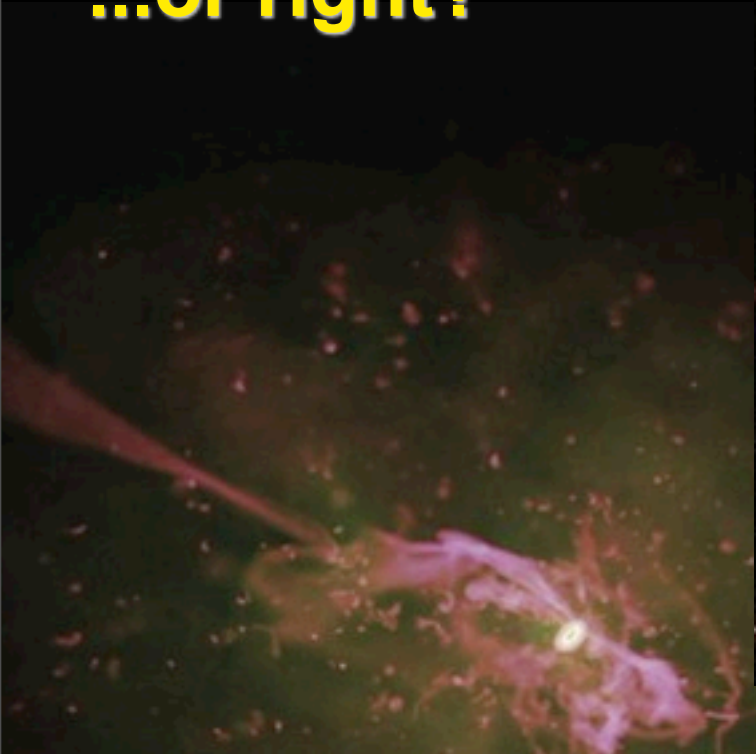


# The Merger-AGN Connection: What Models Say and How Observations Can Show them Wrong

...or right?



Philip Hopkins

10/30/08

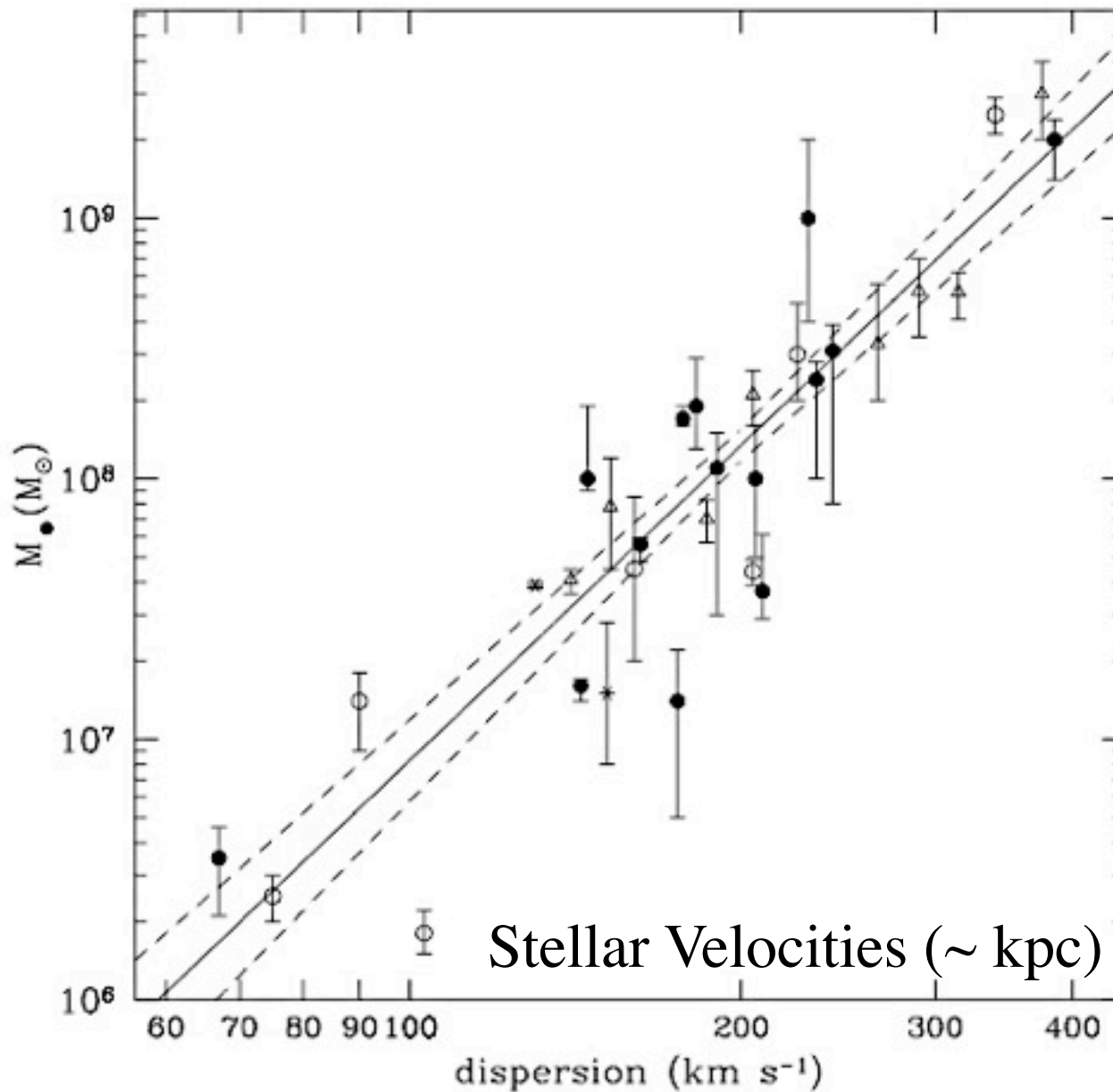
Lars Hernquist, T. J. Cox, Dusan Keres, Josh Younger, Desika Narayanan, Volker Springel, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Gordon Richards, Alison Coil, Kevin Bundy, Adam Myers, and many more

# Motivation

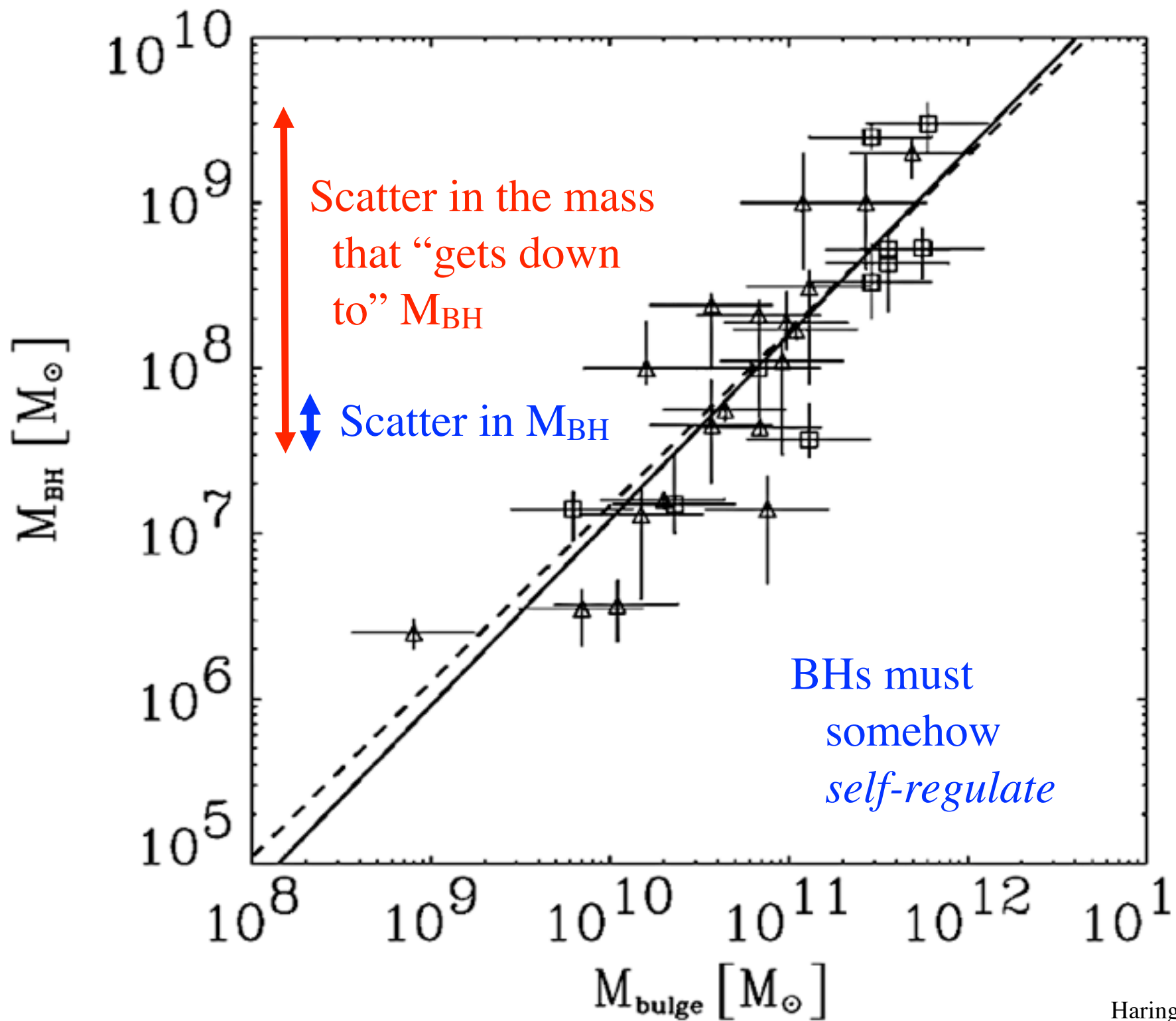
## WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Black holes are somehow sensitive to their host galaxies (bulges):

BH Mass  
(~ pc)



Ferrarese & Merritt '00,  
Gebhardt+ '00  
Tremaine et al. '02



Haring & Rix '04

# Simplest Idea:

## FEEDBACK ENERGY/MOMENTUM BALANCE (SILK & REES '98)

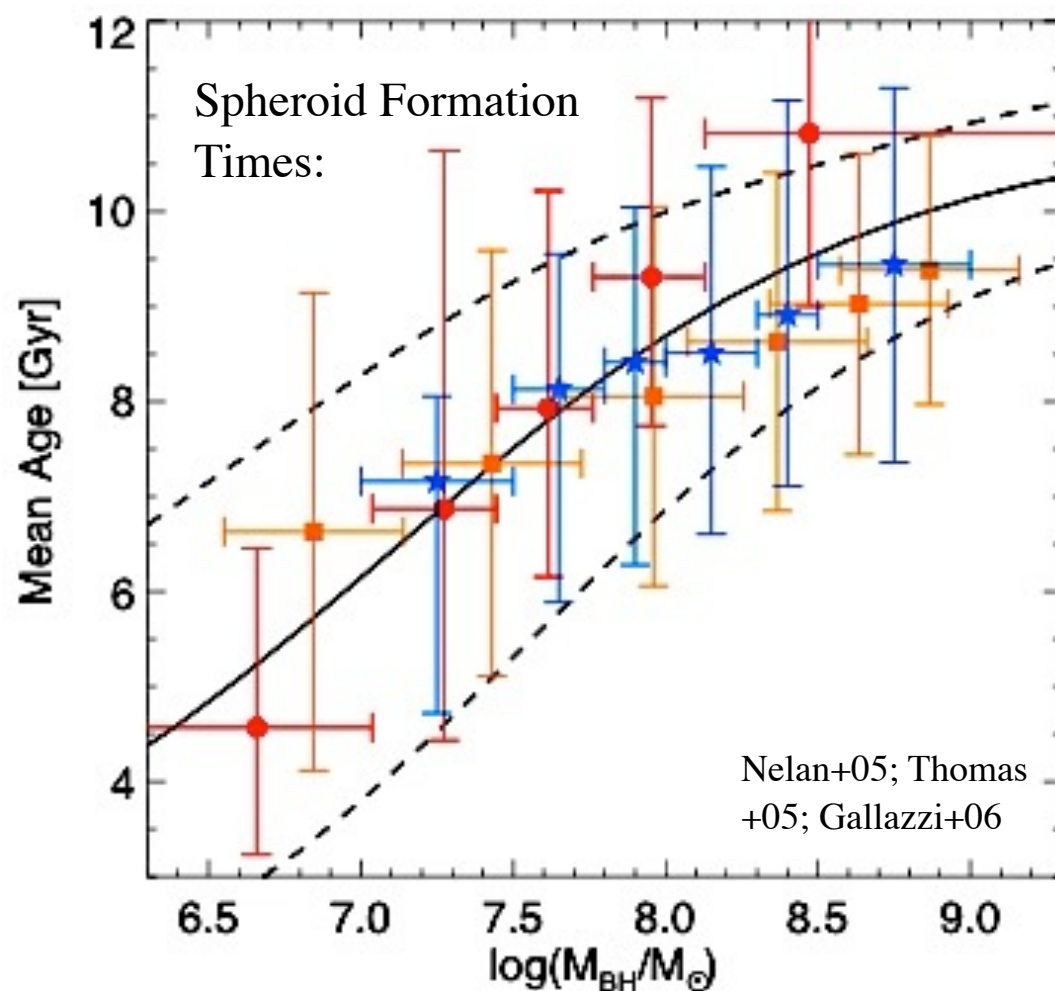
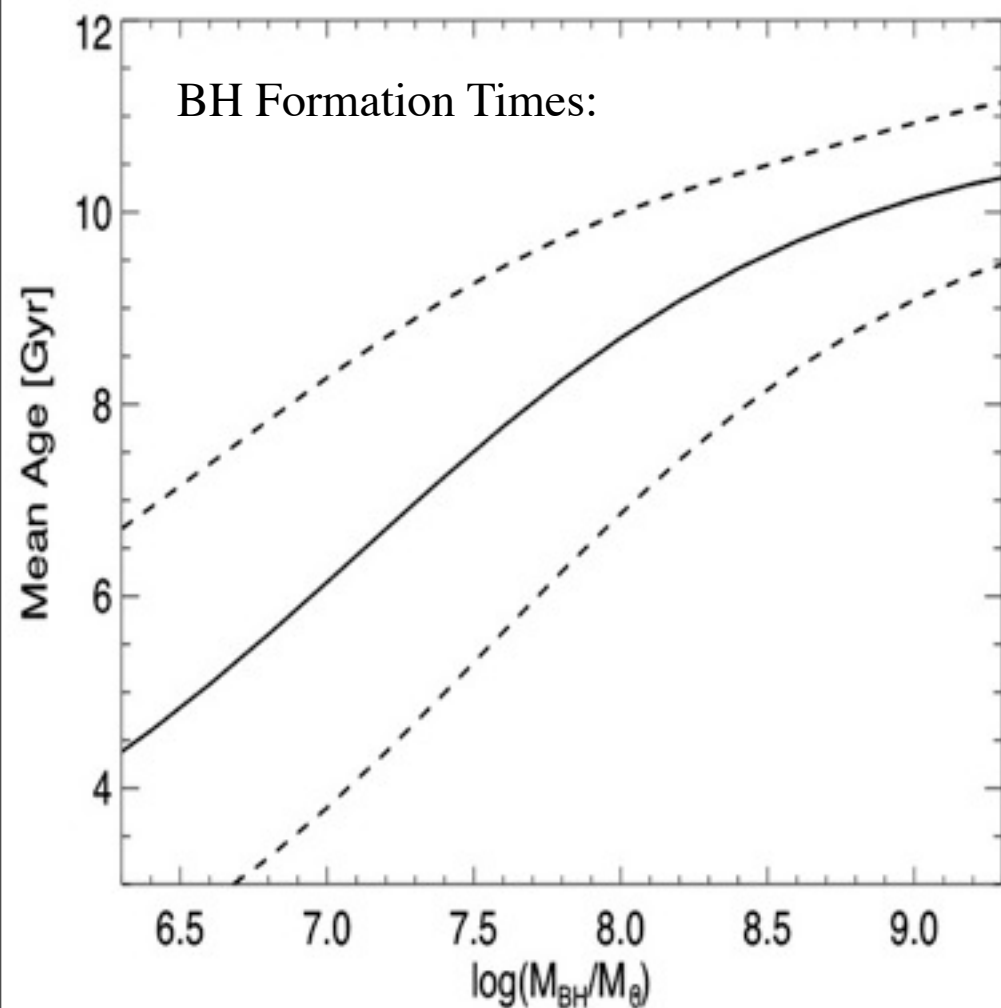
- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r (dM_{\text{BH}}/dt) c^2$  ( $e_r \sim 0.1$ )
- Total energy radiated:
  - $\sim 0.1 M_{\text{BH}} c^2 \sim 10^{61}$  ergs in a typical  $\sim 10^8 M_{\text{sun}}$  system
- Compare this to the gravitational binding energy of the galaxy:
  - $\sim M_{\text{gal}} s^2 \sim (10^{11} M_{\text{sun}}) (200 \text{ km/s})^2 \sim 10^{59}$  erg!
- If only a few percent of the luminous energy coupled, it would unbind the baryons in the galaxy!
  - Turn this around: *if* some fraction  $h \sim 1\text{-}5\%$  of the luminosity can couple, then accretion *must* stop (the gas will all be blown out the galaxy) when
    - $M_{\text{BH}} \sim (a/h e_r) M_{\text{gal}} (s/c)^2 \sim 0.002 M_{\text{gal}}$



# Motivation

## WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

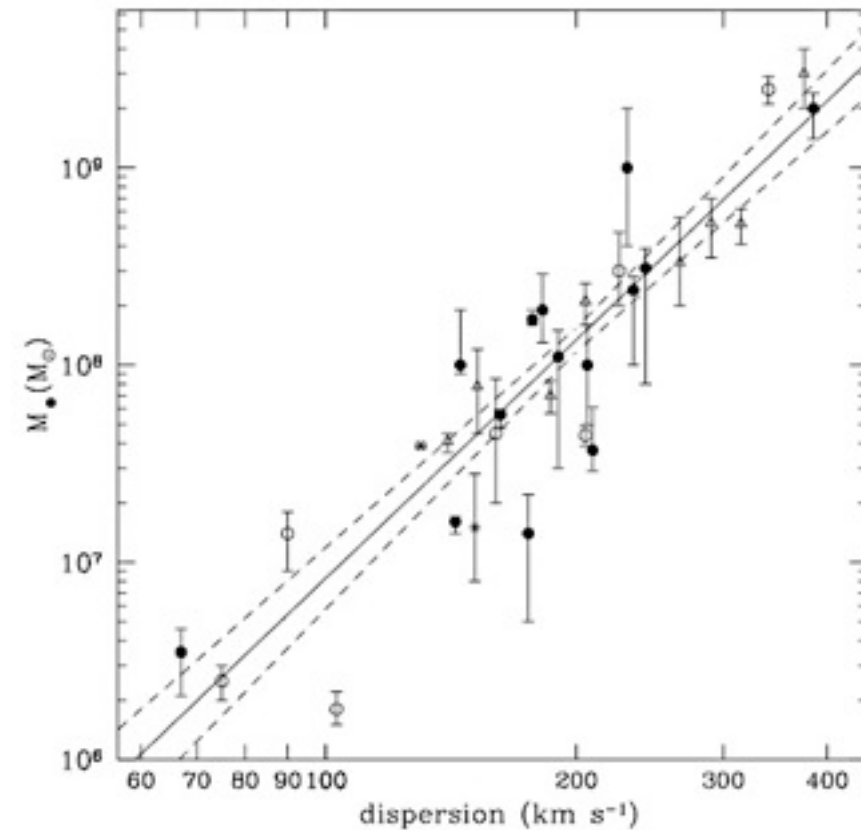
- Quasars were active/BHs formed when SF shut down...



# Triggering & Fueling: “Feeding the Monster”

## WHAT CAN BREAK DEGENERACIES IN DIFFERENT FUELING MODELS?

- If BHs trace spheroids, then
  - \*most\* mass added in mergers
- Other candidates must also be:
- Fast, violent
- Blend of gas & stellar dynamics
- Why?
  - \* Soltan (1982): bulk of SMBH mass density grown through radiatively efficient accretion in quasars
    - gas dynamics; rapid ( $\sim$  few  $10^7$  years)
  - \* Lynden-Bell (1967): orbits of stars redistributed in phase space by large, rapid potential fluctuations
    - stellar dynamics; freefall timescale

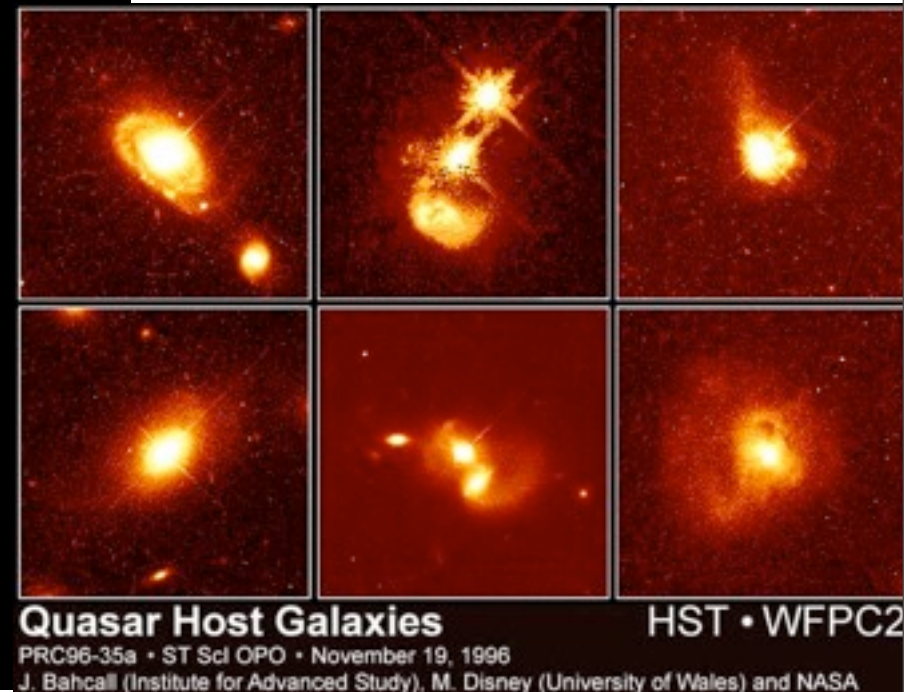
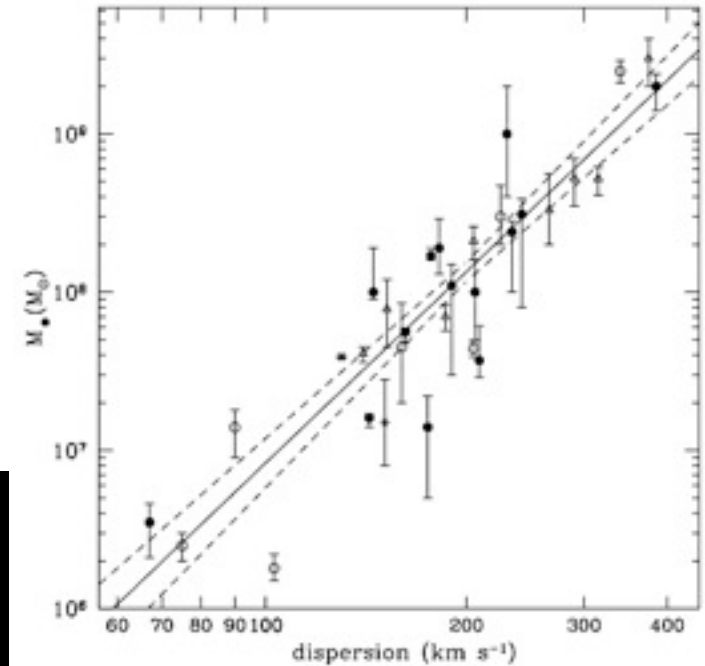


# Triggering & Fueling: “Feeding the Monster”

WHAT CAN BREAK DEGENERACIES IN DIFFERENT FUELING MODELS?

- If BHs trace spheroids, then  
\*most\* mass added in mergers

NGC 6240 Komossa et al. (2003)

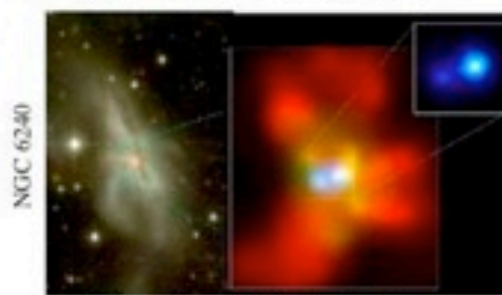


### (c) Interaction/"Merger"



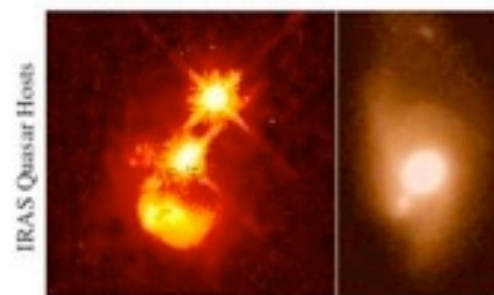
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

### (d) Coalescence/(U)LIRG



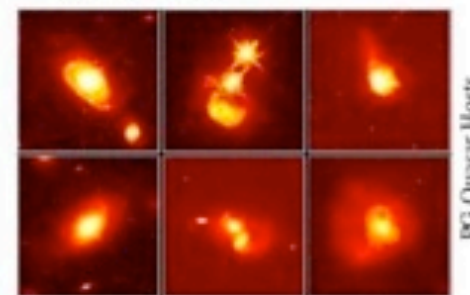
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

### (e) "Blowout"



- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host
- high Eddington ratios
- merger signatures still visible

### (f) Quasar



- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

### (b) "Small Group"

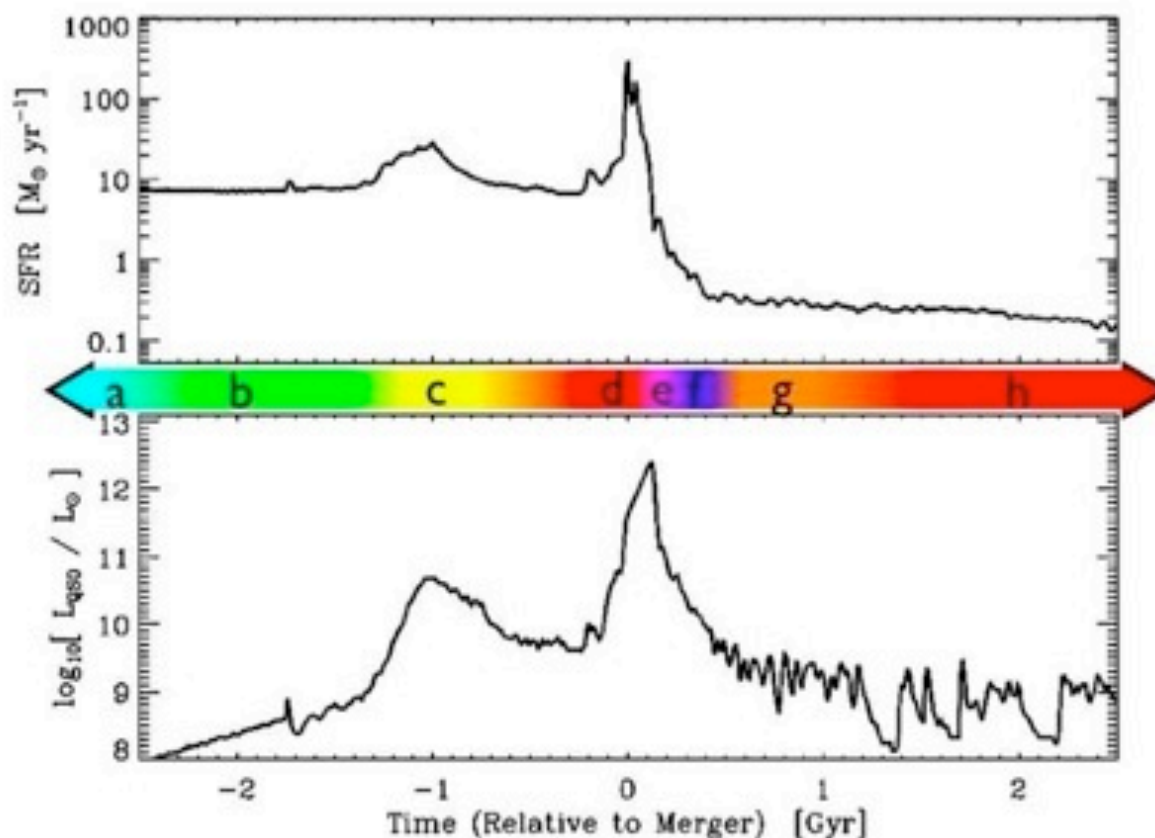


- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{\text{halo}}$  still similar to before: dynamical friction merges the subhalos efficiently

### (a) Isolated Disk



- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with  $M_{\text{BH}} > 10^6 M_{\odot}$ )
- cannot redden to the red sequence



### (g) Decay/K+A



- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
- sets up quasi-static cooling

### (h) "Dead" Elliptical



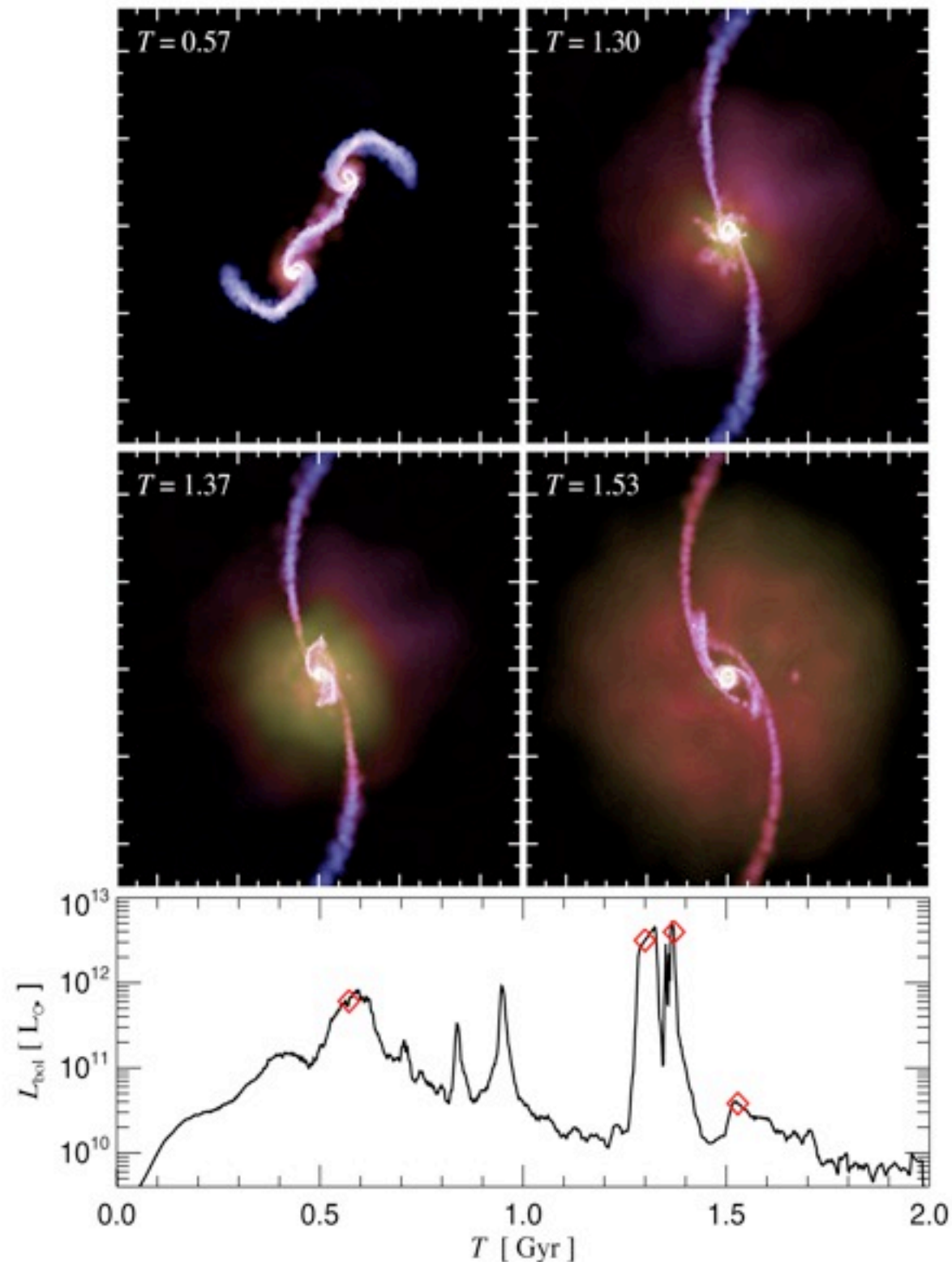
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers



# Let's Try It!

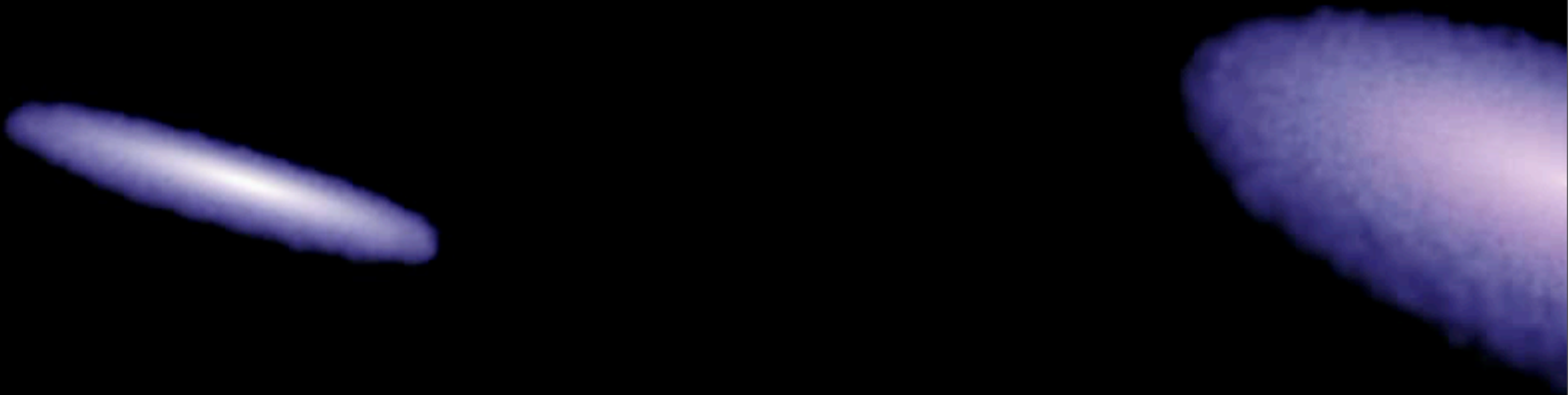
## THE AGN...

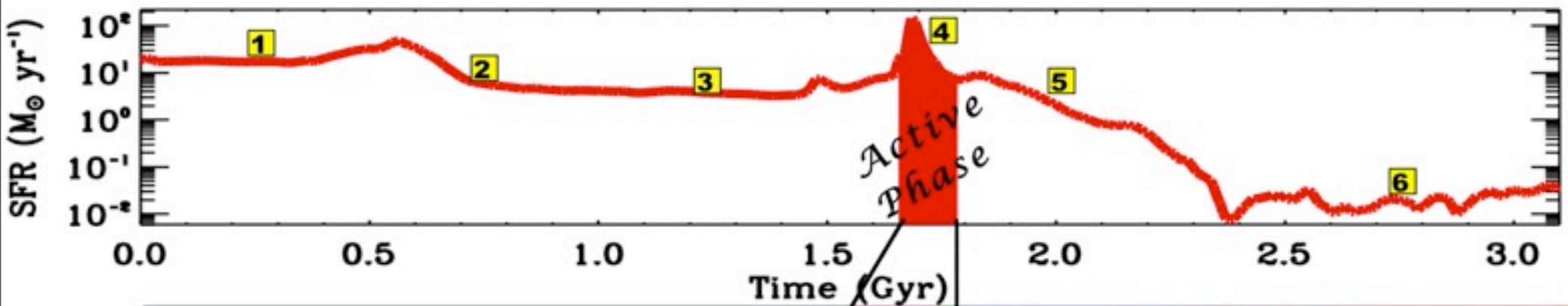
- Merge two galaxies
- $R_{\text{sch}} \sim \text{few AU} \sim 10^{-6} \times \text{our resolution}$
- $R_{\text{Bondi}} \sim 10 \text{ pc (typical)}$ 
  - Bondi-Hoyle accretion rate (max Eddington)
  - $\sim 0.1$  radiative efficiency (high-mdot)
  - $\sim 5\%$  couples to local gas (thermally)



T = 0 Myr

Gas





### Multiple Nuclei

- the majority of stars are formed

**Starburst-driven (transitioning to QSO) winds**

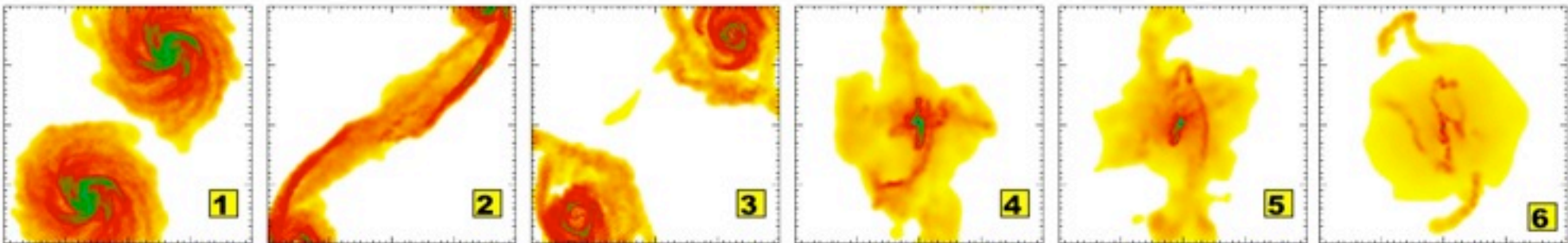
(U)LIRG

QSO

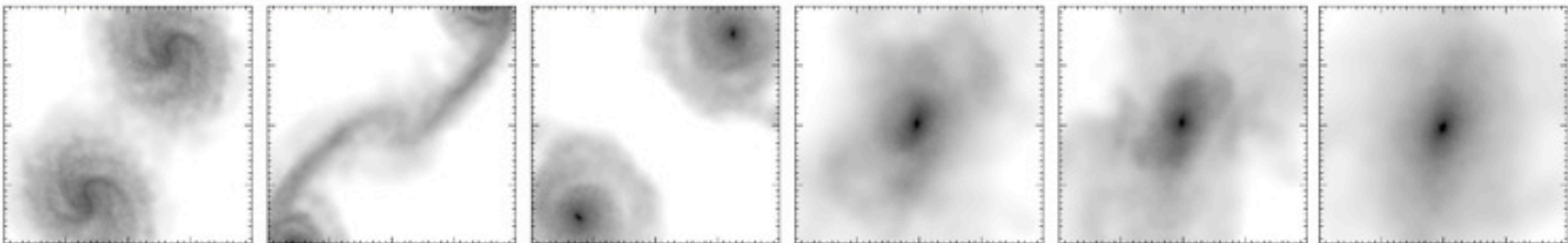
### Merger Remnant → Elliptical

- kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
- colors redden
- formation of a hot gaseous halo
- declining AGN activity
- satisfies  $M_{\text{BH}} - \sigma$  & FP

**Gas**

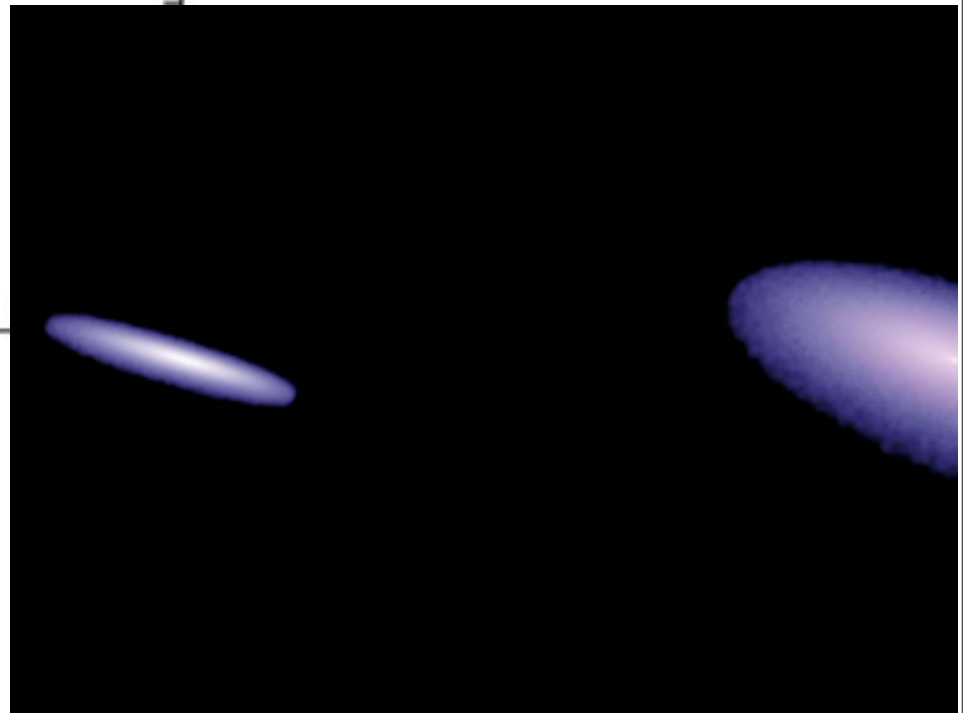
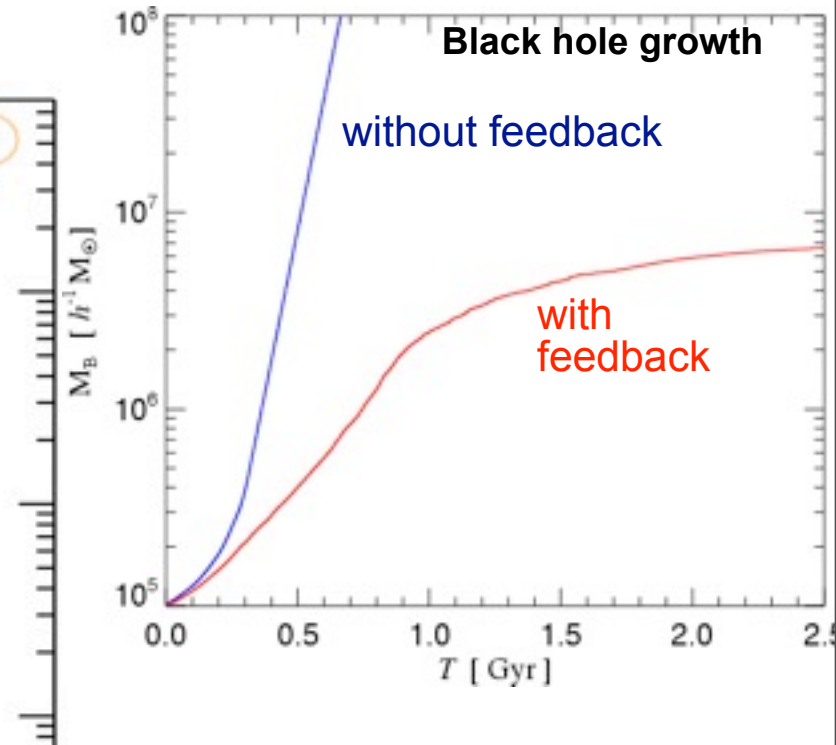
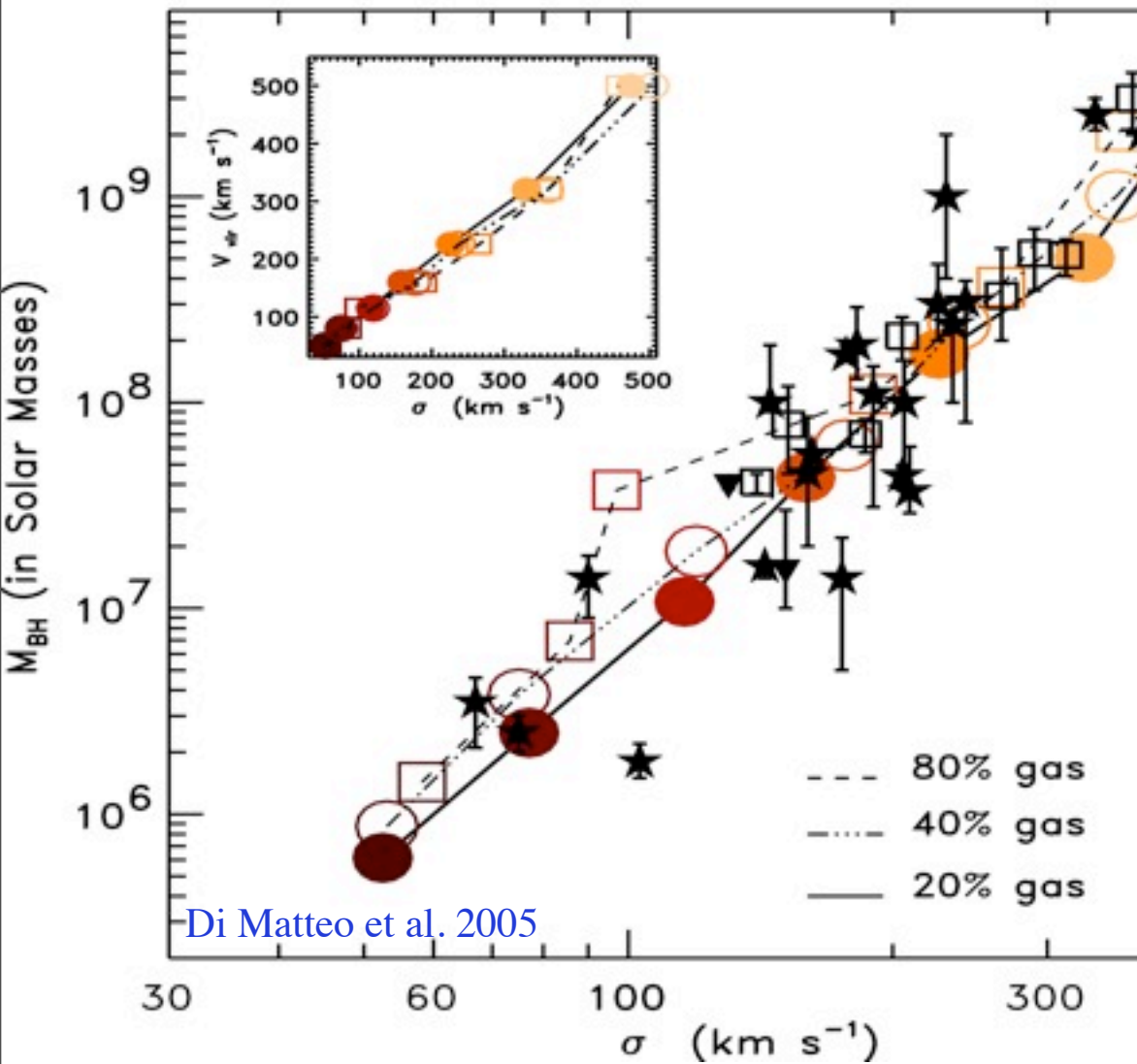


**Stars**

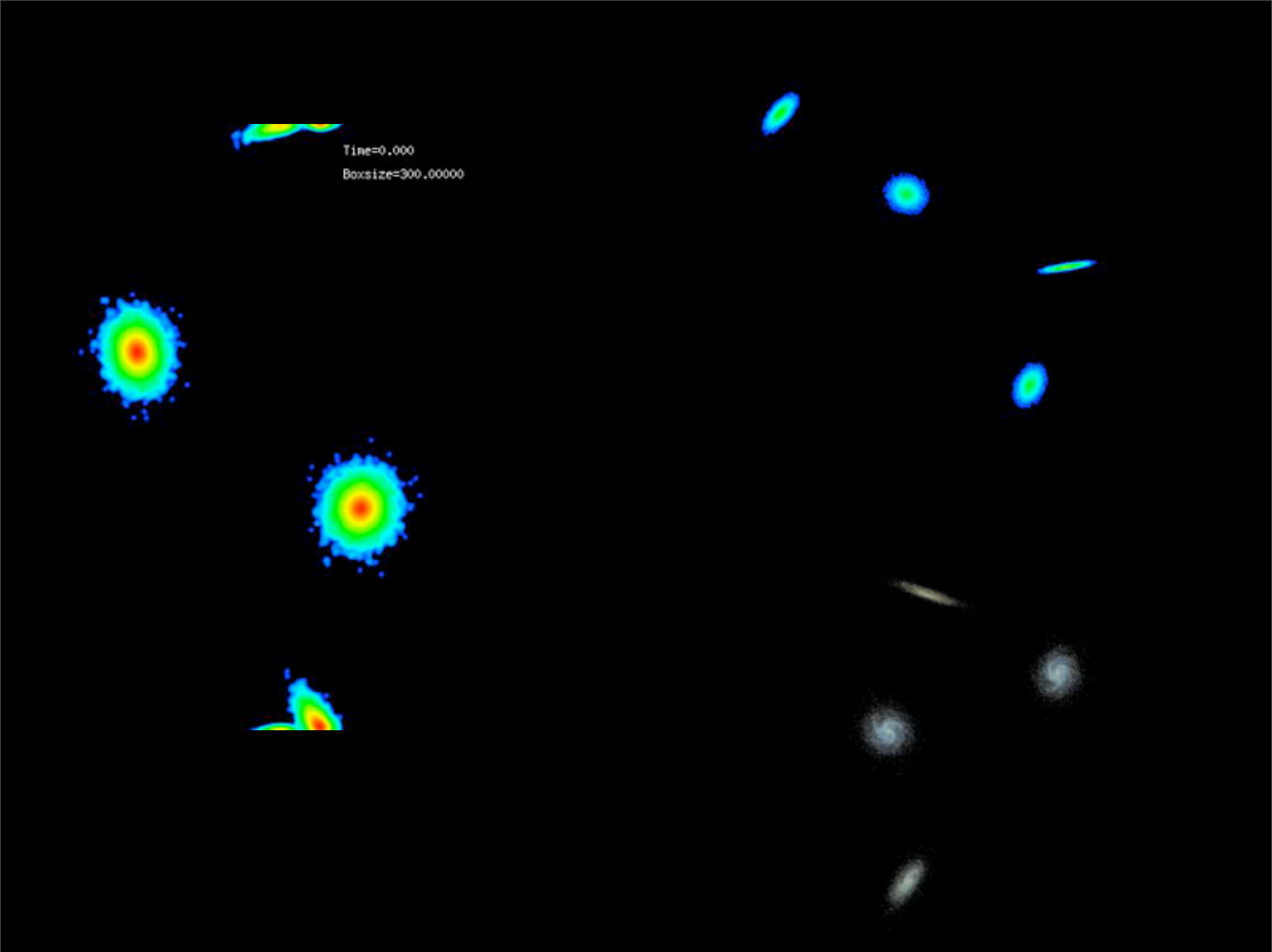


# M-sigma Relation Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



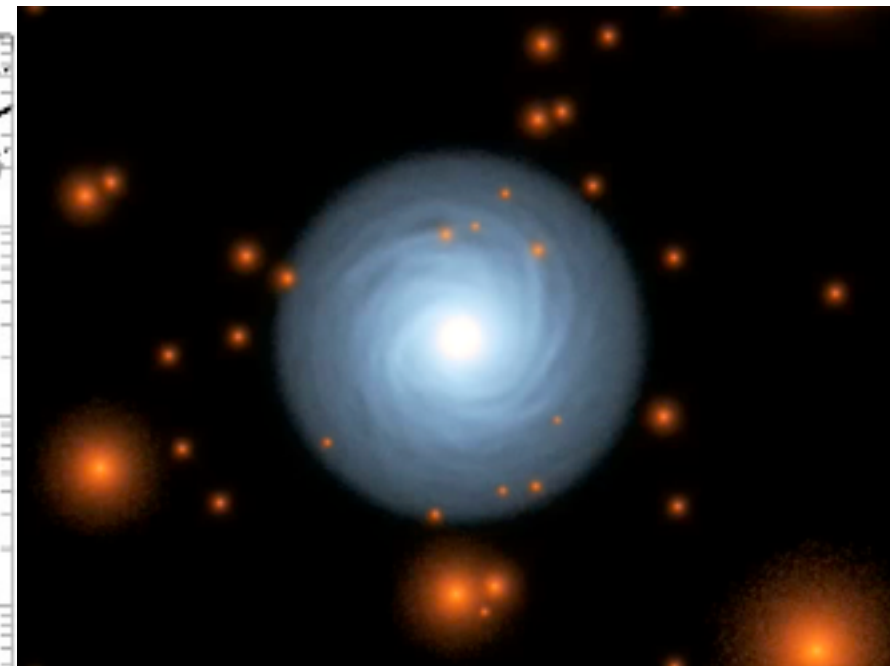
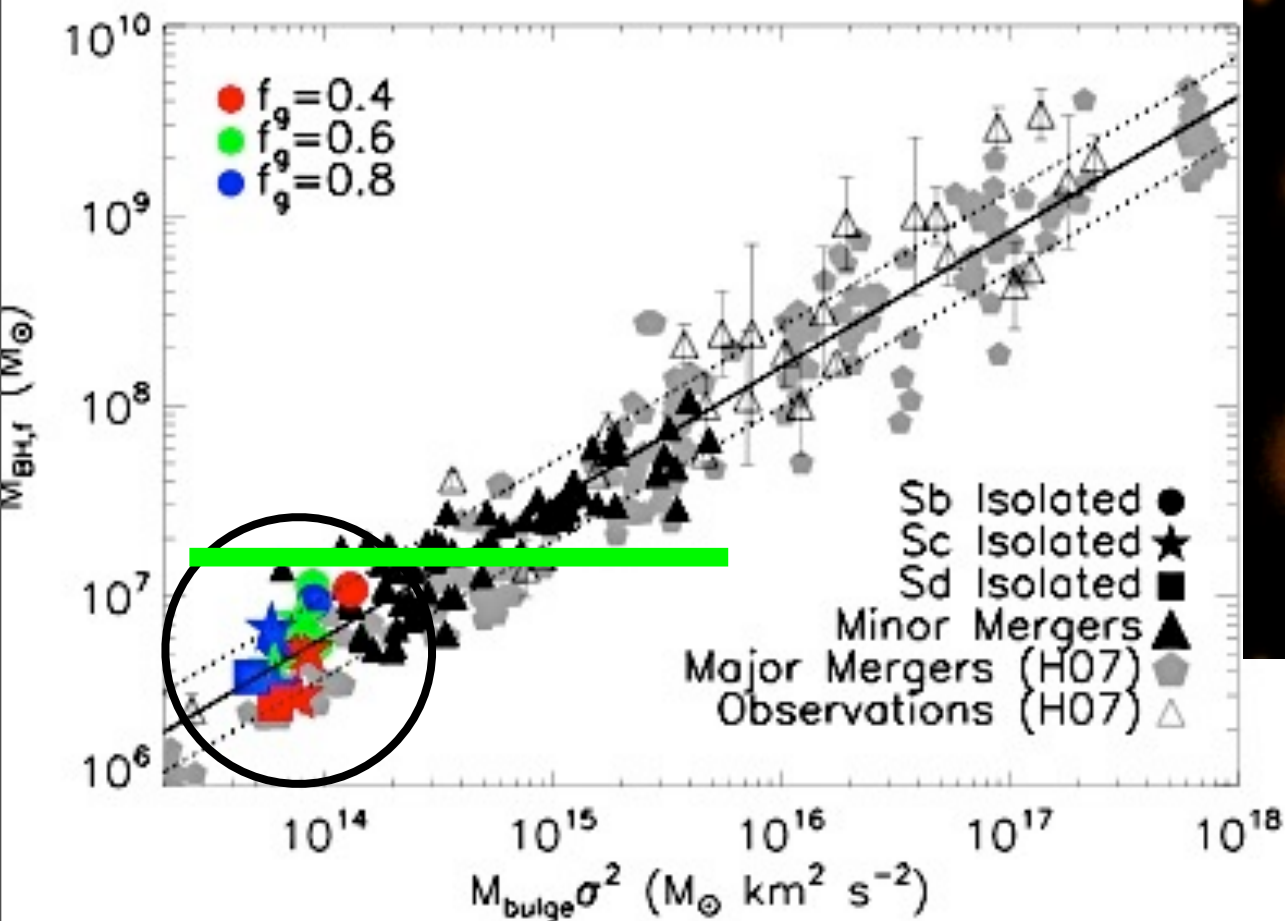
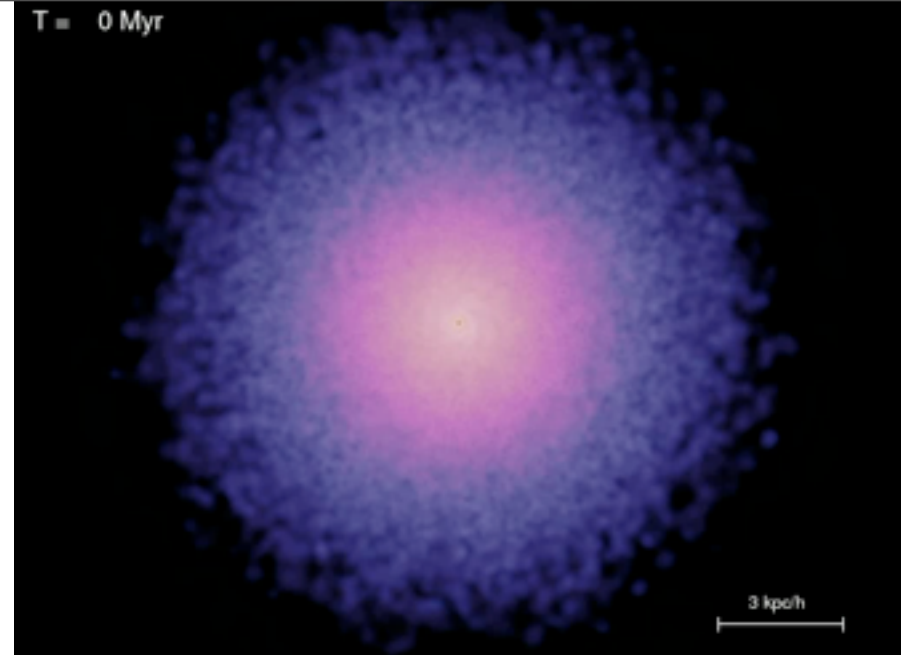




# Of Course, Not *Every* AGN Needs a Merger

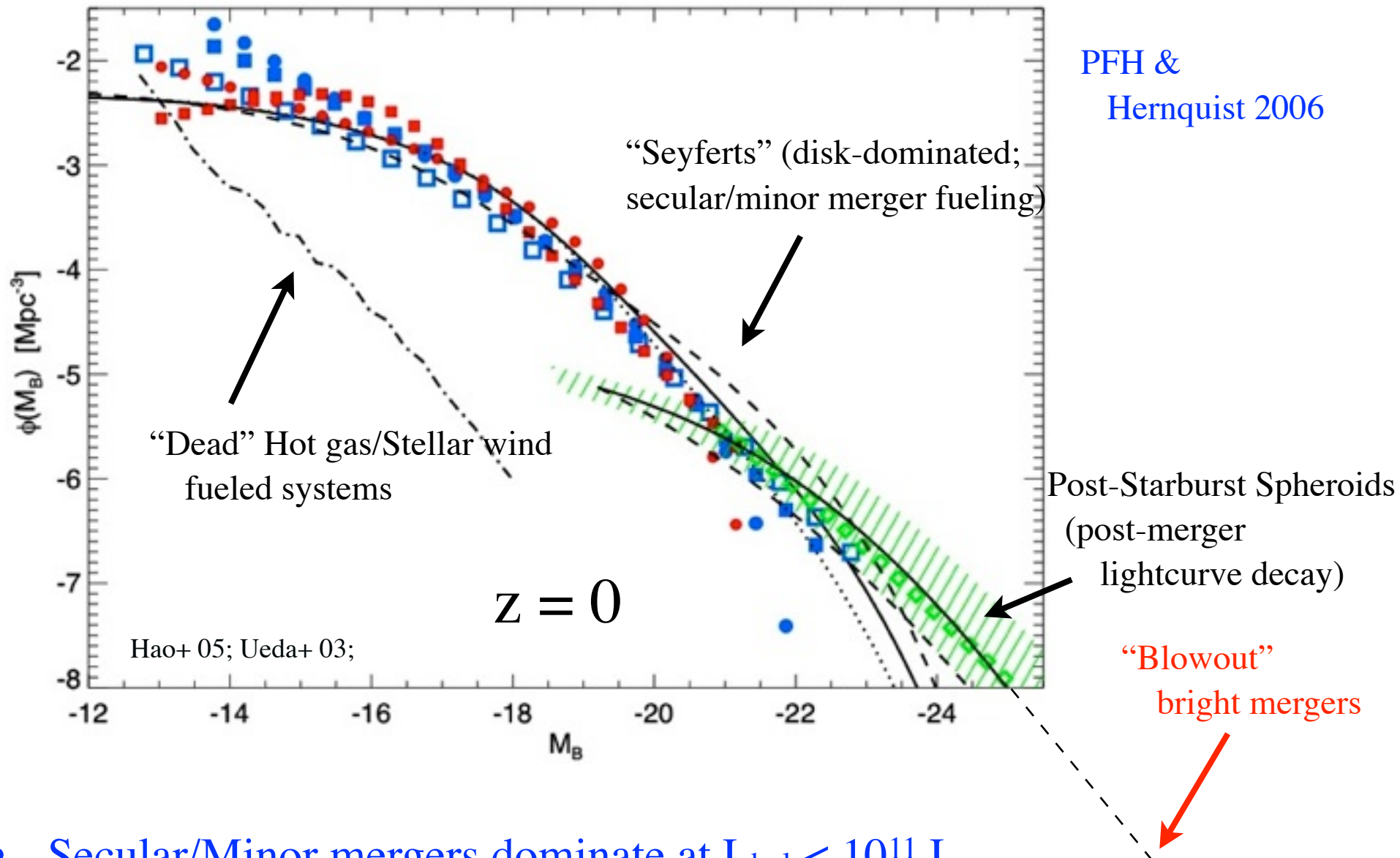
## MORE QUIESCENT GROWTH MODES?

- $z=2$   $L^*$  QSO:  $10^{11} M_{\text{sun}}$  in  $<10\text{pc}$  in  $\sim t_{\text{dyn}}$
- Seyfert: only  $10^8 M_{\text{sun}} \sim 10^{-3} M_{\text{gal}}$ 
  - Minor mergers?
  - Secular instabilities/bars?



- If you don't build massive bulges, doesn't matter if you can get the gas in!

# Emergent Picture:

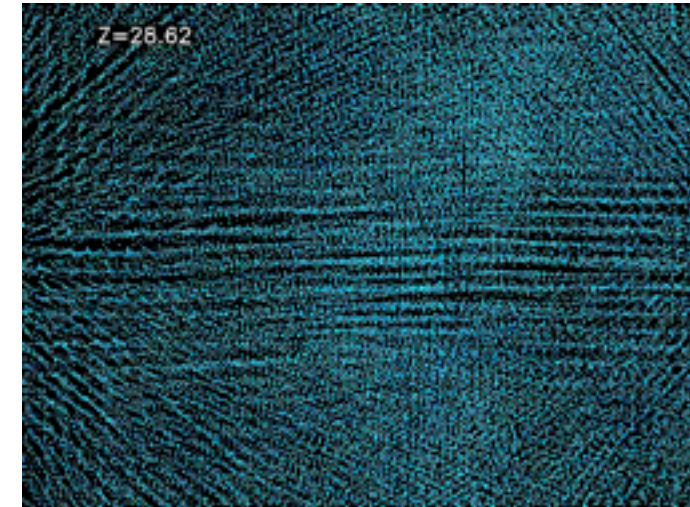
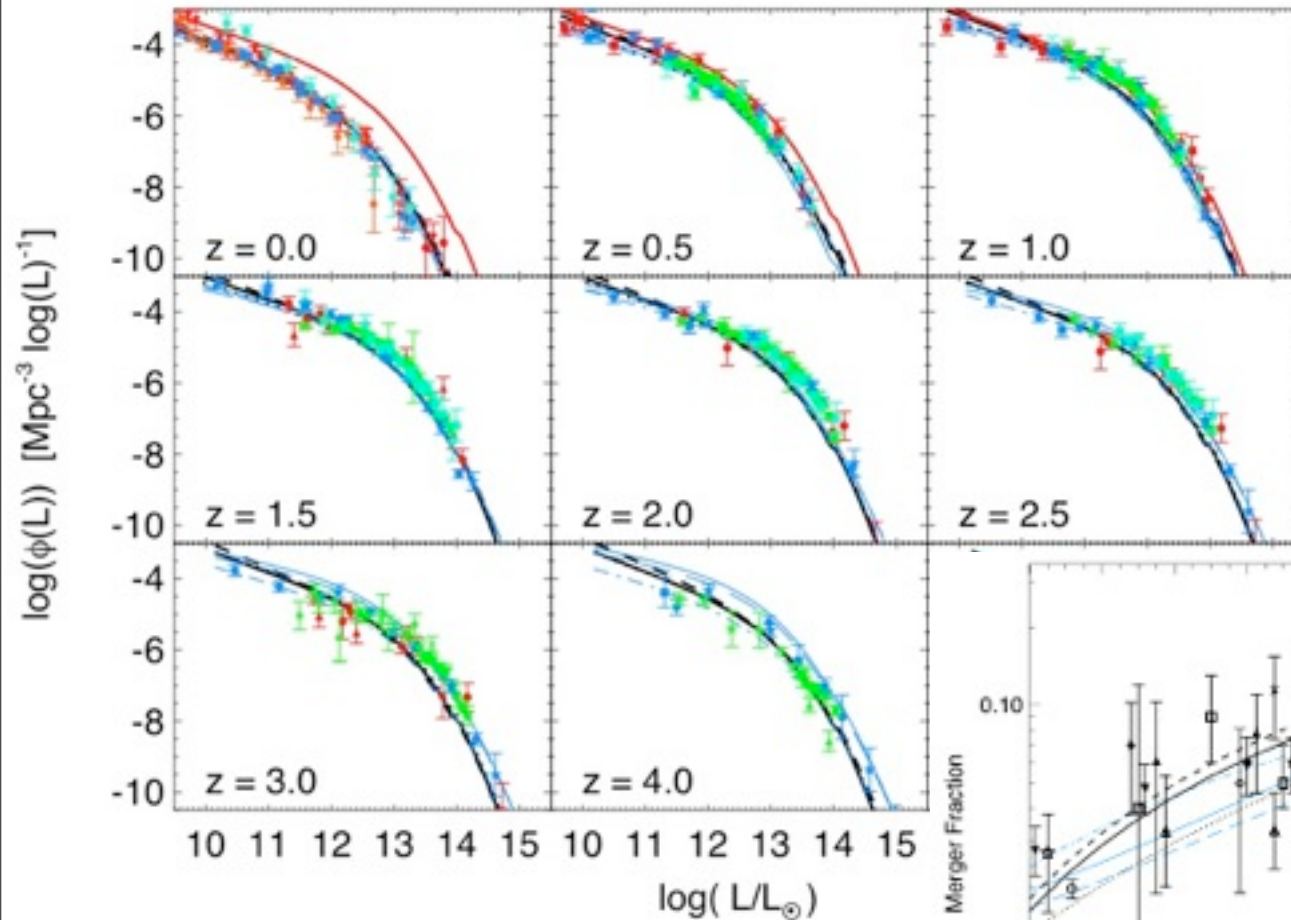


- Secular/Minor mergers dominate at  $L_{\text{bol}} < 10^{11} L_{\text{sun}}$ 
  - Seyfert-Quasar divide is a good proxy!

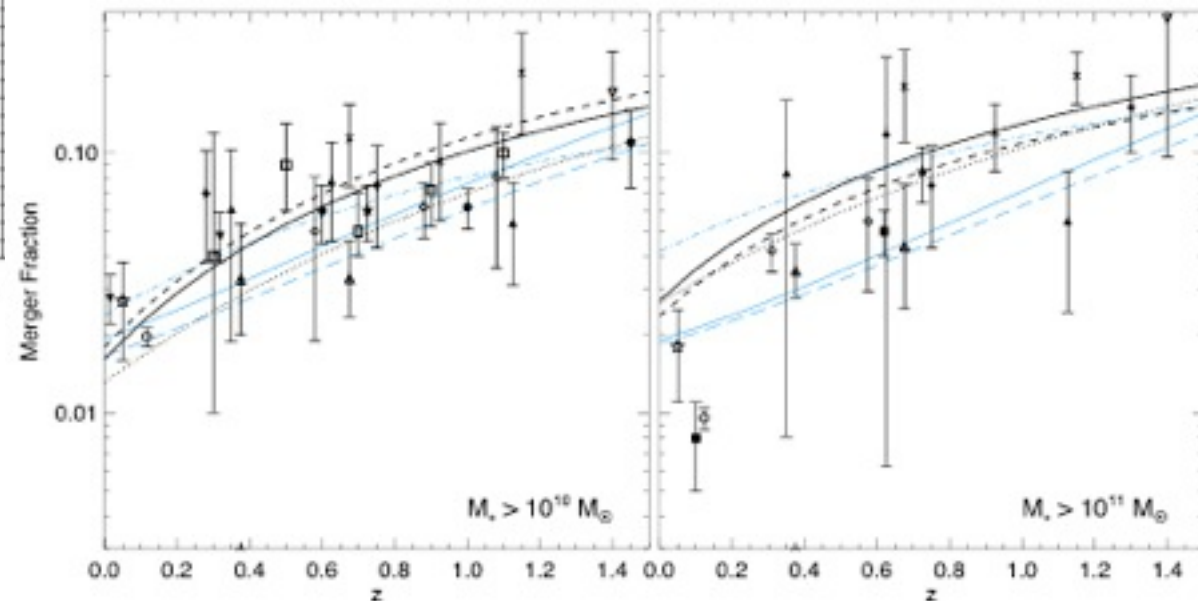
# Testing the models:

## NECESSARY CHECKS:

- Predicts the QLF vs. redshift, luminosity, wavelength



- There are “enough” mergers



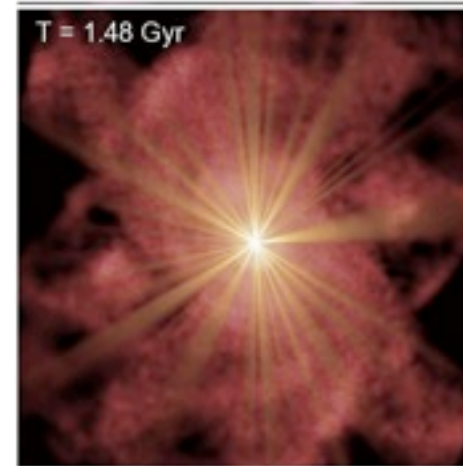


# Testing the models:

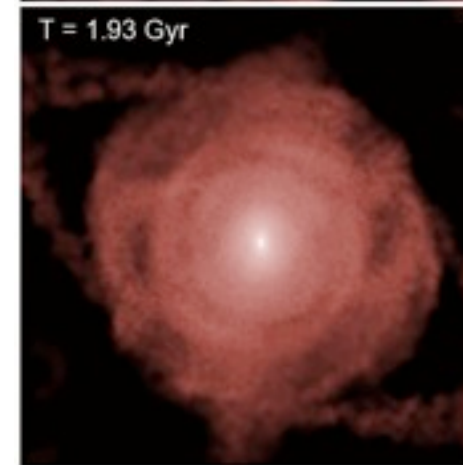
## MORPHOLOGY:

- Quasar is at the \*end\* of the merger
  - Host is relaxed/tidal features fade
  - SB dimming & PSF de-convolution
  - Automated routines classify even \*perfect\* images as “relaxed” spheroids in the quasar phase (Lotz et al.)
- Comparison samples?
  - Same \*galaxy\* masses (not luminosities)

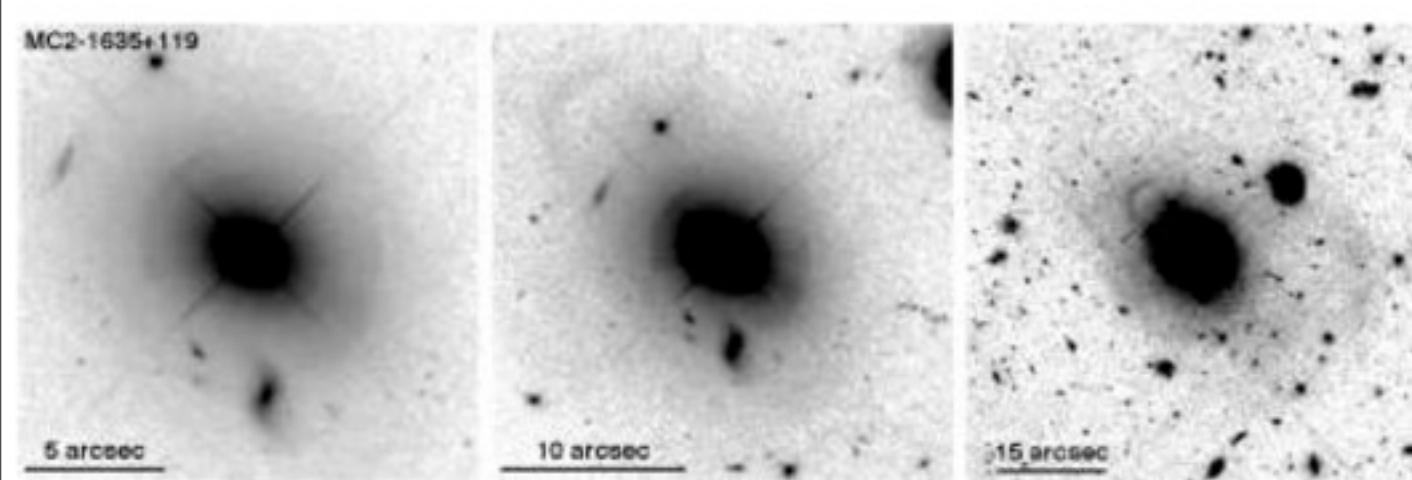
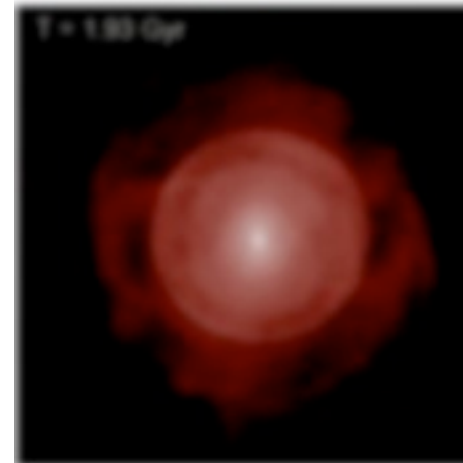
QSO =  
1000xHost



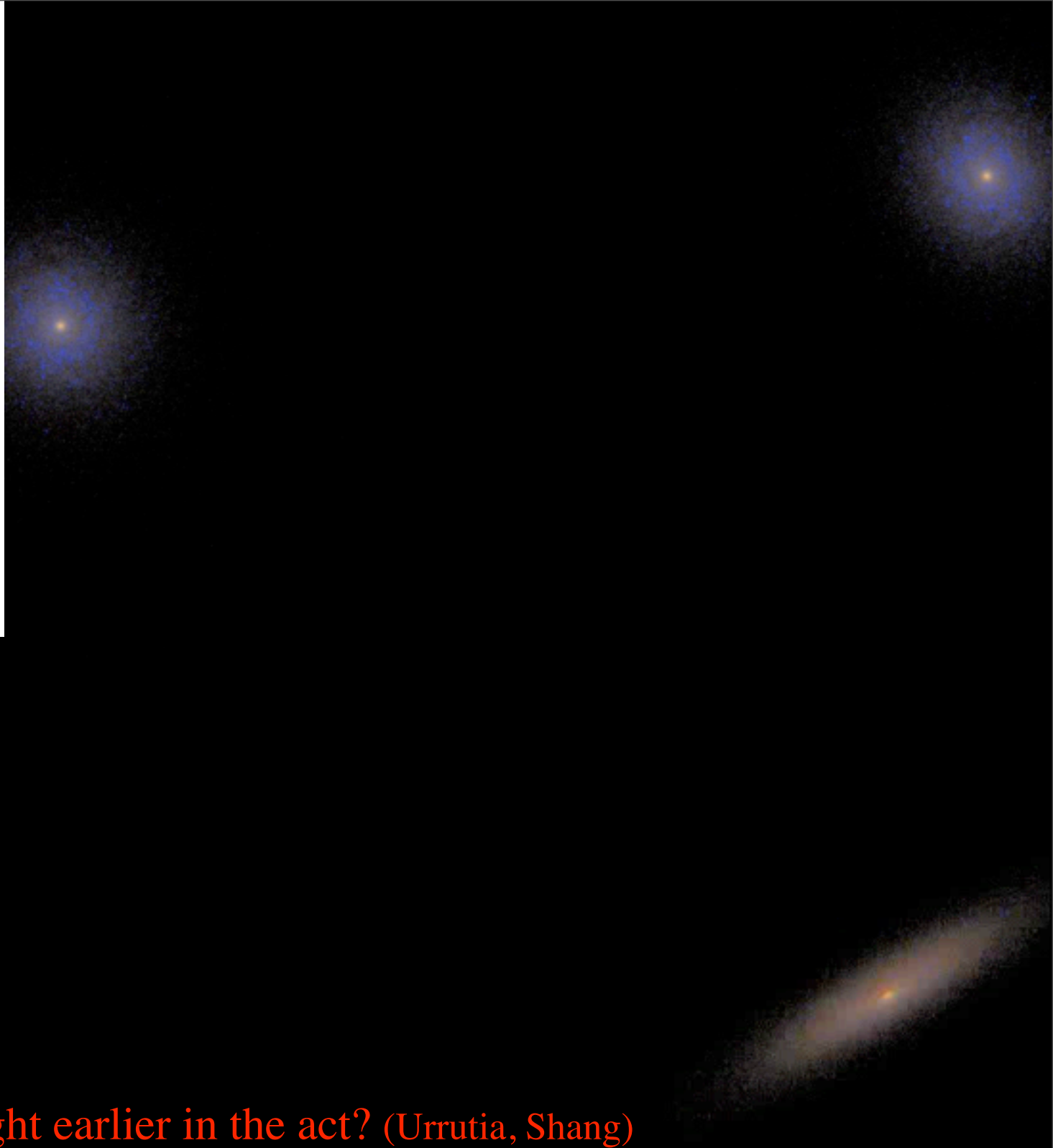
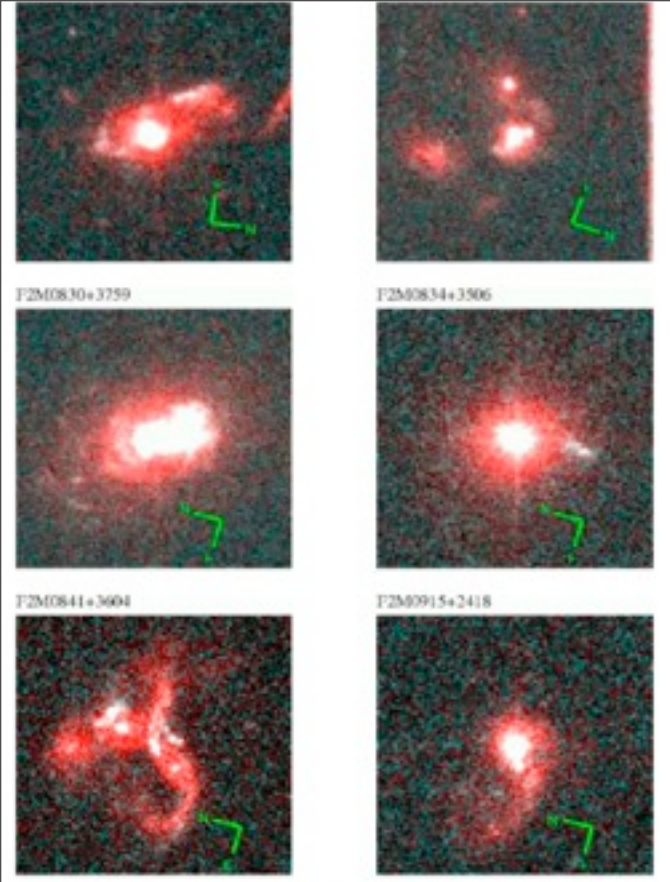
QSO =  
Host



QSO =  
0.1xHost



e.g. Canalizo, Bennert et al.: PG QSO Hosts

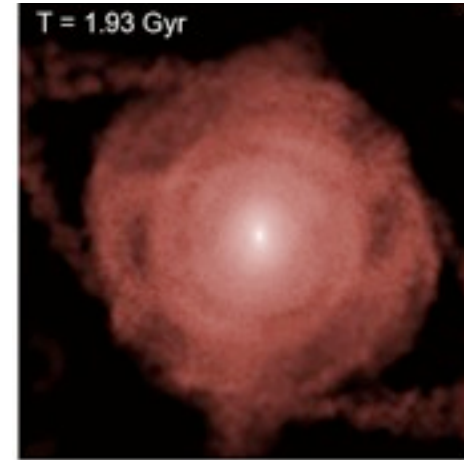
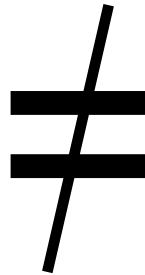


Red/Post-SB QSOs: caught earlier in the act? (Urrutia, Shang)

# Testing the models:

## MORPHOLOGY:

- BUT....

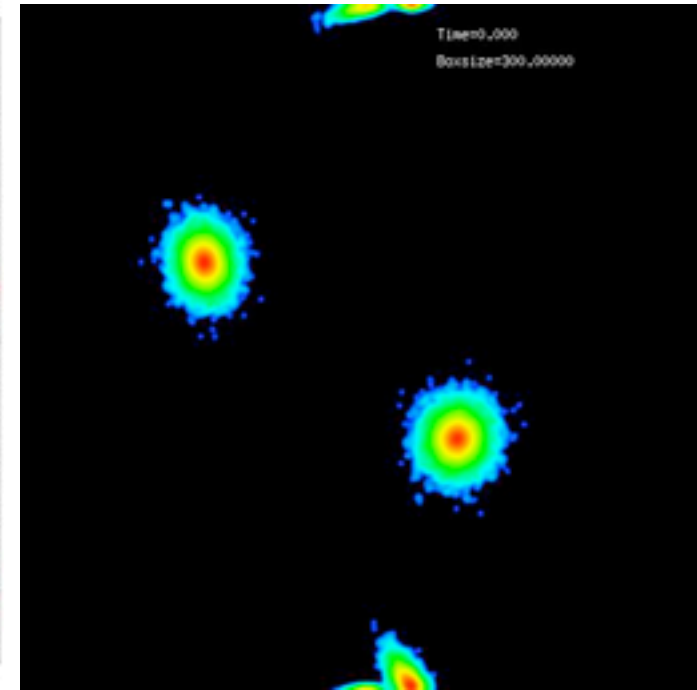
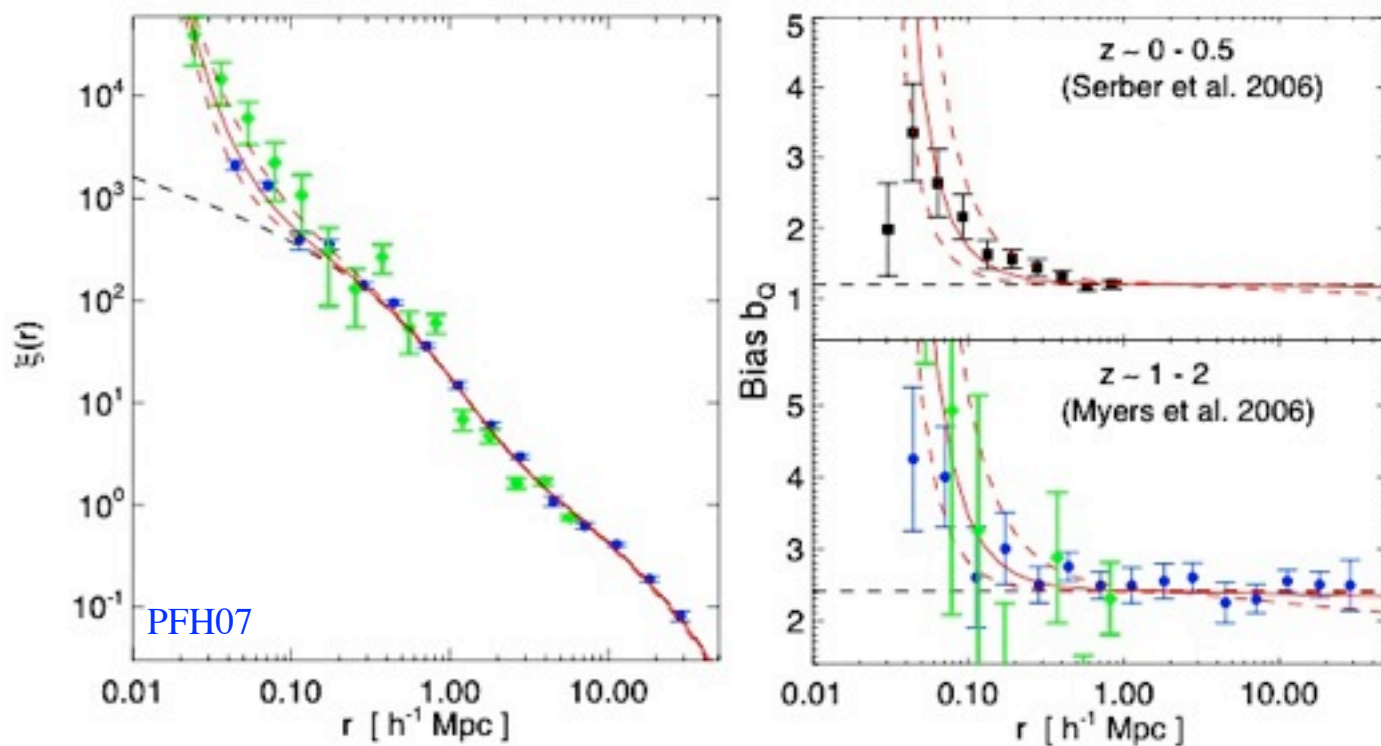


- Transition from “random” host galaxies to preference for elliptical host galaxies around  $L_{\text{bol}} \sim 10^{12} L_{\text{sun}}$ 
  - Dunlop et al. (PG QSOs)
  - Rigby et al. ( $z \sim 0.6$  X-Ray QSOs)
  - Zakamska et al. 2008 ( $z \sim 0.5$  SDSS Type IIs)

## Testing the models:

### CLUSTERING & ENVIRONMENT:

- Observed excess of quasar clustering (quasar-galaxy and quasar-quasar pairs) on small scales, relative to “normal” galaxies with the same masses/large-intermediate scale clustering



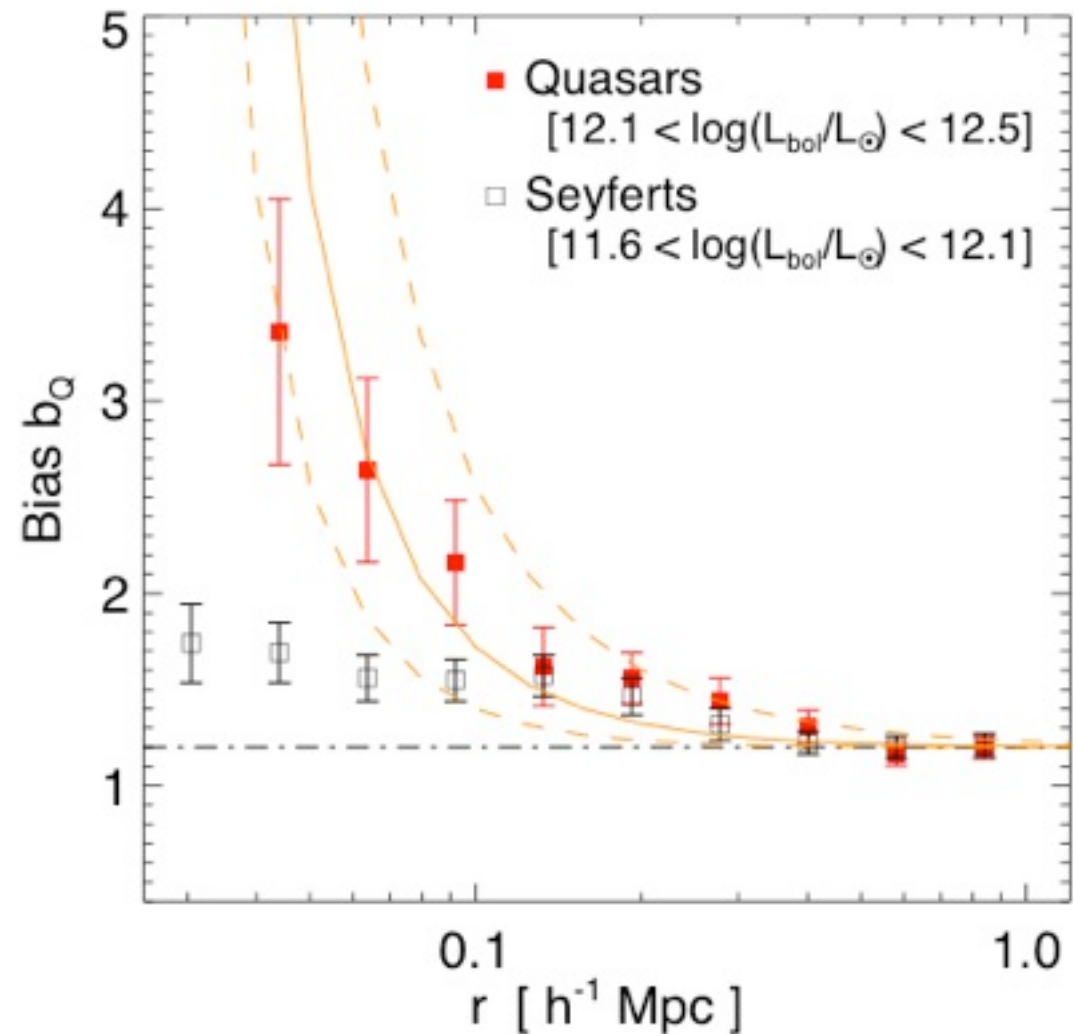
- Expected for mergers (Thacker & Scannapieco et al., PFH)
- Seen in Post-SB Galaxies (Goto et al., Hogg et al., Kauffmann et al.)



## Testing the models:

### CLUSTERING & ENVIRONMENT:

- Small-Scale Excess:
  - Not seen in Seyferts (Serber, Kauffmann)
  - Suggests different processes dominate fueling below  $M_B \sim -23$  ( $M_{BH} \sim 10^7$ )?

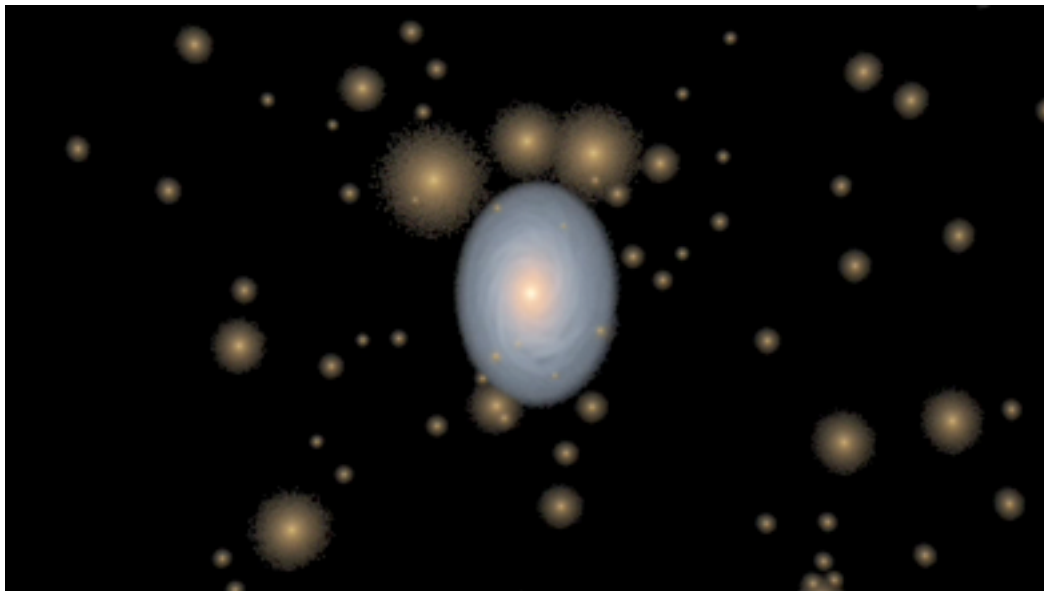
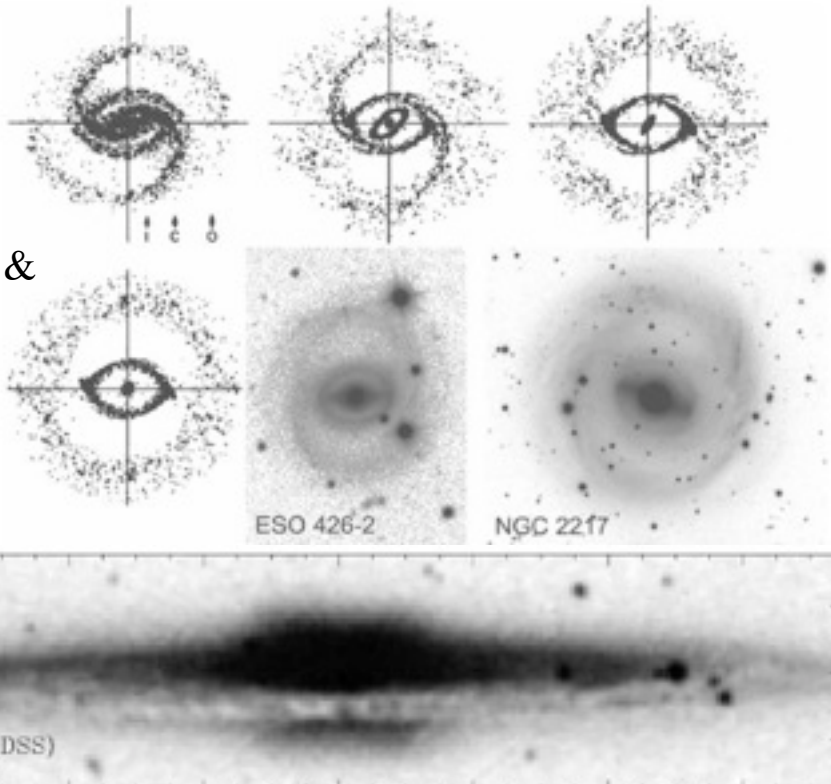


Serber et al. 2006

## Testing the models:

### REMNANT MORPHOLOGY:

Kormendy &  
Kennicutt

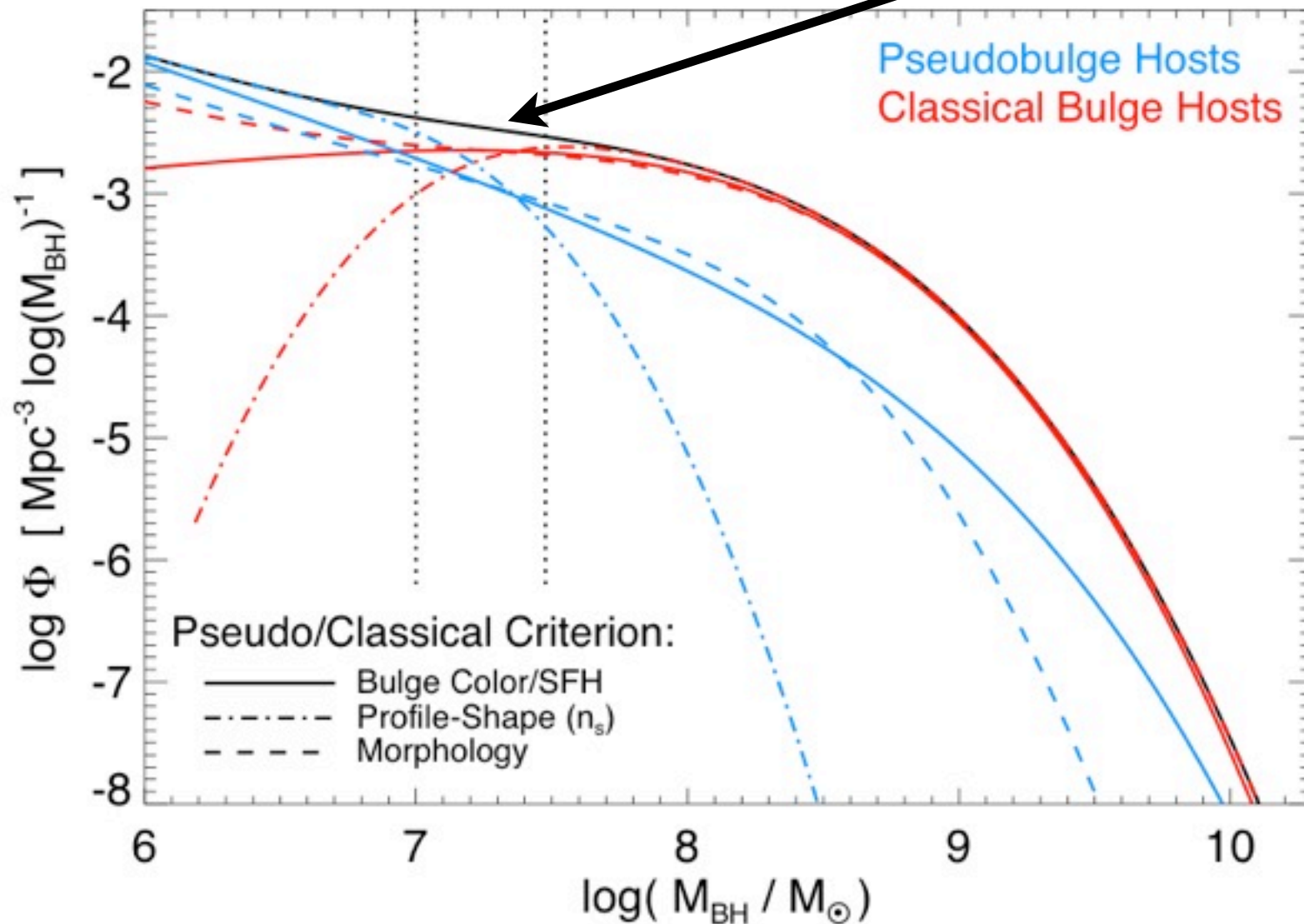


- Disk instability/secular evolution *does not* make normal/classical bulges (mergers do)
  - Athanassoula, Mayer, Combes, Barnes, Naab, Cox, et al.
  - Conservation laws
- Make pseudobulges:
  - boxy/peanut shape
  - high rotation
  - flattened
  - low Sersic index
  - bluer
- Sufficiently minor mergers *indistinguishable* from secular

## Testing the models:

REMNANT MORPHOLOGY:

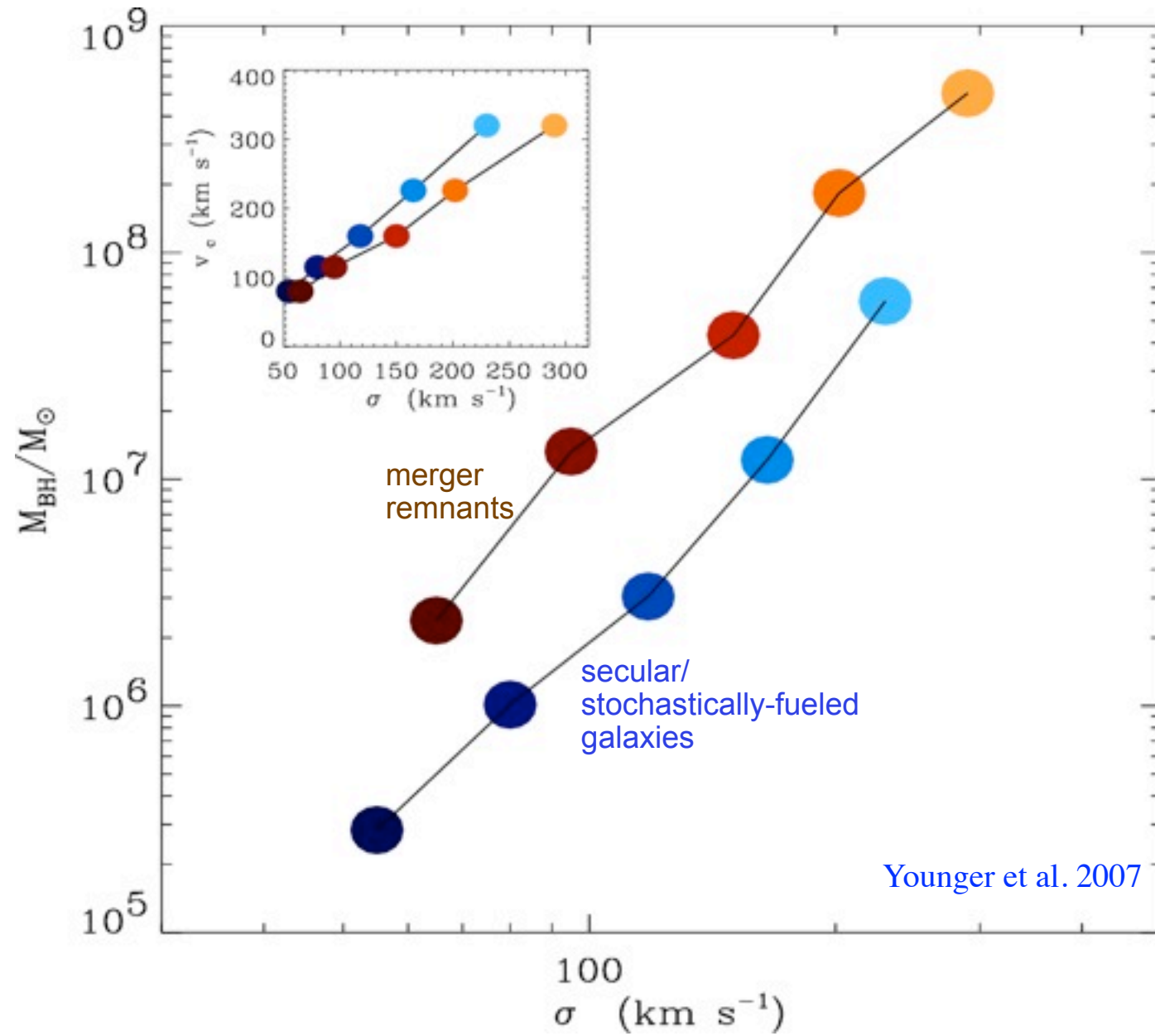
$\sim 10^{12} L_{\text{sun}}$  at  
Eddington



- Most mass in “classical” bulges, not “pseudobulges”
  - But, *\*are\** important below  $< \sim$  Sa-types

## Testing the models:

### REMNANT MORPHOLOGY: CORRELARY



- Recently claimed in observations: Hu et al., Greene & Ho et al.



# Clarifications & Caveats

- Most SF in extended (“disk”) mode: only ~10% in <kpc bursts
  - $M_{\text{BH}}$  tracks  $M_{\text{gal}}$  on average: “synched” by disk disruption events
- SF primarily shuts *itself* down (gas exhaustion)
  - BH just “sweeps up” ~ few - few 10s x  $M_{\text{BH}}$  (not ~ $M_{\text{gal}}$ !)
    - Still important to get ellipticals to properly turn red
  - Bulge tells BH how big to grow; not the other way around
- QSO winds add to & (on large scales) indistinguishable from SF winds
  - Except occasional >1000 km/s (but not typical)
- Expect AGN to be “quenching”, not “quenched”
  - Post-SB/green valley -- not “more red” than non-AGN
- “Groups” of interest = slightly overdense regions
- $M_{\text{bh}}-M_{\text{gal}}$  evolution expected: doesn’t mean BH grows “before” spheroid

# Summary

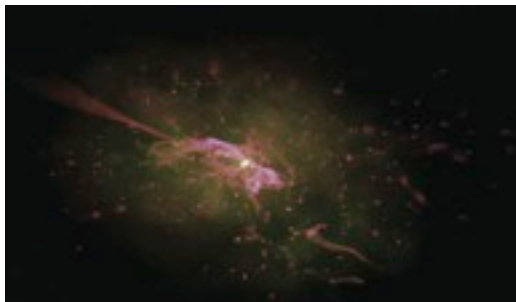
- $M_{\text{BH}}$  traces spheroid  $E_{\text{binding}}$ 
  - Suggests *self-regulated* BH growth
  
- If self-regulated, this feedback is potentially radically important:
  - Heating gas, ejecting metals, shutting down SF
  - Self-regulated decay of QSO luminosity:
    - Luminosity-dependent quasar lifetimes
    - Changes the meaning of the QLF
  
- “Are AGN mergers?” is the *wrong* question: we should ask:
  - “Where (as a function of  $L$ ,  $z$ ,  $d$ ) do mergers vs. secular processes dominate the AGN population?”
    - Clustering vs. scale
    - Host galaxy colors/SFH
    - Host morphology/kinematics
      - Both “merger signatures” and e.g. disk vs. elliptical, pseudobulge vs. classical bulge
  - Models & (tentative) observations suggest division at Seyfert-QSO line

## “Transition”

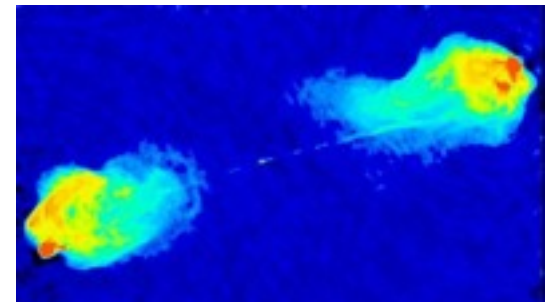
vs.

## “Maintenance”

- Move mass from Blue to Red
- Rapid
- Small scales
- “Quasar” mode (high  $\dot{m}$ )
- Morphological Transformation
- Gas-rich/Dissipational Mergers



- Keep it Red
- Long-lived ( $\sim$ Hubble time)
- Large ( $\sim$ halo) scales
- “Radio” mode (low  $\dot{m}$ )
- Subtle morphological change
- “Dry”/Dissipationless Mergers

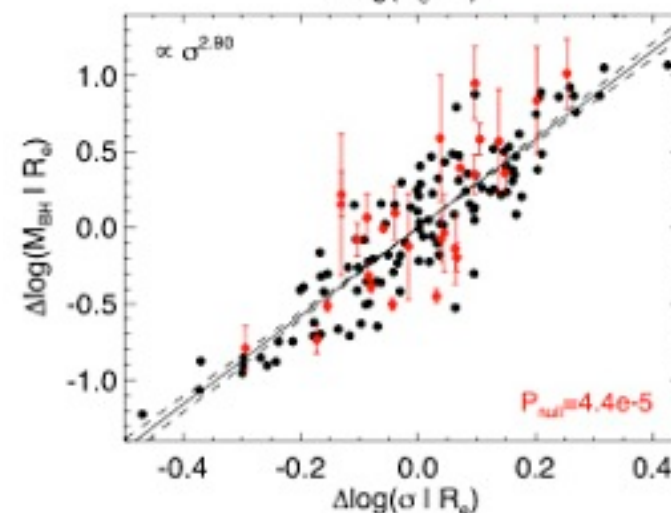
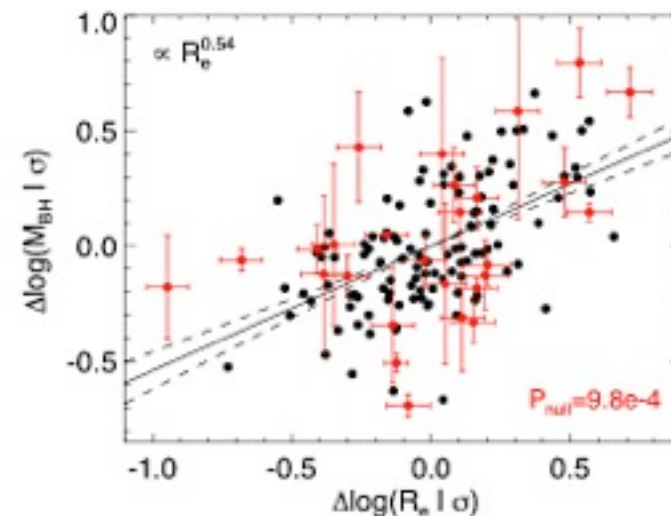
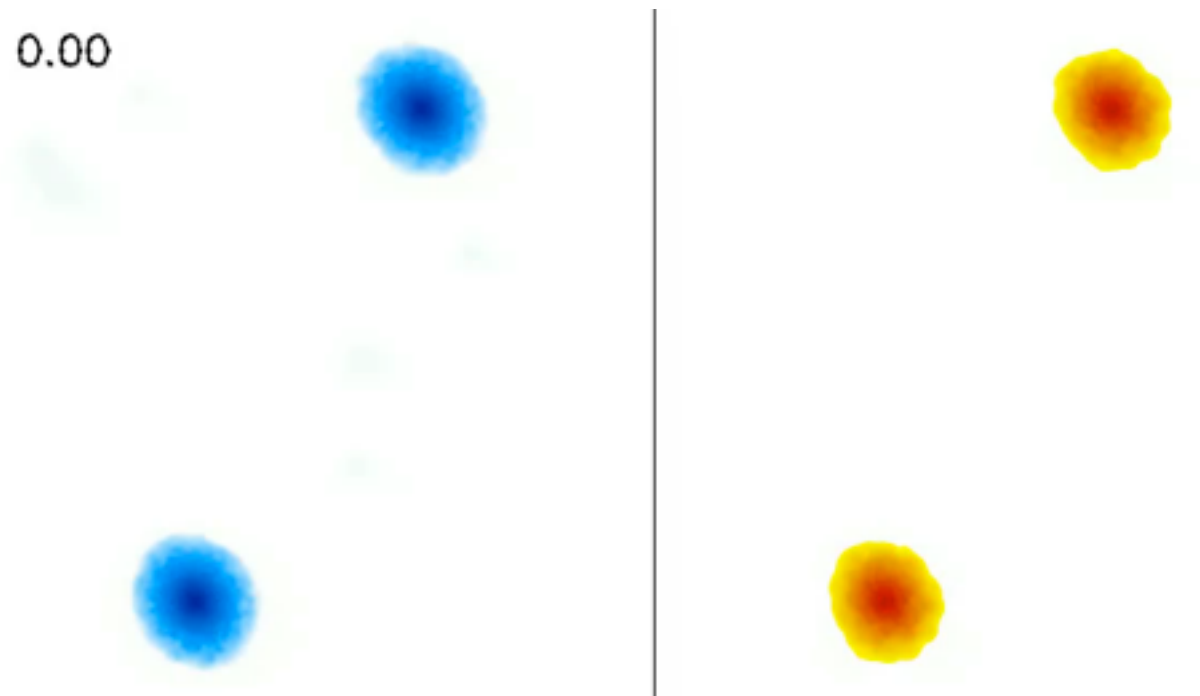


No reason these should be the same mechanisms... what connections?

# Observations & Simulations Suggest this Simple Picture Works

## SIMPLE COUPLING OF BH RADIATED ENERGY TO SURROUNDING GAS IN A MERGER

PFH et al. 2007



- Supports basic Silk & Rees '98 argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential of material to be unbound

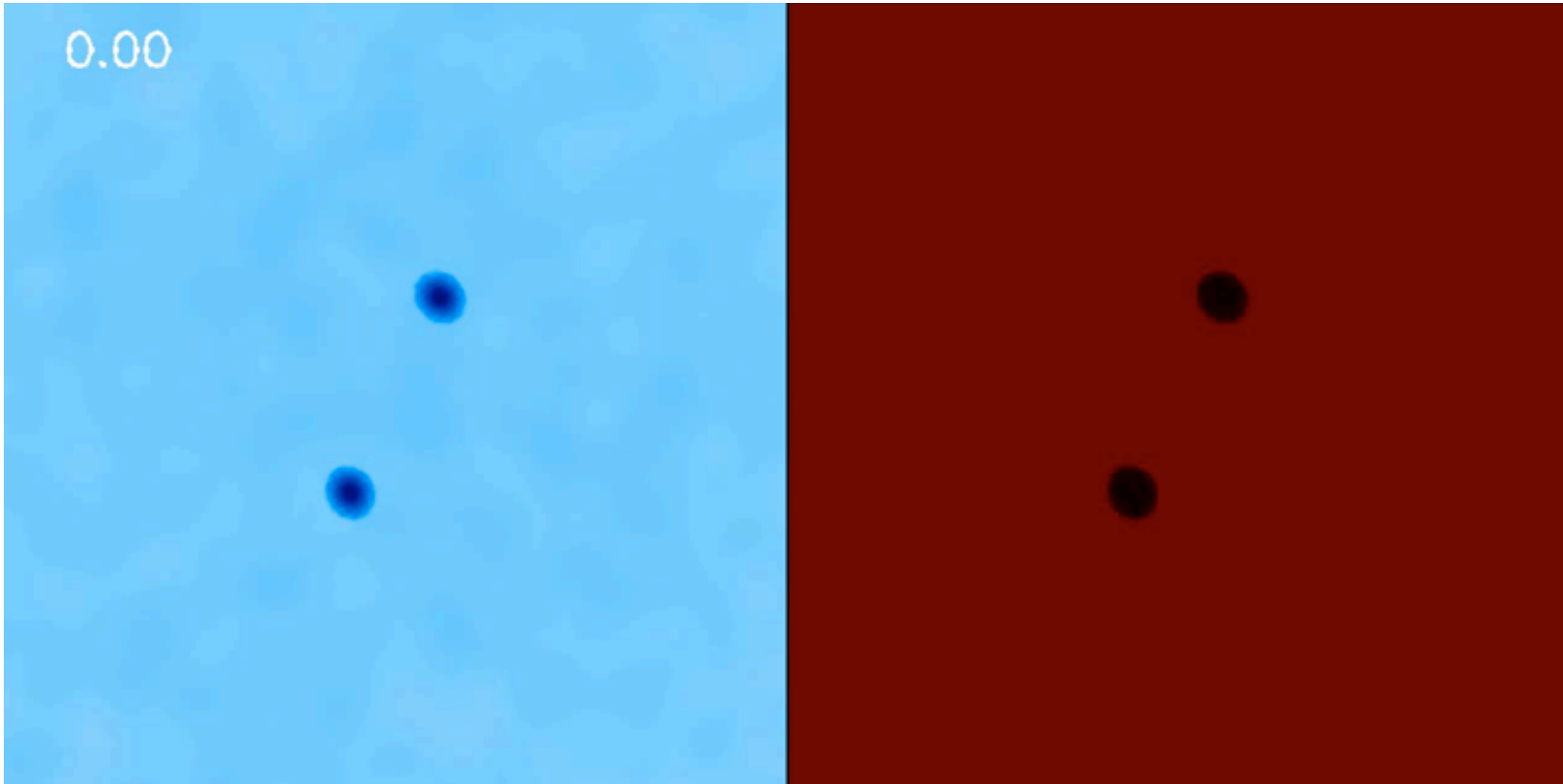


# Quasar Outflows May Be Significant for the ICM & IGM

SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?

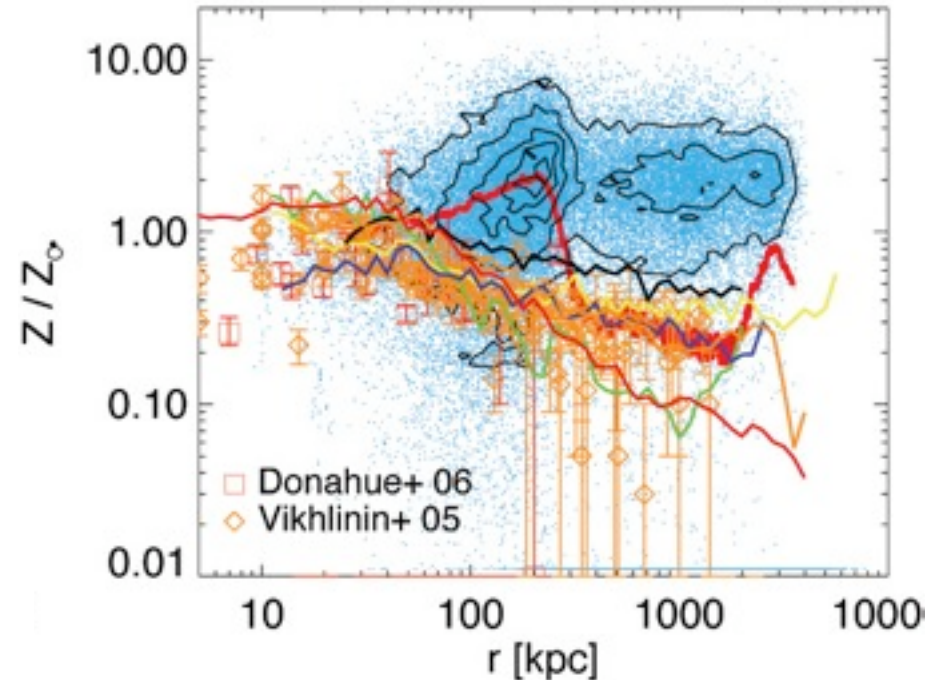
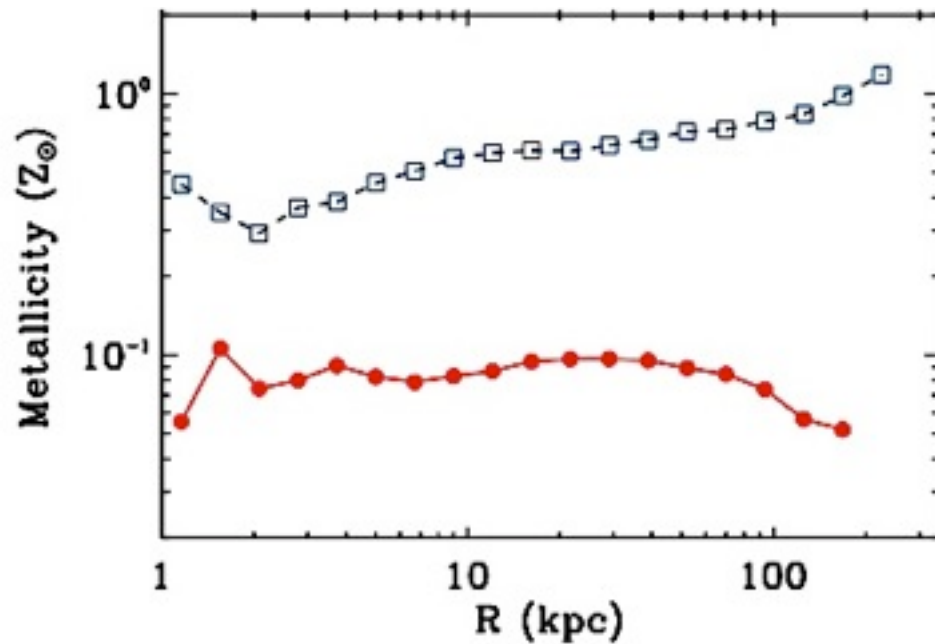
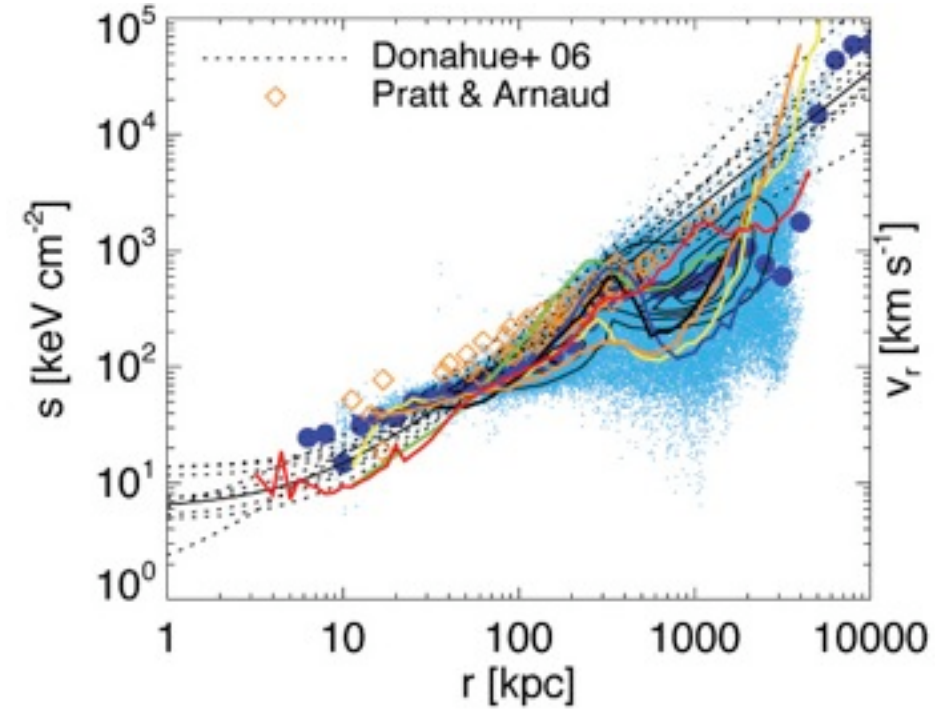
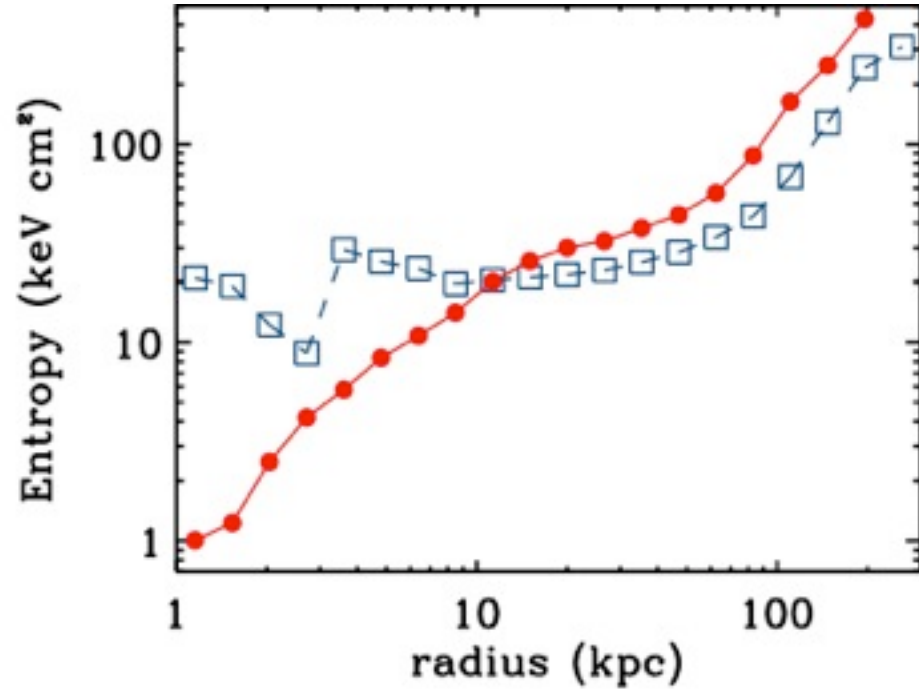
**Gas Density**

**Gas Temperature**



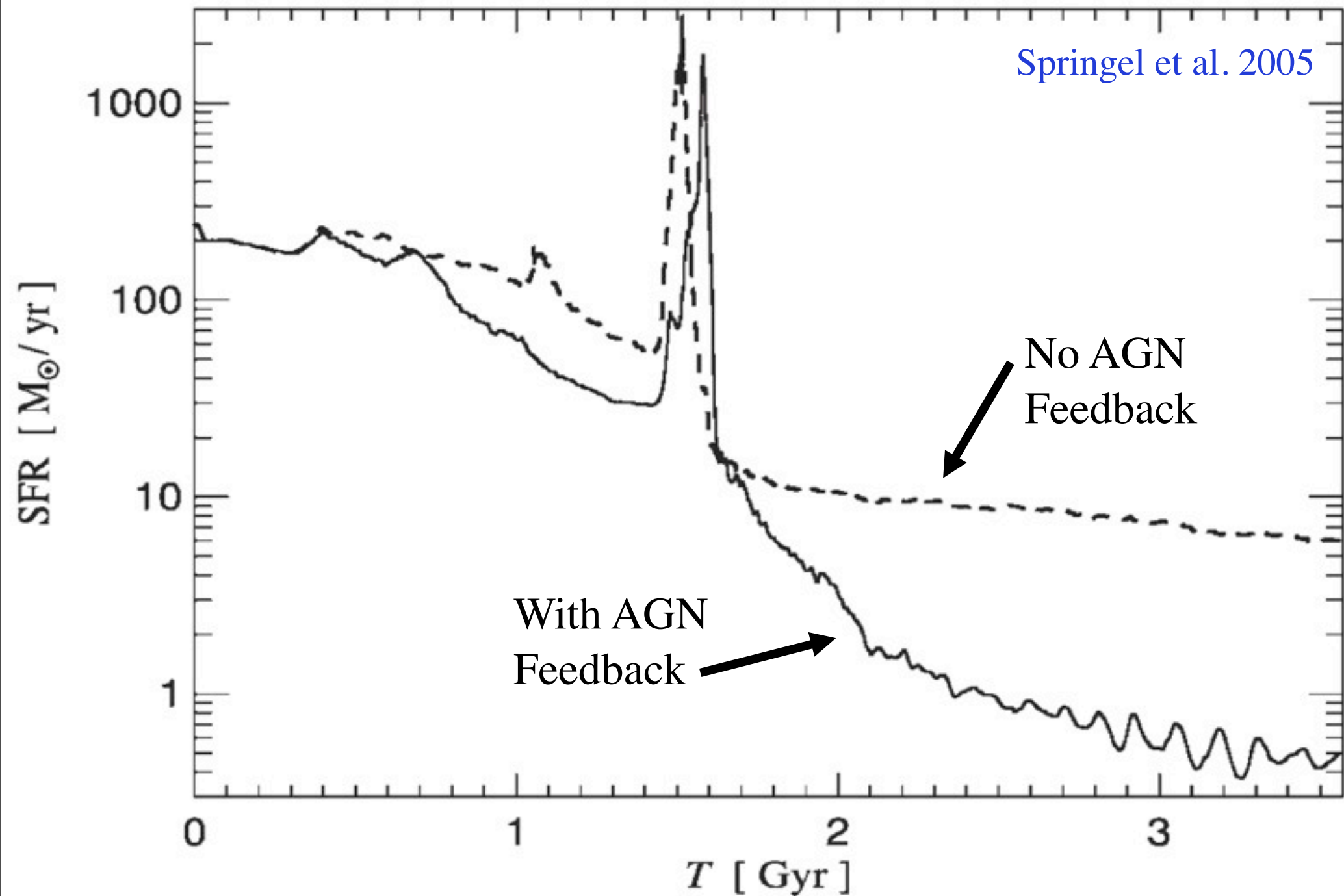
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SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?



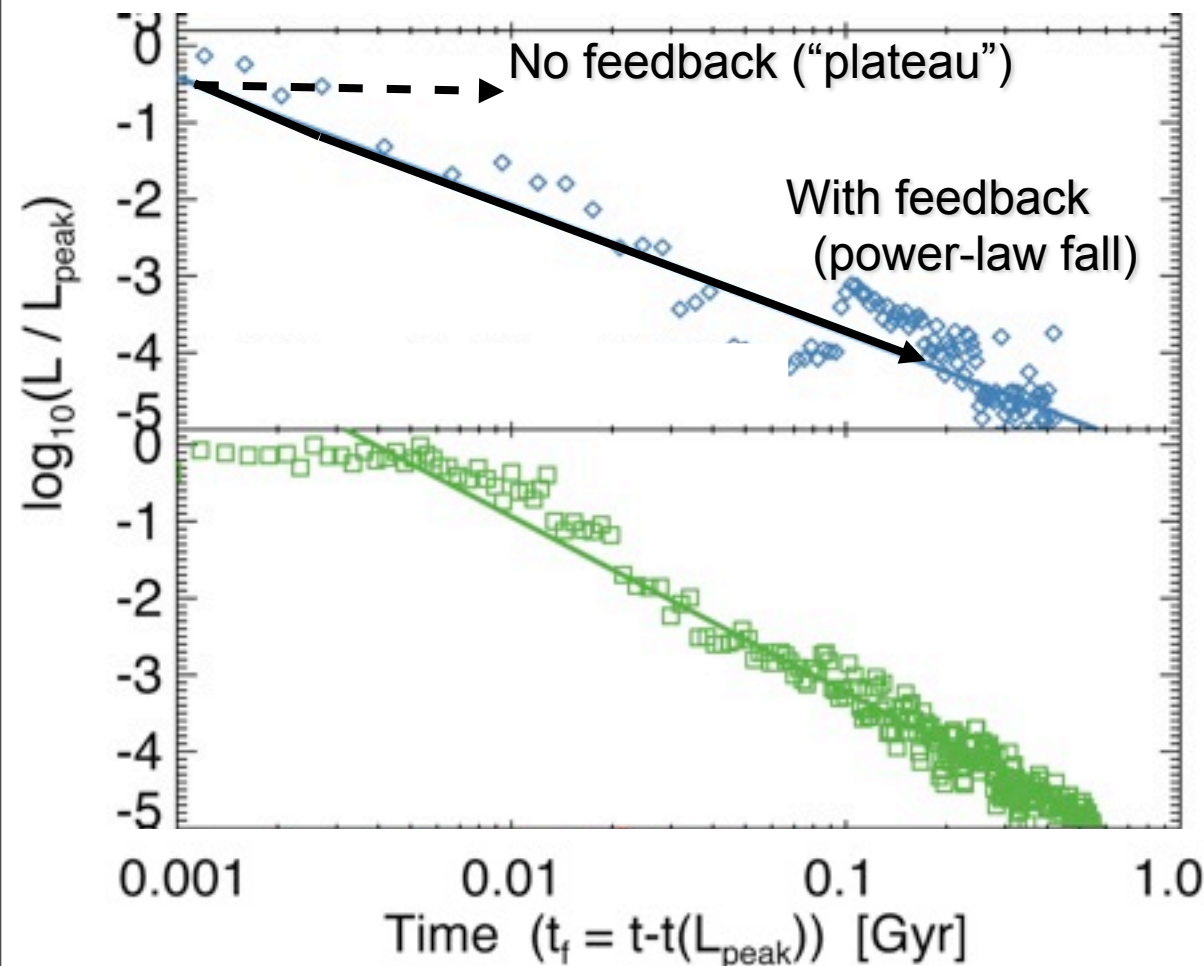
# Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?



# Quasar Light Curves & Lifetimes

- Feedback determines the decay of the quasar light curve:



- Explosive blowout drives power-law decay in  $L$
- No Feedback:
  - Runaway growth (exponential light curve)
  - “Plateau” as run out of gas but can’t expel it (extended step function)

PFH et al. 2006a



# This is Very General: (EVEN THOUGH NOT ALL AGN ARE MERGER-DRIVEN)

➤ Almost any (ex. radio) AGN feedback will share key properties:

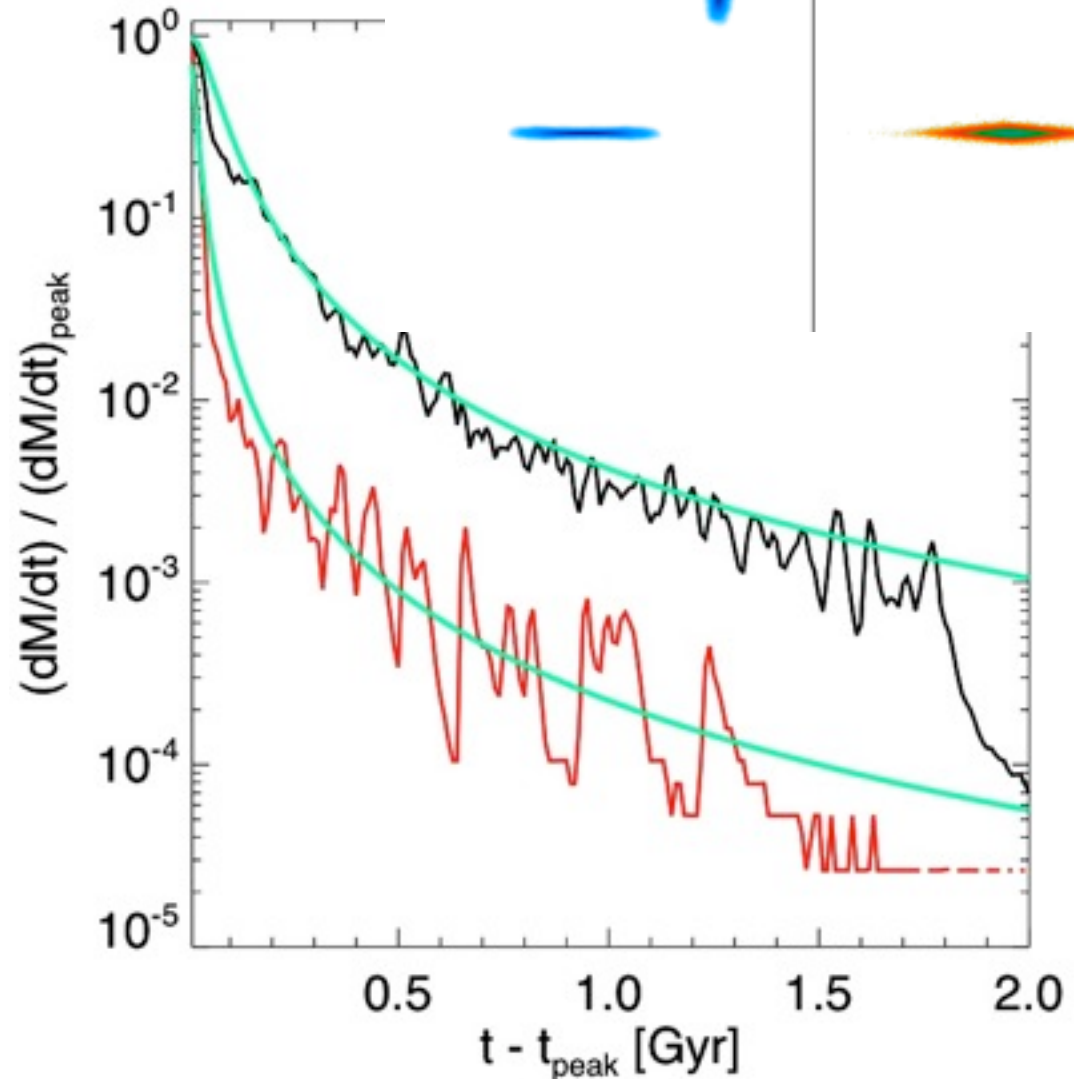
- Point-like
- Short input ( $\sim t_{\text{Salpeter}}$ )
- $E \sim E_{\text{binding}}$

➤ Simple, analytic solutions:

- $L \sim (t / t_Q)^{-1.7(\text{ish})}$
- Agrees well with simulations!

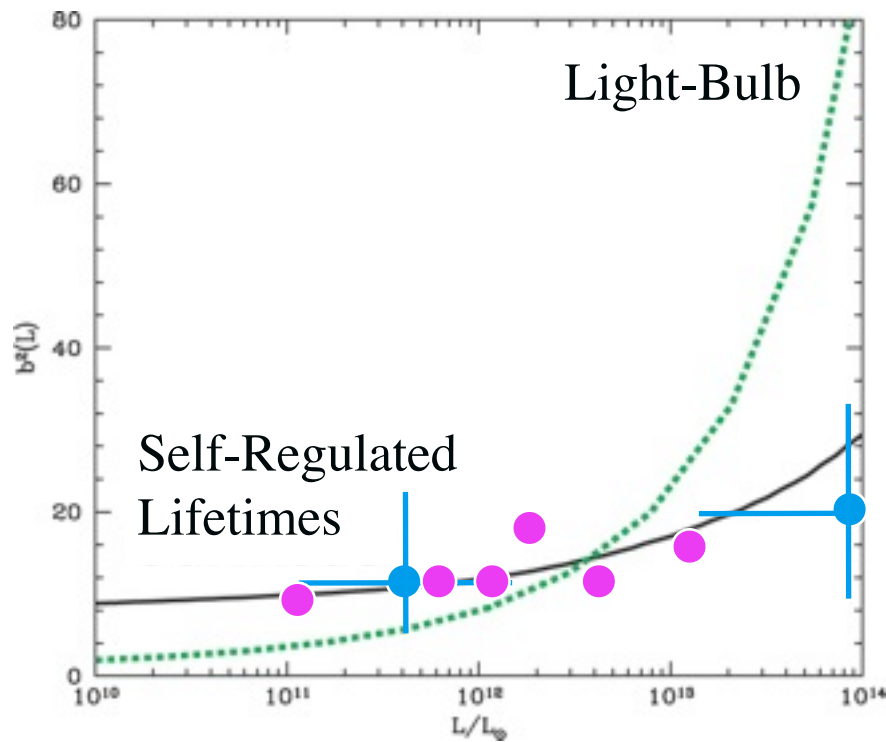
➤ Generalize to “Seyferts”

- Disk-dominated galaxies with bars
- Minor mergers



# Quasar Clustering is a Strong Test of this Model

IF FAINT QSOS ARE DECAYING BRIGHT QSOS - SHOULD BE IN SIMILAR HOSTS



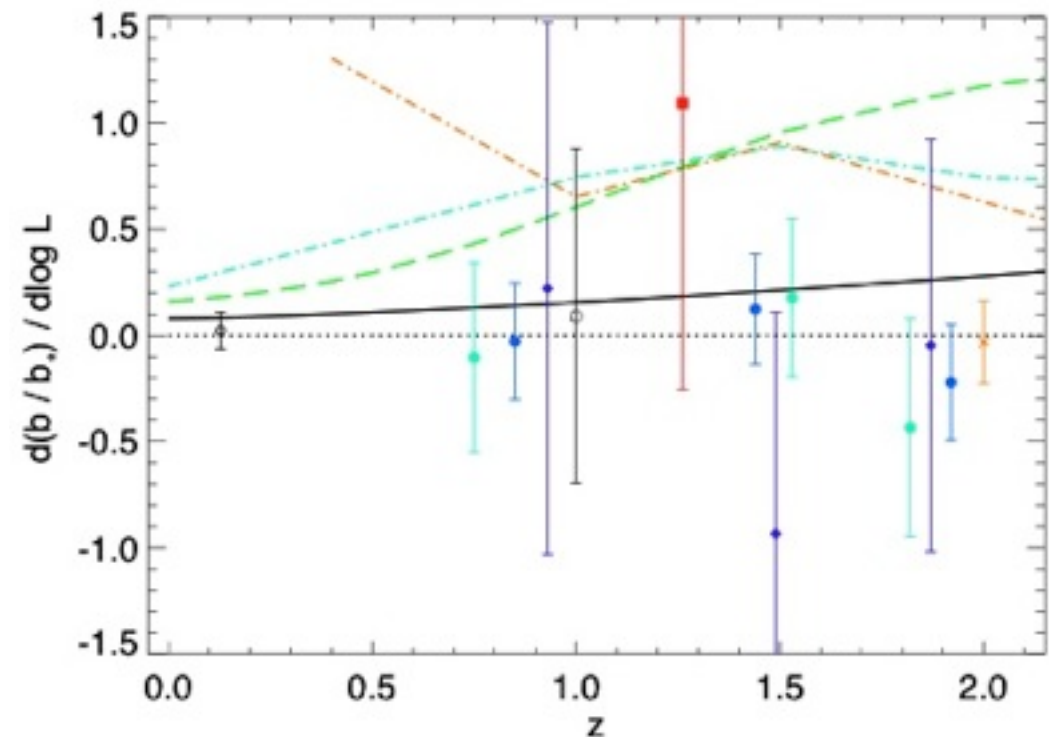
● Adelberger & Steidel 05  
● Myers et al. 05

Lidz et al. 2005

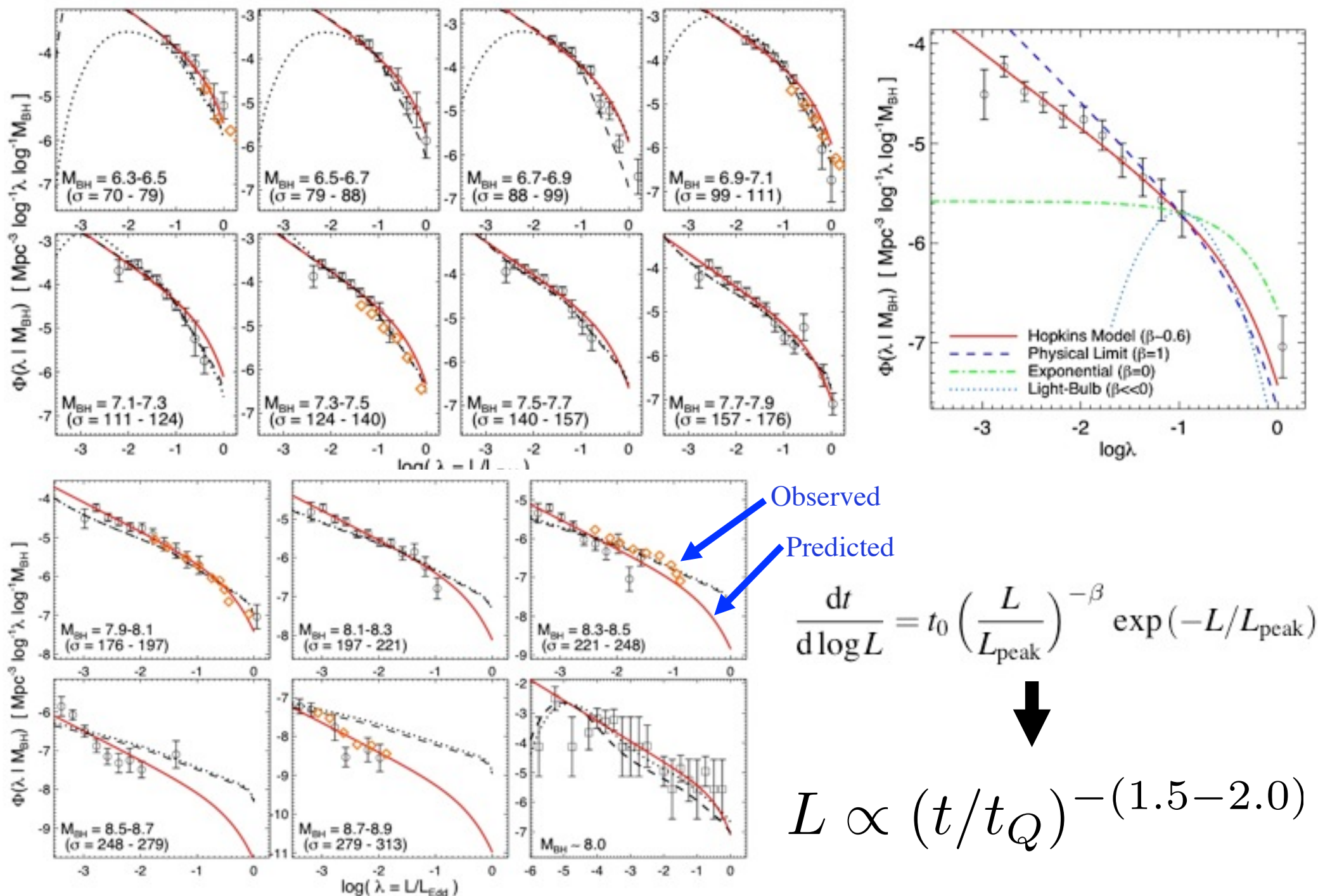
Hopkins, Lidz, Coil,  
Myers et al. 2007

➤ Weak dependence of clustering on observed luminosity

(Croom et al.,  
Adelberger & Steidel,  
Myers et al.,  
Coil et al., Porciani et al.)



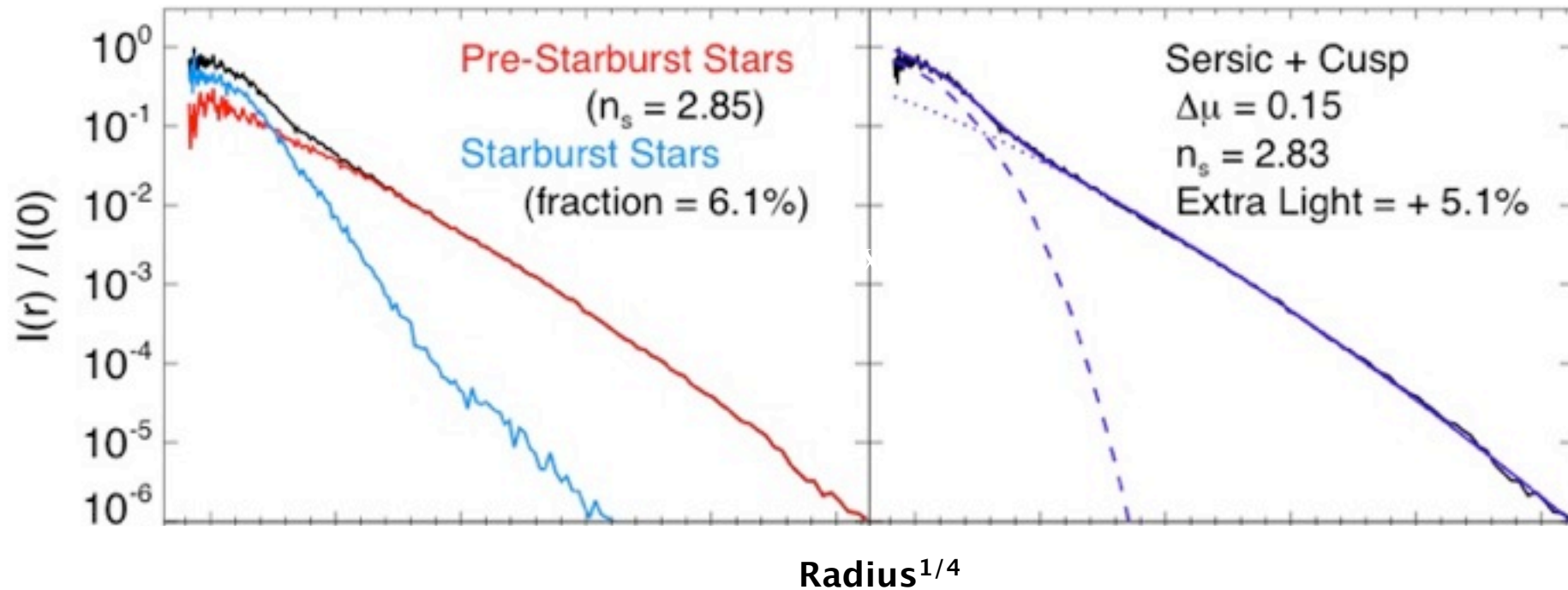
# Directly Apparent in the Observed Eddington Ratio Distribution



# Structure in Elliptical Light Profiles

## RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

Q: Can we design a decomposition that separates disk/starburst stars in the final profile?





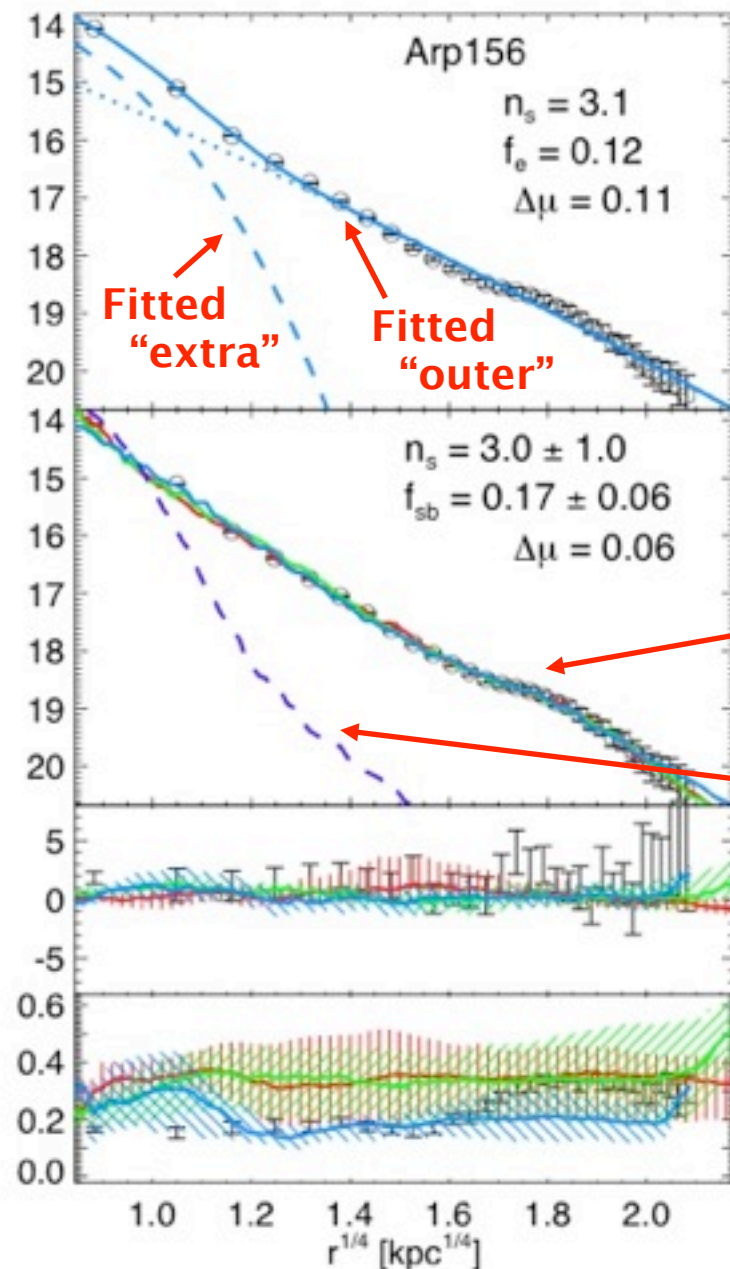
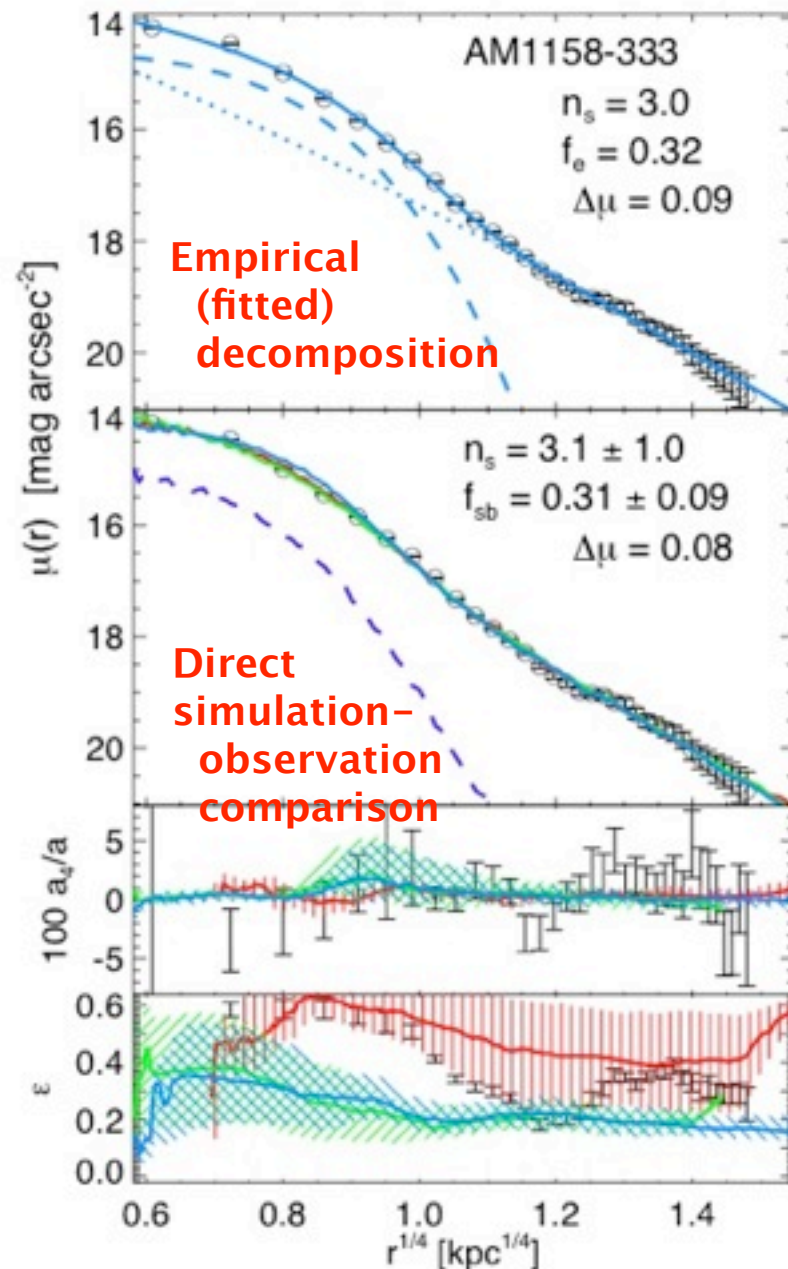
# Application: Merger Remnants

## RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

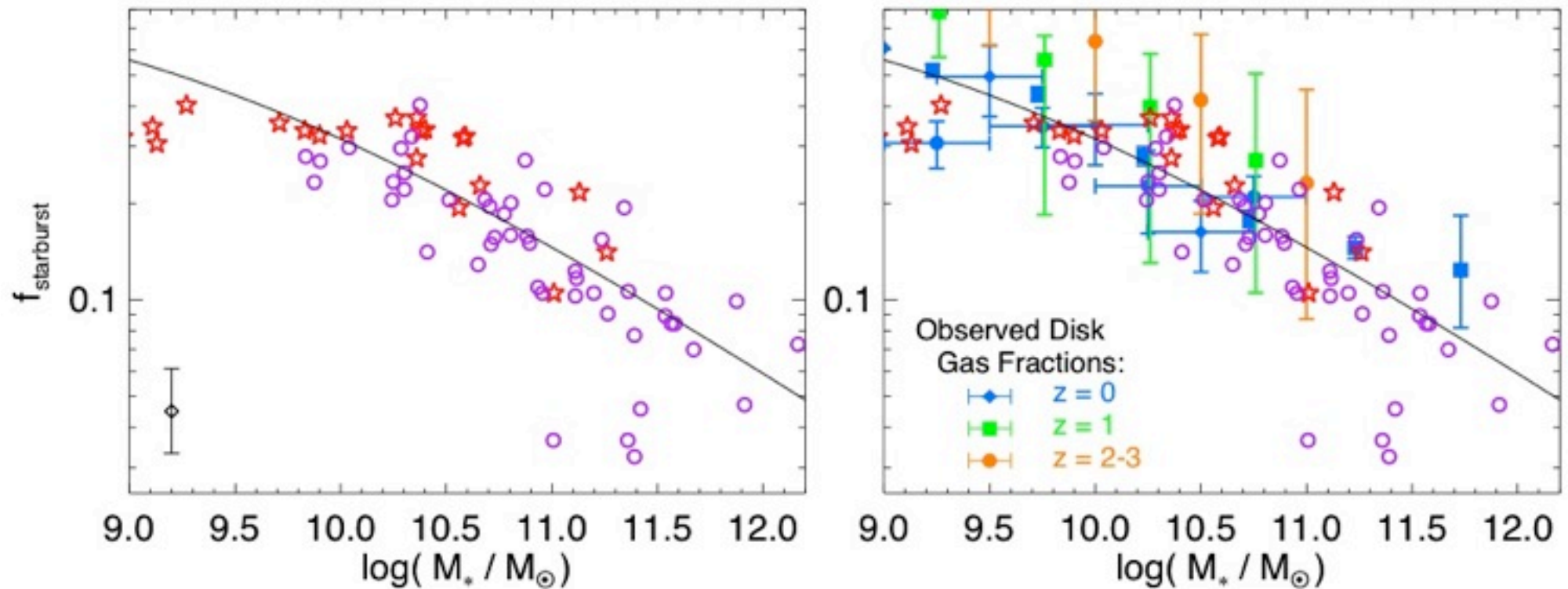
- Apply this to a well-studied sample of local merger remnants & ellipticals:



# Structure in Elliptical Light Profiles

## RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

Starburst gas mass needed to match observed profile (or fitted to profile shape):



- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks