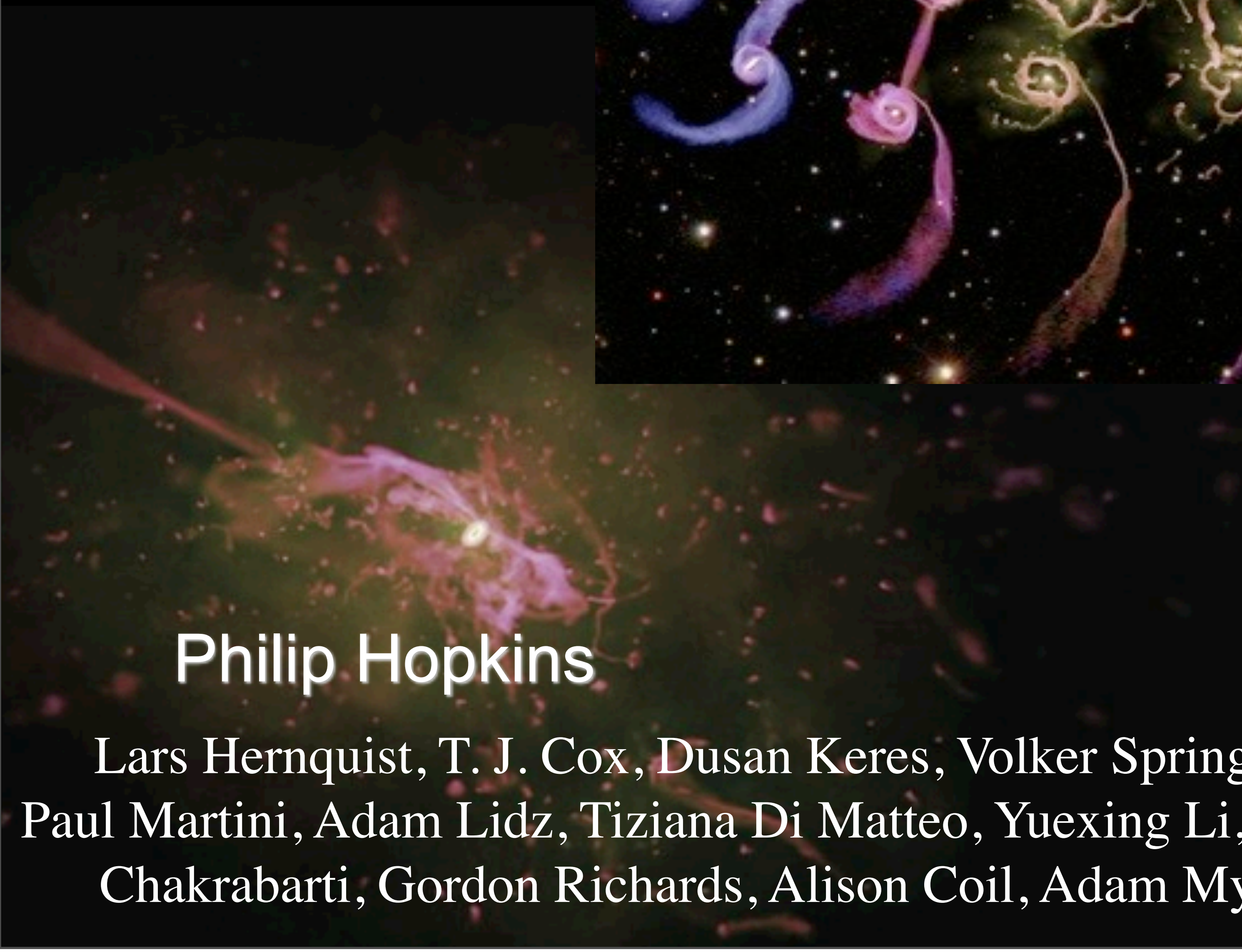
# Quasars, Feedback, and Galaxy Interactions



Philip Hopkins

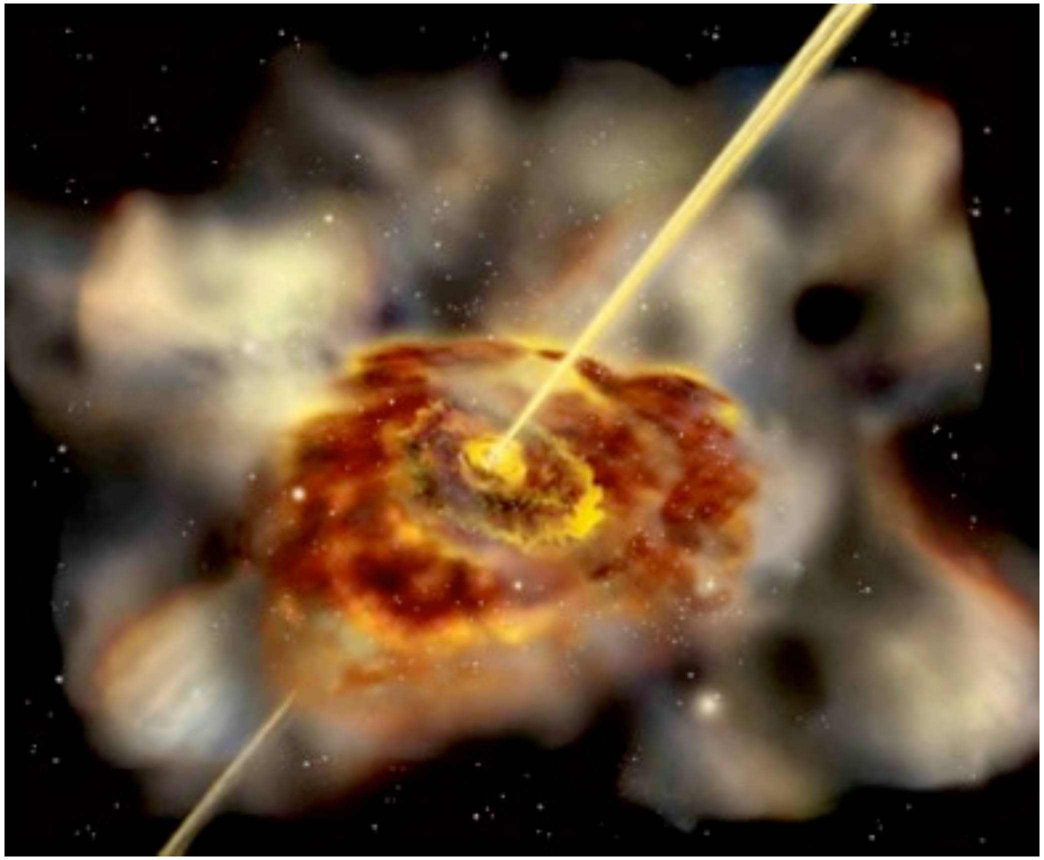
09/24/08

Lars Hernquist, T. J. Cox, Dusan Keres, Volker Springel, Brant Robertson, Paul Martini, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Josh Younger, Sukanya Chakrabarti, Gordon Richards, Alison Coil, Adam Myers, and many more

# Motivation

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

- Every massive galaxy hosts a supermassive black hole

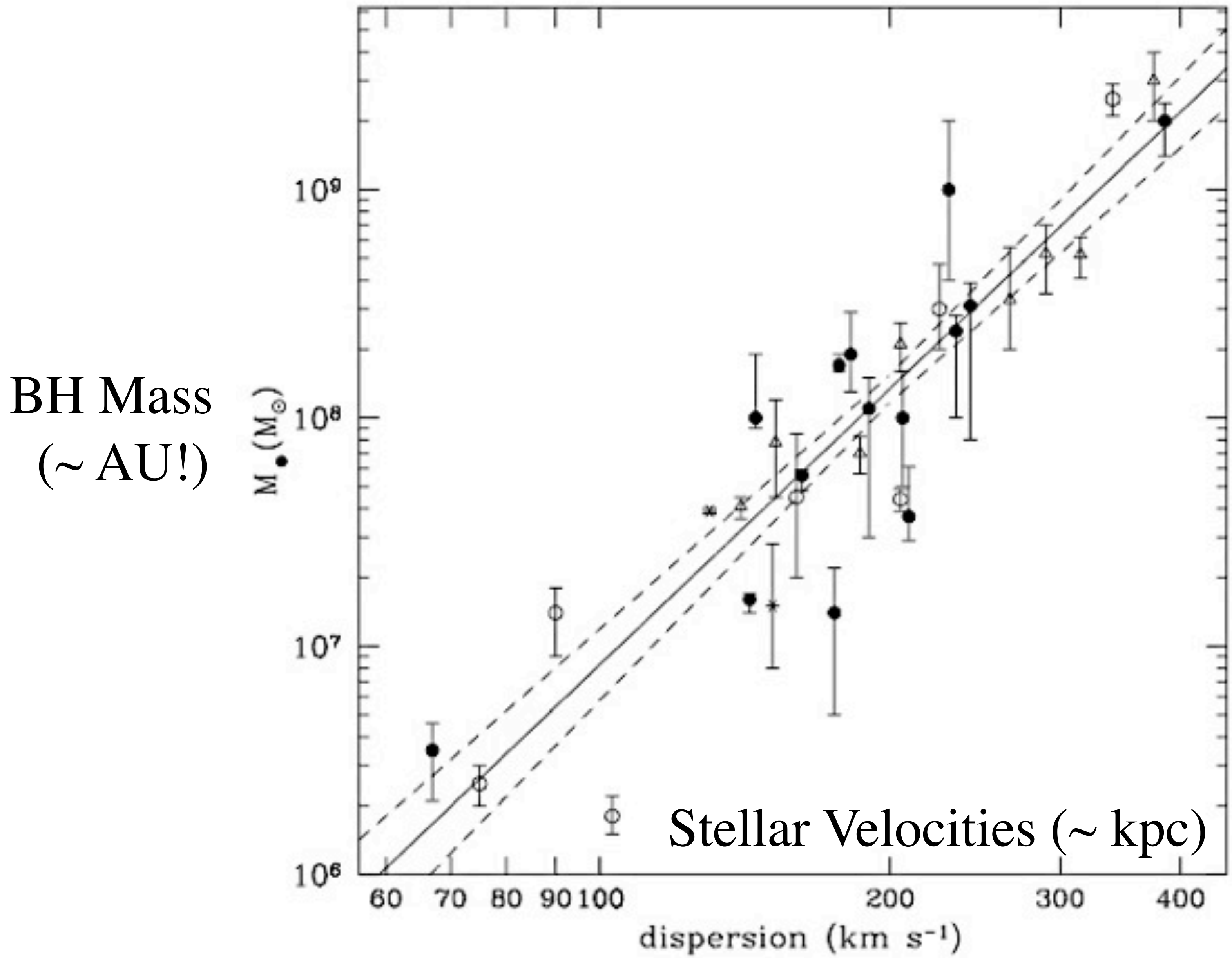



- These BHs accreted most of their mass in bright, short lived quasar accretion episodes: the “fossil” quasars

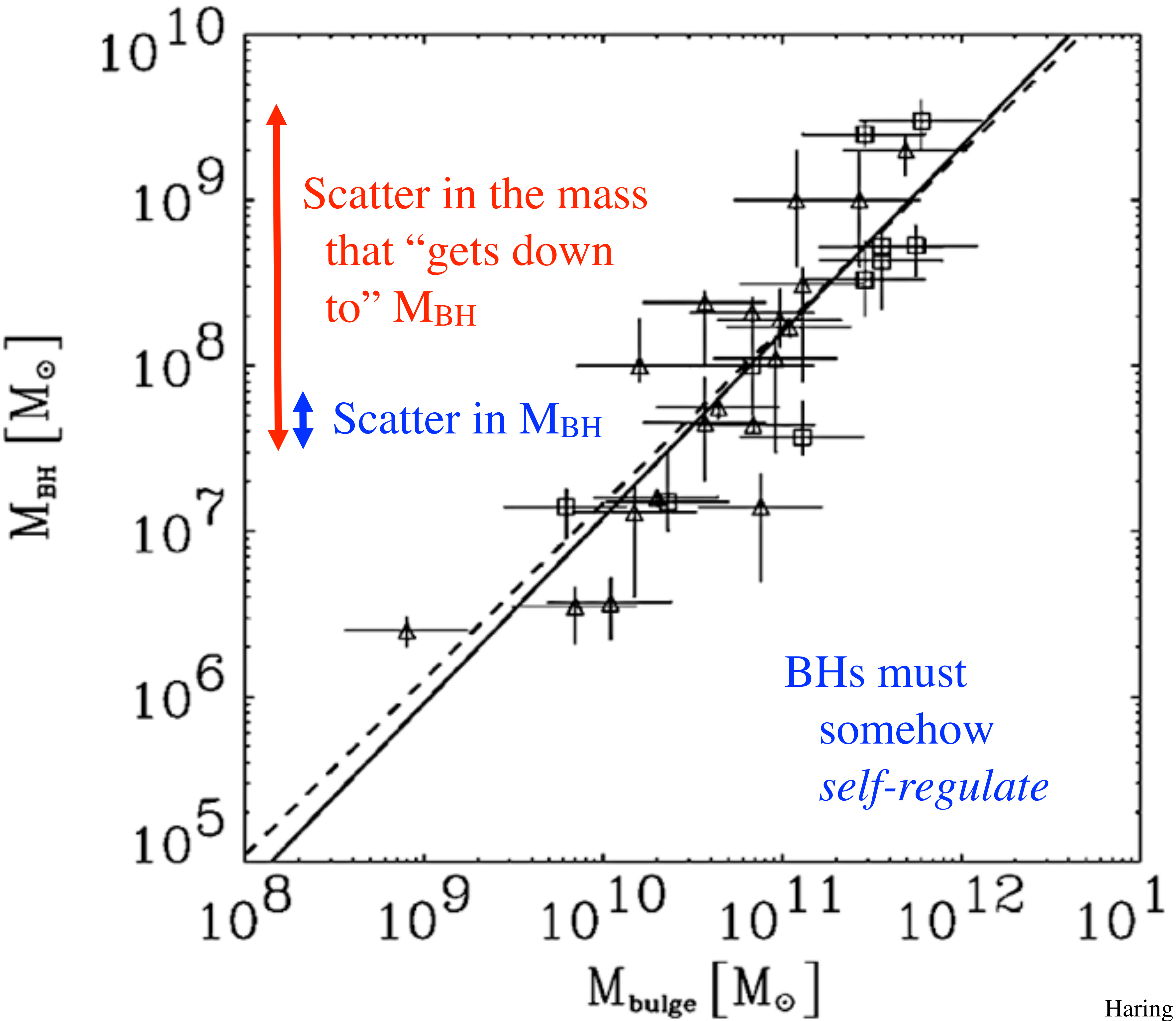
# Motivation

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

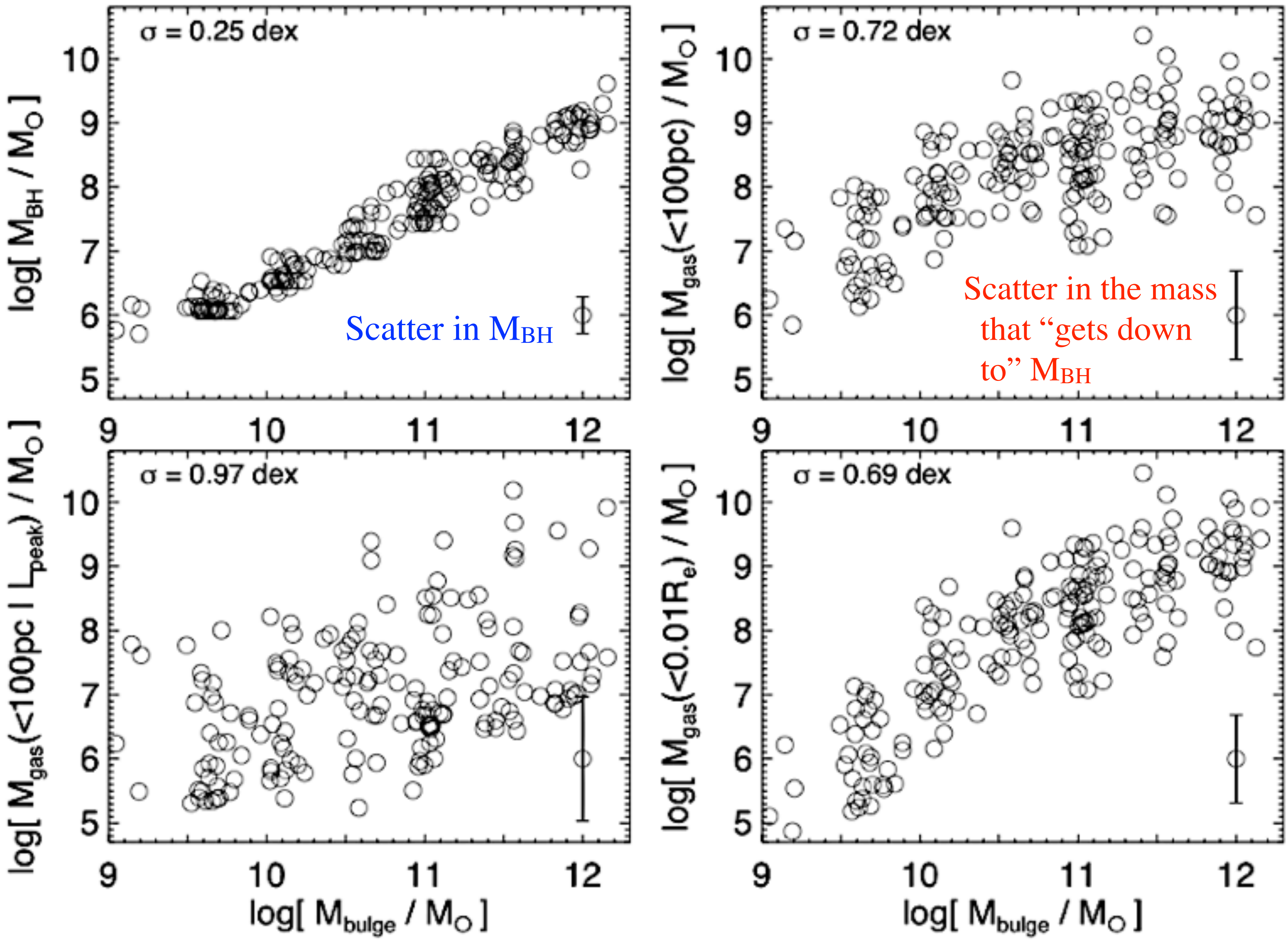
- Black holes are somehow sensitive to their host galaxies (bulges):




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




Haring & Rix '04


σ = 0.25 dex
log[ M_BH / M_O ]
Scatter in M_BH
σ = 0.72 dex
log[ M_gas(<100pc) / M_O ]
Scatter in the mass that "gets down to" M_BH
σ = 0.97 dex
log[ M_gas(<100pc | L_peak) / M_O ]
σ = 0.69 dex
log[ M_gas(<0.01R_e) / M_O ]
log[ M_bulge / M_O ]
log[ M_bulge / M_O ]

# Simplest Idea:

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

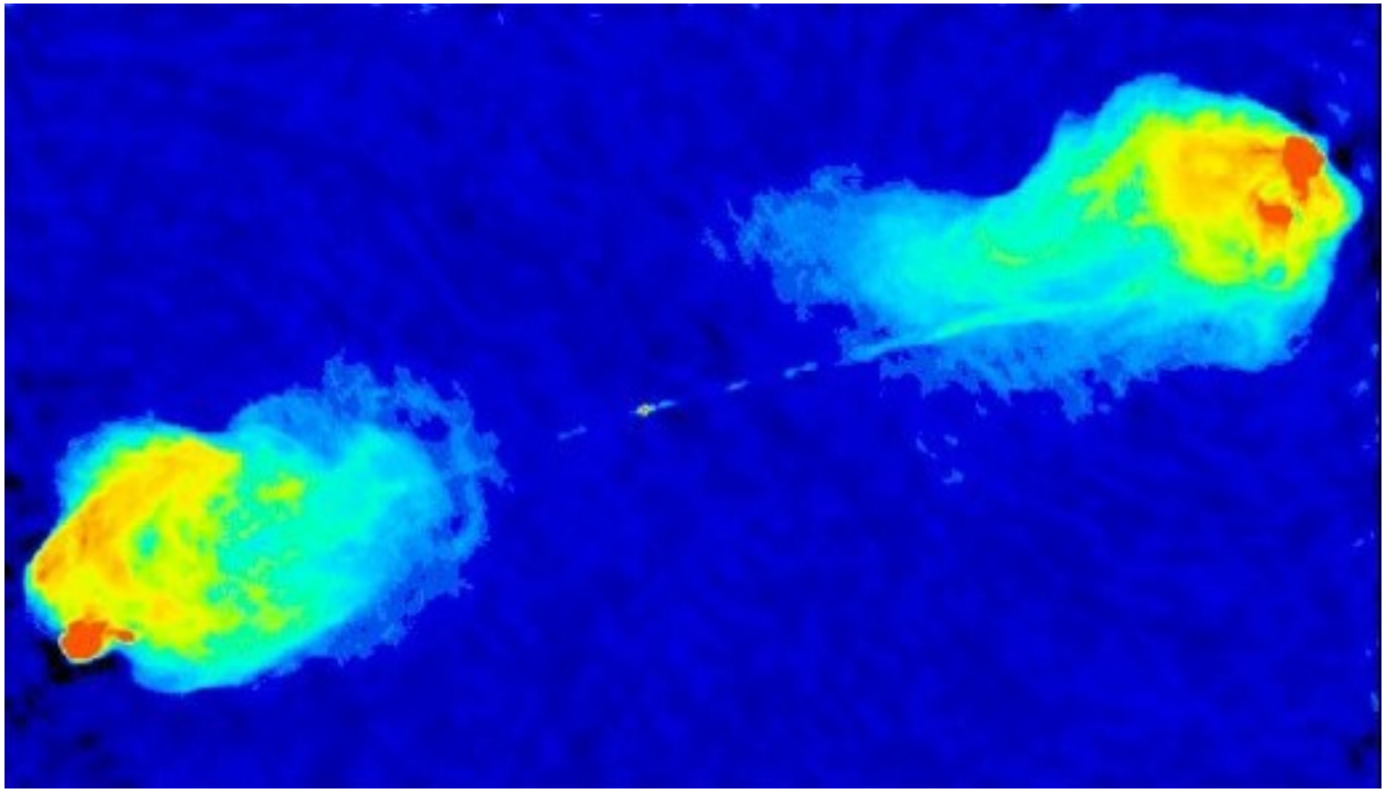
- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r\,(dM_{BH}/dt)\,c^2$ ($e_r \sim 0.1$)
- Total energy radiated:
  - $\sim 0.1\, M_{BH}\, c^2 \sim 10^{61}$ ergs in a typical $\sim 10^8\, M_{sun}$ system
- Compare this to the gravitational binding energy of the galaxy:
  - $\sim M_{gal}\, s^2 \sim (10^{11}\ \mathrm{Msun})\,(200\ \mathrm{km/s})^2 \sim 10^{59}$ 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 ~ 1-5% of the luminosity can couple, then accretion *must* stop (the gas will all be blown out the galaxy) when
    - $MBH \sim (a/he_r)\, M_{gal}\, (s/c)^2 \sim 0.002\, M_{gal}$

# Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- This "feedback" energy can affect other things:
  - star formation
  - cooling
  - subsequent growth of the galaxy
  - subsequent growth of nearby galaxies!

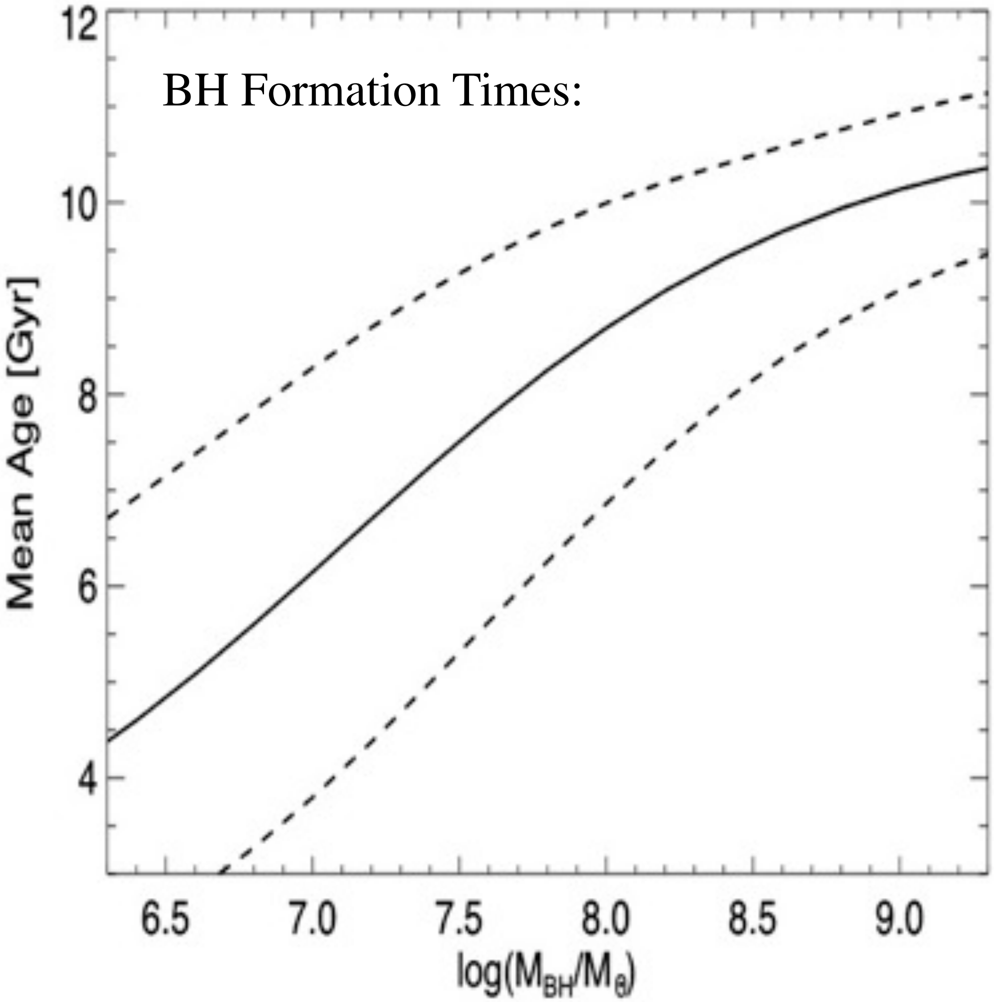
- It comes in many forms:
  - radio jets
  - winds (from the accretion disk)
  - radiation pressure/ galactic winds
  - Compton heating
  - ionization

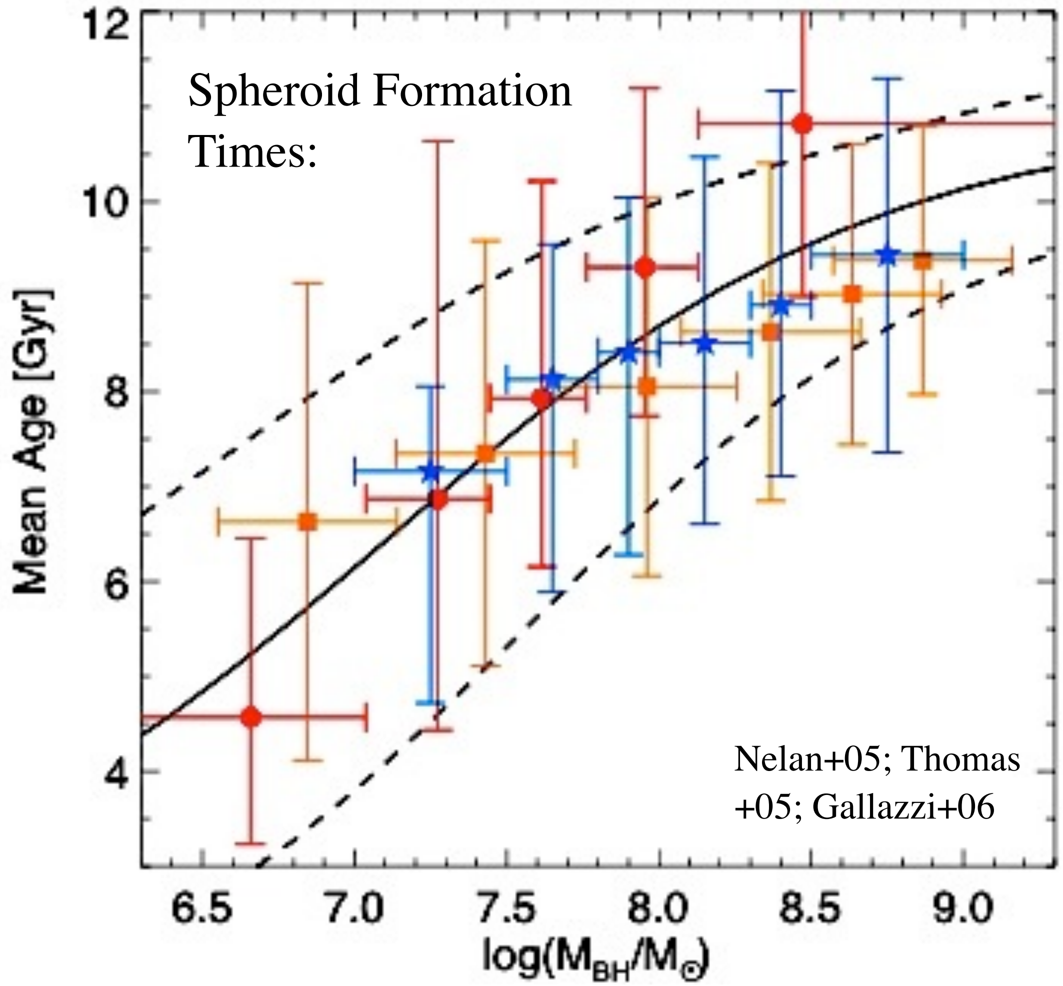


# Motivation

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

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

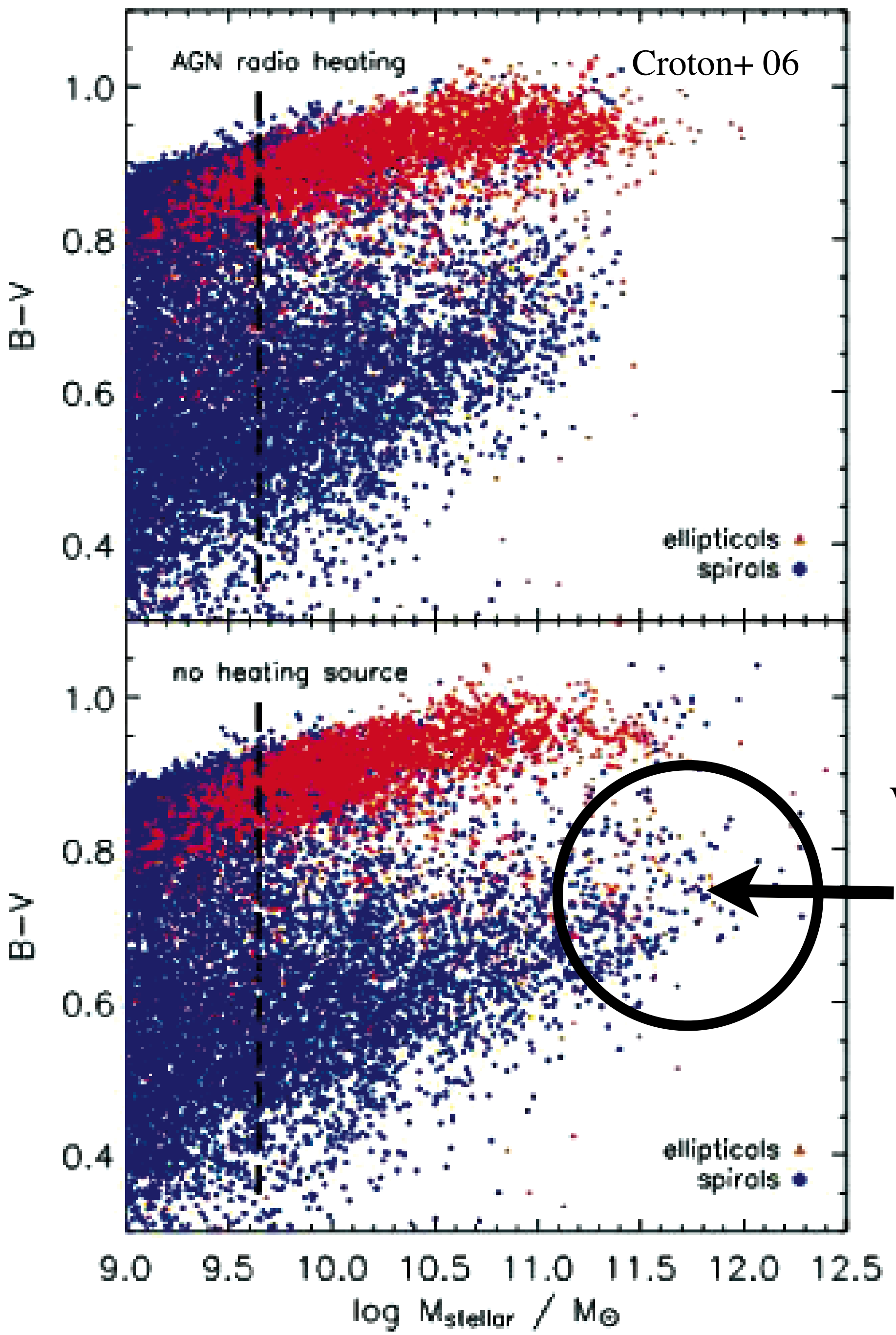


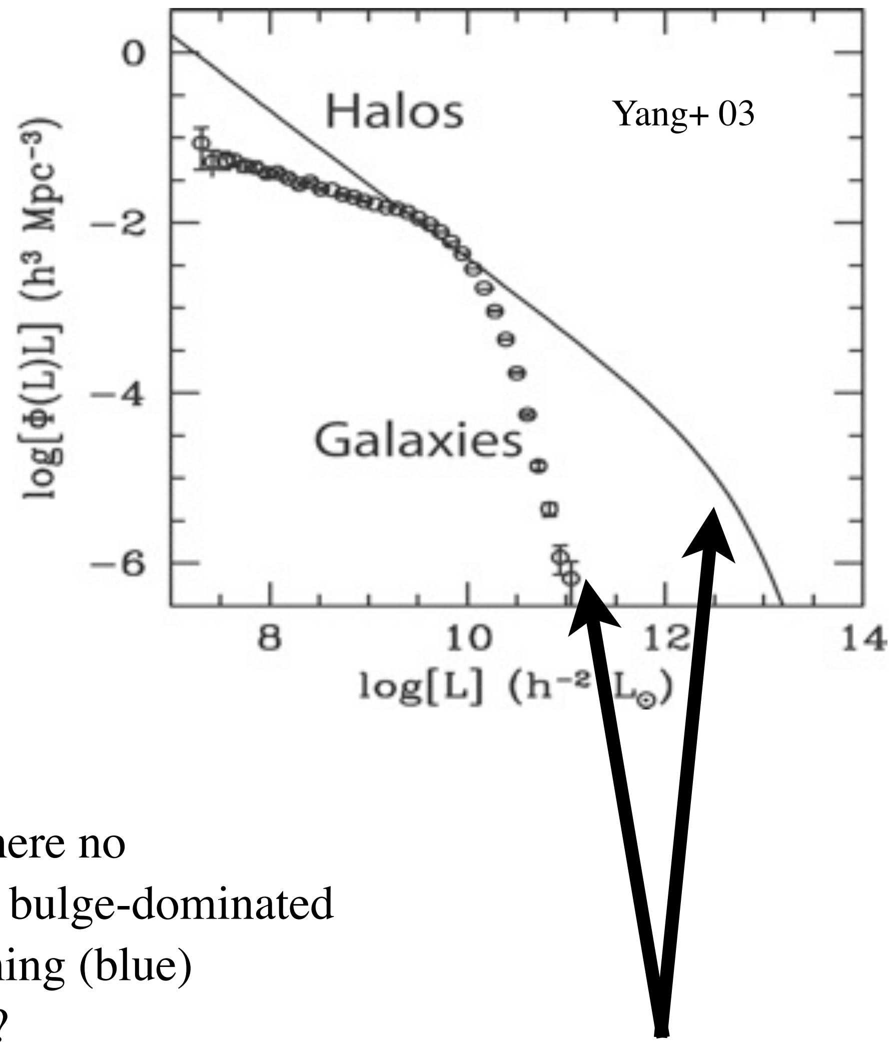

PFH, Lidz, Coil, Myers, et al. 2007

# Motivation

## MAYBE THIS CAN EXPLAIN OTHER, LONG-STANDING PROBLEMS?



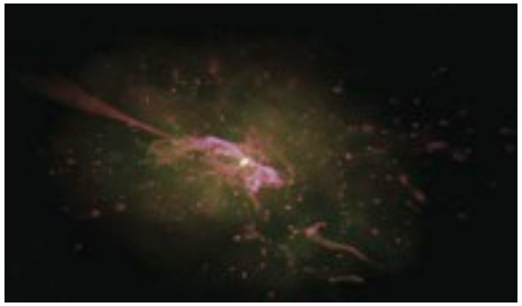

Why are there no massive, bulge-dominated star forming (blue) galaxies?



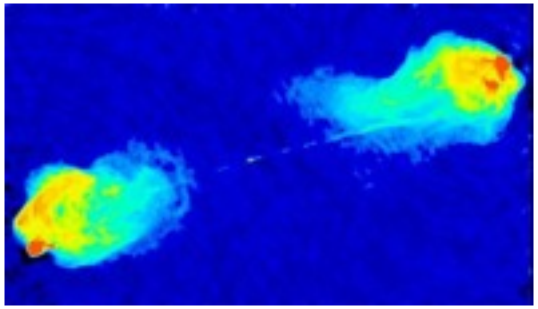

Why do massive galaxies *stop* growing while their host halos keep growing?

## "Transition" vs. "Maintenance"

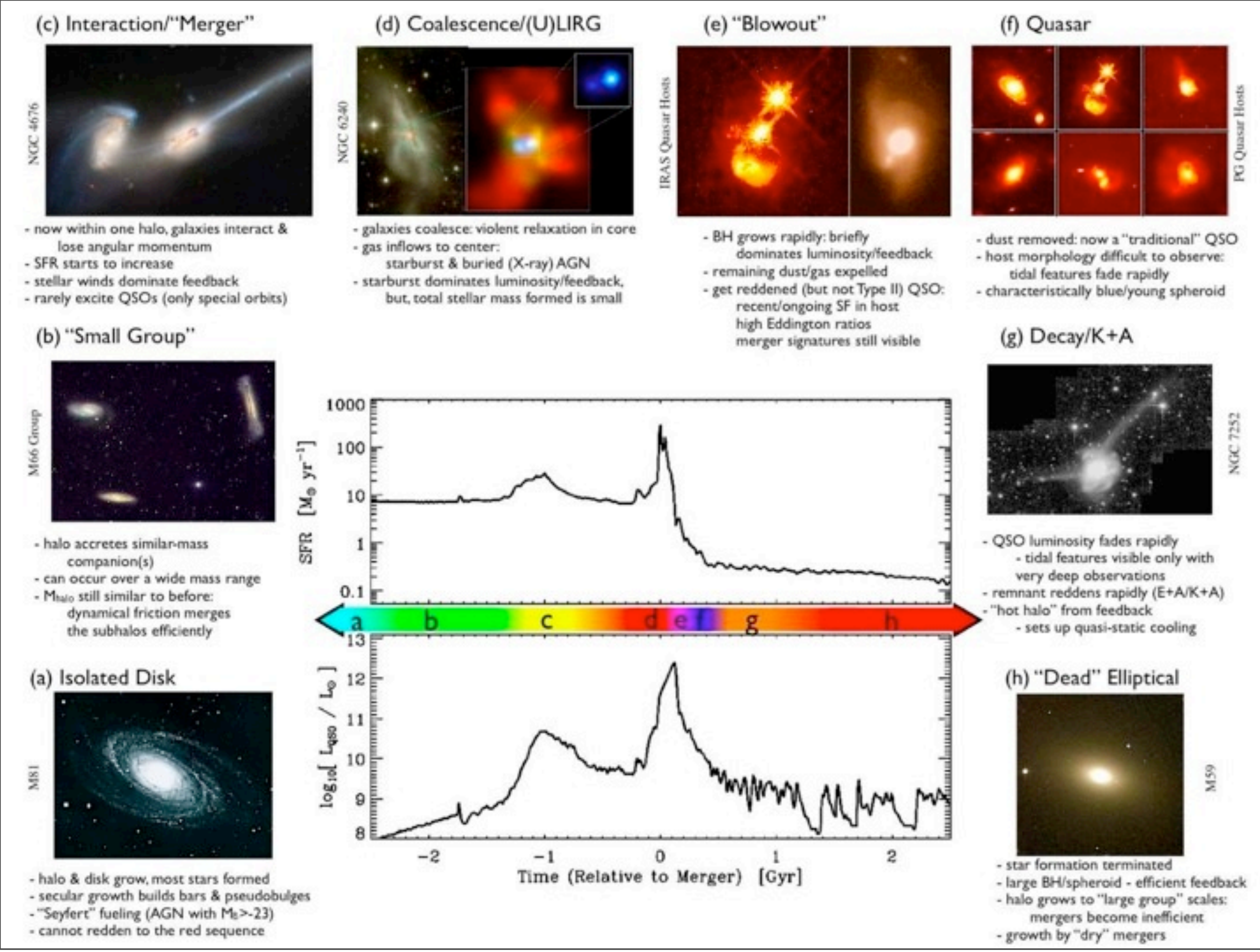
- Move mass from Blue to Red
- Rapid
- Small scales
- "Quasar" mode (high mdot)
- Morphological Transformation
- Gas-rich/Dissipational Mergers



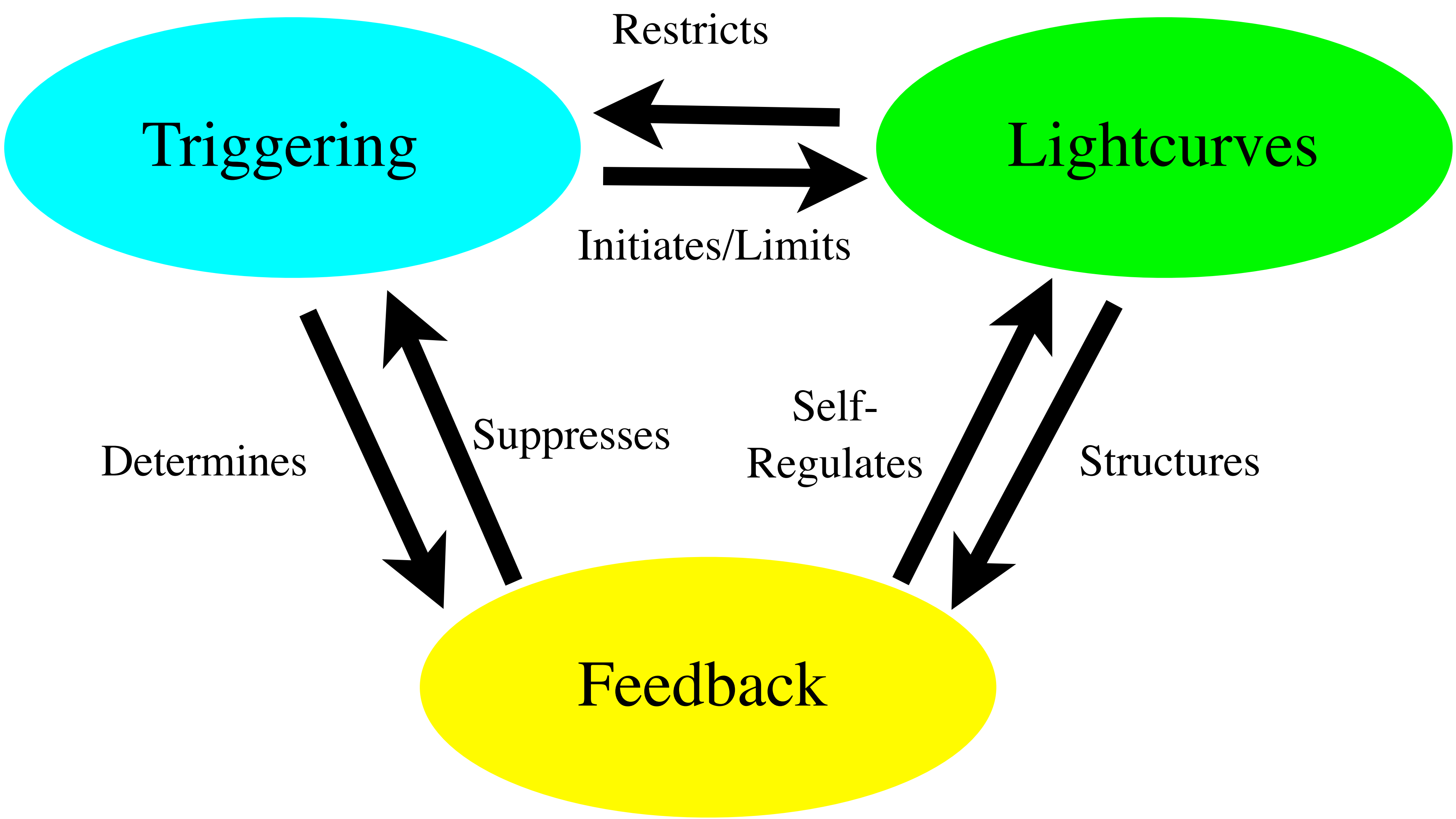
- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- "Radio" mode (low mdot)
- Subtle morphological change
- "Dry"/Dissipationless Mergers



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

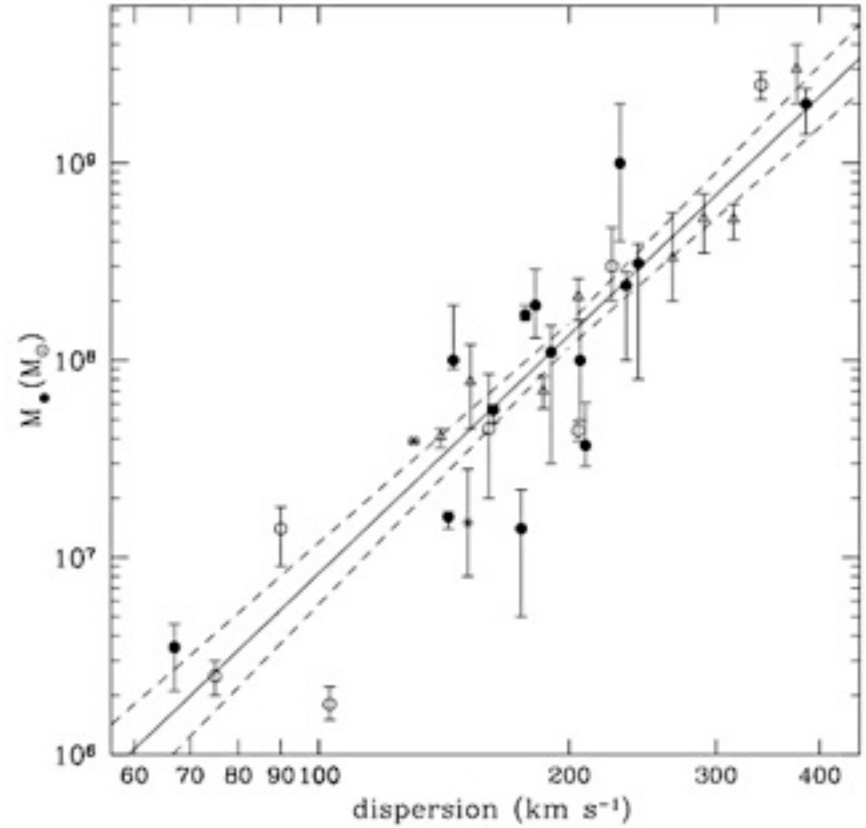

(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small
(e) "Blowout"
IRAS Quasar Hosts
- 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
PG Quasar Hosts
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{halo}$ still similar to before: dynamical friction merges the subhalos efficiently
(g) Decay/K+A
NGC 7252
- 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
SFR $[M_\odot\ yr^{-1}]$
1000
100
10
1
0.1
a b c d e f g h
$\log_{10}[L_{QSO}/L_\odot]$
13
12
11
10
9
8
−2 −1 0 1 2
Time (Relative to Merger) [Gyr]
(a) Isolated Disk
M81
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with $M_B$>-23)
- cannot redden to the red sequence
(h) "Dead" Elliptical
M59
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers

# Three Outstanding (Inseparable?) Questions:



## 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 (~ few $10^7$ years)

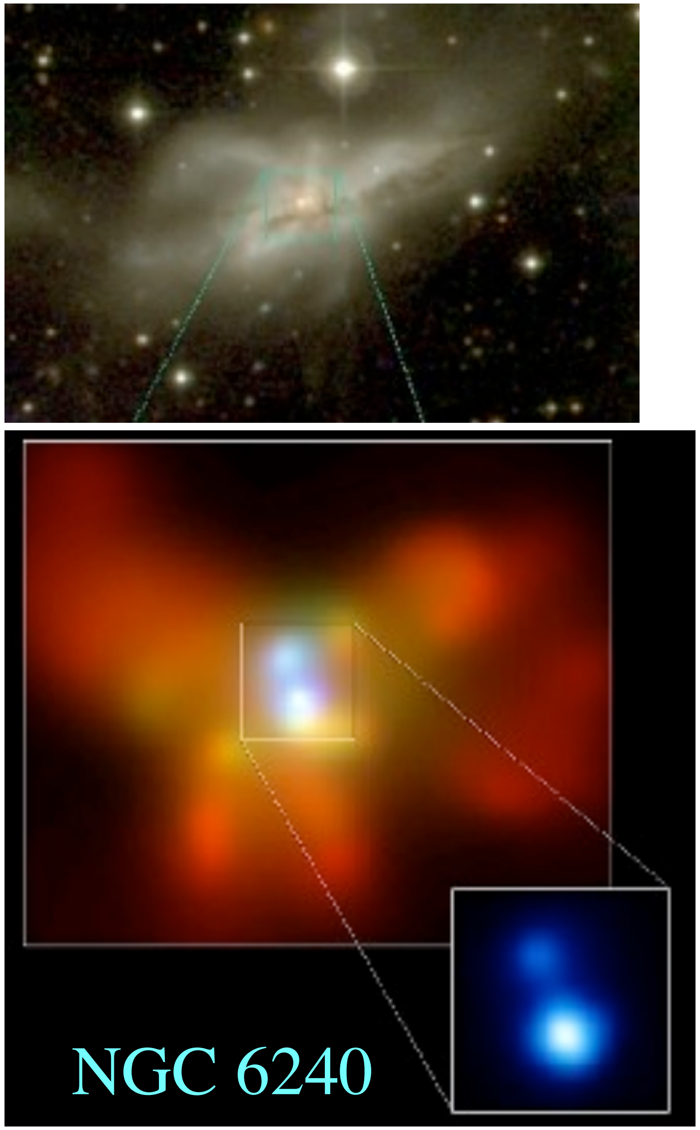
* Lynden-Bell (1967): orbits of stars redistributed in phase space by large, rapid potential fluctuations

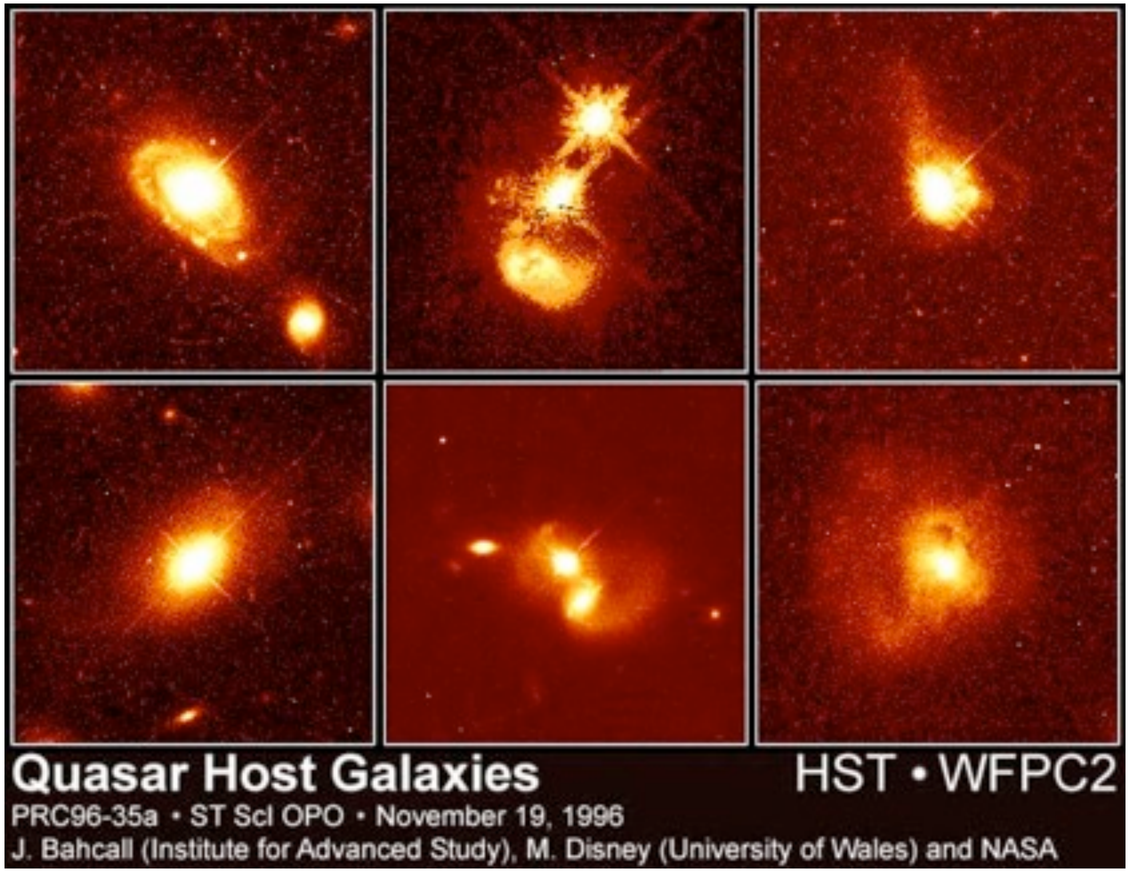
  → stellar dynamics; freefall timescale

# Candidate Process: Gas-Rich, Major Merger

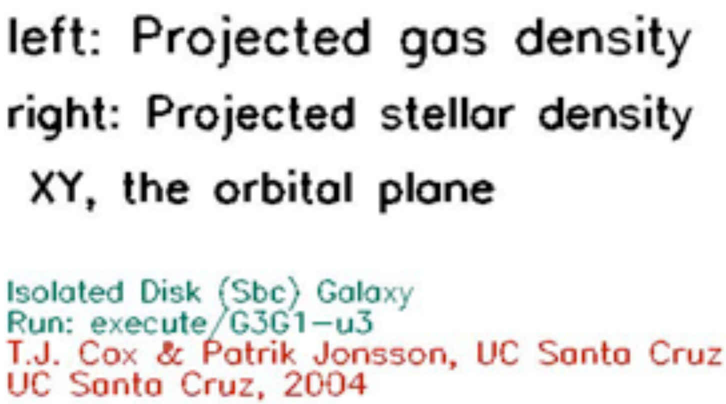
- Locally, seen related to:
  - growth of spheroids
  - causing starbursts (ULIRGs)
  - fueling SMBH growth, quasar activity

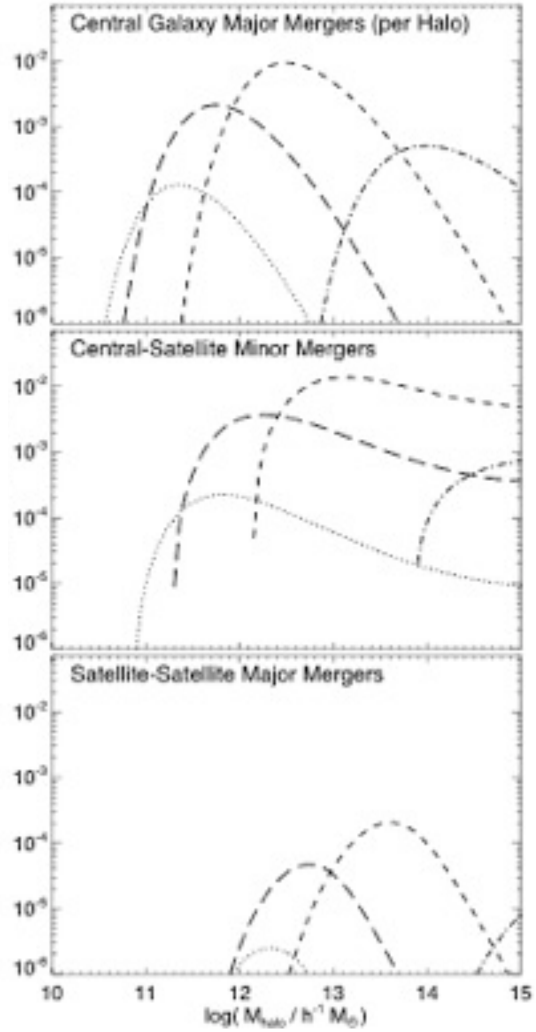
Komossa et al. (2003)

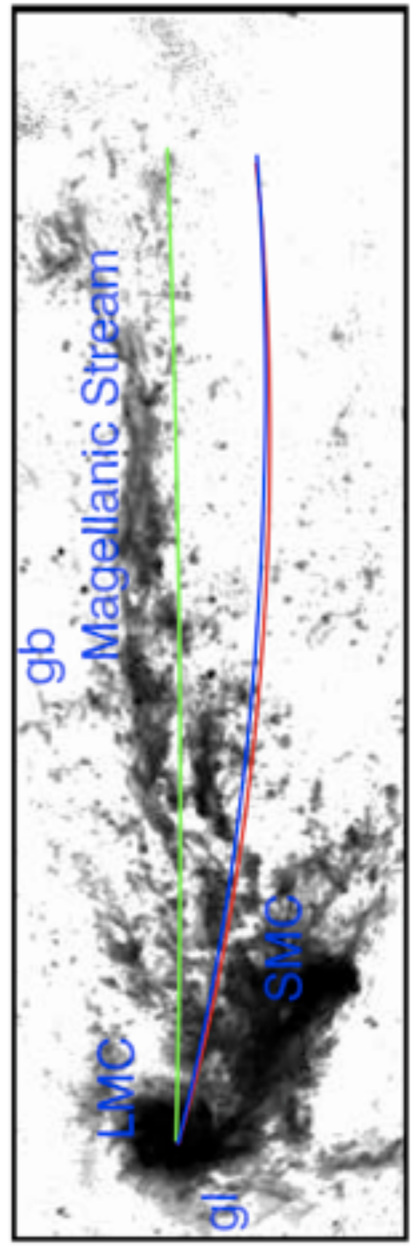


# Other Fueling Mechanisms: Minor Mergers



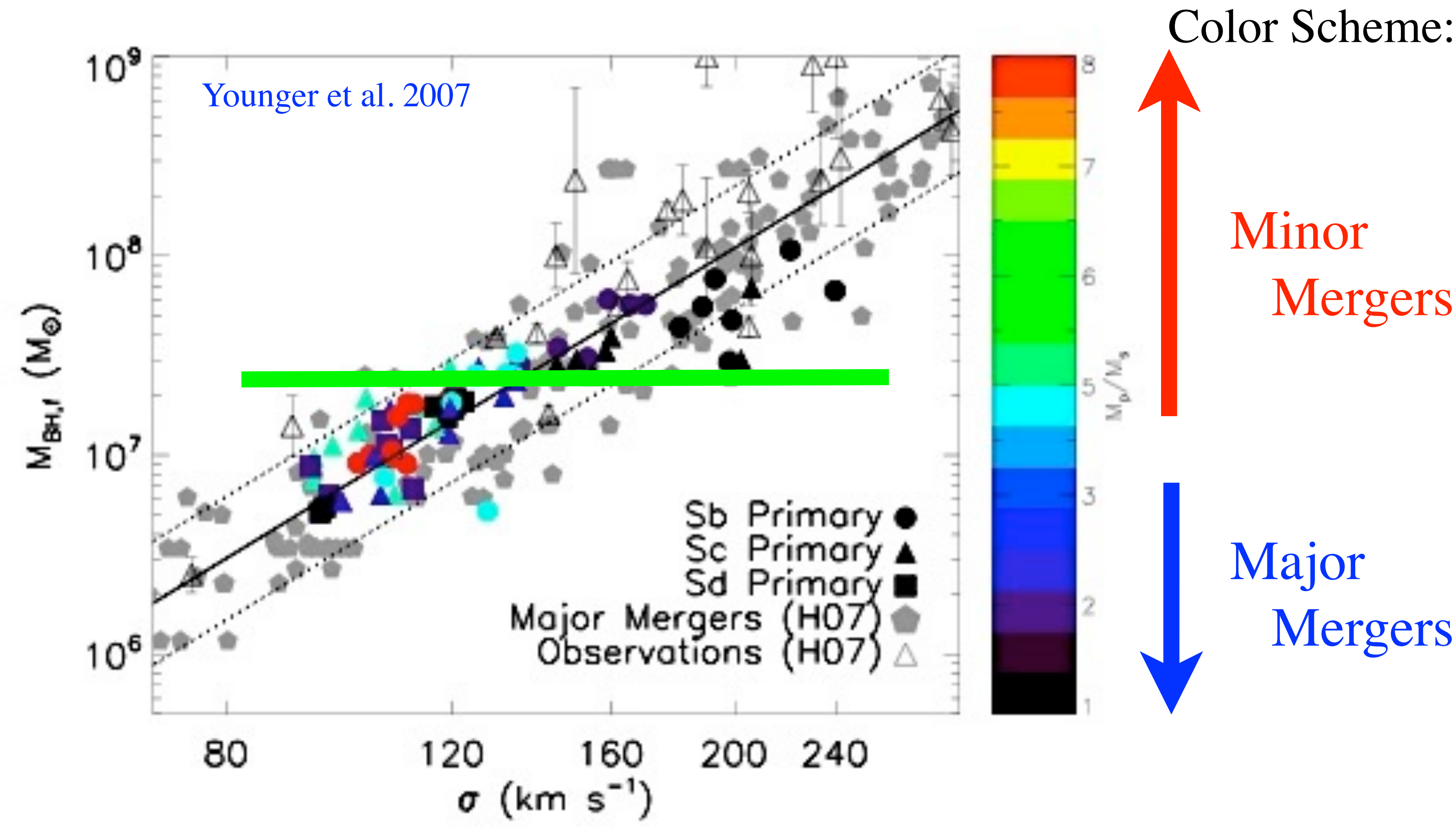




Besla et al. (2007)

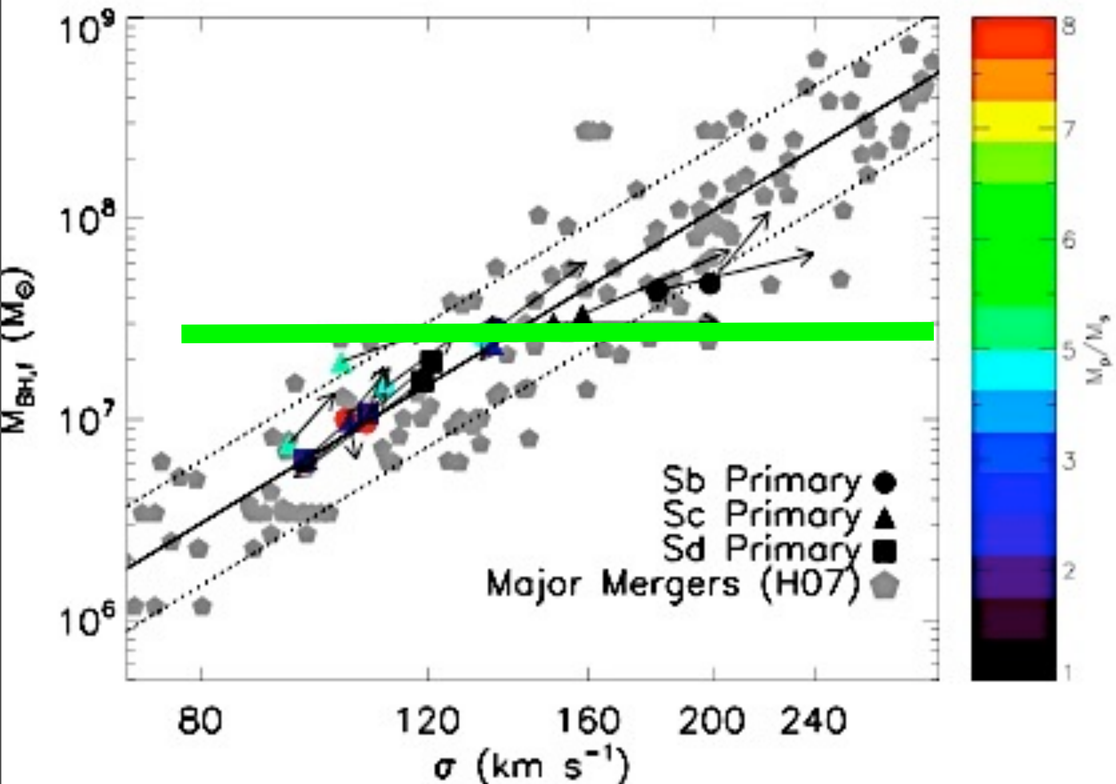
- Minor Mergers
  - Not so violent -probably don't dominate spheroid formation (LMC/SMC)
  - Not very efficient: even if growth ~ M_secondary/M_primary, major mergers "win"

# Other Fueling Mechanisms: Minor Mergers



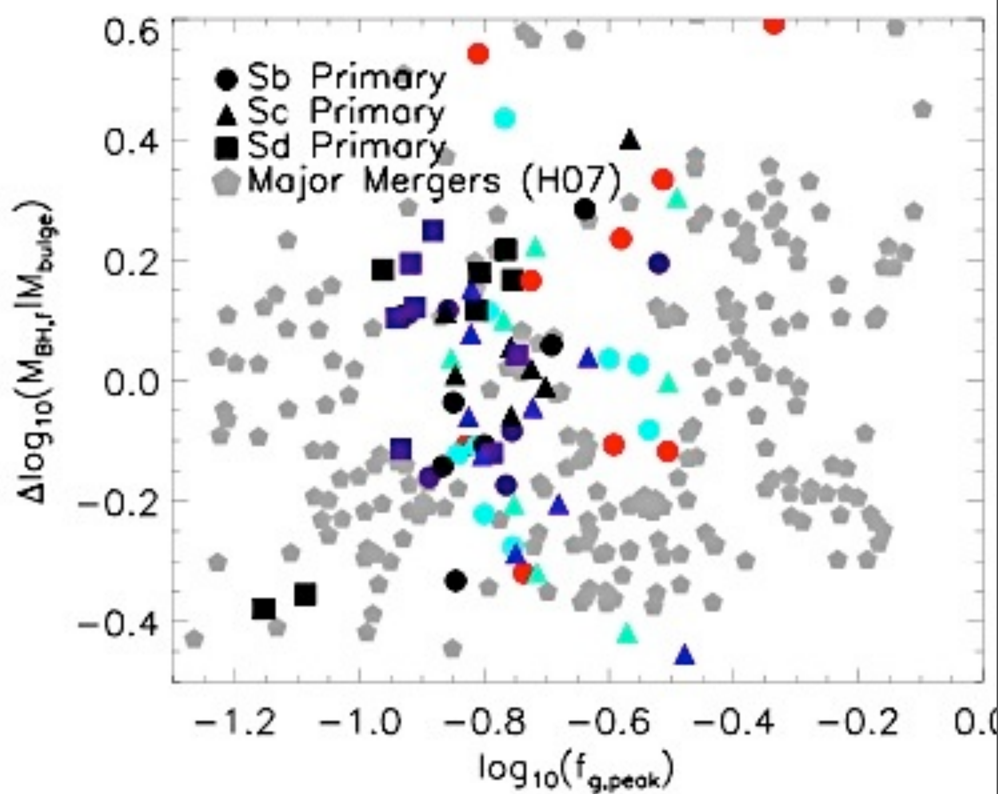

- Minor Mergers
  - Can get to ~1-2 10^7 M_sun ::: *very* hard to push beyond this

# Other Fueling Mechanisms: Minor Mergers




- Increase f_gas to ~0.8-1.0: *same* upper limits

Final M_BH relative to mean

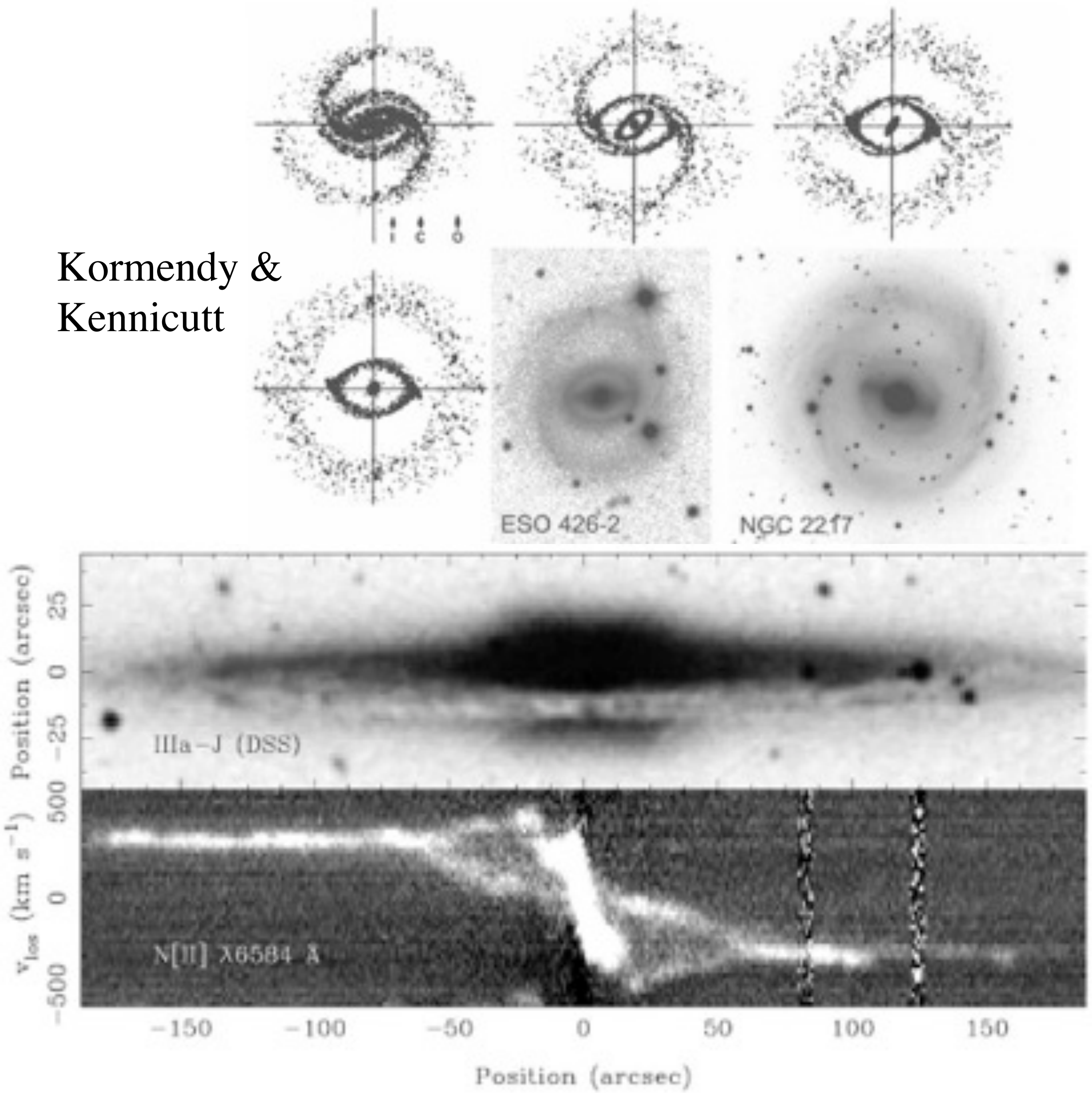


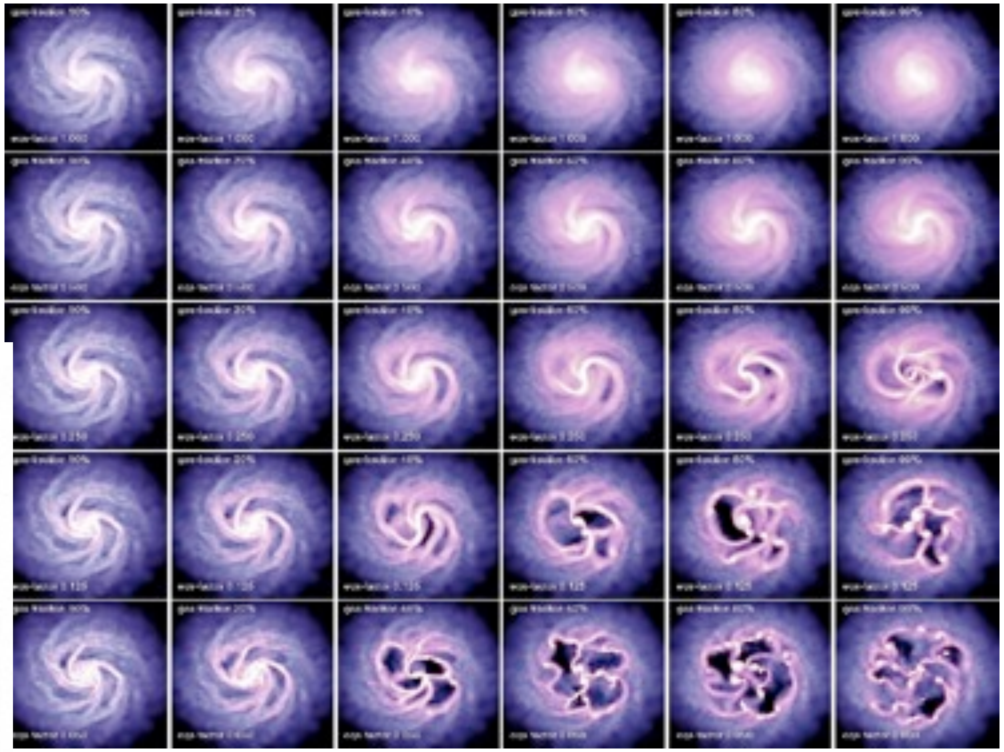

Mass of gas supplied to BH

- BH doesn't care how much gas you give it:: building the potential depth is the hard part -- the BH will easily "catch up"

# Other Fueling Mechanisms: Disk/Bar Instabilities

Kormendy & Kennicutt



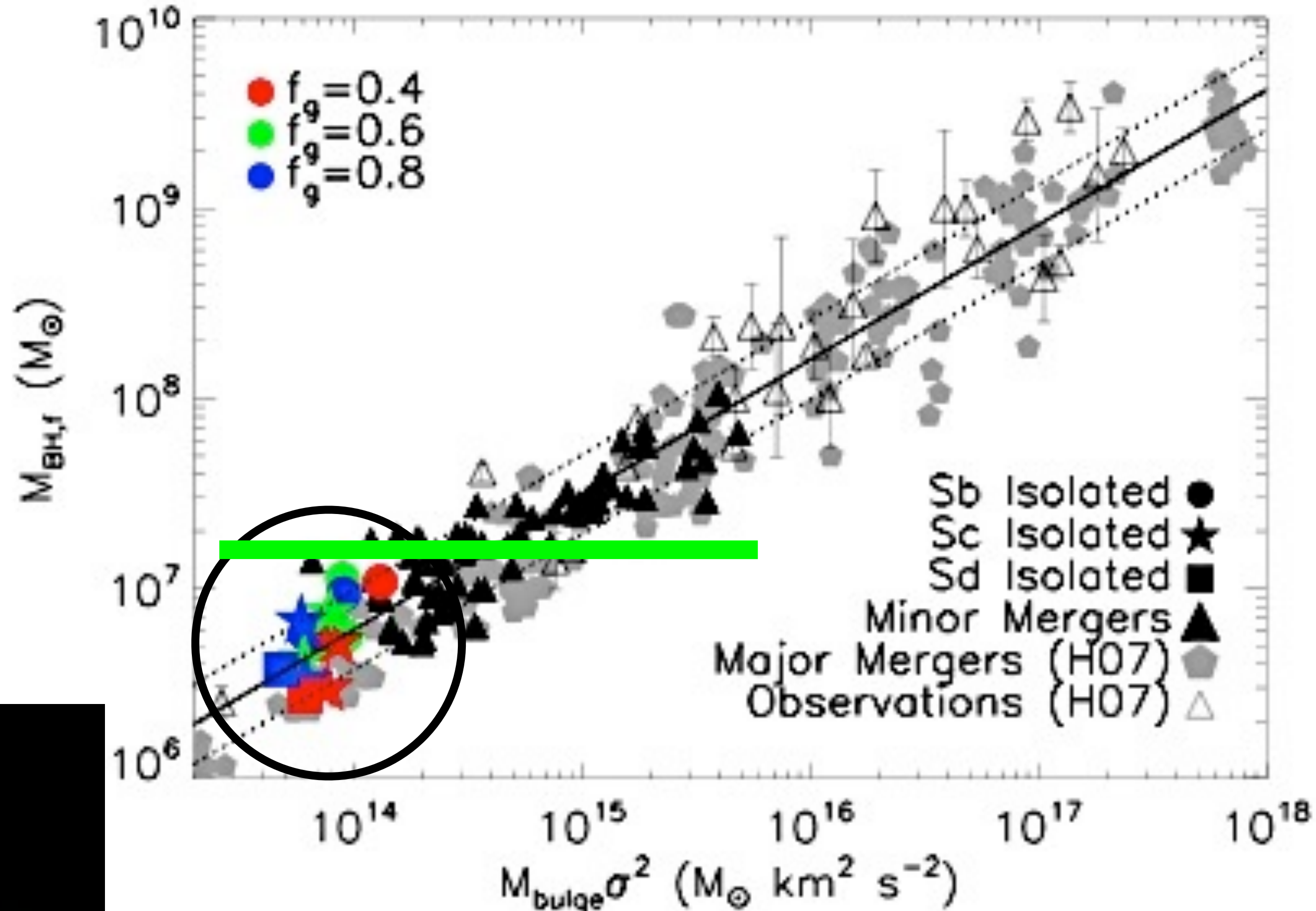



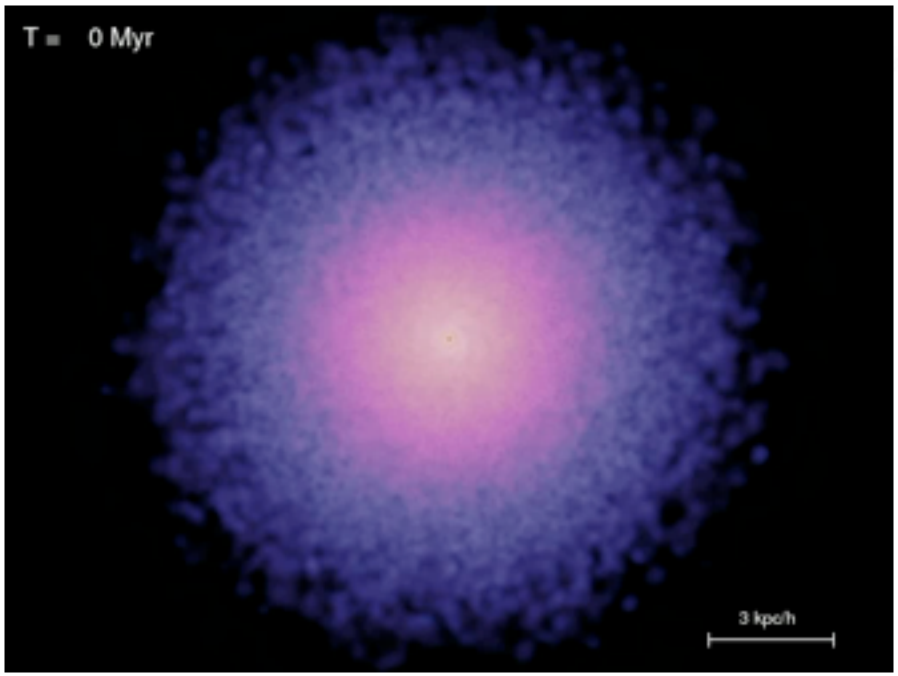
Springel et al. (2005)

- Secular Evolution/Disk Instabilities
  - Most mass in "classical" bulges, not "pseudobulges":
    - But, *are* important below <~ Sa-types
  - Does it really solve the angular momentum problem? (Jogee et al.)

# Other Fueling Mechanisms: Disk/Bar Instabilities

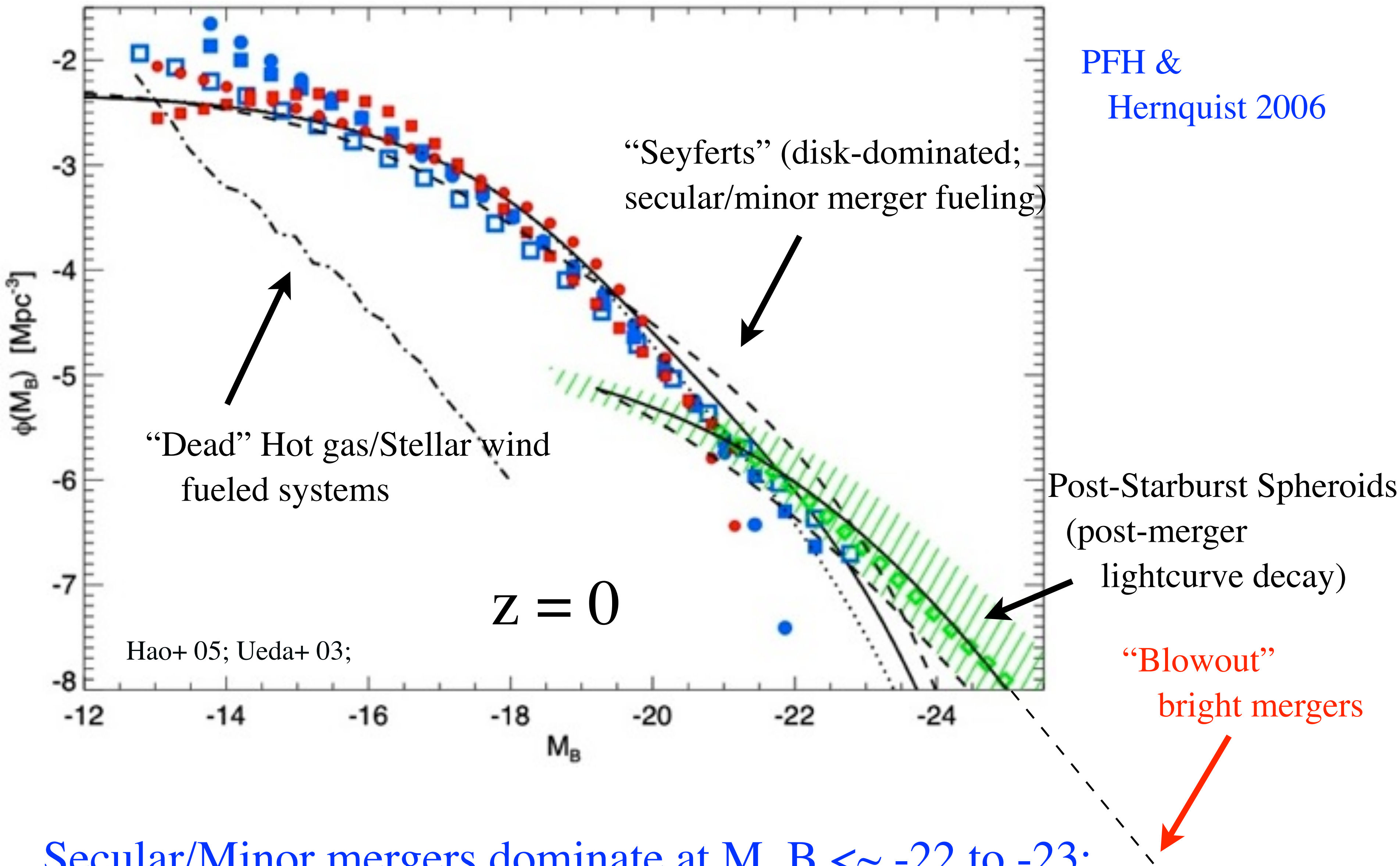
Bar & Toomre-unstable disk simulations:




- Same caveats as minor mergers:
  don't build massive bulges:
  doesn't matter if you can get the gas in!

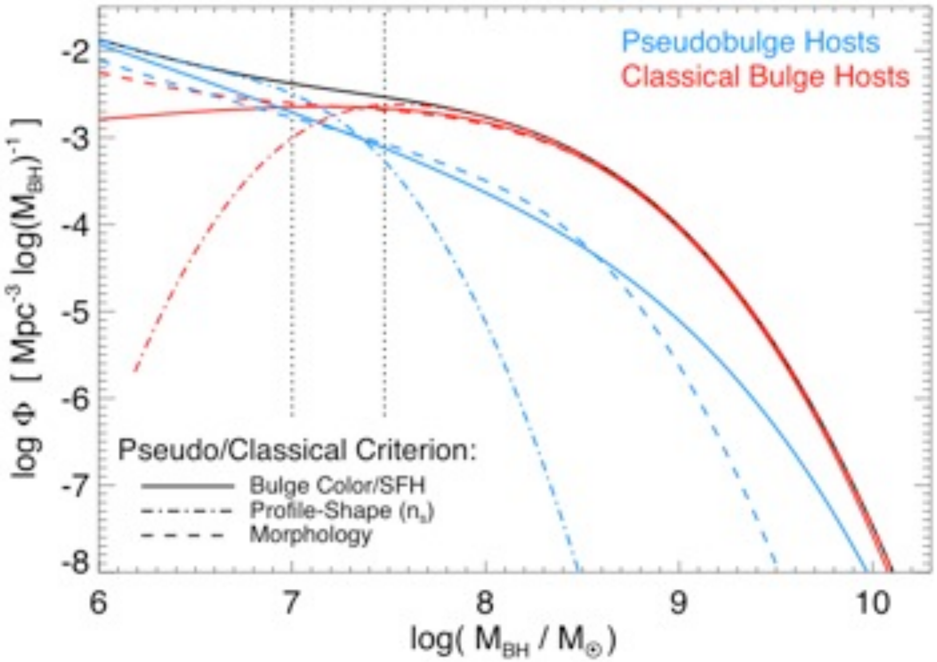
# Emergent Picture:

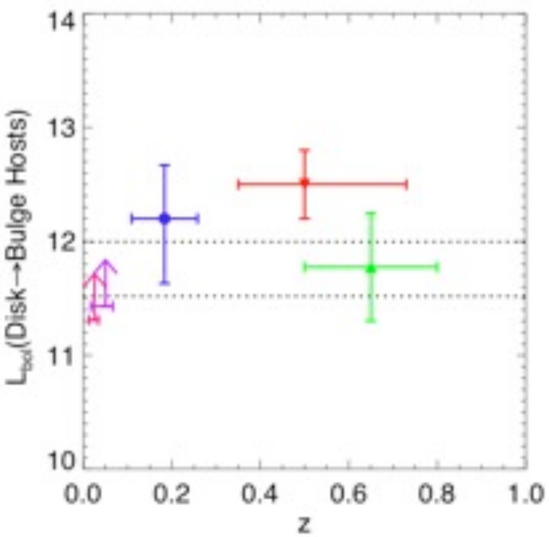



- Secular/Minor mergers dominate at M_B <~ -22 to -23: (L_x <~ a few 10^43)
  - Seyfert-Quasar divide is a good proxy!

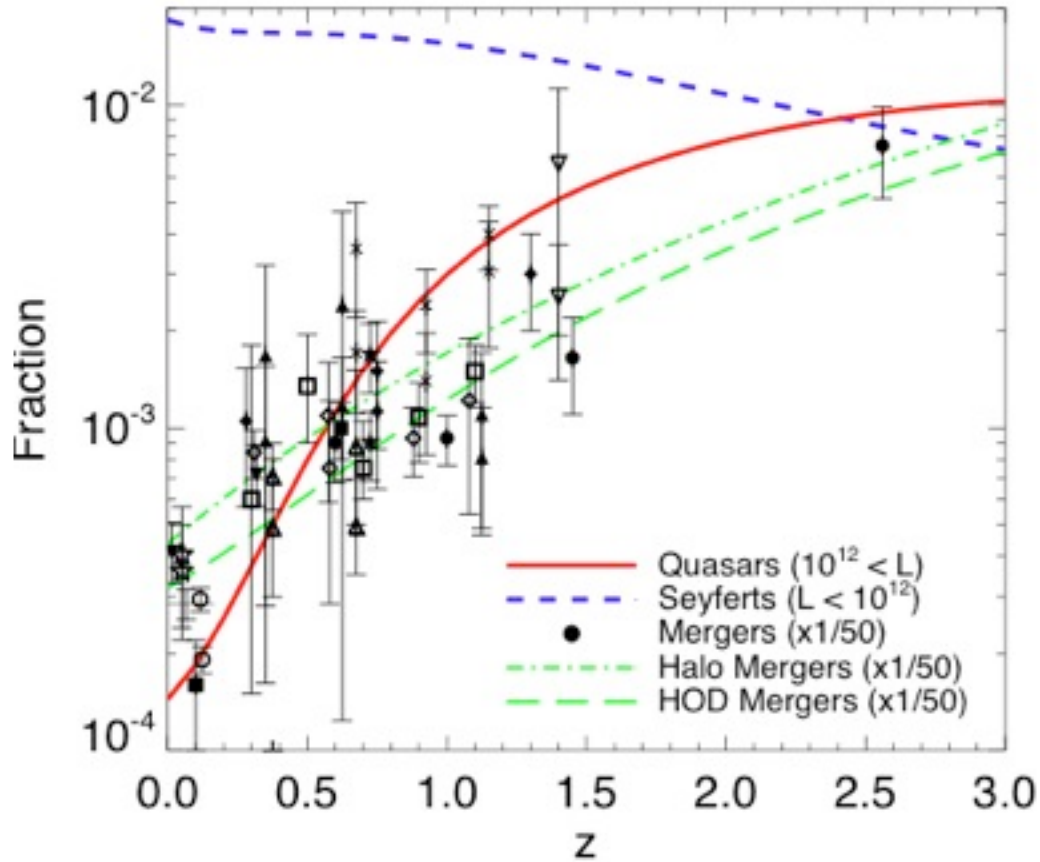
# Does that picture hold up?

Appears to be true for hosts...



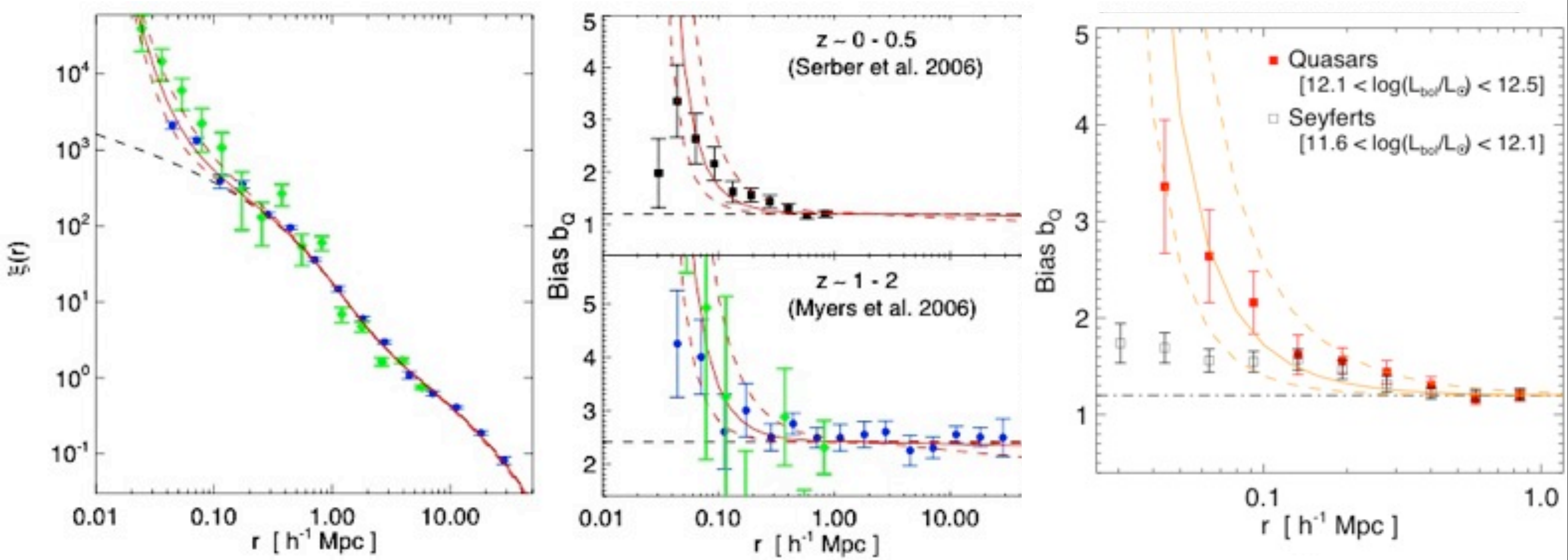




And may explain "downsizing" of AGN populations



# Does that picture hold up?

- 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

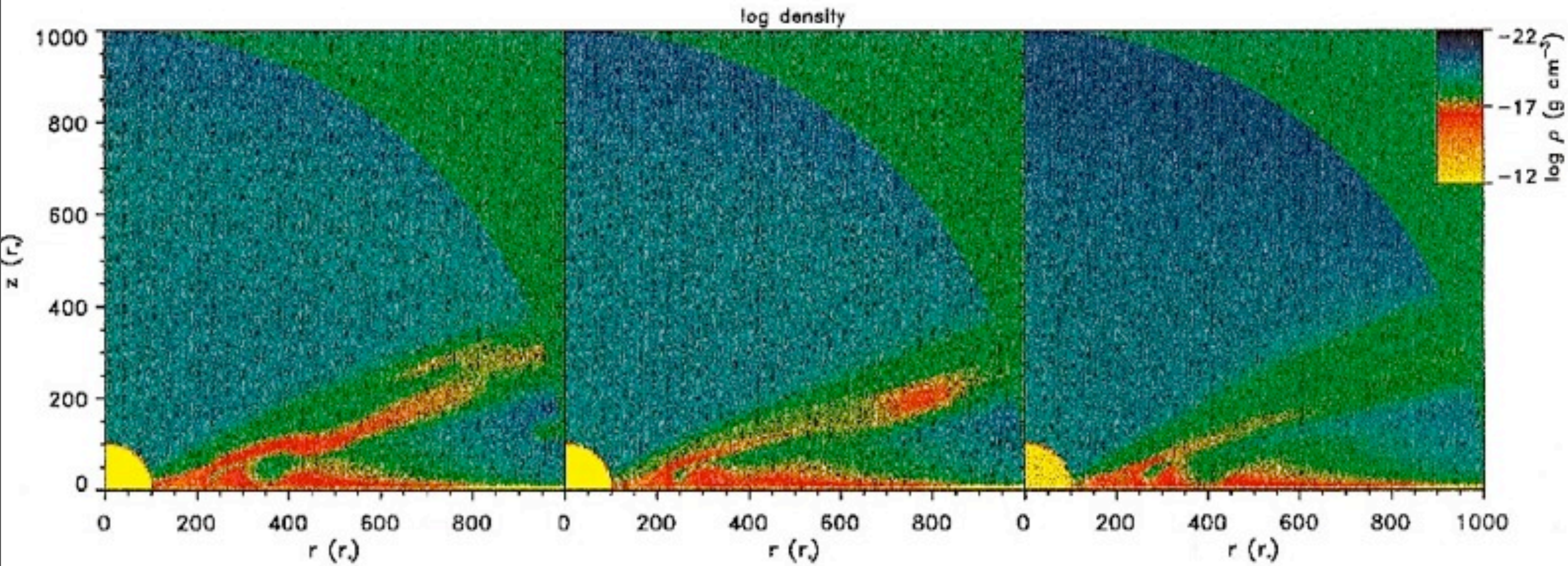



- Predicted by merger models (Thacker & Scannapieco et al., PFH)

# So let's (for now) consider mergers & bright quasars:

CAN WE MODEL IT?

- Modeling "Quasar" Feedback
- ~5% to match observed M-sigma normalization (Silk & Rees '98)
  - Line opacities + AGN spectrum (Sazonov et al.)
  - Momentum driven winds (Murray et al.)
  - Disk wind simulations (Proga et al.)

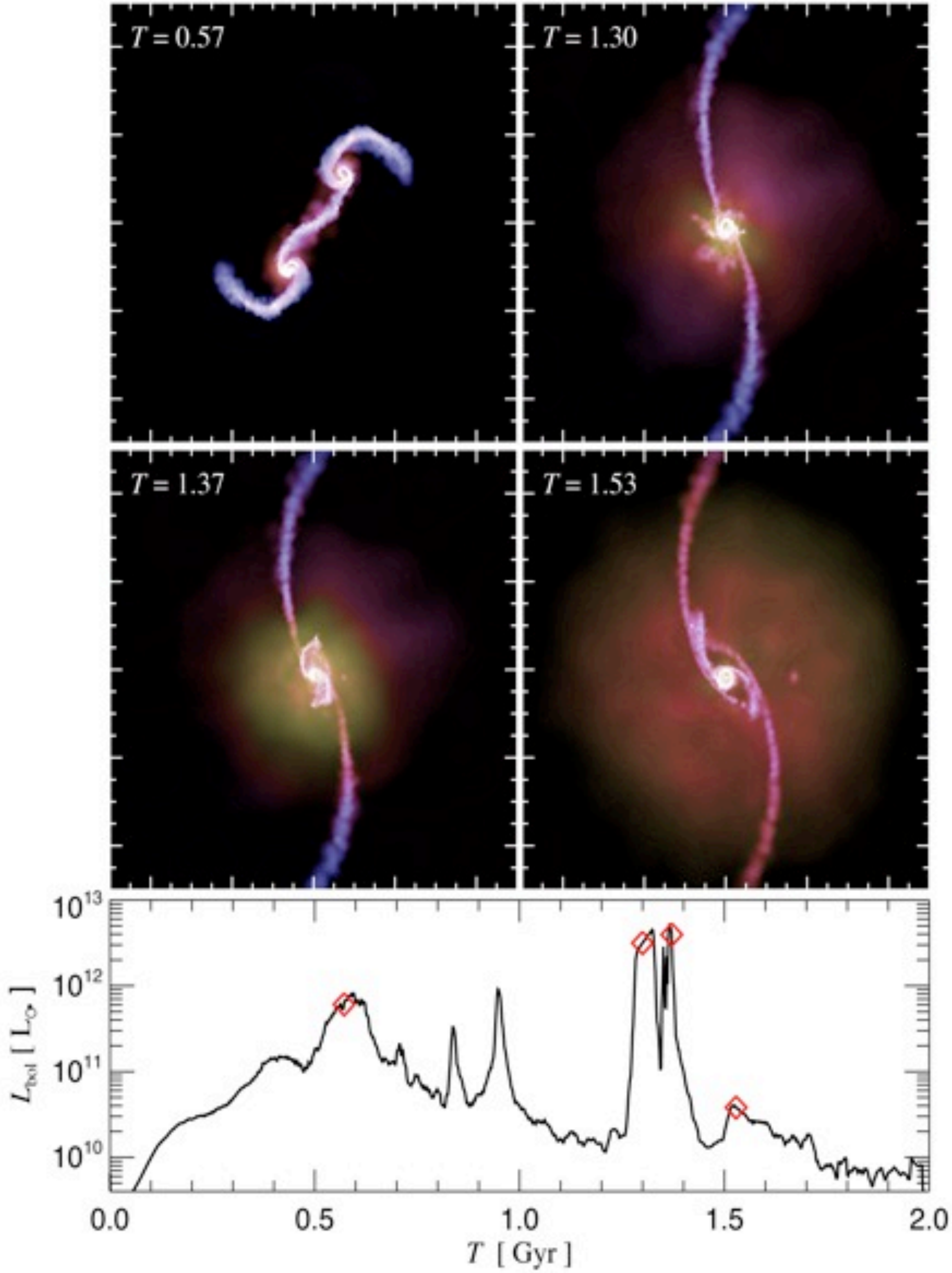


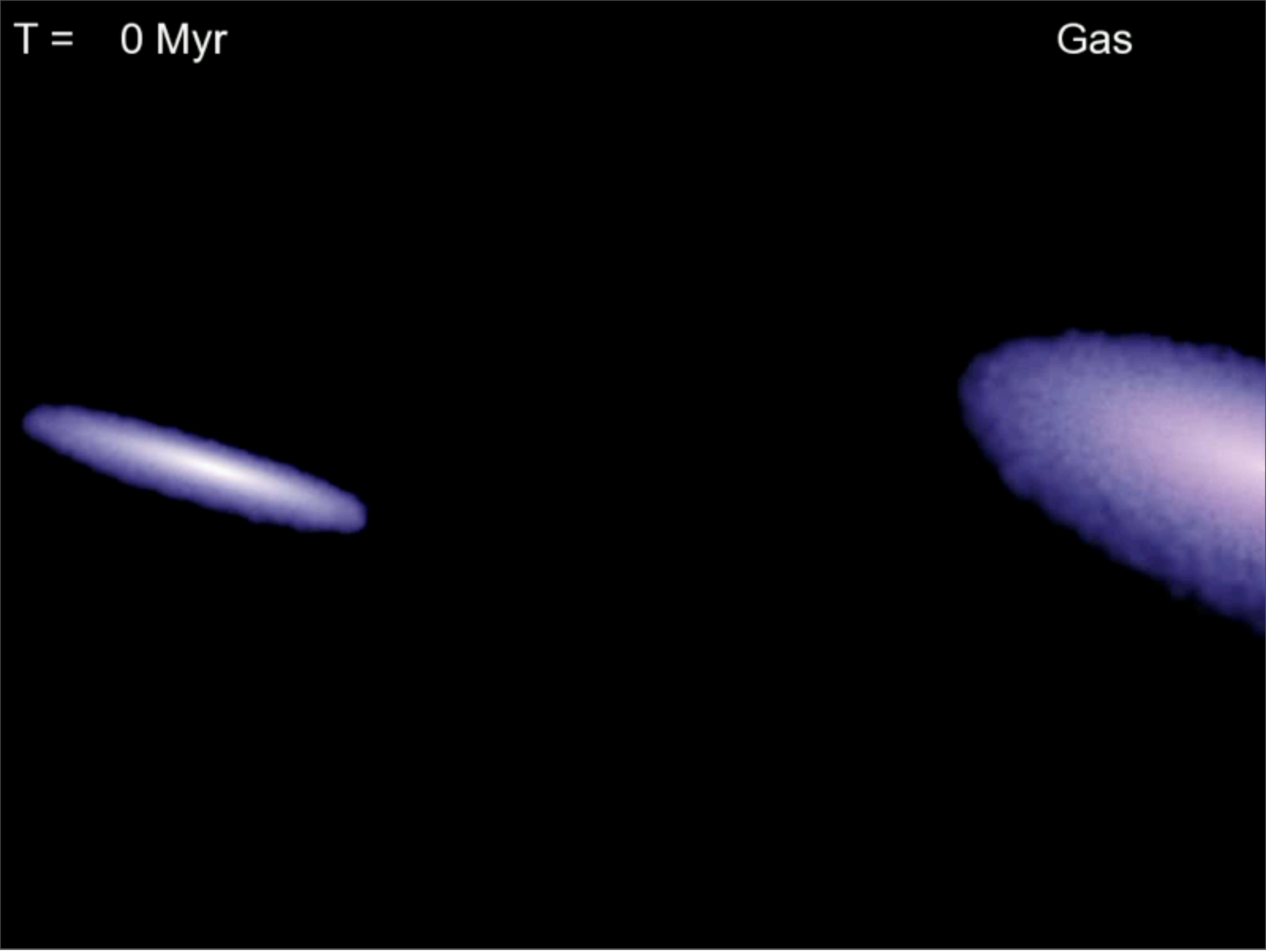

- Probably *not* radio jets

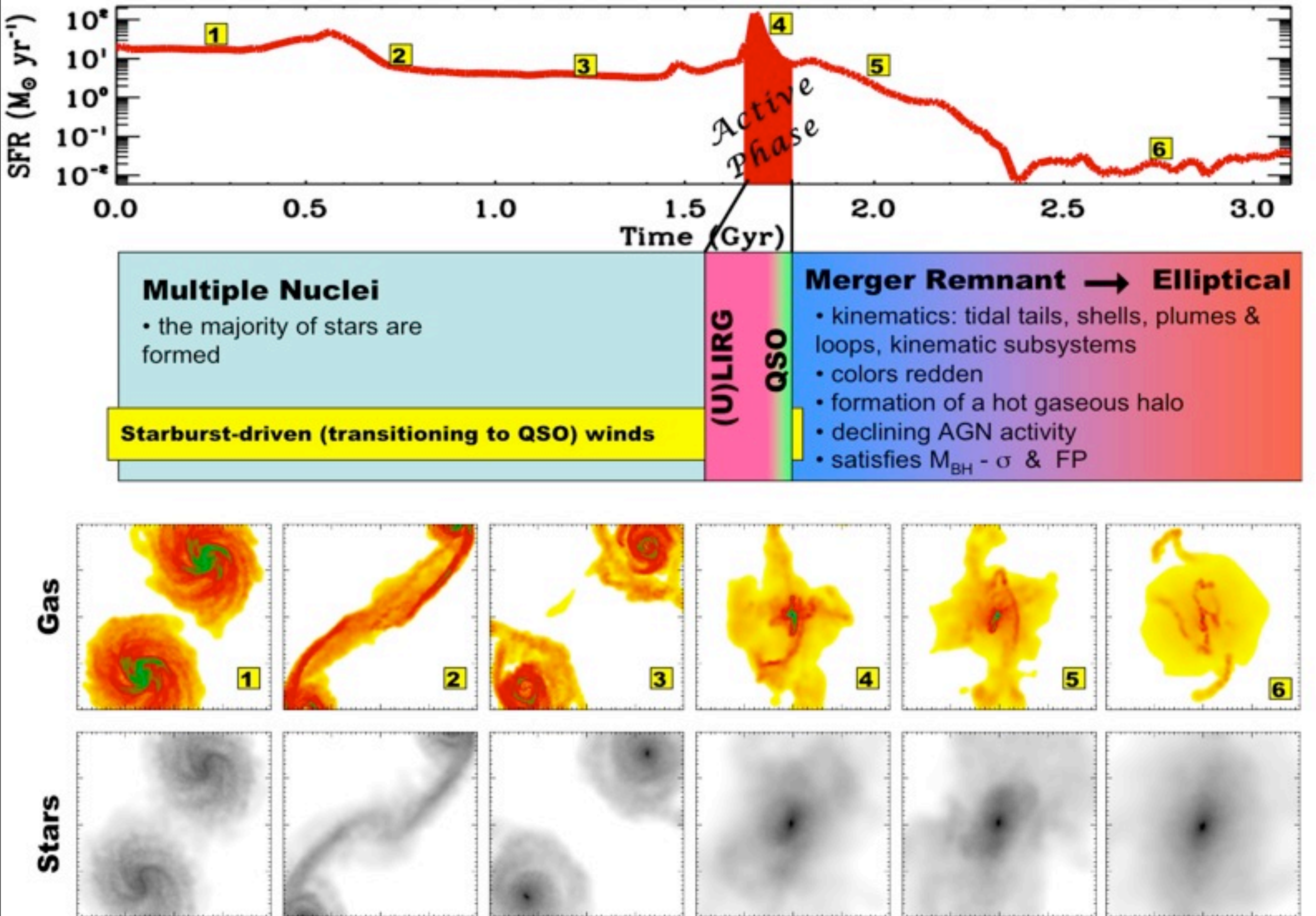
# The Simulations

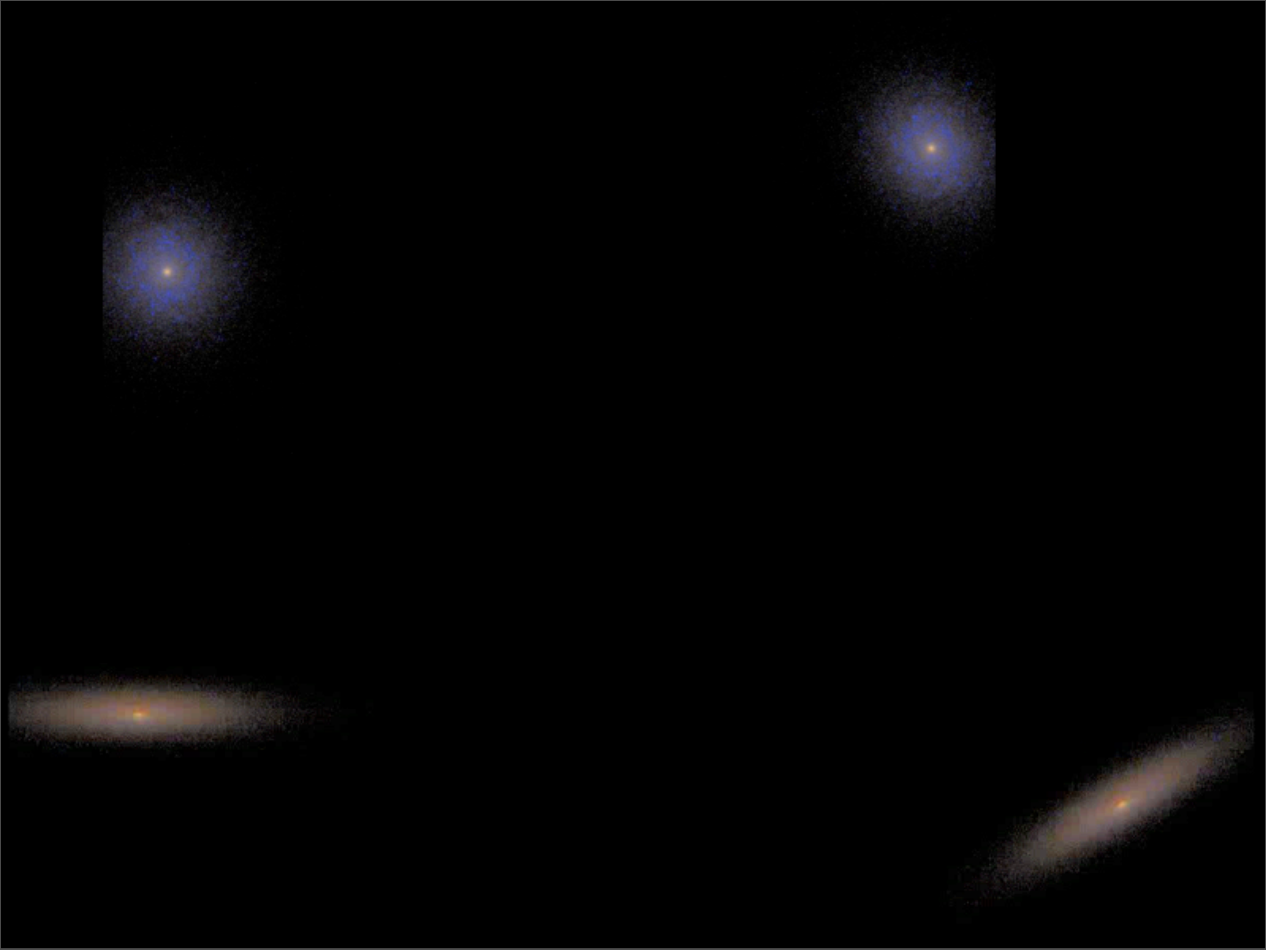
## THE AGN...

- $R_{sch}$ ~ few AU ~ $10^{-6}$ x our resolution
- $R_{Bondi}$ ~ 10 pc (typical)
  - Bondi-Hoyle accretion rate (max Eddington)
  - ~0.1 radiative efficiency (high-mdot)
  - ~5% couples to local gas (thermally)

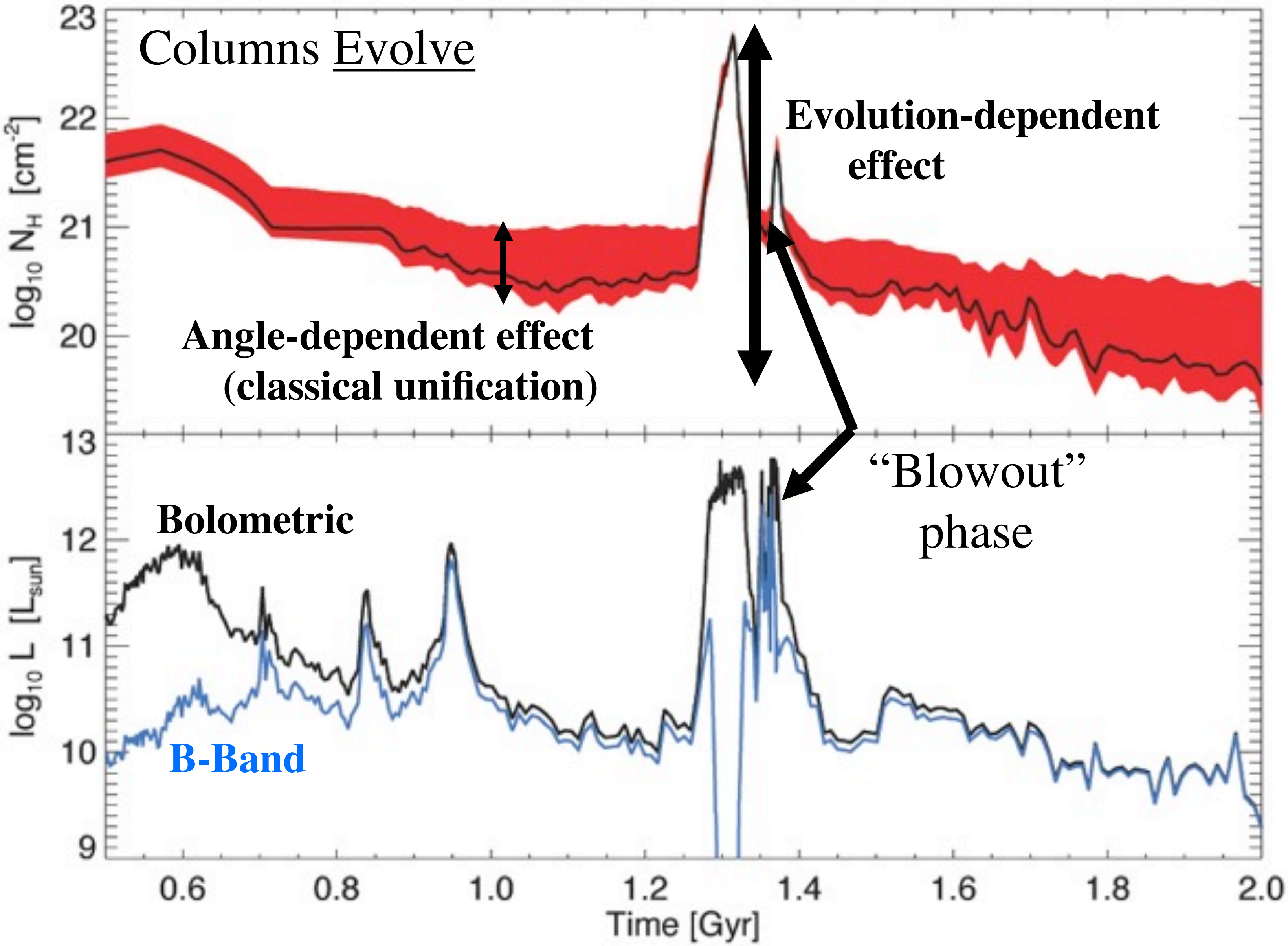



T = 0 Myr
Gas


SFR ($M_\odot$ yr$^{-1}$)
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
1
2
3
4
5
6
Active Phase
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Gyr)
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 $M_{BH}$ - σ & FP
Gas
Stars



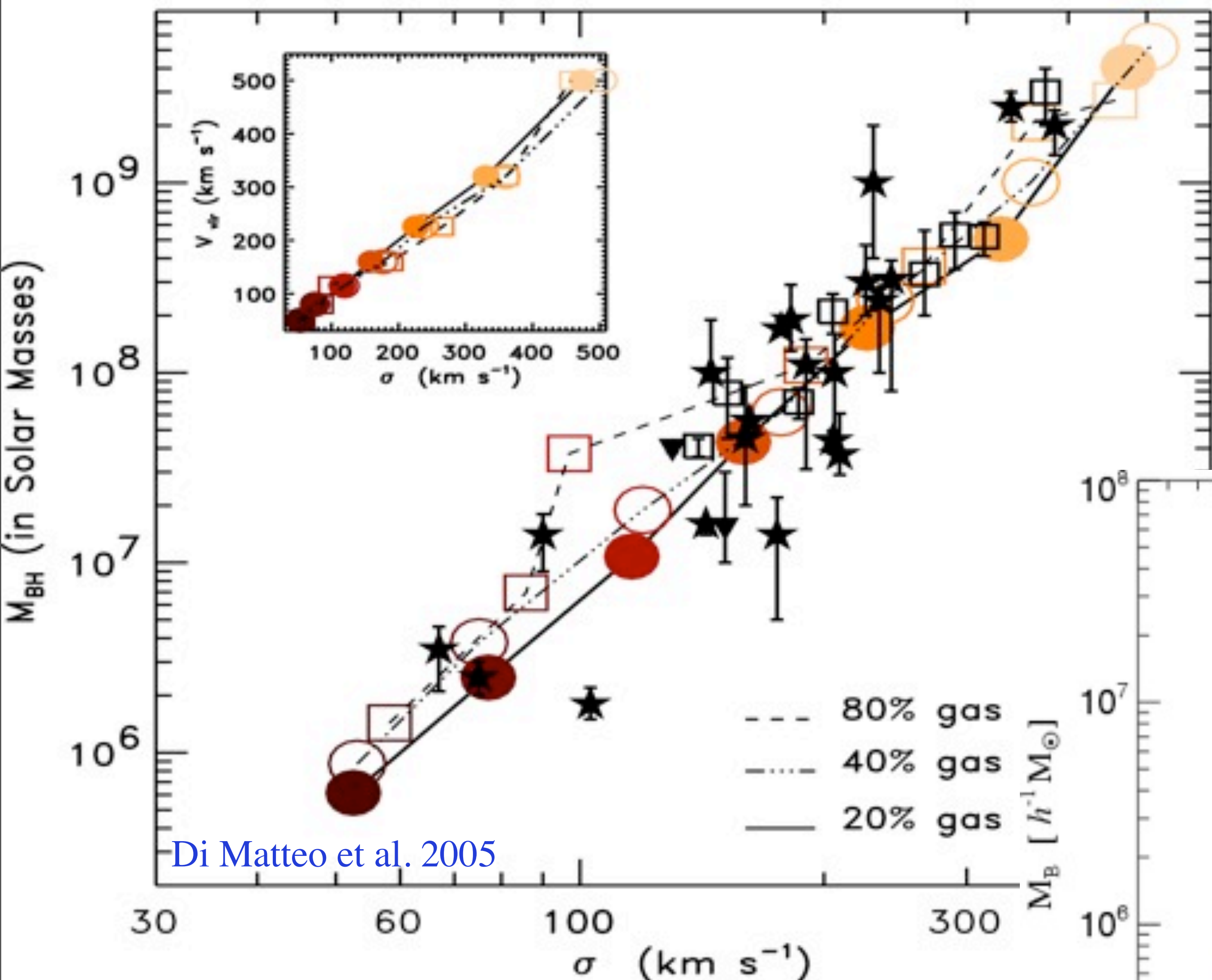
# Quasar Lightcurves:

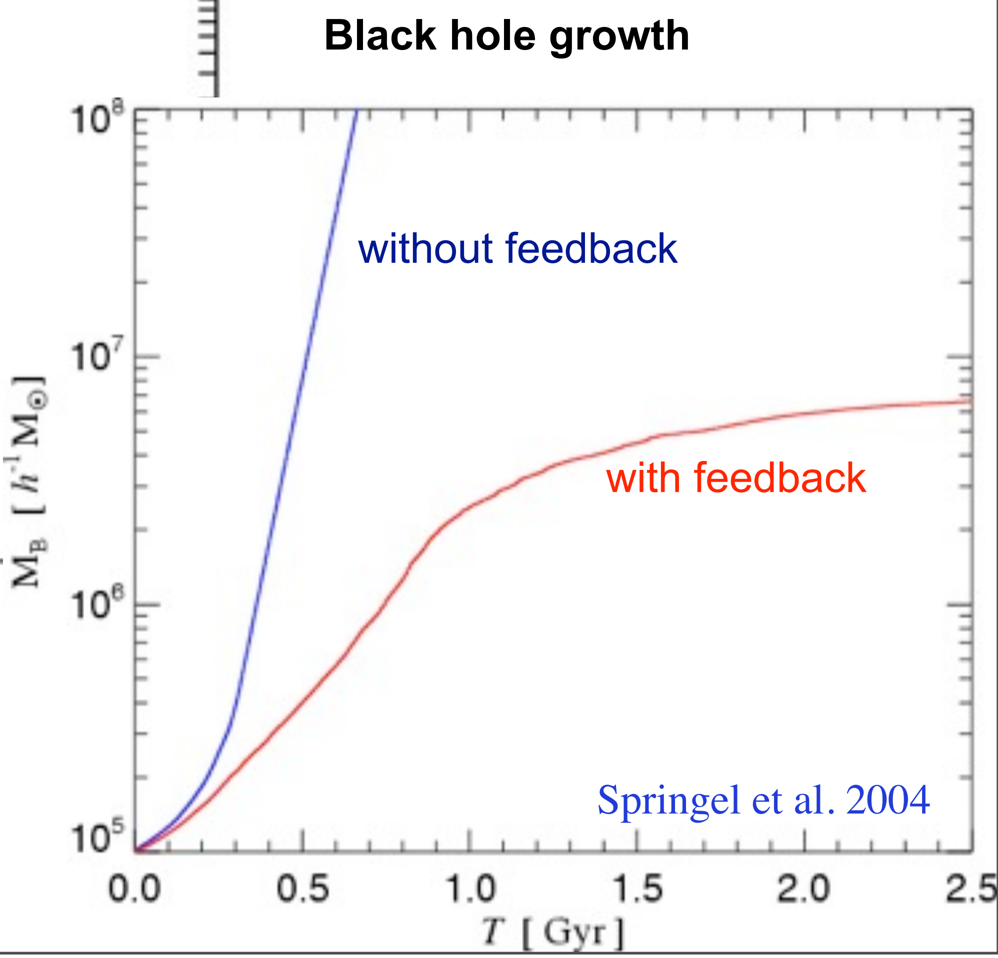



- Multi-phase ISM decomposition: gas+dust+metal columns

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

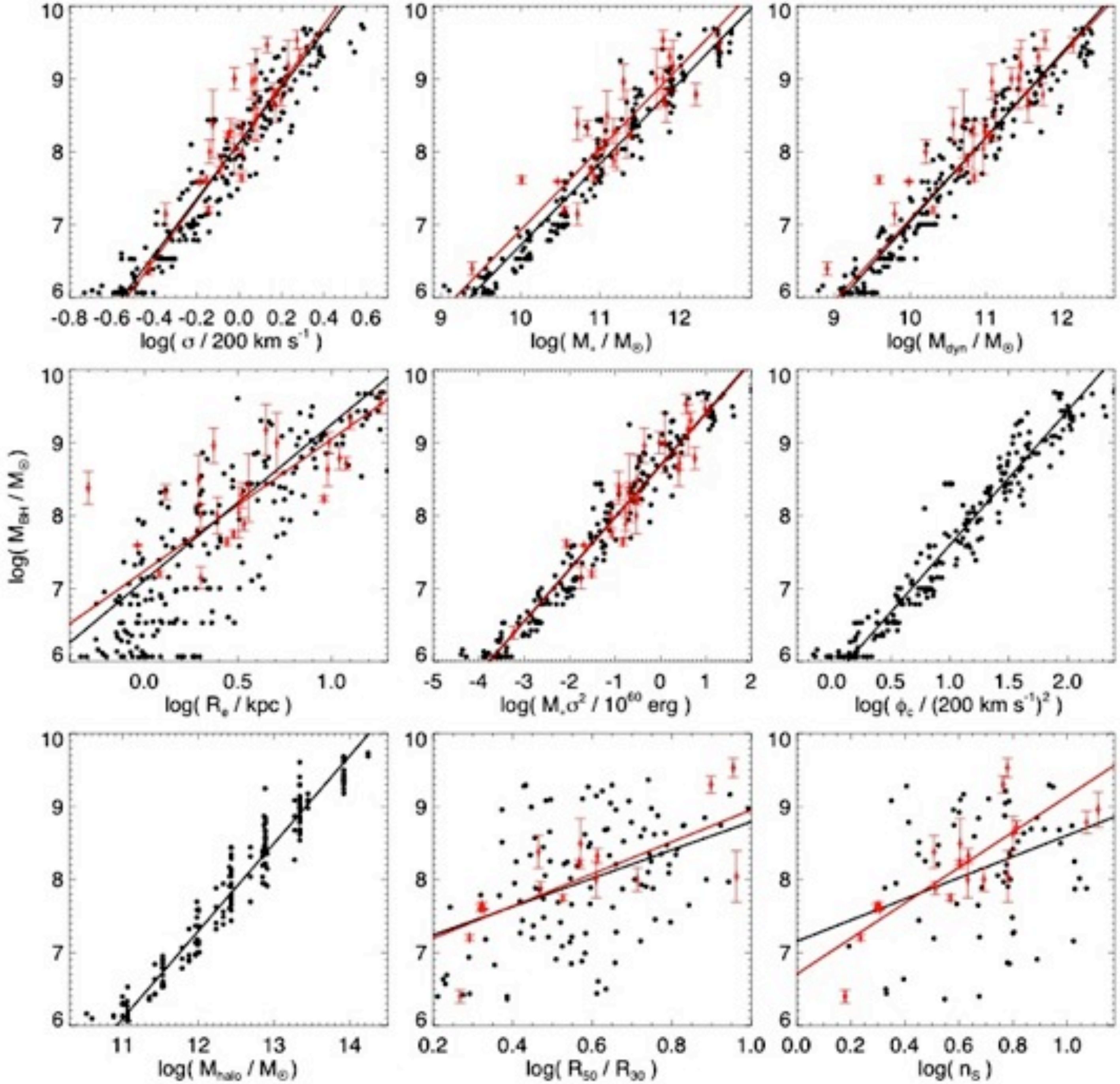
## PREVENTS RUNAWAY BLACK HOLE GROWTH



# Explains all the observed BH-Host Correlations

## BUT WHAT IS THE "FUNDAMENTAL" CORRELATION?



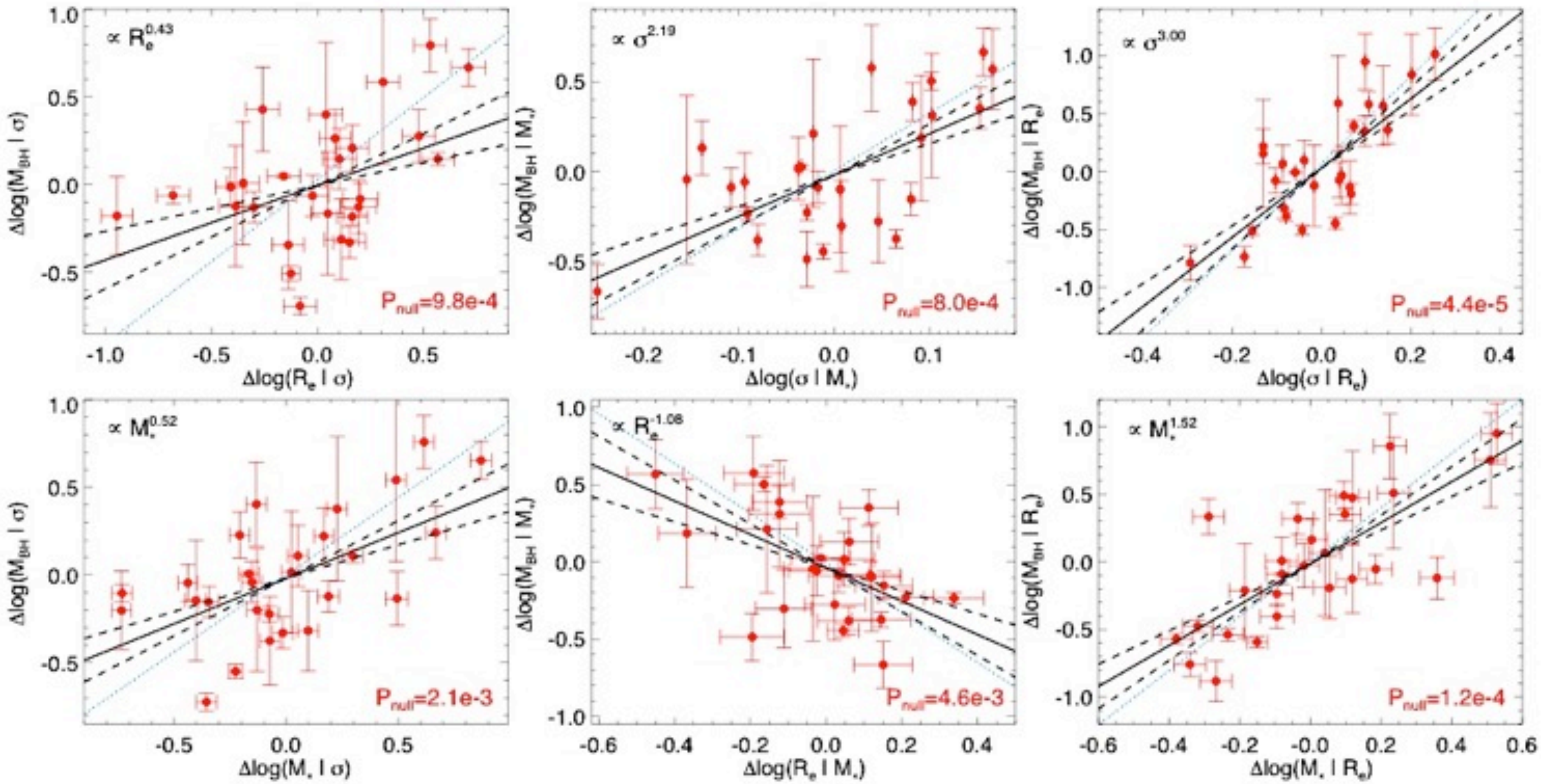

PFH et al. 2007

# Which Correlation Is “Most Fundamental”?

PFH et al. 2007

## COMPARE RESIDUALS

at fixed sigma: at fixed M_bul: at fixed R_e:



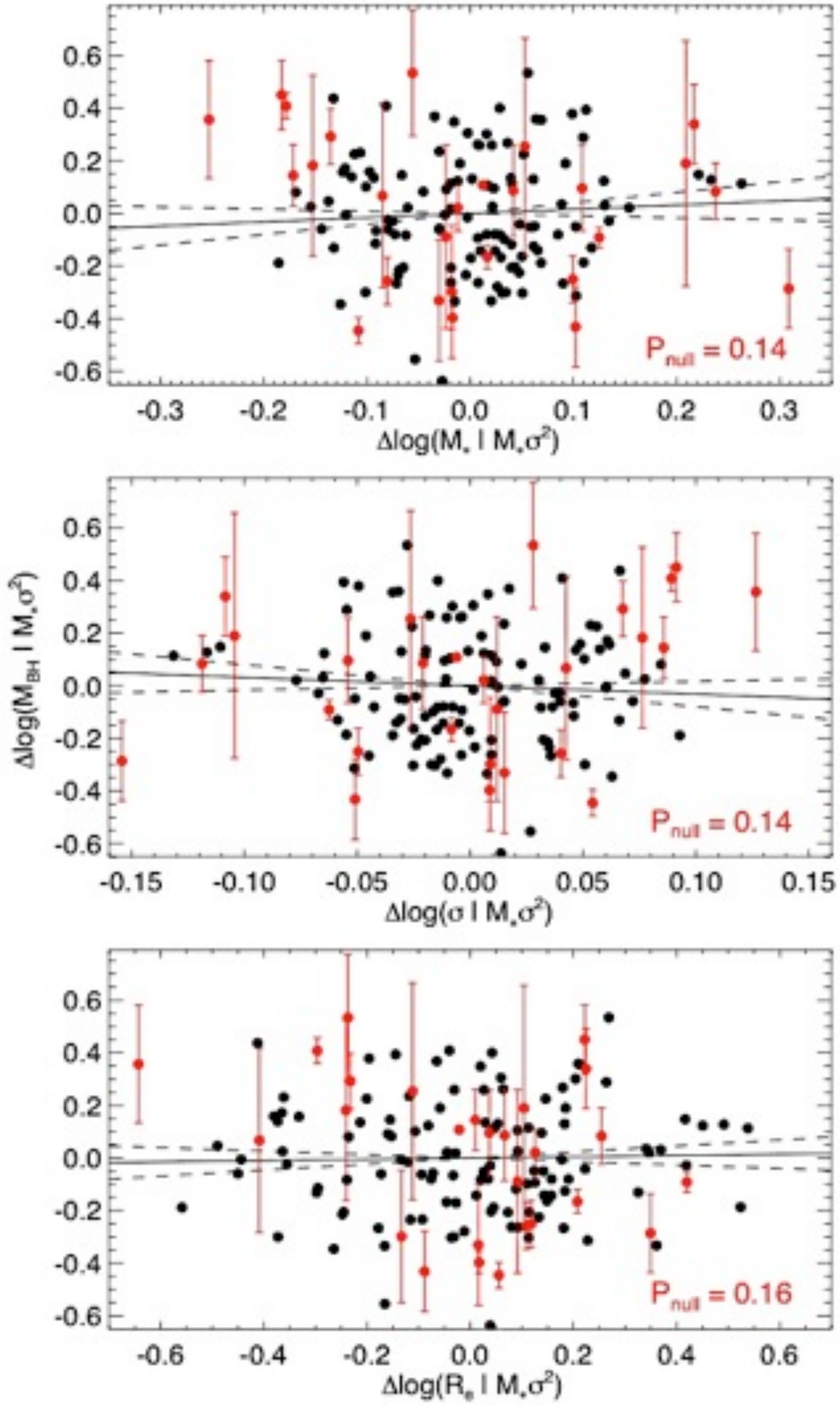

~3s significant residual trend with respect to ANY single variable correlation!

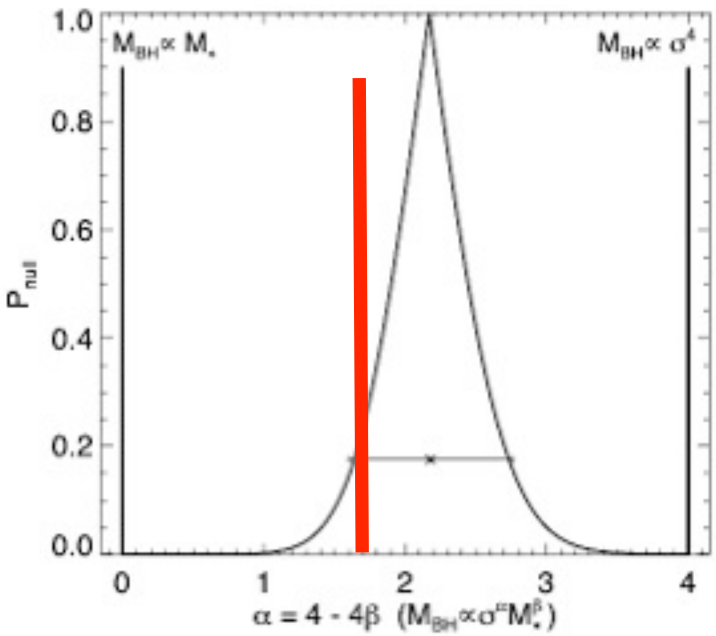
# Which Correlation Is "Most Fundamental"?

## WHAT ELIMINATES THE SECONDARY VARIABLES?

- Find a FP-like correlation:
  - $M_{bh} \sim M_{bul}^{a}\ s^{b}$
  - $M_{bh} \sim R_{e}^{a}\ s^{b}$
  - $M_{bh} \sim M_{bul}^{a}\ R_{e}^{b}$

- Roughly, bulge binding energy:
  - $M_{bh} \sim E_{binding}^{0.7\text{-}0.8} \sim (M_{bul}\ s^{2})^{0.7\text{-}0.8}$

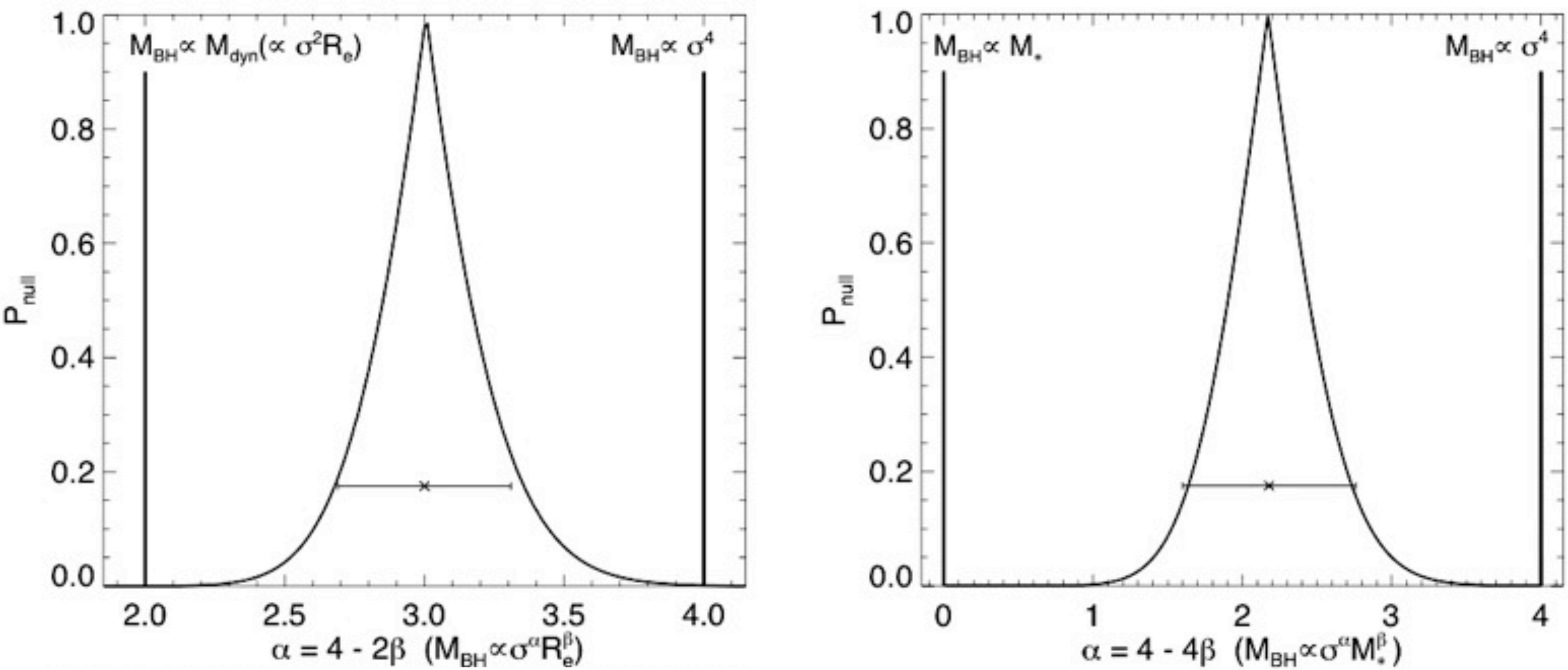



PFH et al. 2007

# Which Correlation Is "Most Fundamental"?

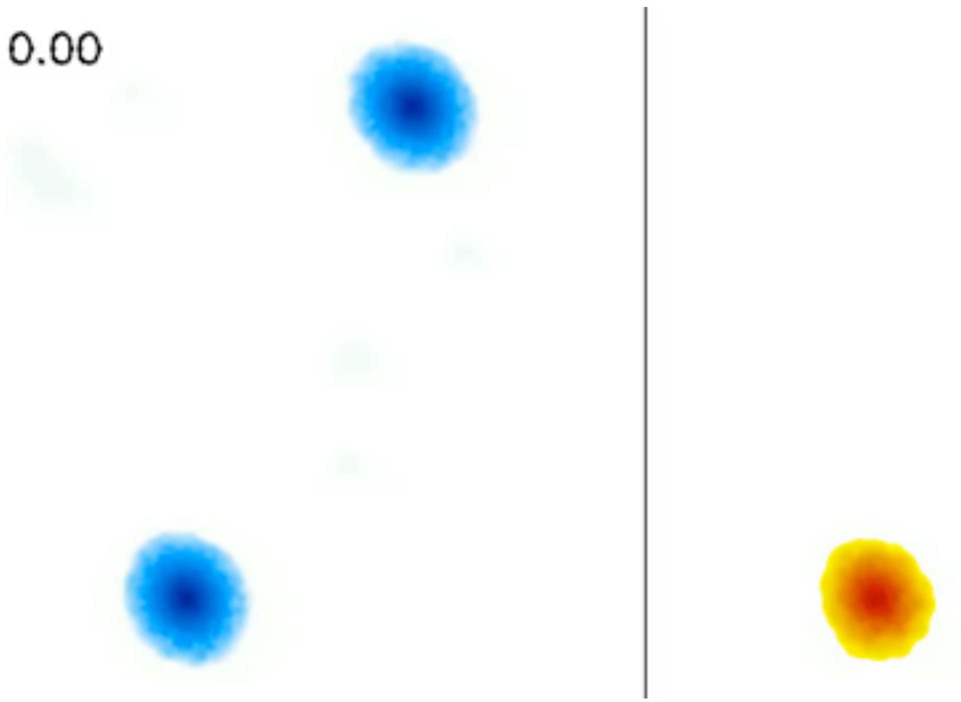
WHAT ELIMINATES THE SECONDARY VARIABLES?



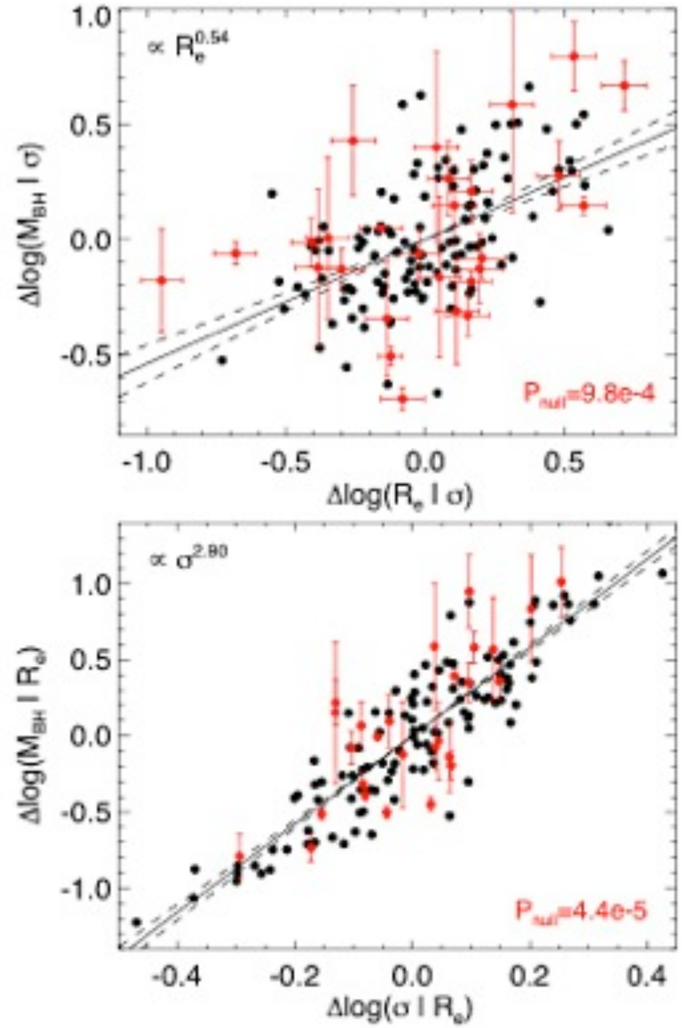

PFH et al. 2007

# Observations & Simulations Suggest this Simple Picture Works

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



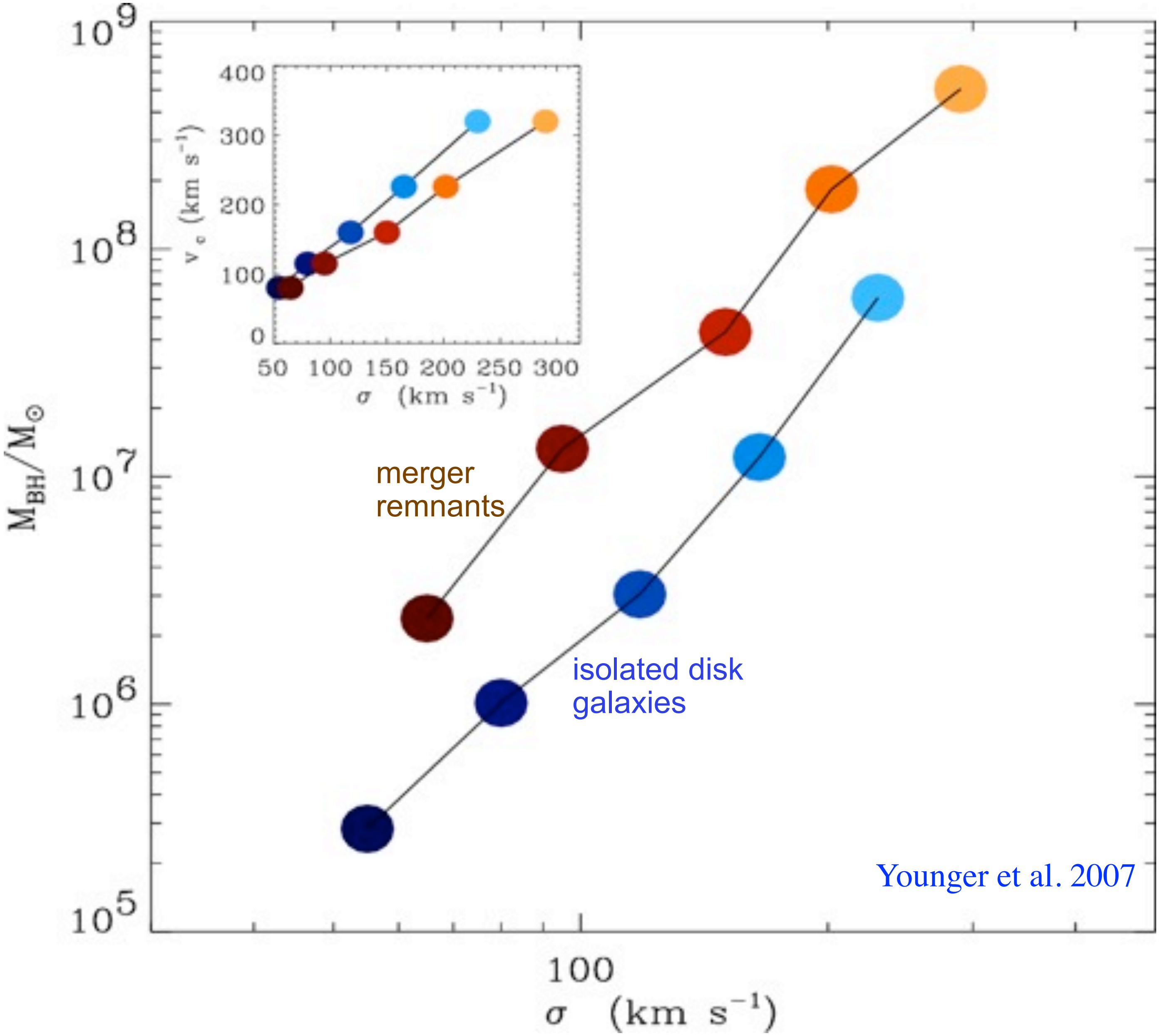

PFH et al. 2007




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

# What about other fueling mechanisms?

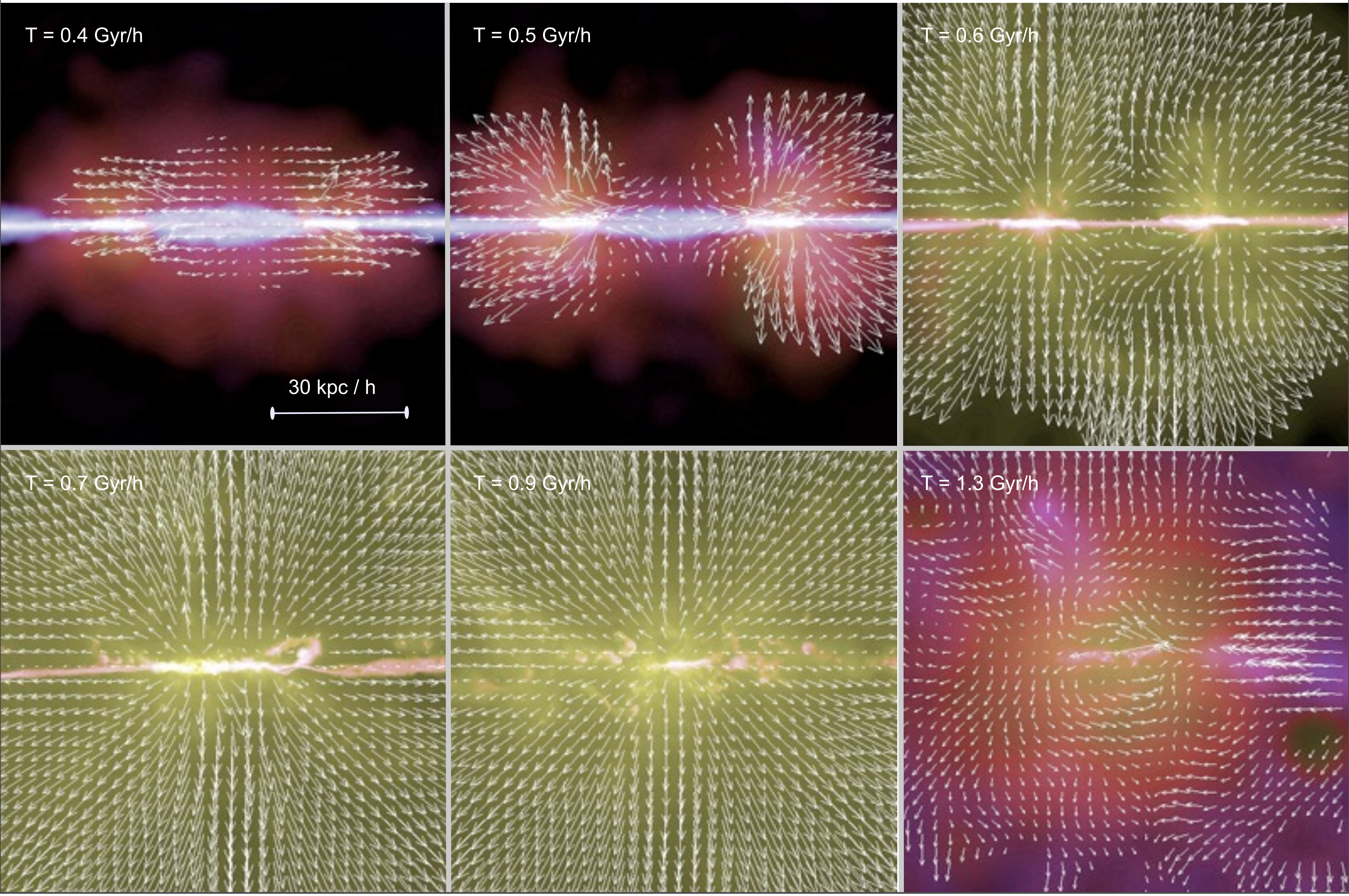
## BLACK HOLE MASSES IN ISOLATED GALAXIES AND MERGER REMNANTS



# Where Does the Energy/Momentum Go?

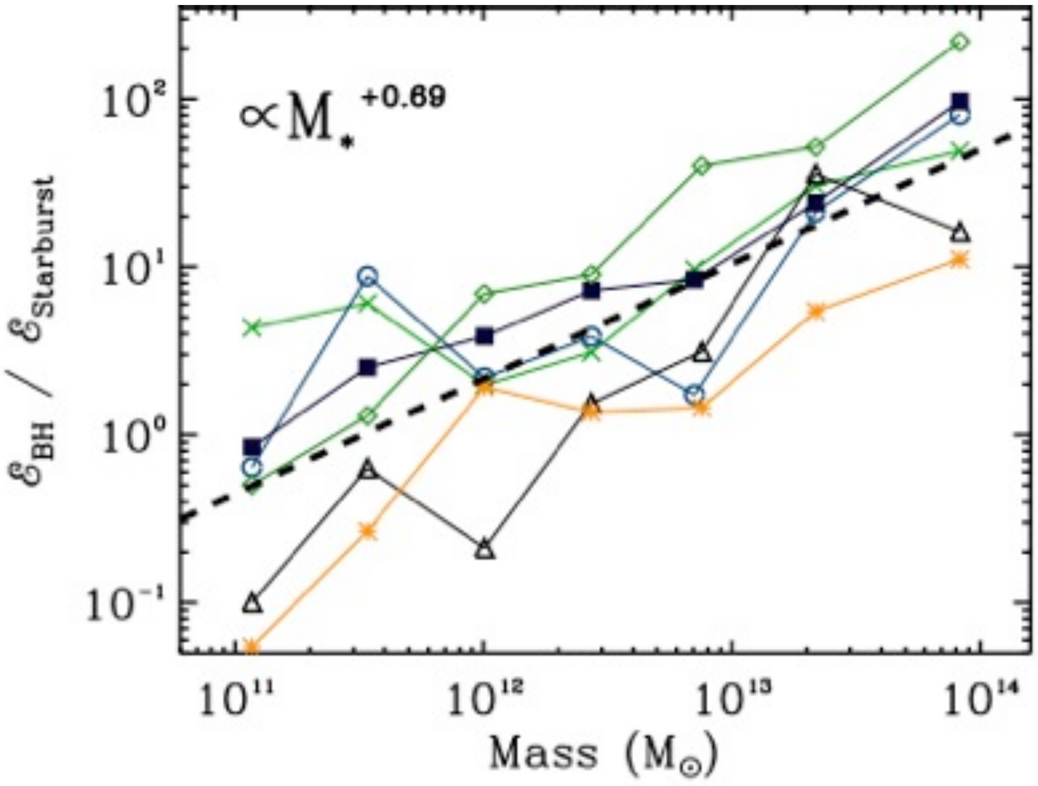
## QUASAR-DRIVEN OUTFLOWS?

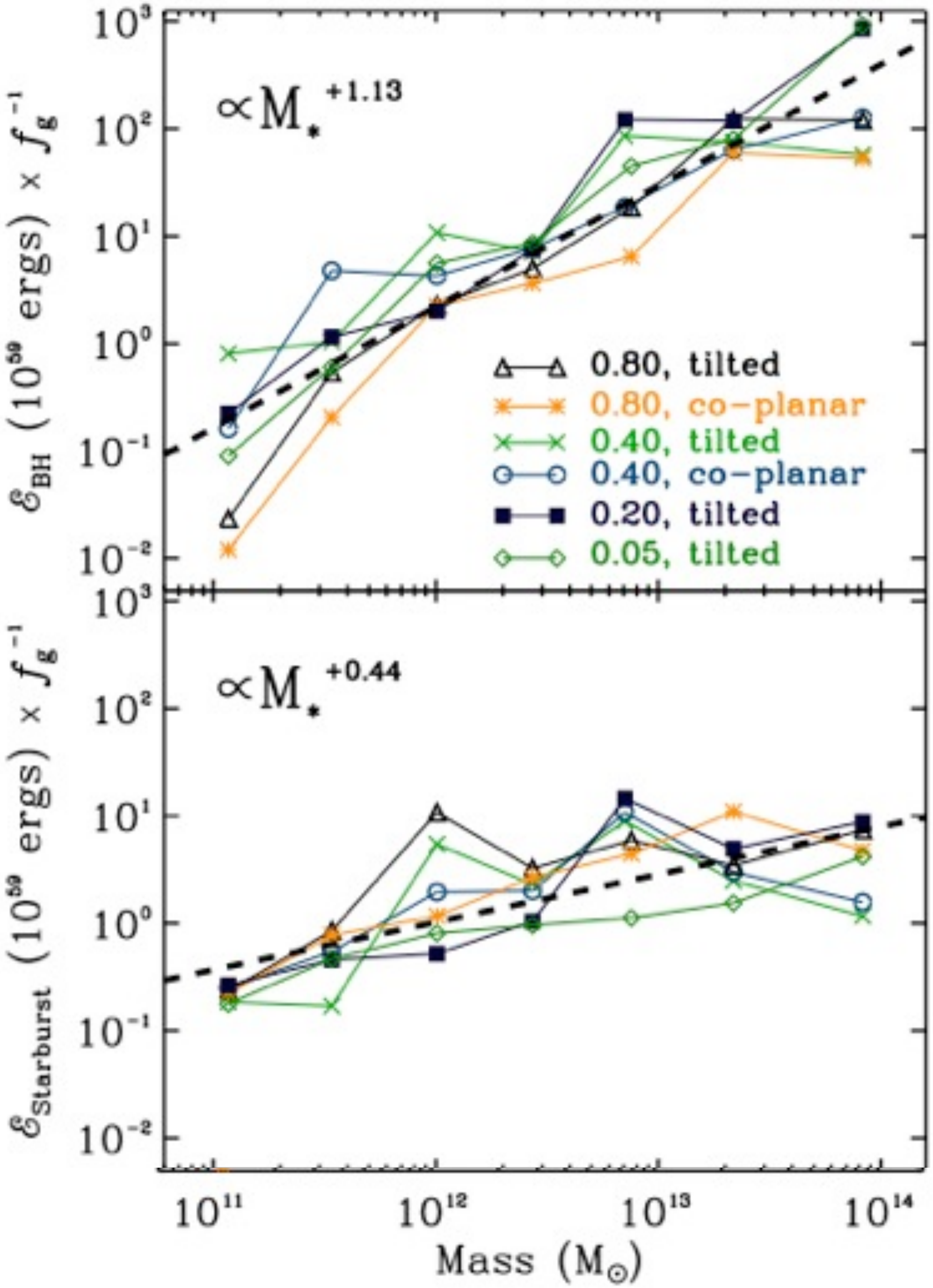
(outflow reaches speeds of up to ~1800 km/sec)



# Feedback-Driven Winds

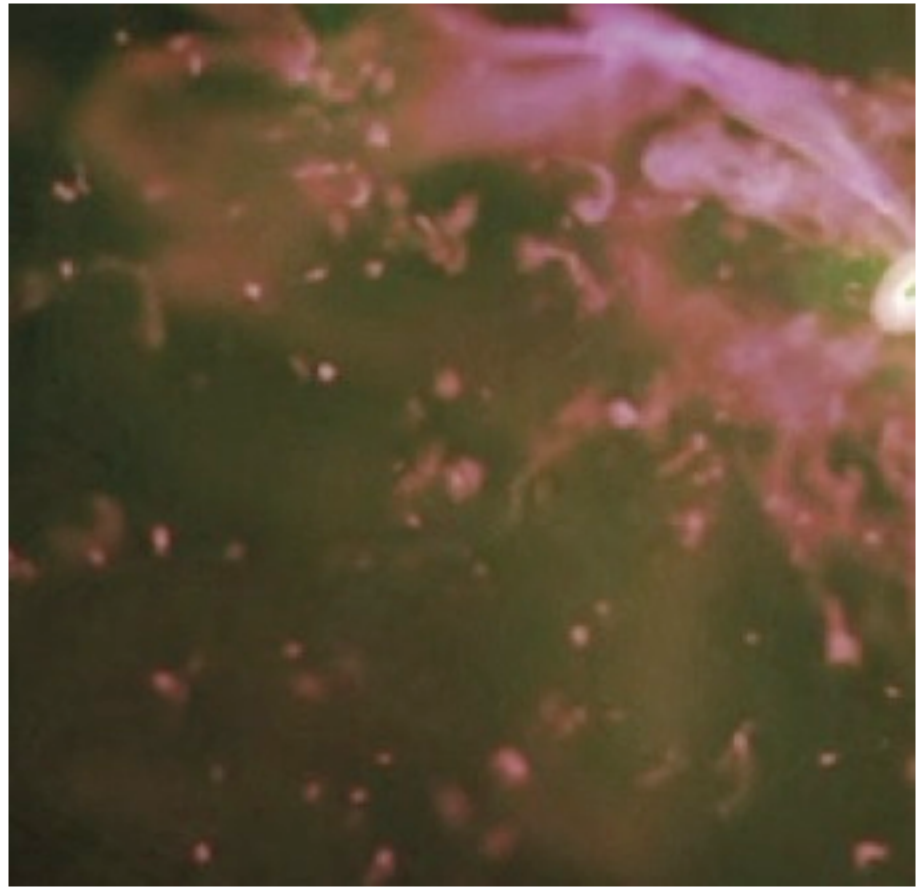
## COMPARISON TO STARBURST-DRIVEN WINDS

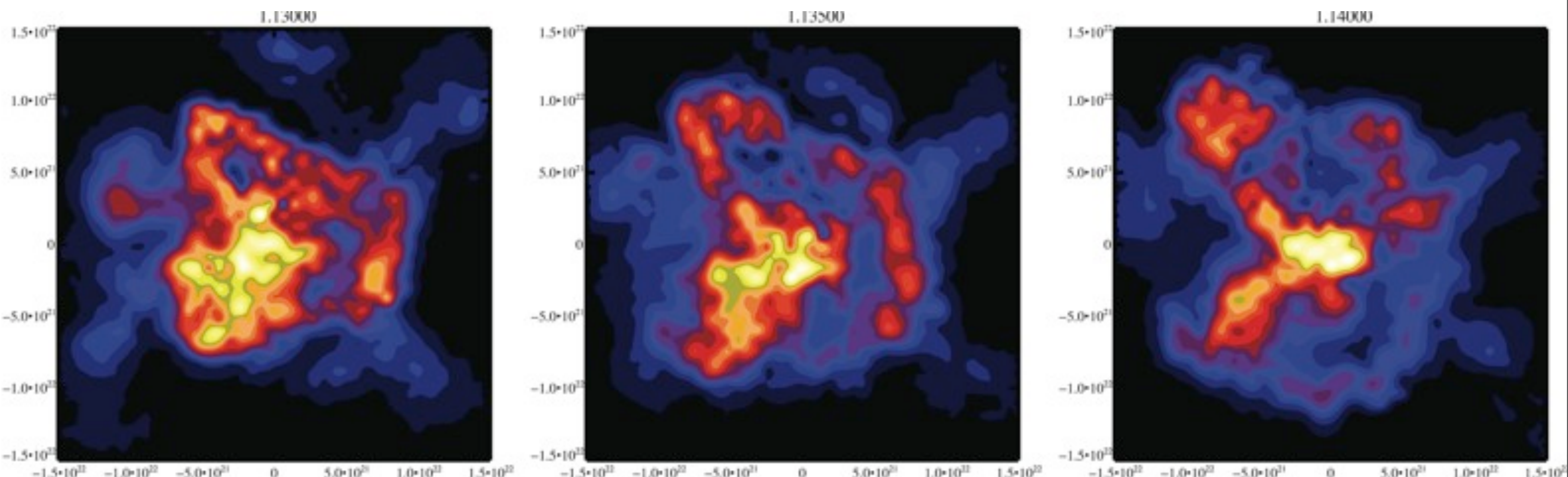


# Outflows are Explosive and Clumpy

- Rapid BH growth => point-like injection
  - "Explosion-like", independent of coupling
- Clumpy
  - ULIRG cold/warm transition (S. Chakrabarti)
  - CO outflows (D. Narayanan)
- Cold shell (through galaxy)

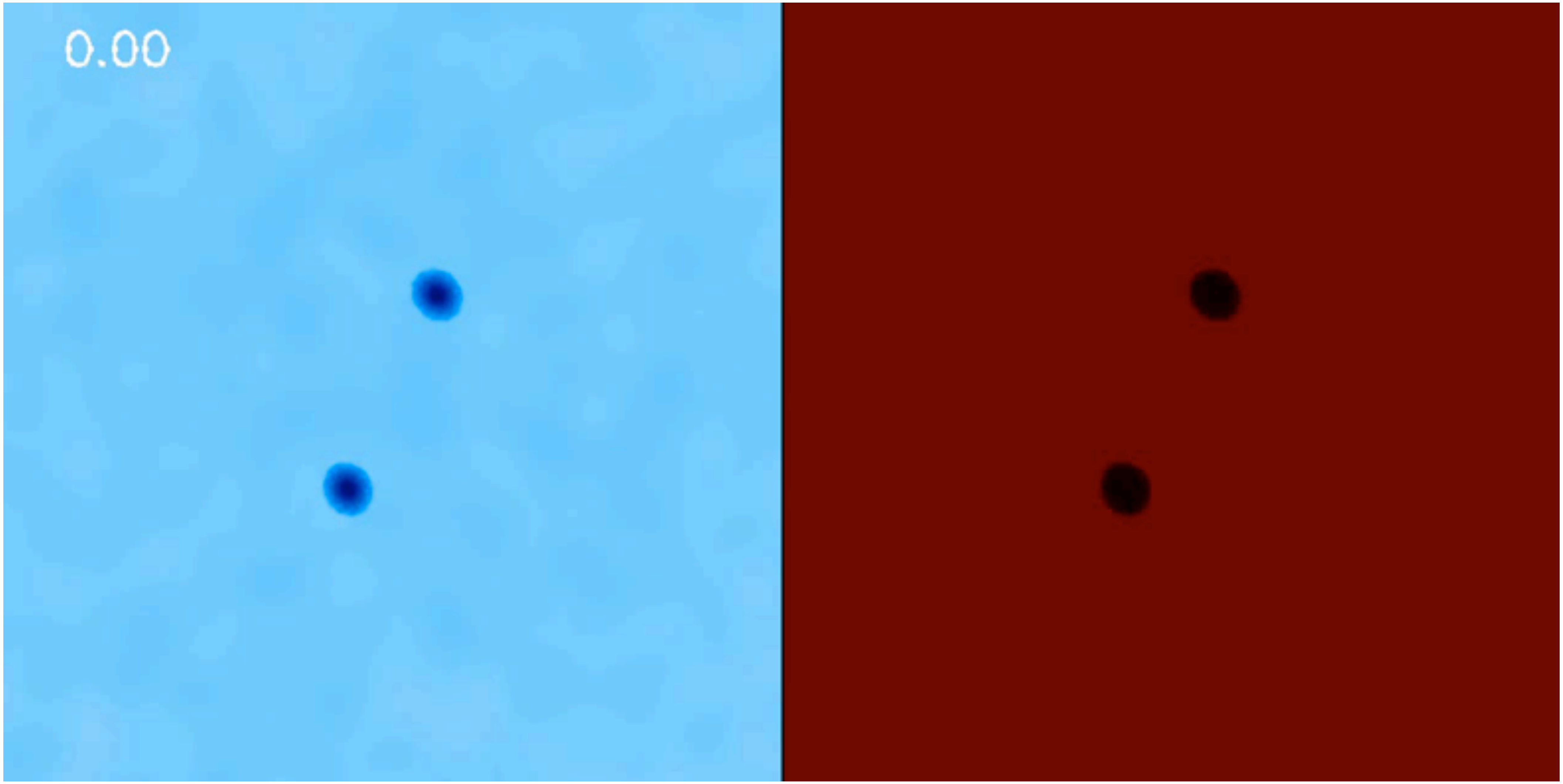




# Quasar Outflows May Be Significant for the ICM & IGM

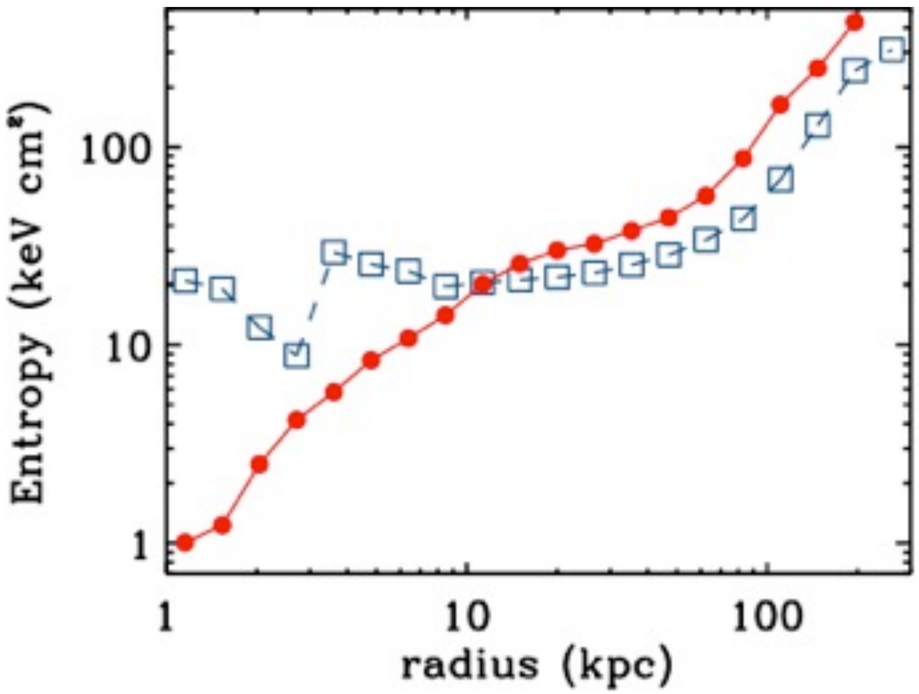
## SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?

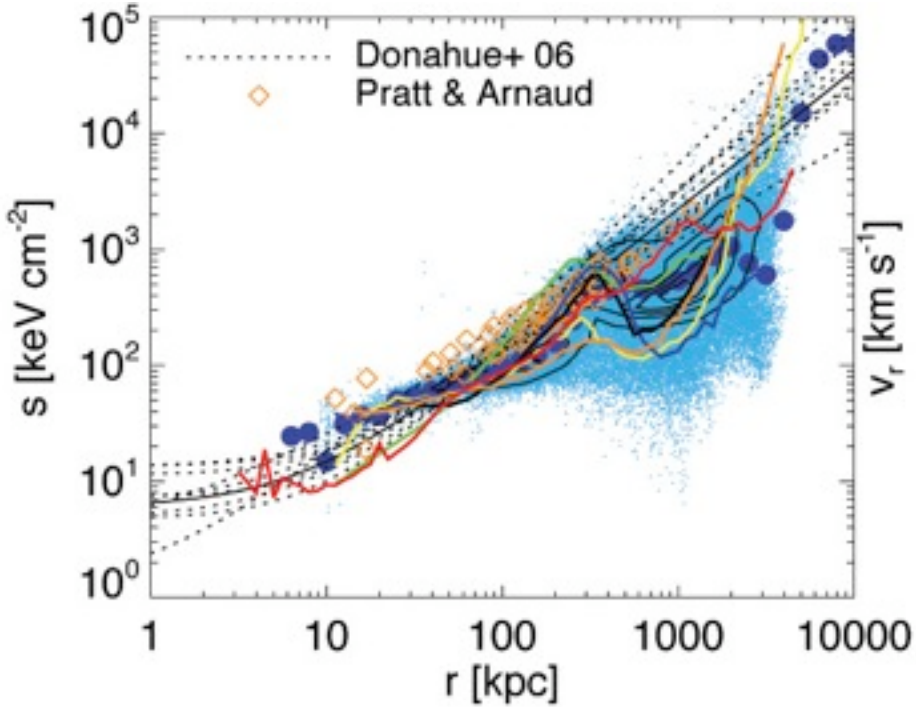
**Gas Density** **Gas Temperature**

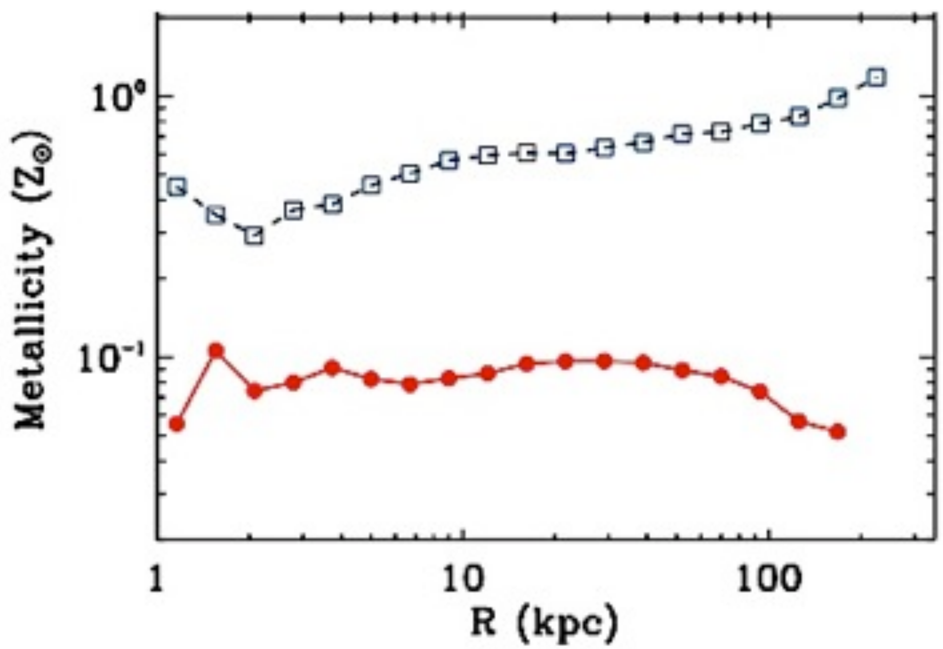


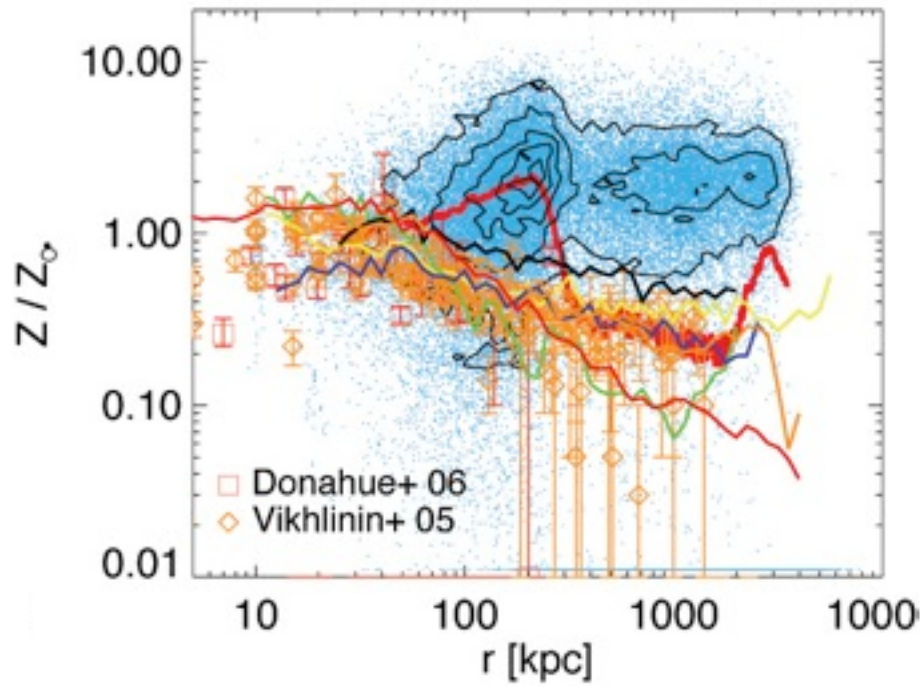
# Quasar Outflows May Be Significant for the ICM & IGM

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



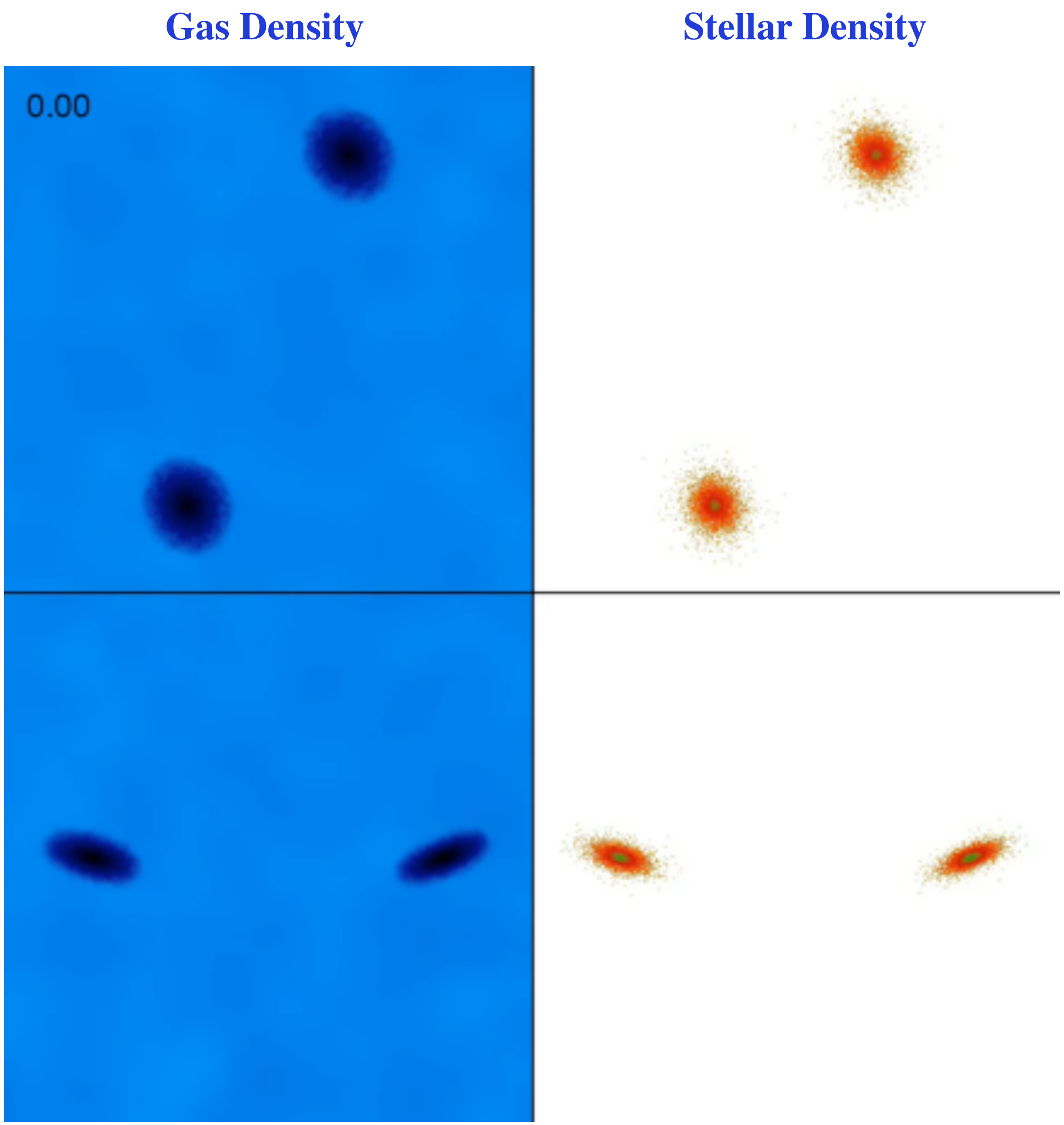



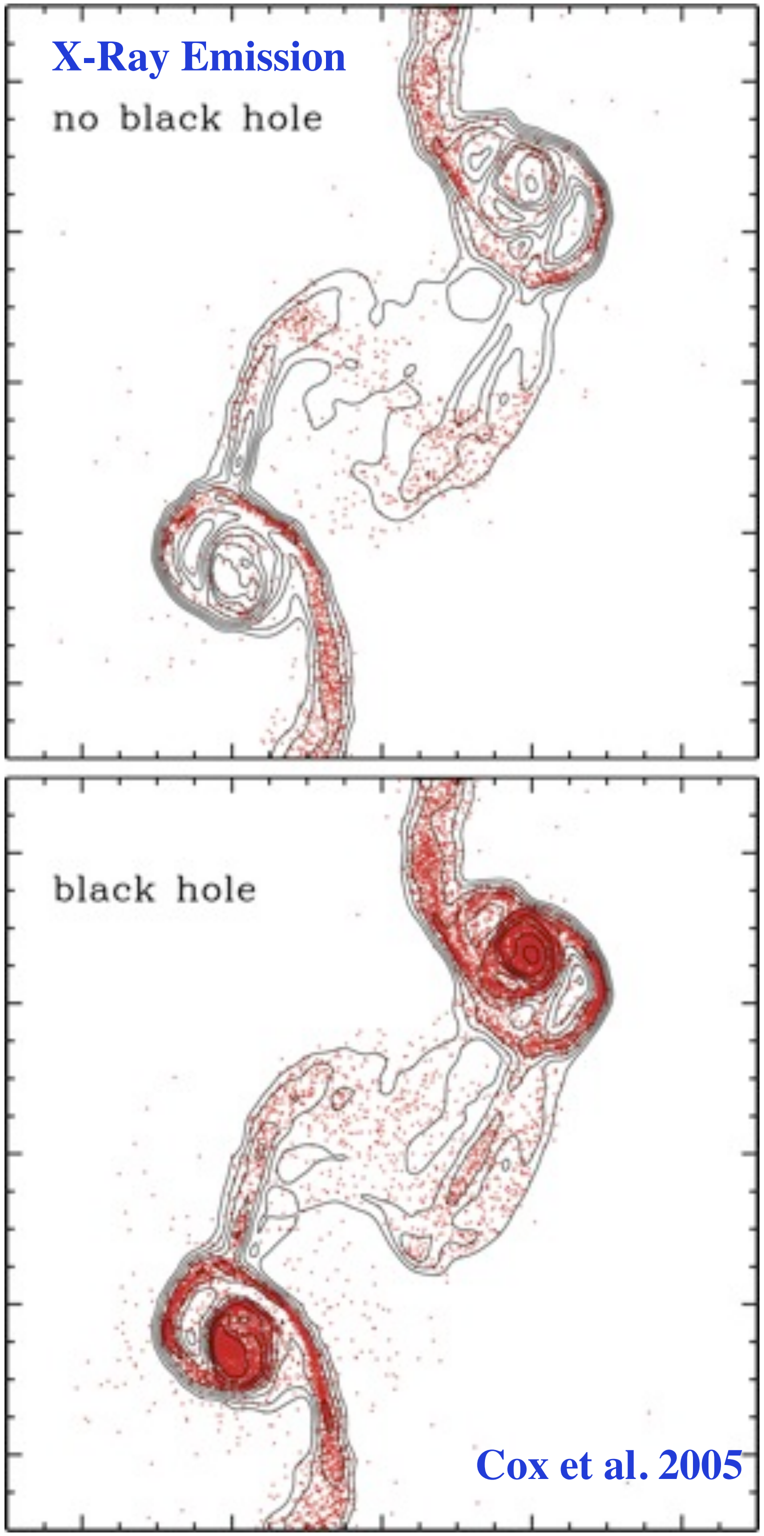



# Feedback-Driven Winds

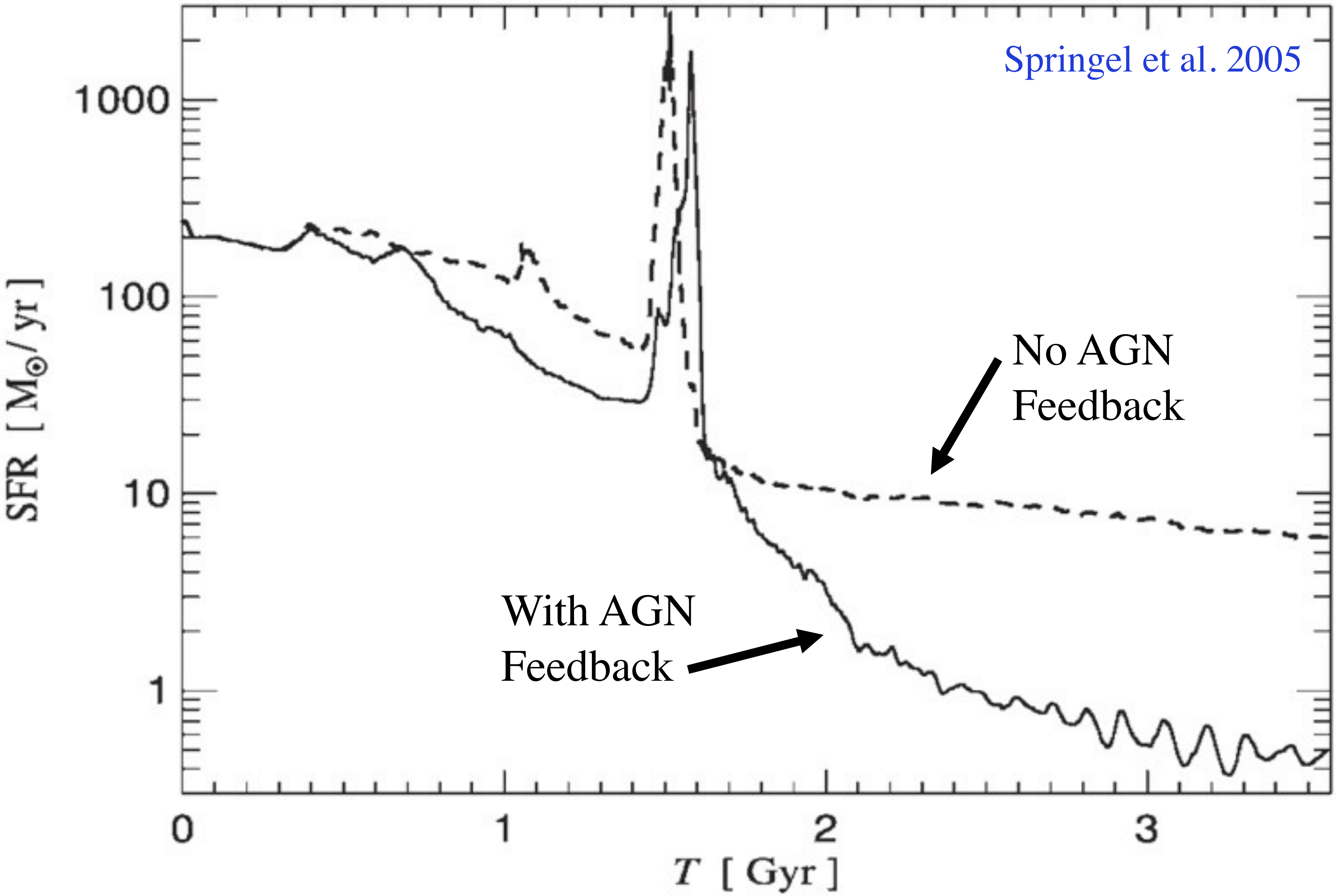
## METAL ENRICHMENT & BUILDING THE X-RAY HALO



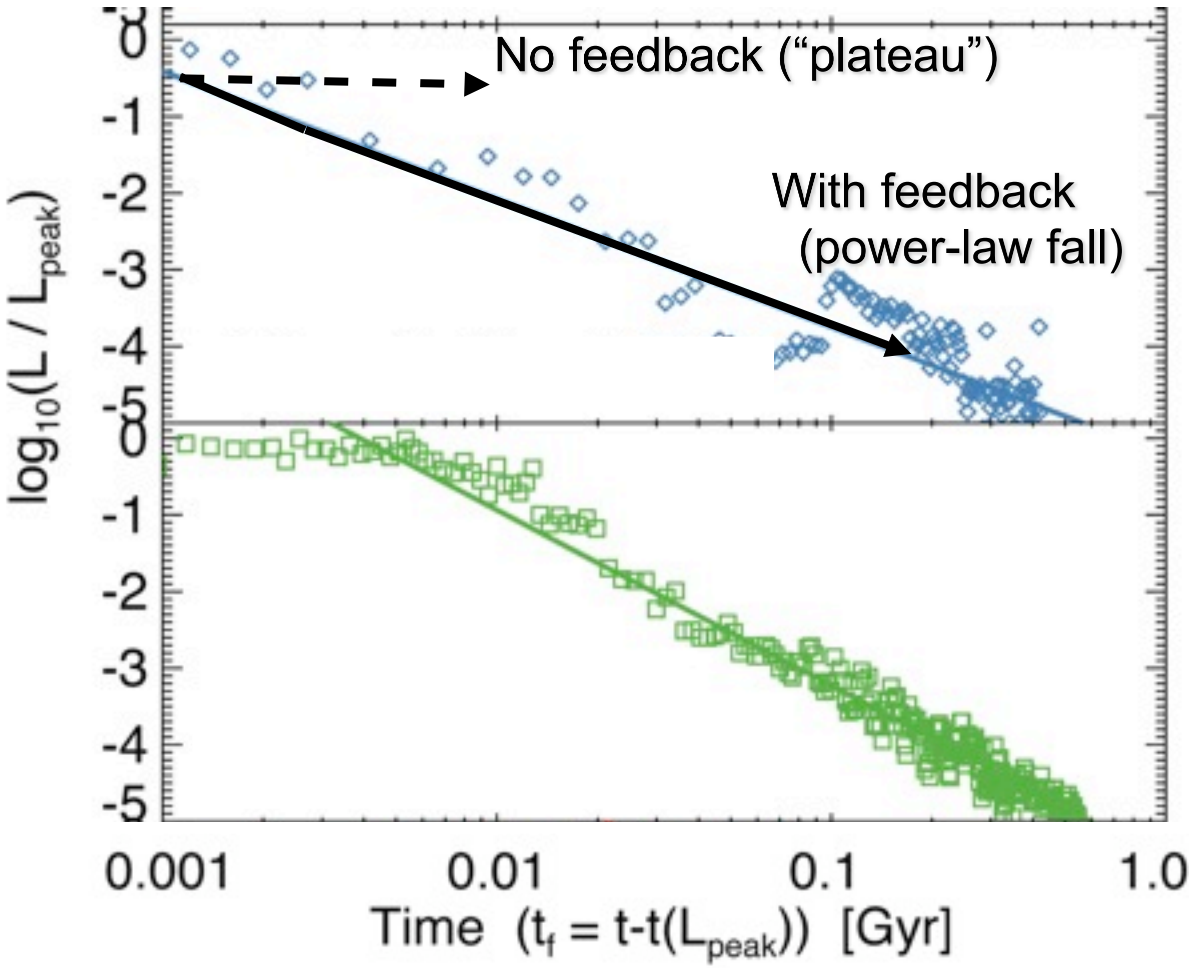
# Expulsion of Gas Turns off Star Formation

## ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?



# Quasar Light Curves & Lifetimes

- Feedback determines the decay of the quasar light curve:

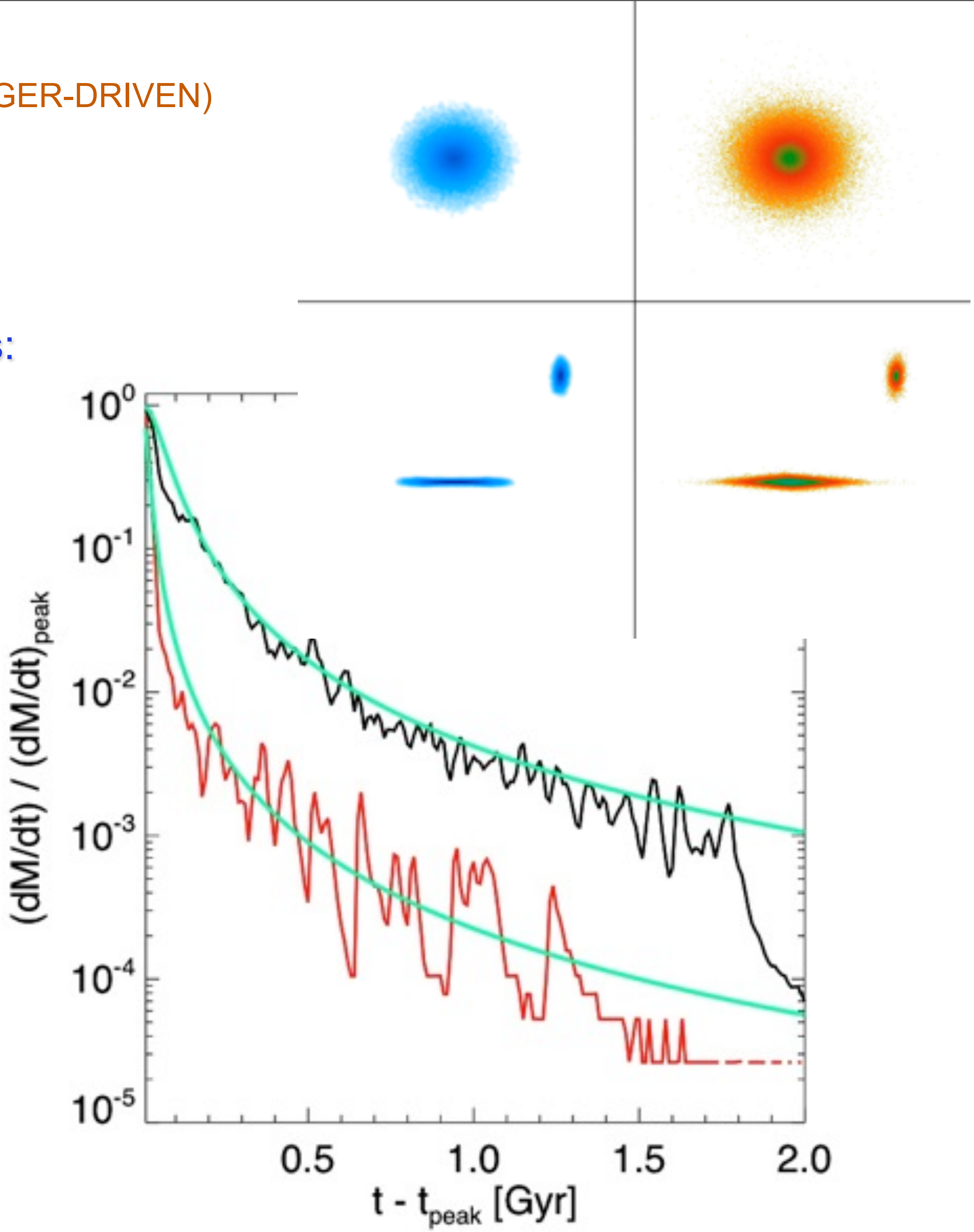



- Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)

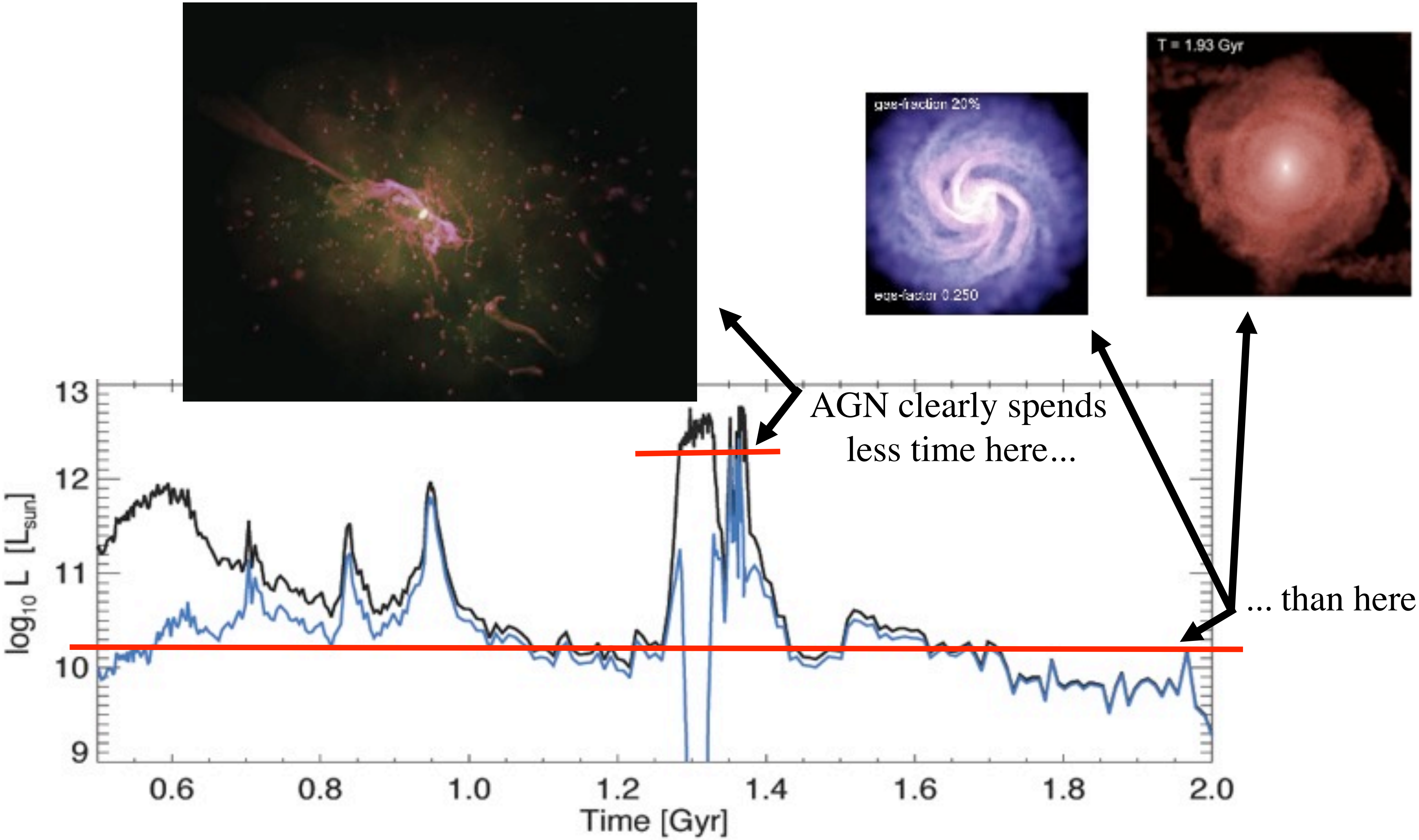
PFH et al. 2006a

# 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 (~ $t_{Salpeter}$)
  - E~E_binding
- Simple, analytic solutions:
  - $L \sim (t / t_Q)^{-1.7(ish)}$
  - Agrees well with simulations!
- Generalize to "Seyferts"
  - Disk-dominated galaxies with bars
  - Minor mergers



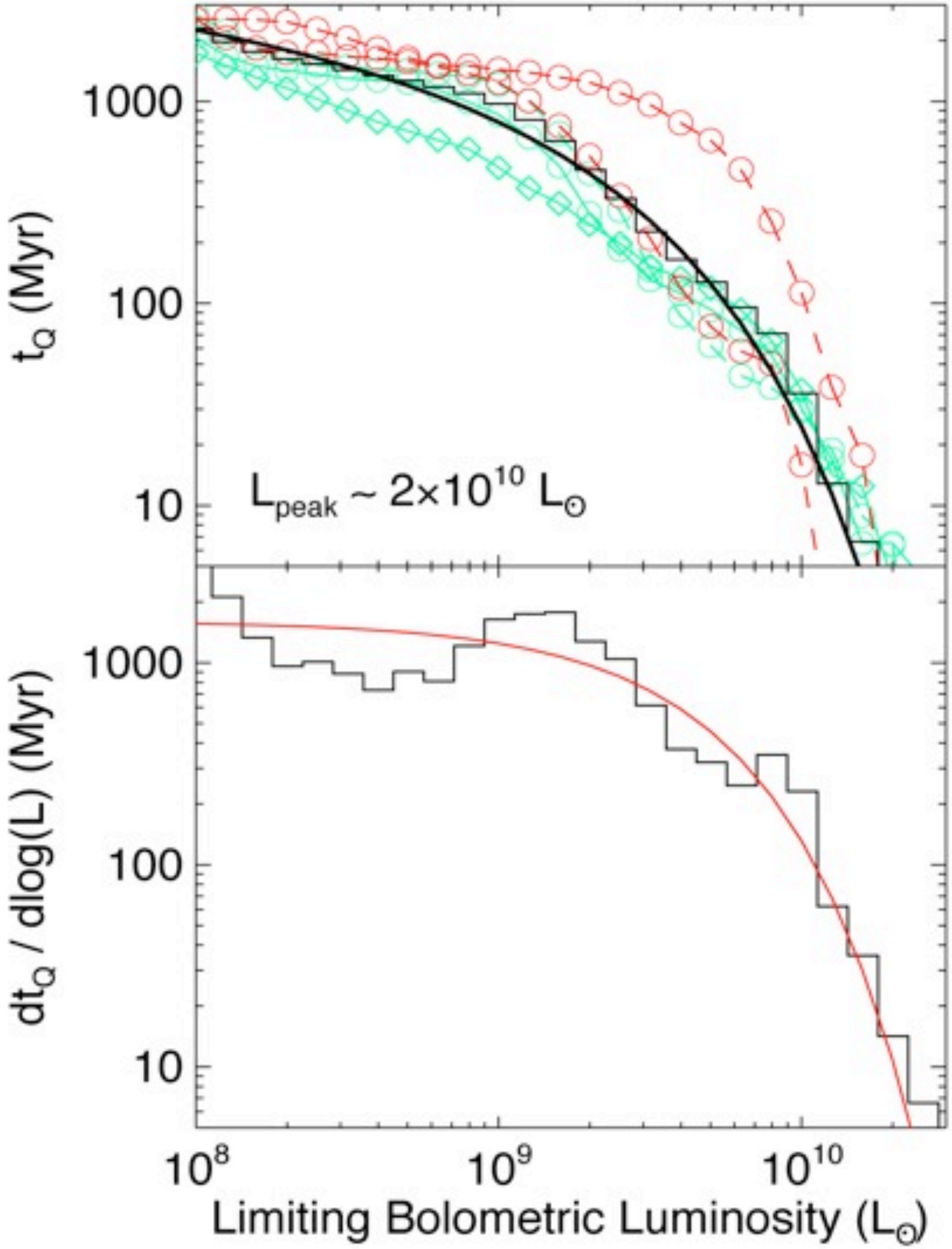
# So What Is the “Quasar Lifetime”?




- “Quasar Lifetime”: a conditional, *luminosity-dependent* distribution

# Feedback Determines the Decay of the Quasar Light Curve

## LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME

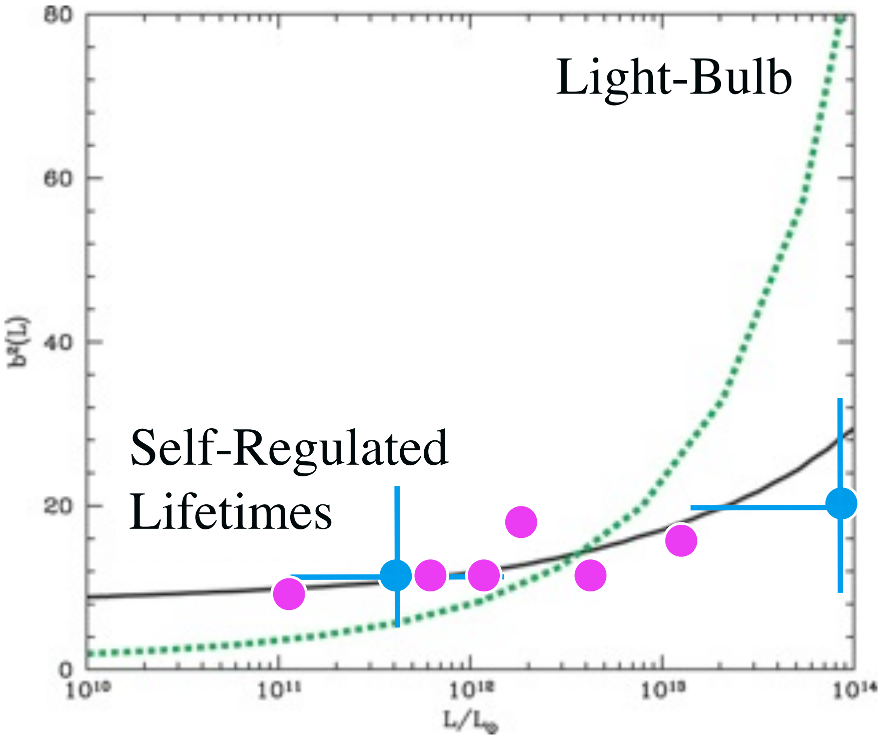



- "Quasar Lifetime": a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity

PFH et al. 2006b

# Quasar Clustering is a Strong Test of this Model

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

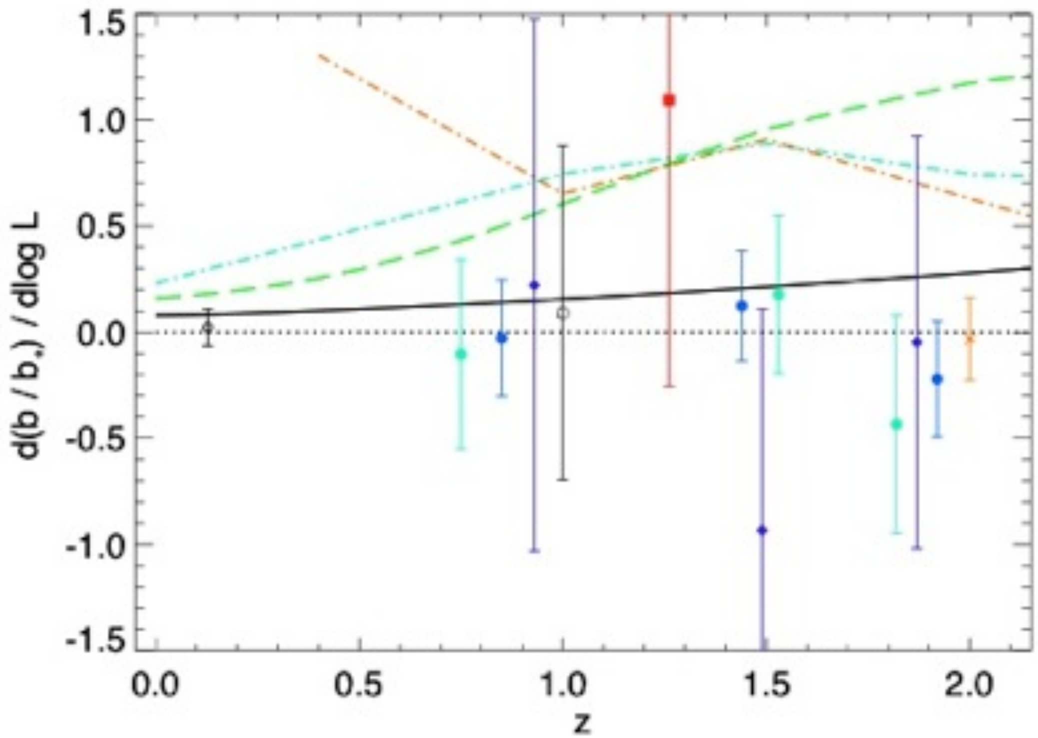



Adelberger & Steidel 05

Myers et al. 05

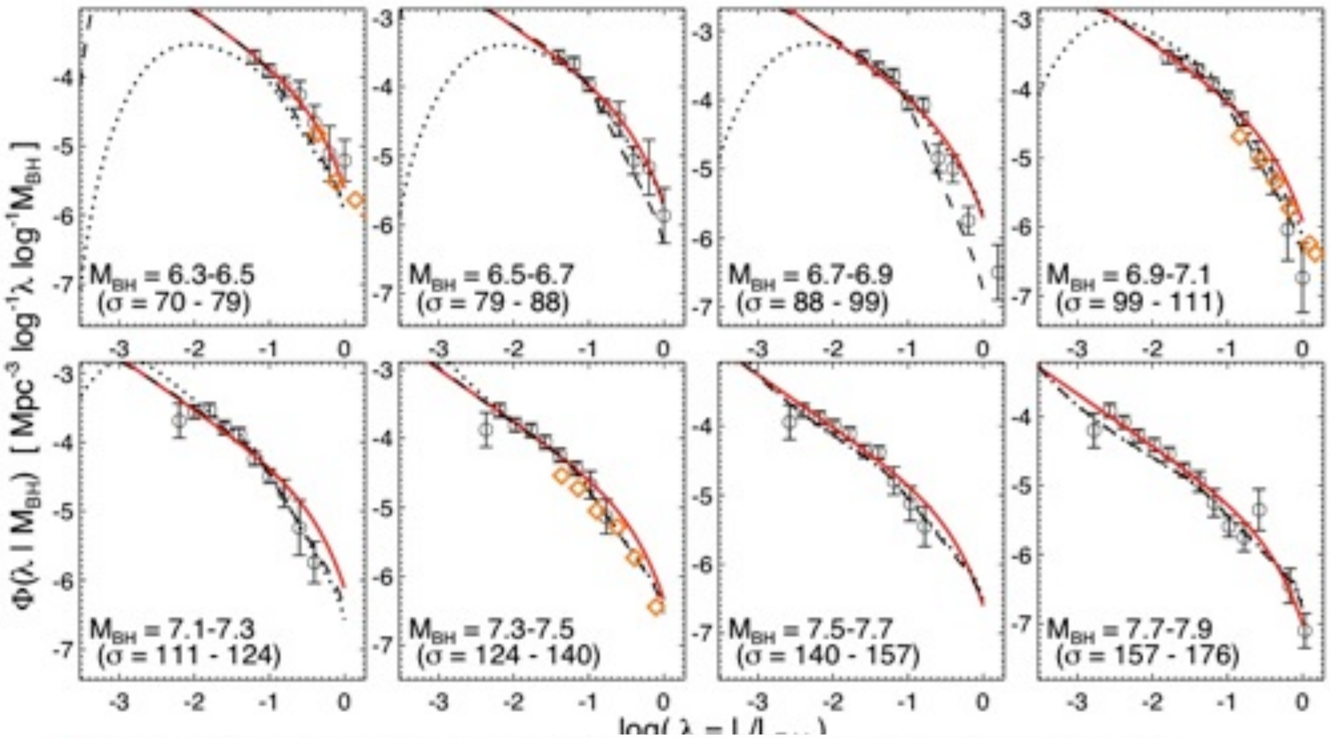
Lidz et al. 2005

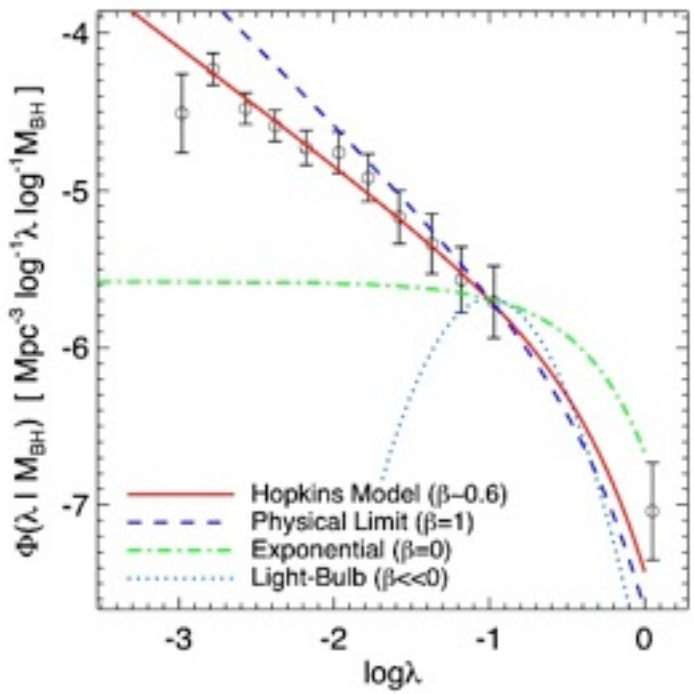
- Weak dependence of clustering on observed luminosity
  - (Croom et al., Adelberger & Steidel, Myers et al., Coil et al., Porciani et al.)

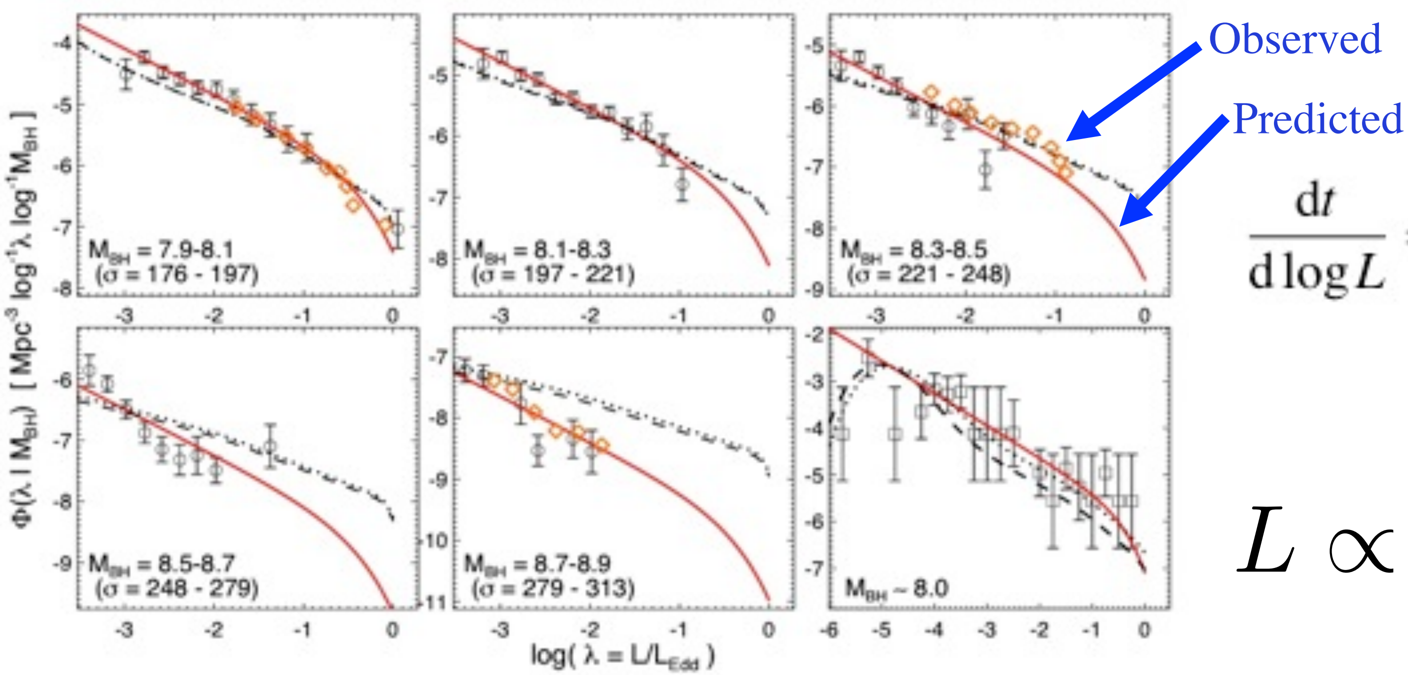



Hopkins, Lidz, Coil, Myers et al. 2007

# Directly Apparent in the Observed Eddington Ratio Distribution



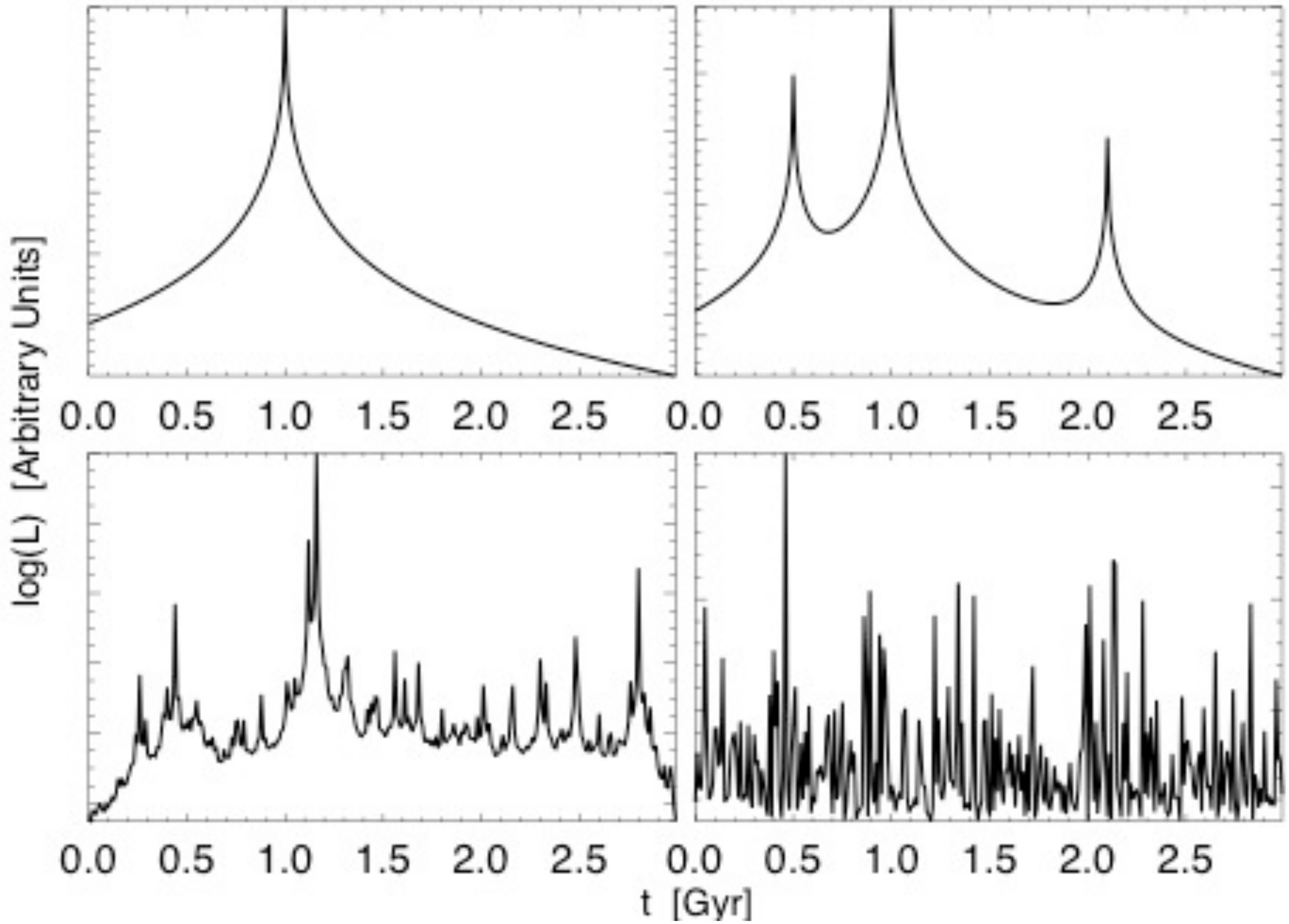




$$\frac{dt}{d\log L} = t_0 \left(\frac{L}{L_{\rm peak}}\right)^{-\beta} \exp\left(-L/L_{\rm peak}\right)$$

$$\Downarrow$$

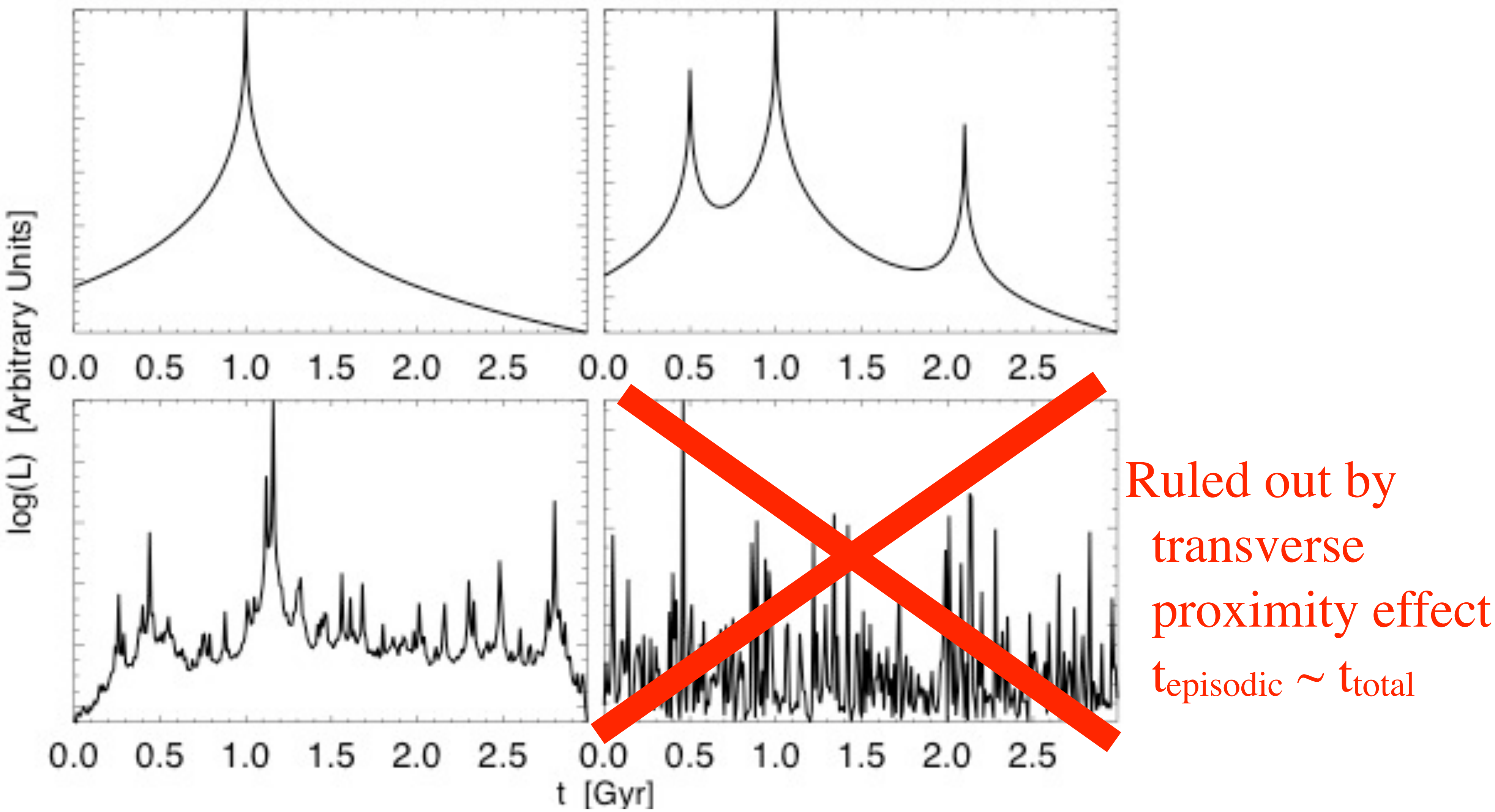
$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

# Directly Apparent in the Observed Eddington Ratio Distribution




$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

Directly Apparent in the Observed Eddington Ratio Distribution

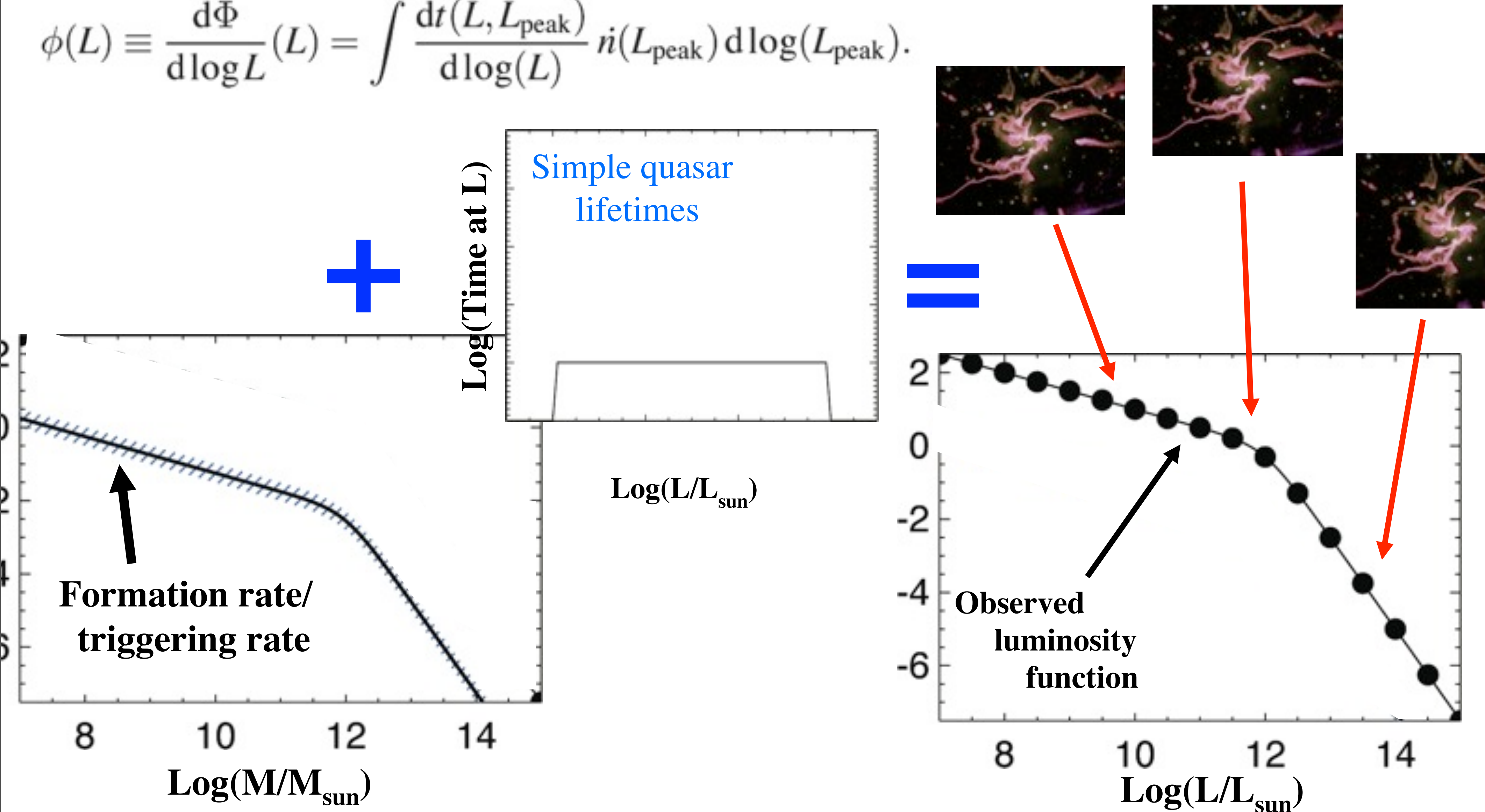



$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

# Given the Conditional Quasar Lifetime, De-Convolve the QLF

QUANTIFIED IN THIS MANNER, UNIQUELY DETERMINES THE RATE OF “TRIGGERING”

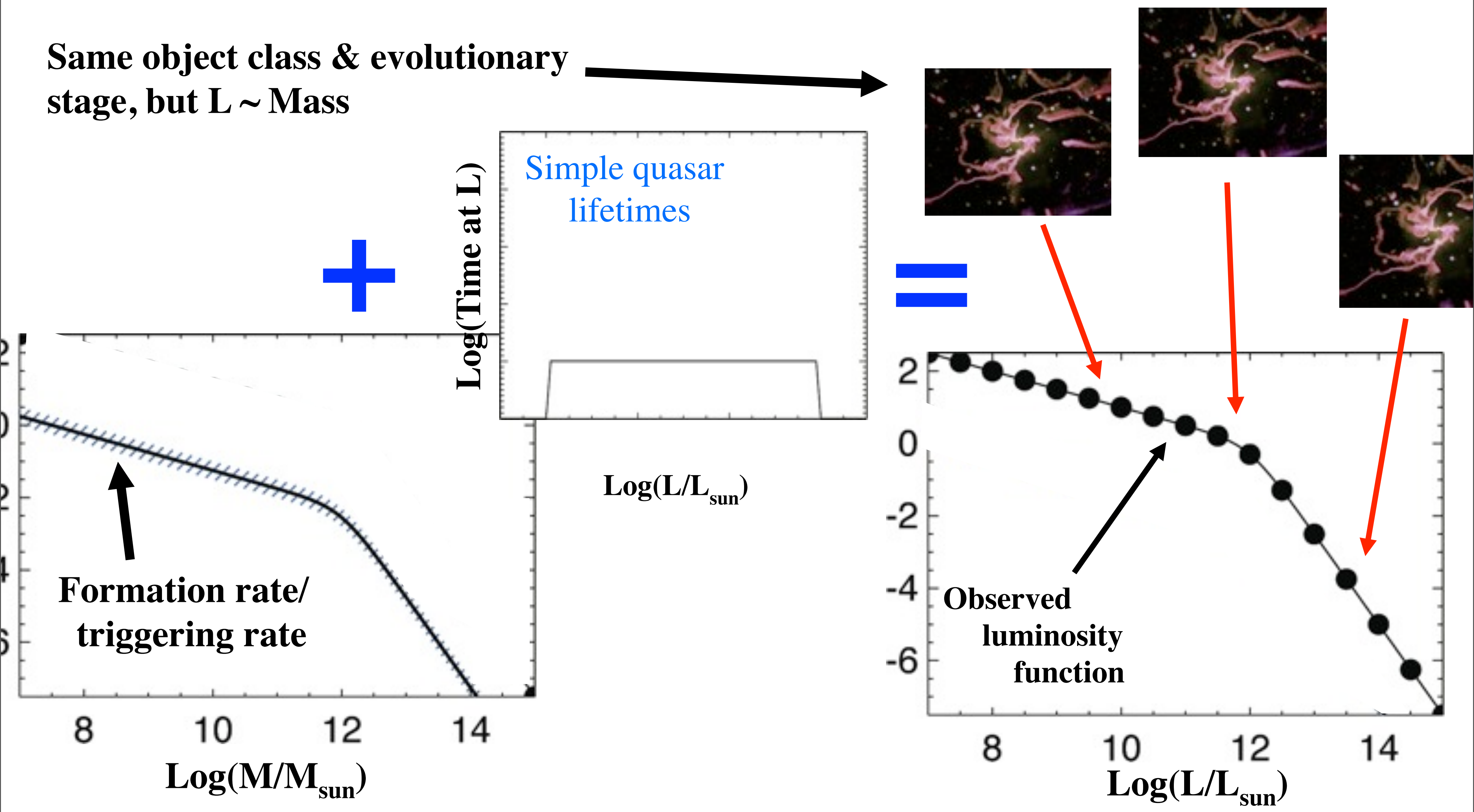
$$\phi(L) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\log L}(L) = \int \frac{\mathrm{d}t(L, L_{\mathrm{peak}})}{\mathrm{d}\log(L)}\,\dot{n}(L_{\mathrm{peak}})\,\mathrm{d}\log(L_{\mathrm{peak}}).$$



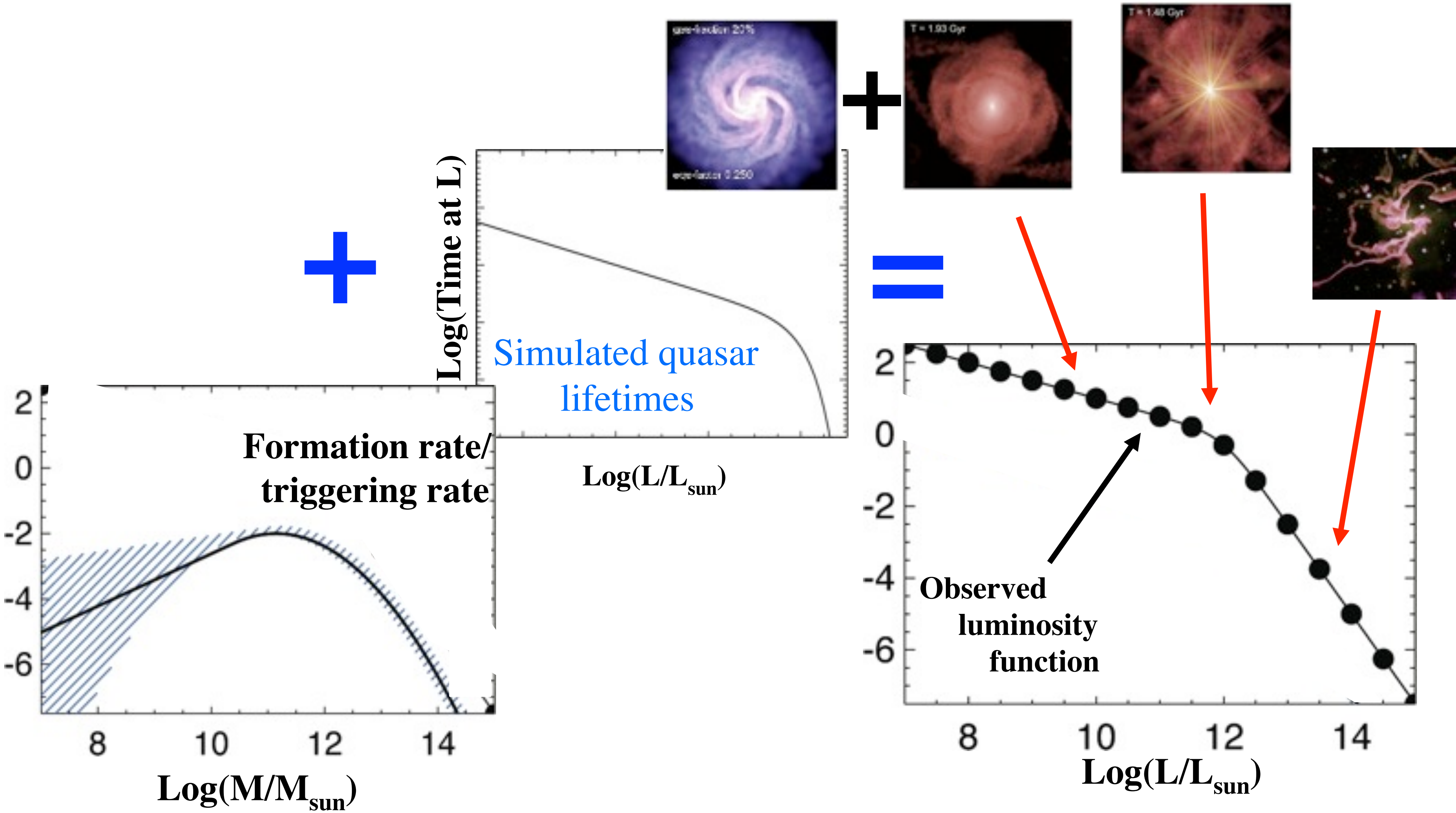

- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF

# Given the Conditional Quasar Lifetime, De-Convolve the QLF

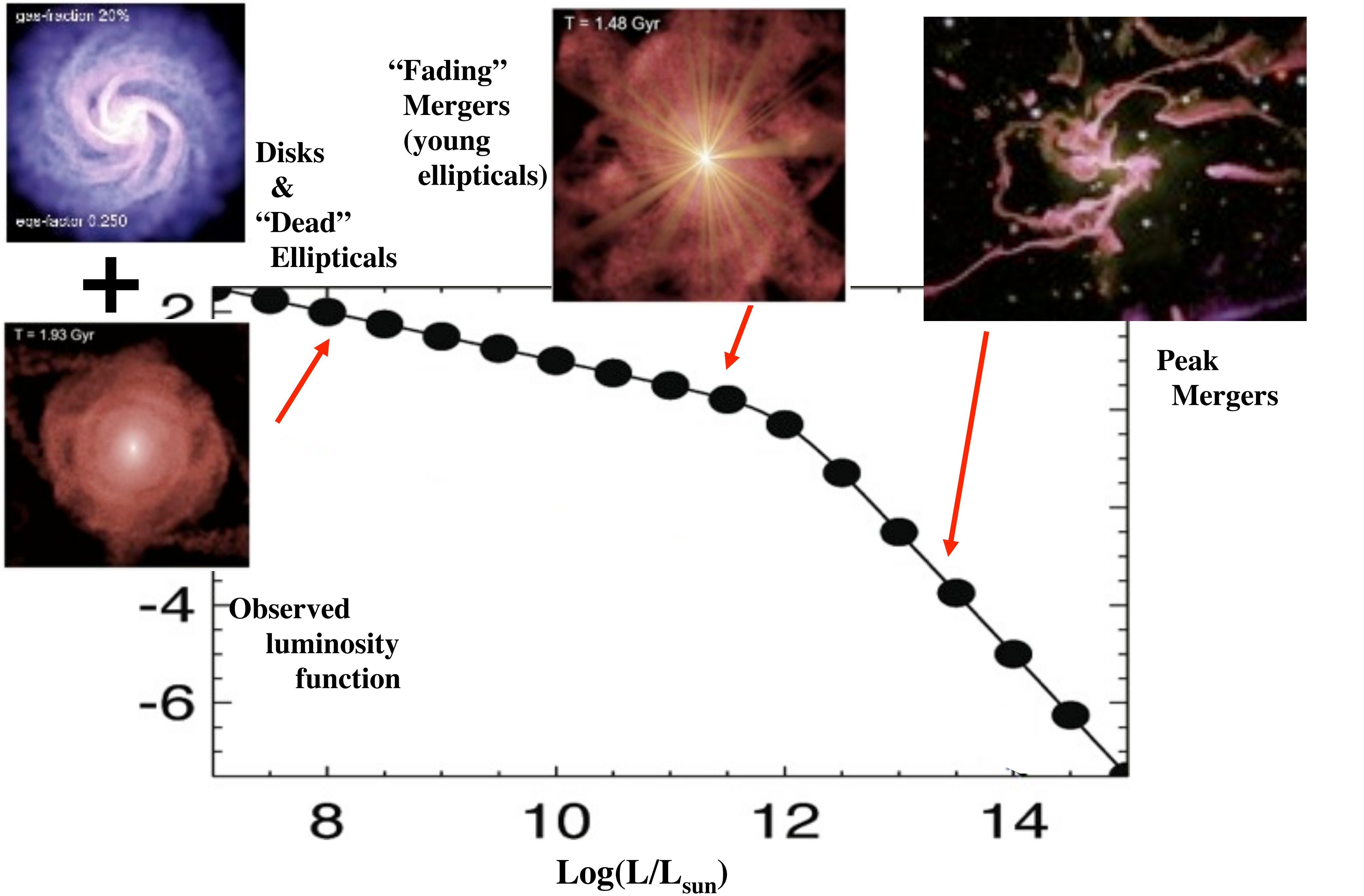
QUANTIFIED IN THIS MANNER, UNIQUELY DETERMINES THE RATE OF “TRIGGERING”




- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF




- *Different* shapes
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts




- Similar populations at different (short) *evolutionary* stages dominate QLF

# Summary

- $M_{BH}$ traces spheroid $E_{binding}$
  - Suggests *self-regulated* BH growth

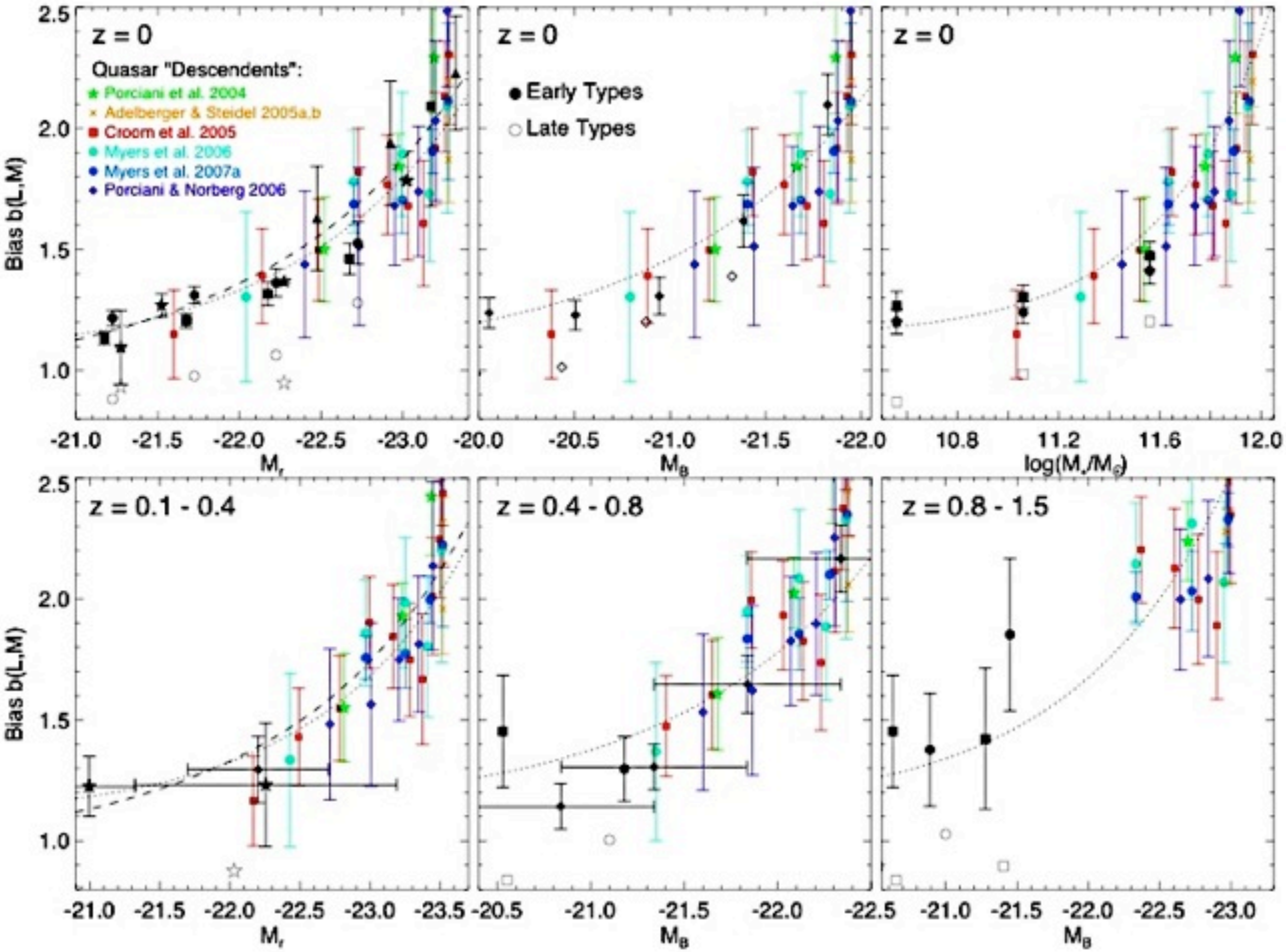
- If self-regulated, this feedback is potentially radically important:
  - Heating gas, ejecting metals, shutting down SF
  - Self-regulated decay of QSO luminosity:
    - Luminosity-dependent quasar lifetimes
    - Changes the meaning of the QLF

- "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

# Motivation

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

- Yesterday's Quasar is today's Red, Early-Type Galaxy:




PFH, Lidz, Coil, Myers+