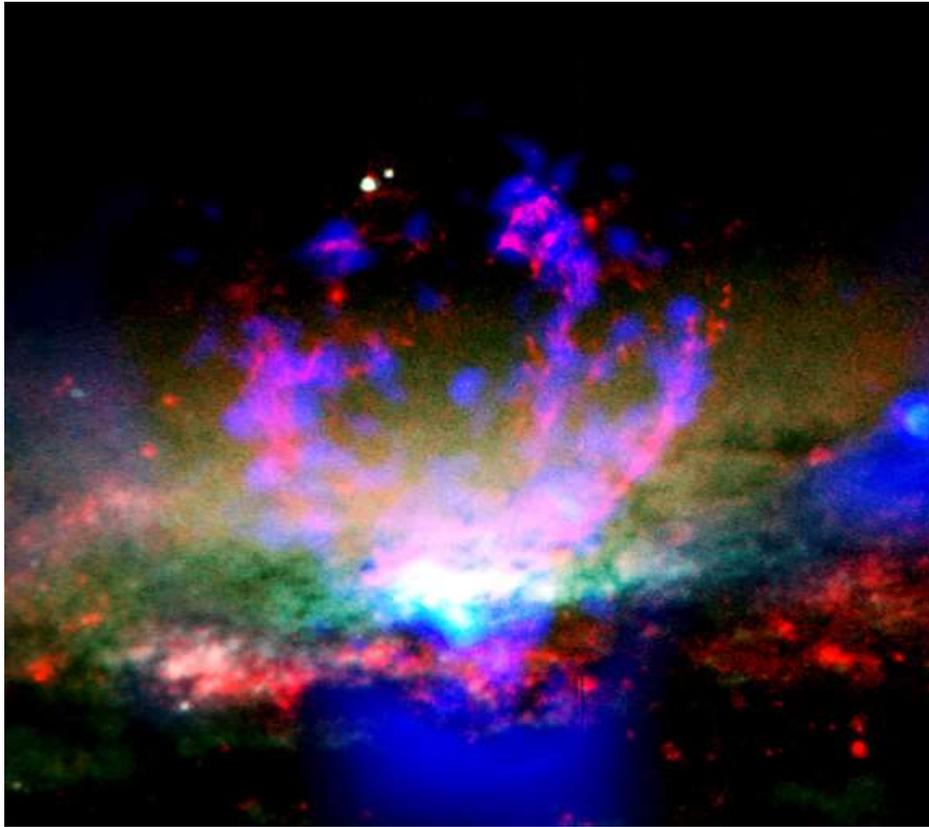
Ratio of SF/black-hole-growth: volume average over early-type galaxy population is  $\sim 1000$

# DOWNSIZING



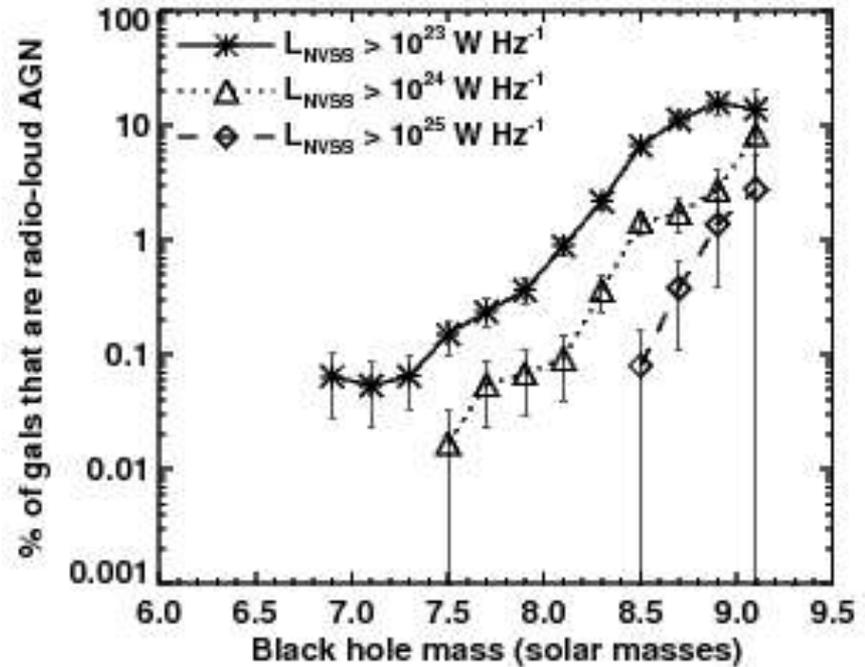
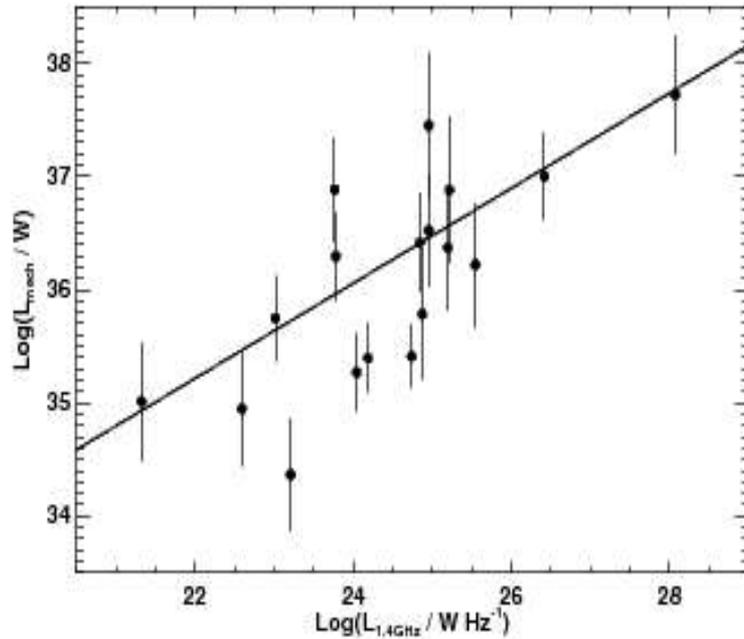
- The mass-doubling timescales of the populations of black holes and bulges both increase in parallel with increasing mass

# Part II: AGN Feedback



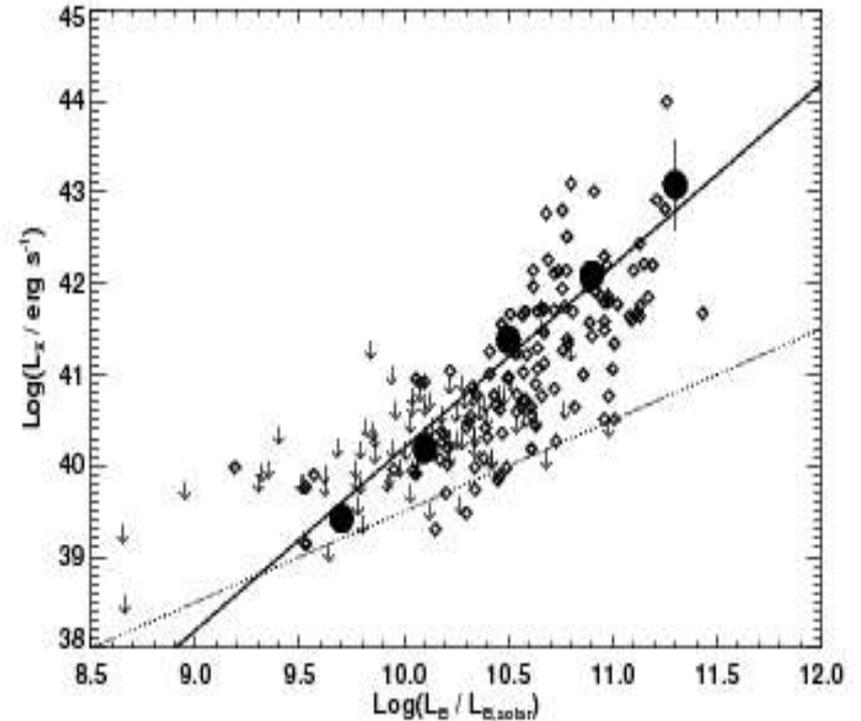
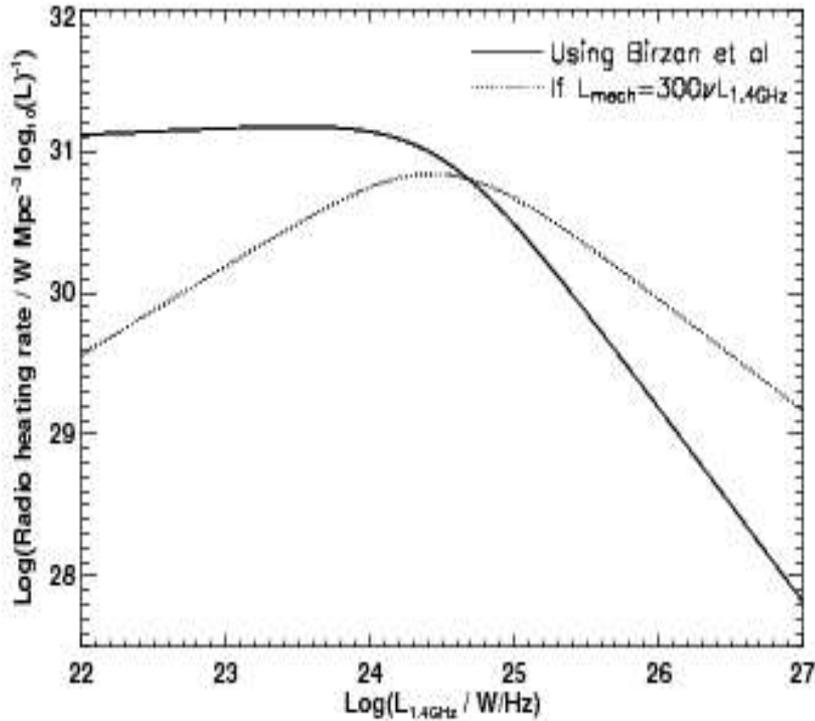
- This comes in three flavors:
- Radio sources, supernovae, and “quasar winds”

# Feedback from Radio Sources



- Can convert radio luminosity into jet KE
  - Integrate over radio luminosity function
- Best et al. (2005;2006)

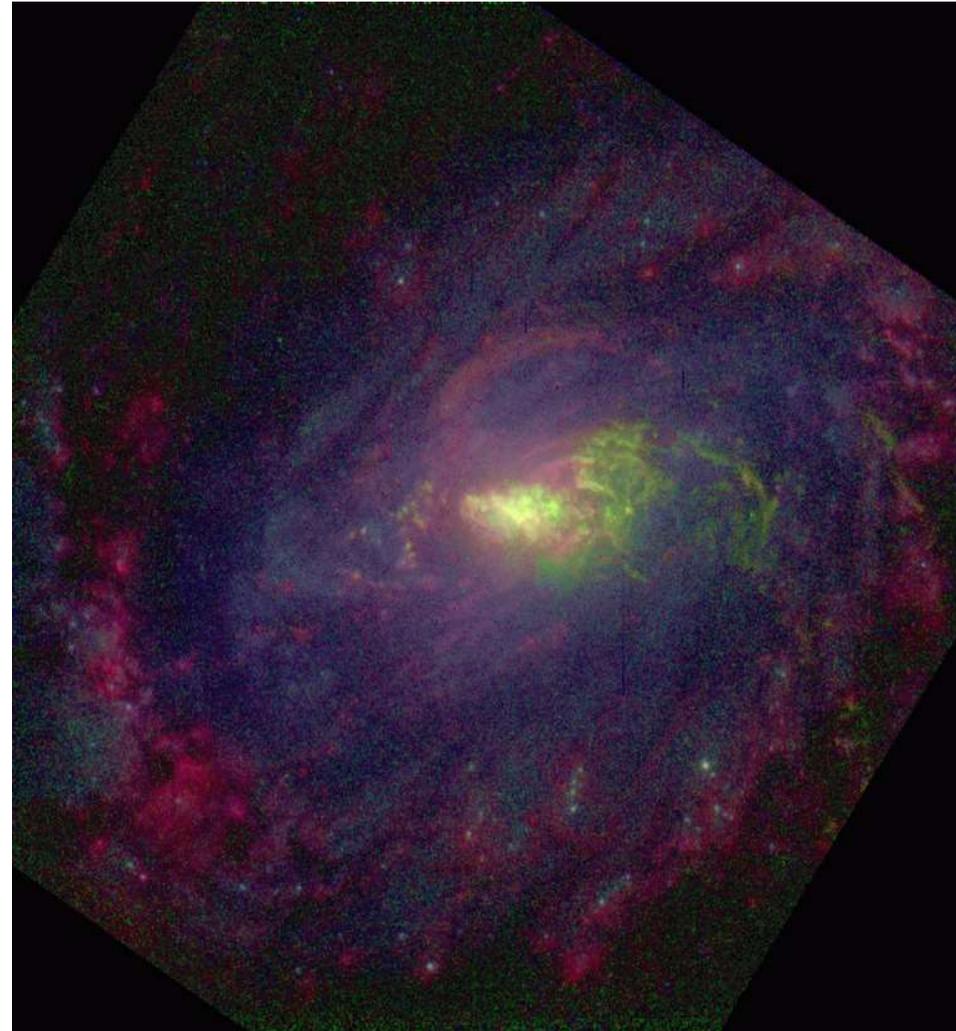
# Radio Feedback: Global Values



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

# Supernovae vs. Quasar Winds

- Strong link between black hole growth (strong AGN) and star formation in the bulge
- How do we sort out the contributions of supernovae vs. the AGN in driving a wind?

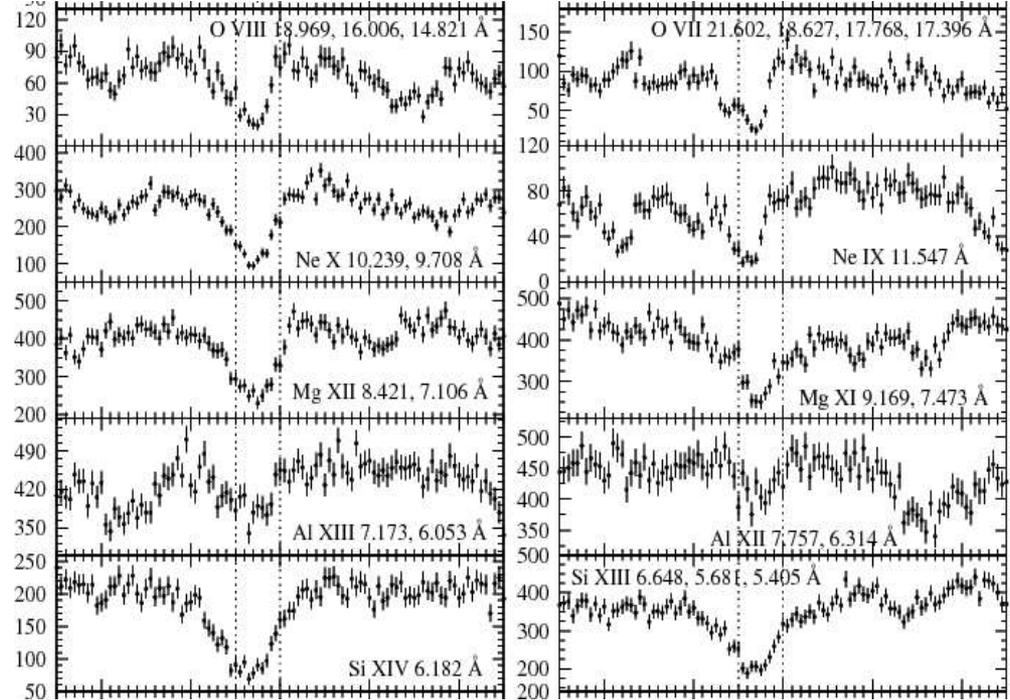
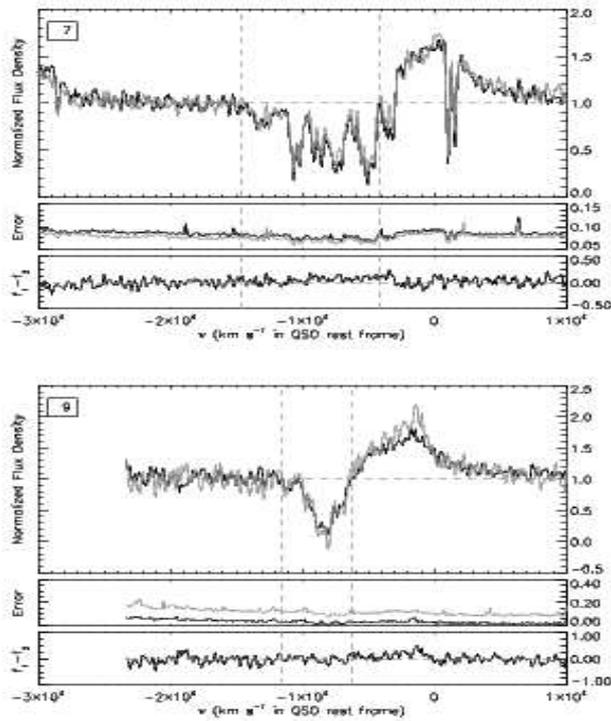


# Supernova-Driven Winds



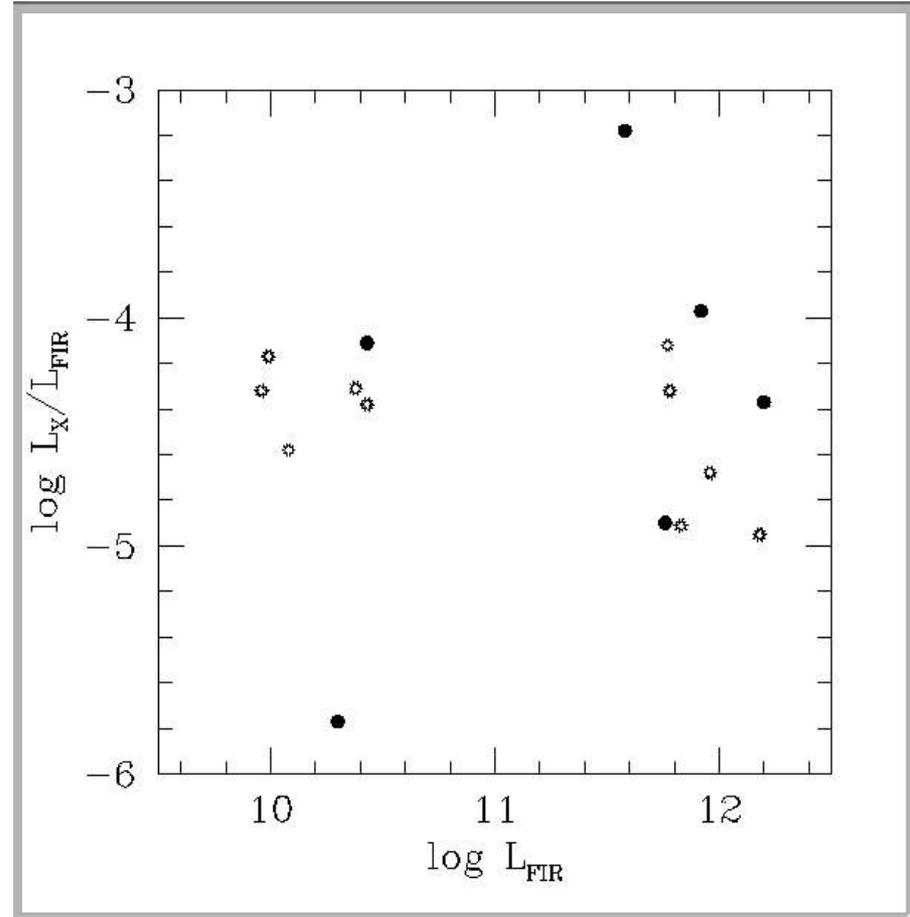
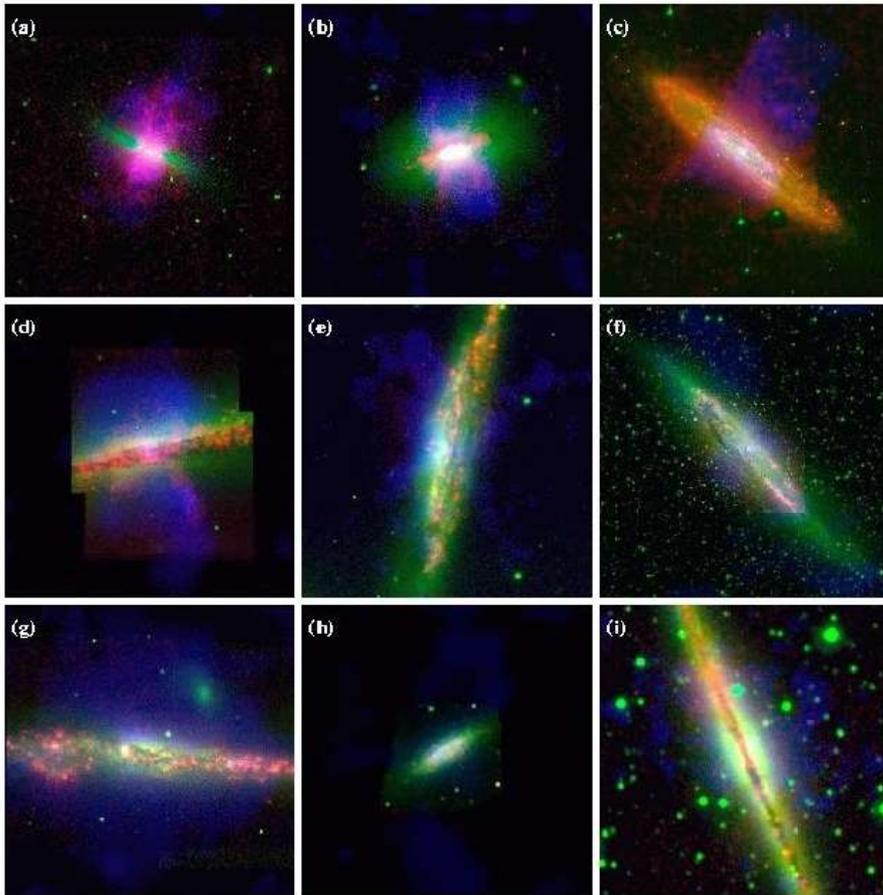
- Star formation accompanies black hole growth
- Star formation drives winds (with or without an AGN)
- $KE \sim 10^{60}$  ergs for  $10^8$  solar mass BH ( $\sim 1\% Mc^2$ )

# AGN Winds



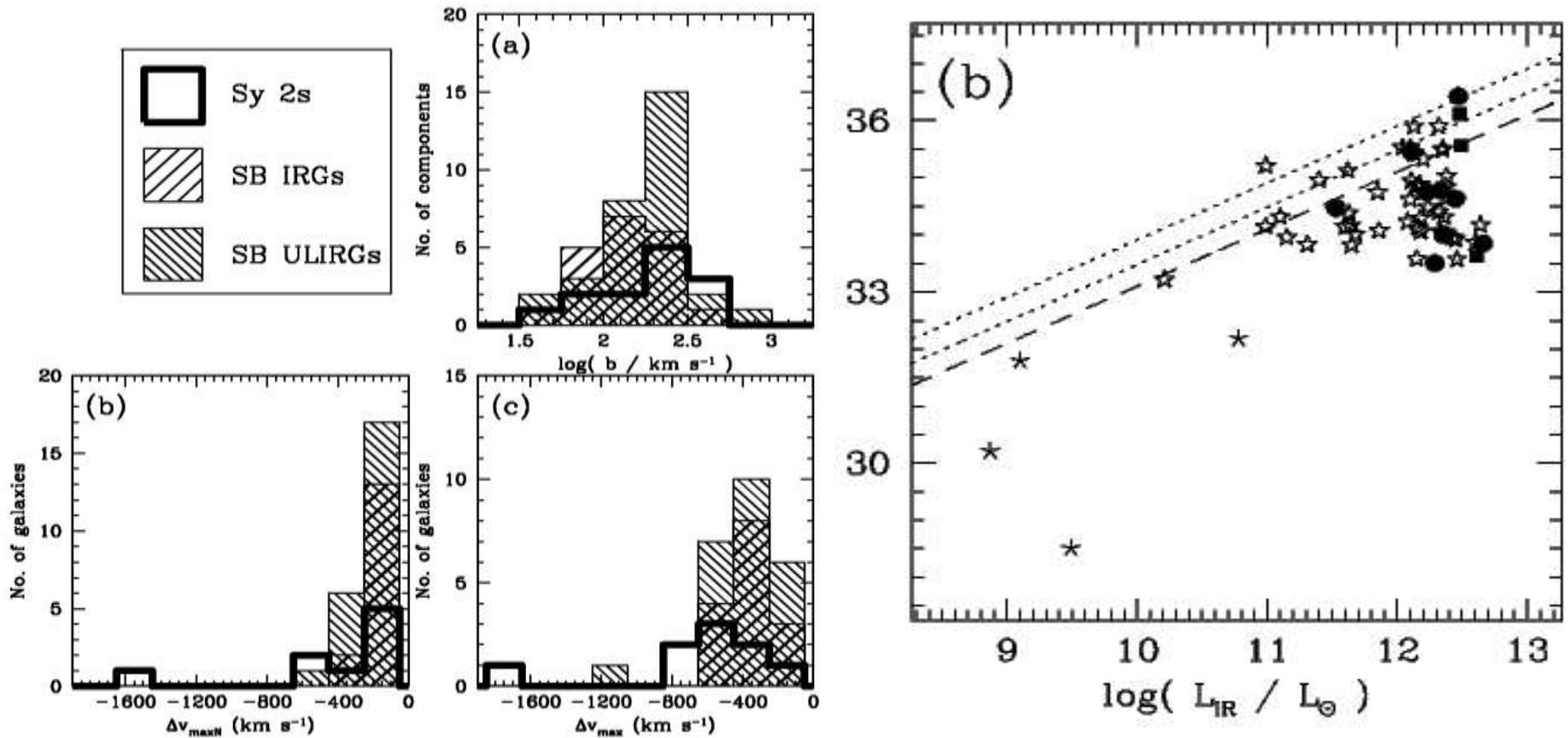
- High velocity outflows seen in Type 1 AGN
- BAL QSOs and lower velocity flows in Seyfert 1
- Energetics highly uncertain
- Small physical dimensions imply low KE

# Does the AGN Matter?



- No excess soft X-ray emission from the wind in AGN+starburst vs. pure starburst

# Does the AGN Matter?



- No evidence for higher outflow rates or velocities in Na D absorption-lines in AGN vs. starbursts

Rupke et al.

# THE LIVING...

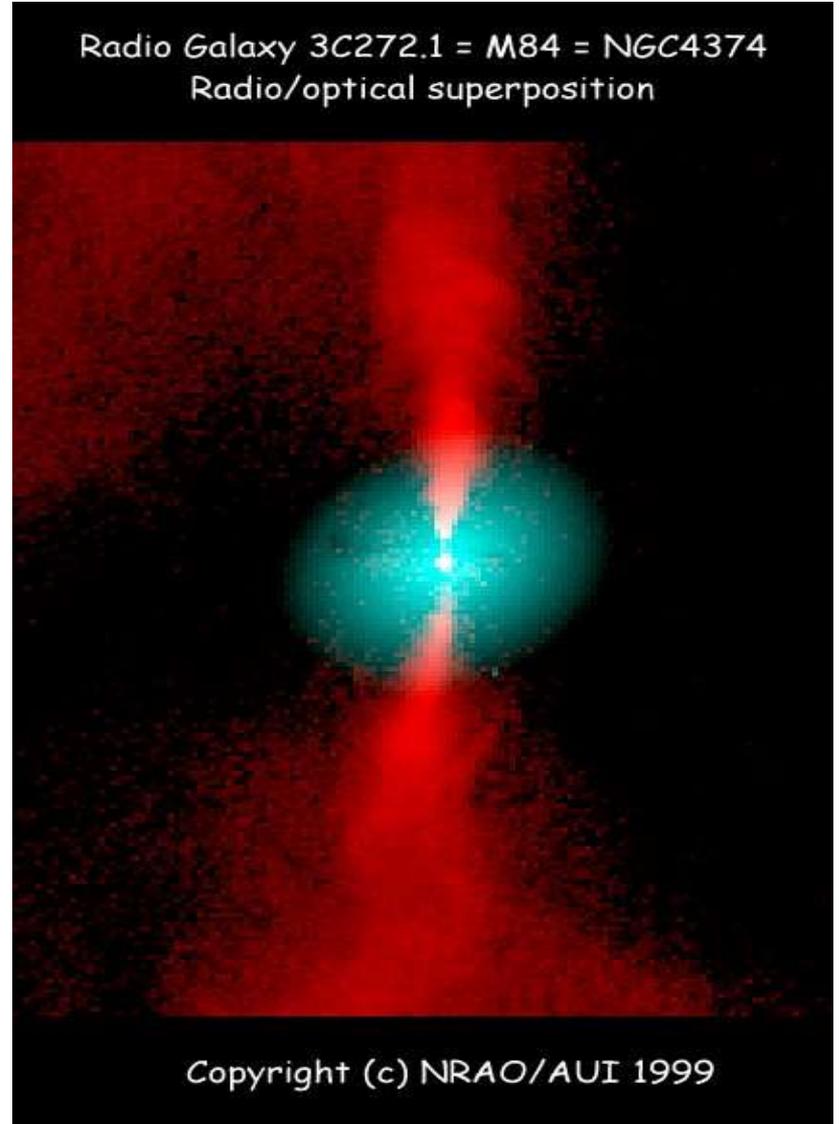
- Powerful AGN need a black hole & cold fuel
- Also fuels star formation
- This combination now exists only in less massive bulges (“downsizing”)
- Just above transition in galaxy population
- Fueling: Not major mergers
- Feedback: supernova-driven winds dominate
- Not clear that this drives an abrupt “transformation”



# ...AND THE DEAD

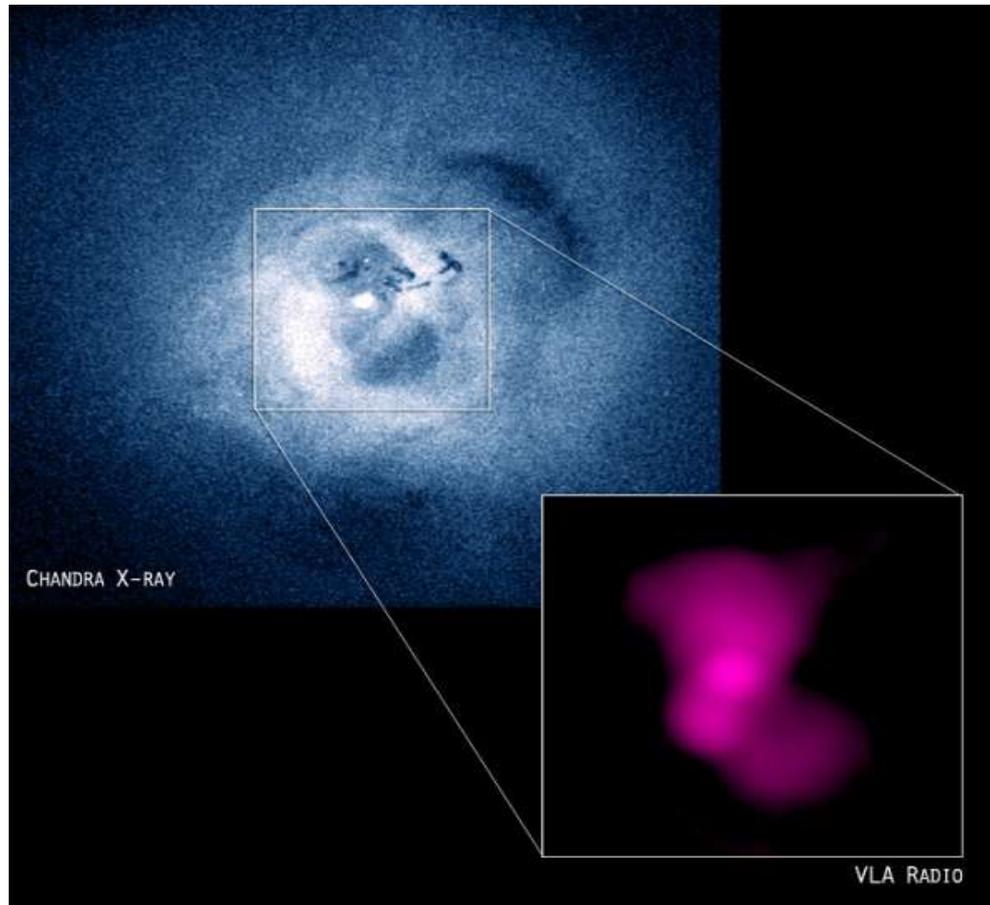
- The most massive black holes (and their host galaxies) formed at redshifts  $\sim 2$  to  $3$
- “Dead quasars” simmer as radio galaxies

Radio Galaxy 3C272.1 = M84 = NGC4374  
Radio/optical superposition



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# FUELING & QUENCHING



- Fuel source: the cooling of hot gas?
- Star formation suppressed by radio source heating?
- Maintains the red sequence