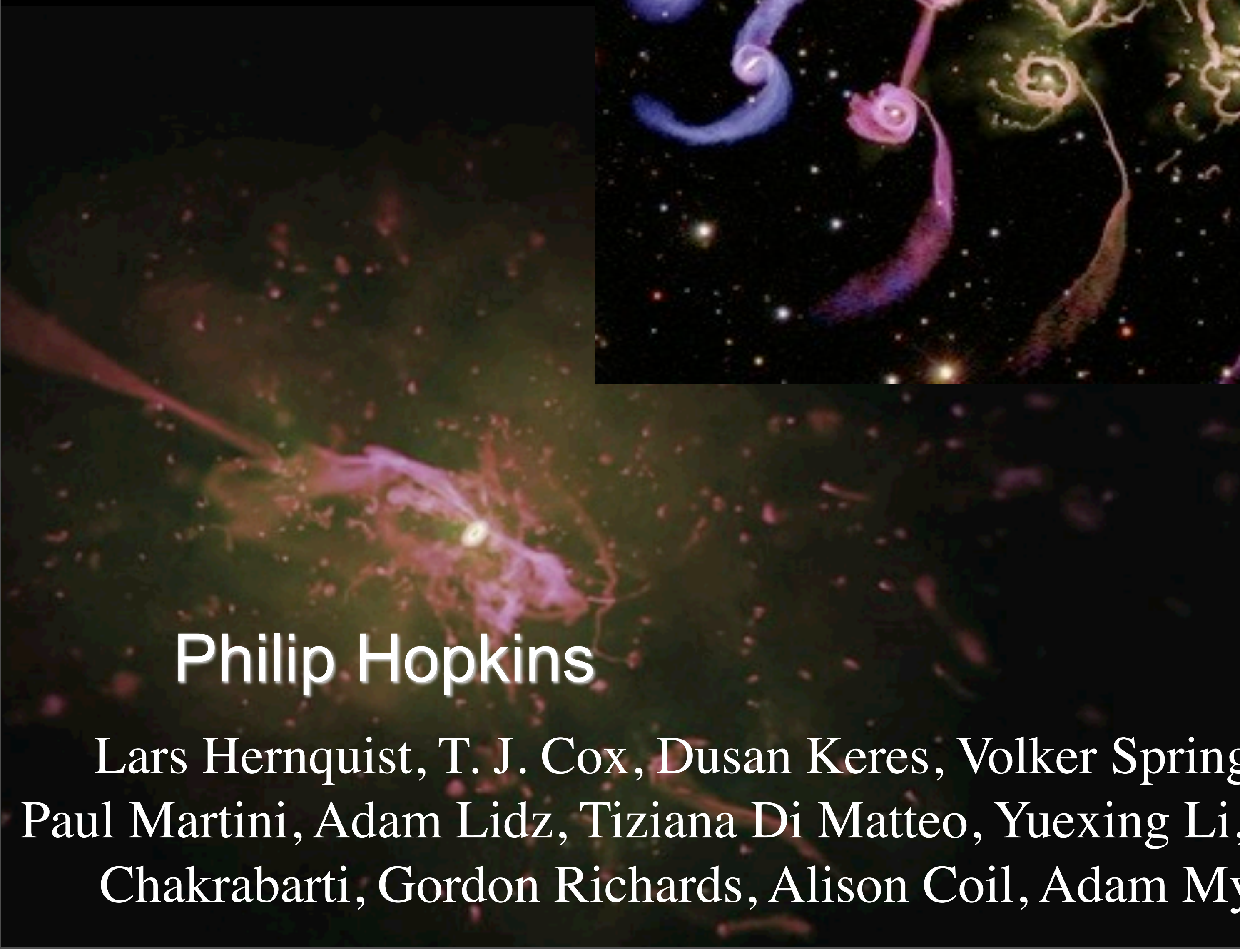
Quasars, Mergers, and Spheroid Evolution



Philip Hopkins

04/04/08

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

Too many people to thank...

Lars Hernquist...

my advisor on all things related to wine... also, the thesis

Too many people to thank...

T. J. Cox...

Without whom most of these simulations wouldn't exist, nor would most of my best memories (and pictures)

(TJ's shoes)

Too many people to thank...

Gordon Richards

Alison Coil

Adam Lidz

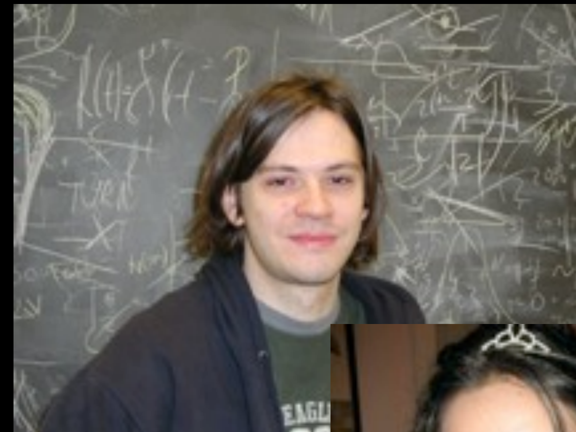
Rachel Somerville

Volker Springel

Paul Martini

And of course the group:

Brant Robertson



Dusan Keres

Josh Younger

Gurtina Besla

Kai Noeske

Desika Narayanan

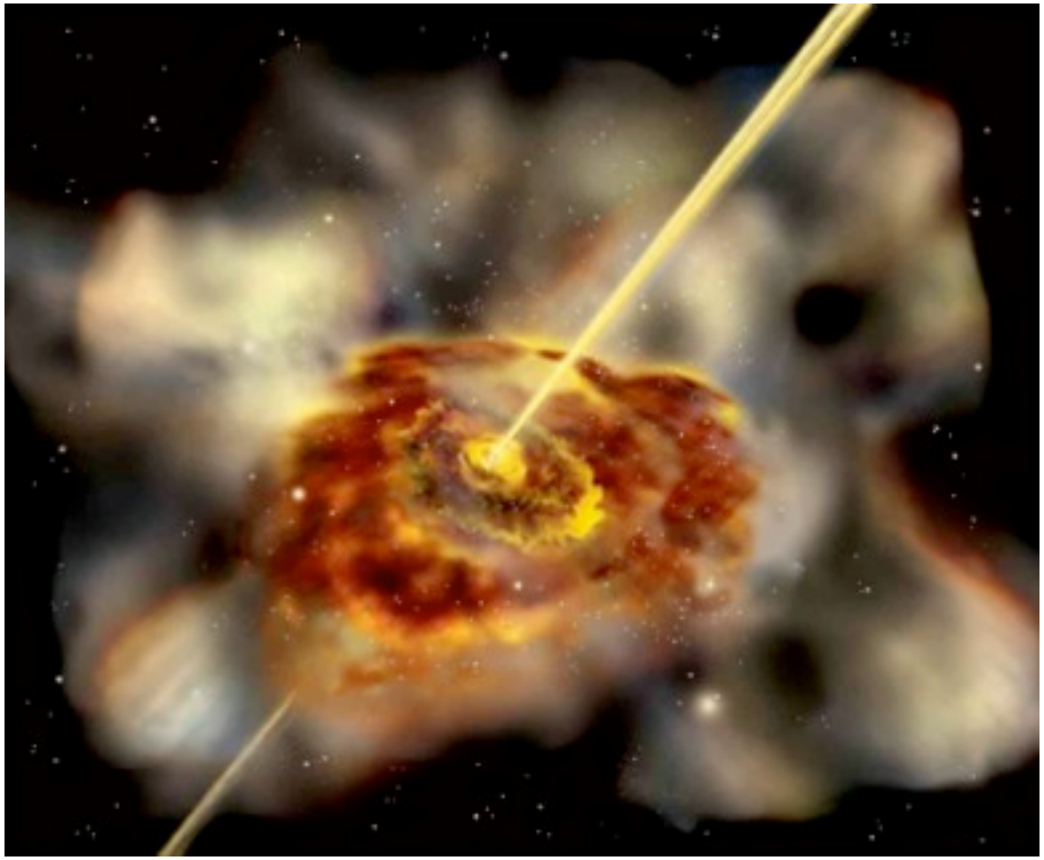
Stijn Wuyts

Chris Hayward

Yuexing Li, Stephanie Bush, Tiziana Di Matteo, and others

SCIENCE

- Every massive galaxy hosts a supermassive black hole

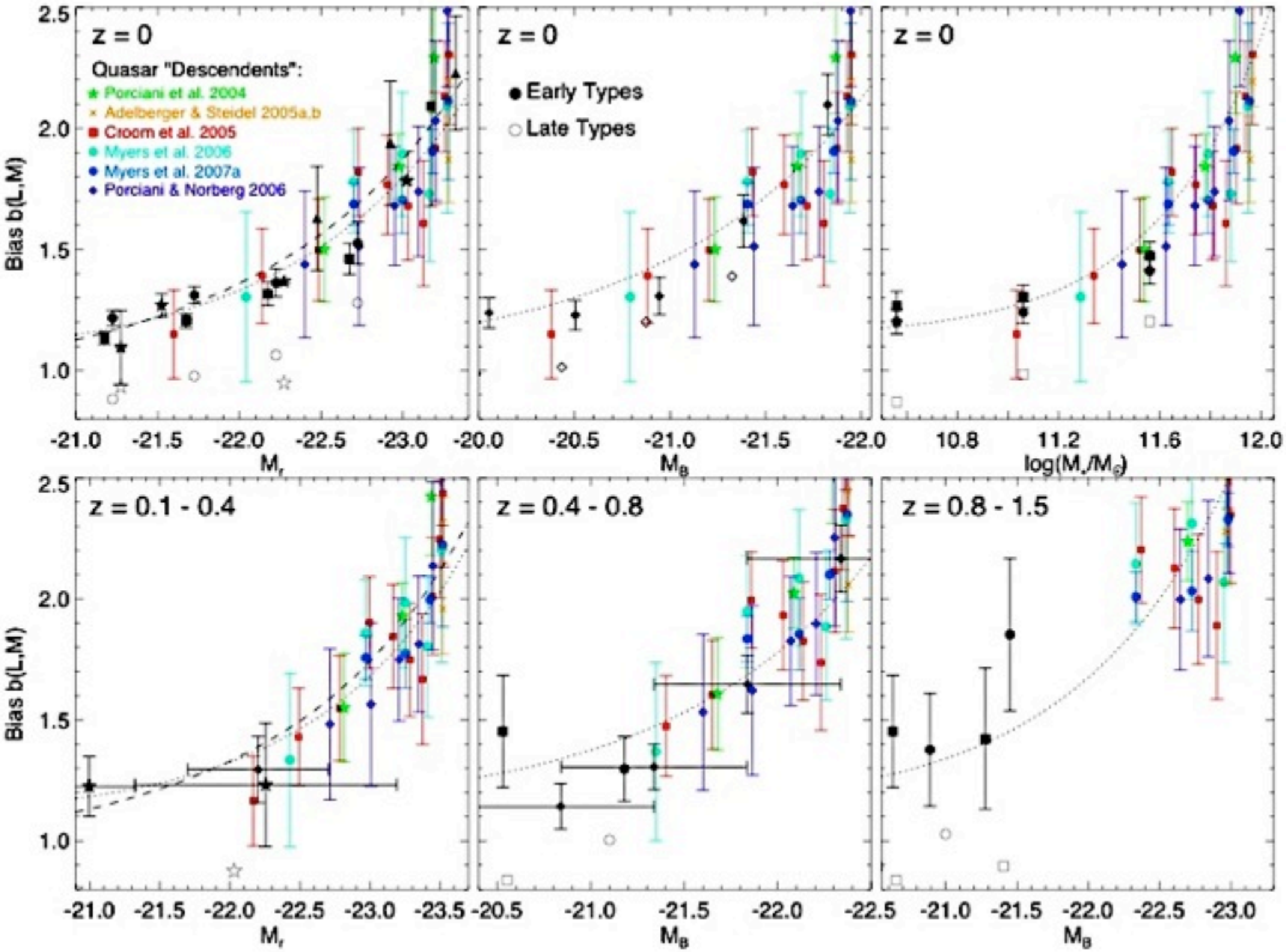


- These BHs accreted most of their mass in bright, short lived quasar accretion episodes: the “fossil” quasars

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

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

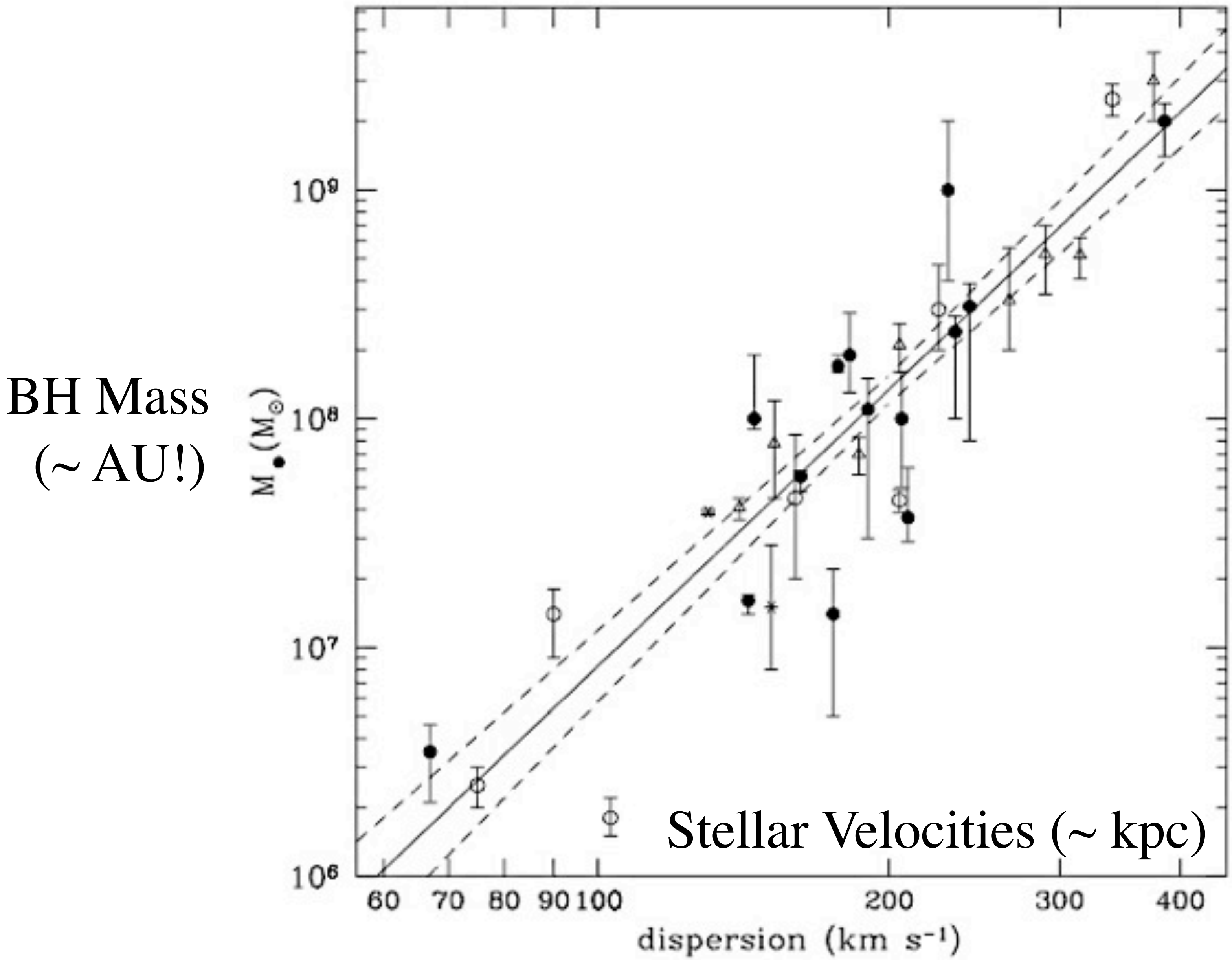


PFH, Lidz, Coil, Myers+

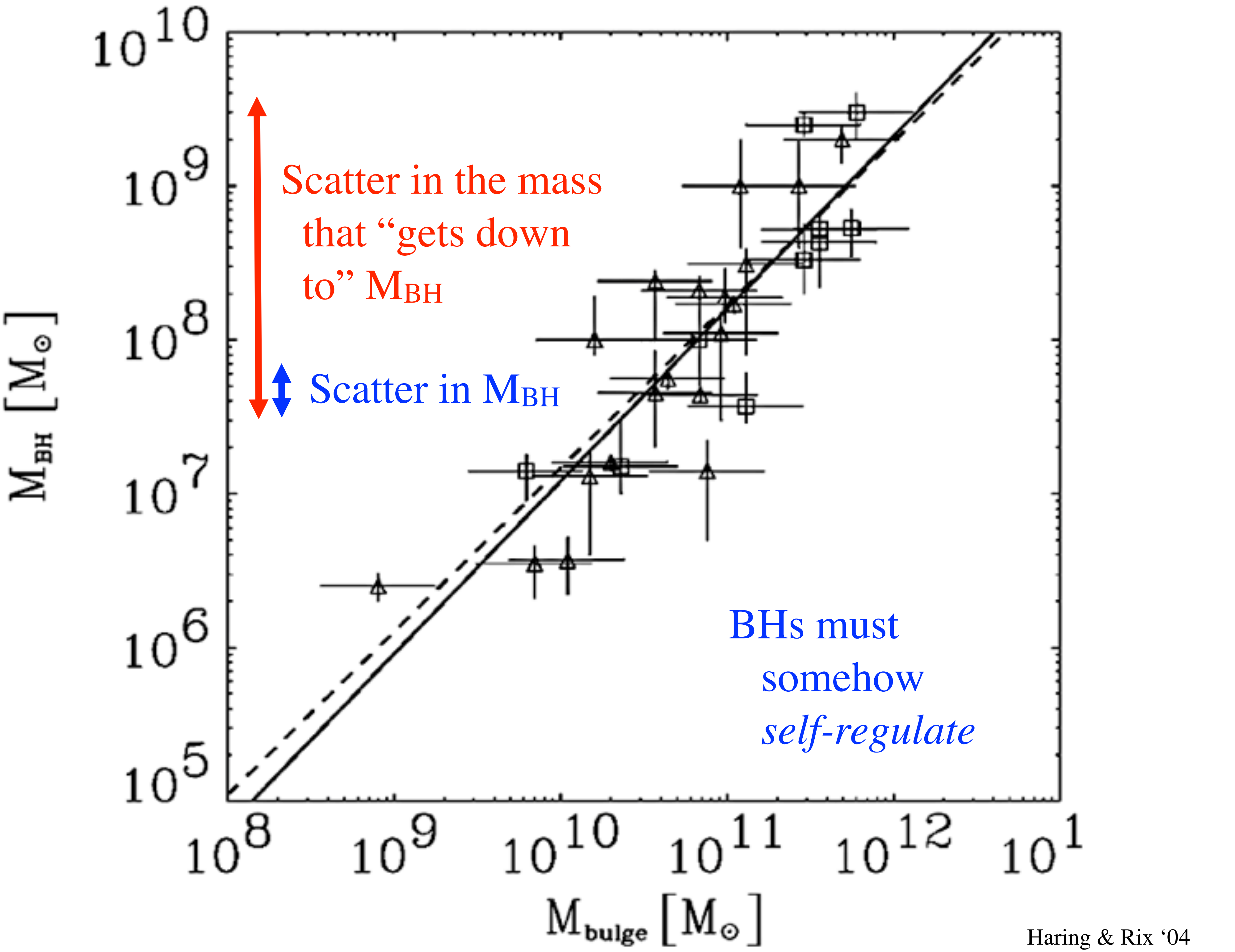
Motivation

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



Scatter in the mass that "gets down to" M_{BH}
Scatter in M_{BH}
BHs must somehow *self-regulate*
M_{BH} [$M_\odot$]
M_{bulge} [$M_\odot$]
10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}
10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{1}
Haring & Rix '04

Simplest Idea:

FEEDBACK ENERGY BALANCE (SILK & REES '98)

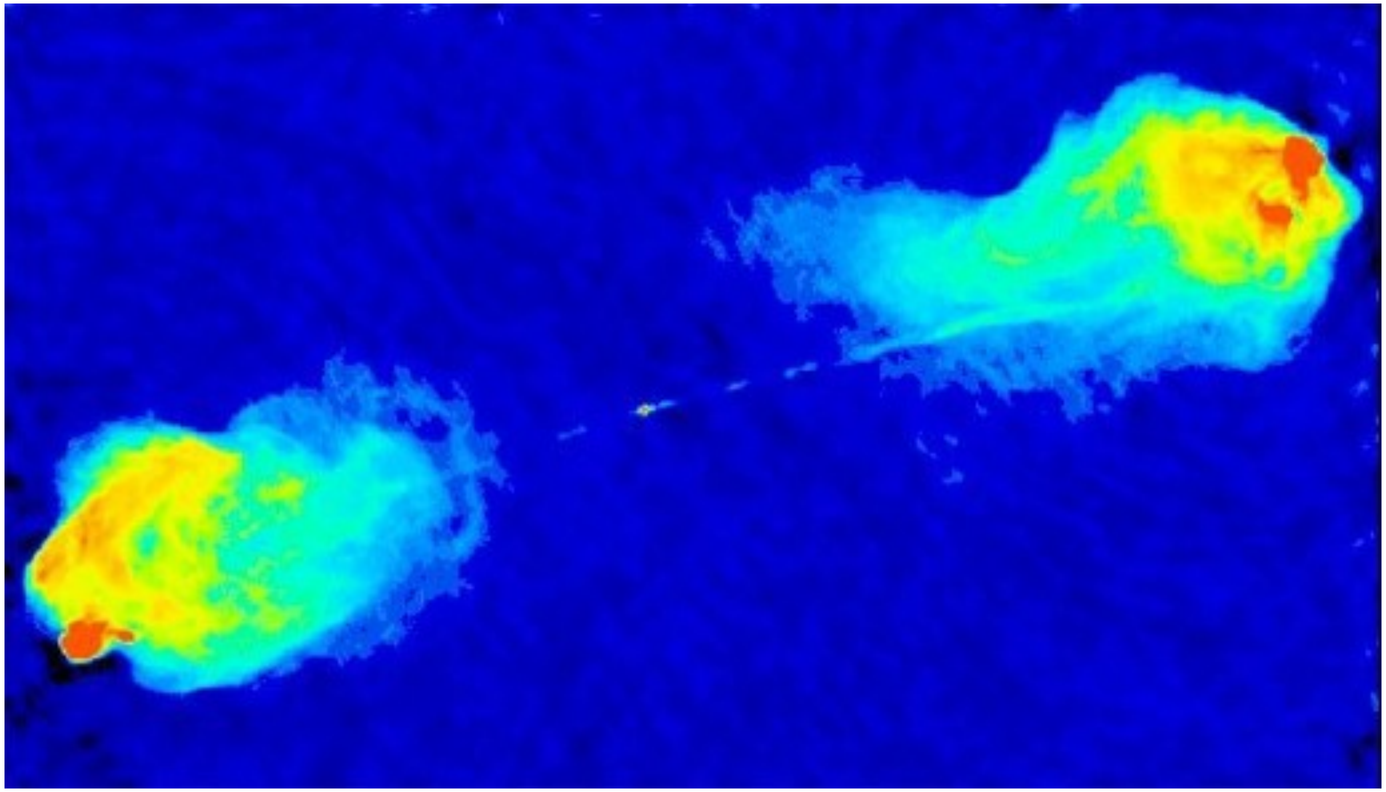
- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r (dM_{BH}/dt) c^2$ $(e_r \sim 0.1)$
- Total energy radiated:
  - $\sim 0.1\ M_{BH}\ c^2 \sim 10^{61}$ ergs in a typical $\sim 10^8\ M_{sun}$ system
- Compare this to the gravitational binding energy of the galaxy:
  - $\sim M_{gal}\ s^2 \sim (10^{11}\ \mathrm{Msun})\ (200\ \mathrm{km/s})^2 \sim 10^{59}$ 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
    - $\mathrm{MBH} \sim (a/he_r)\ M_{gal}\ (s/c)^2 \sim 0.002\ M_{gal}$

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!

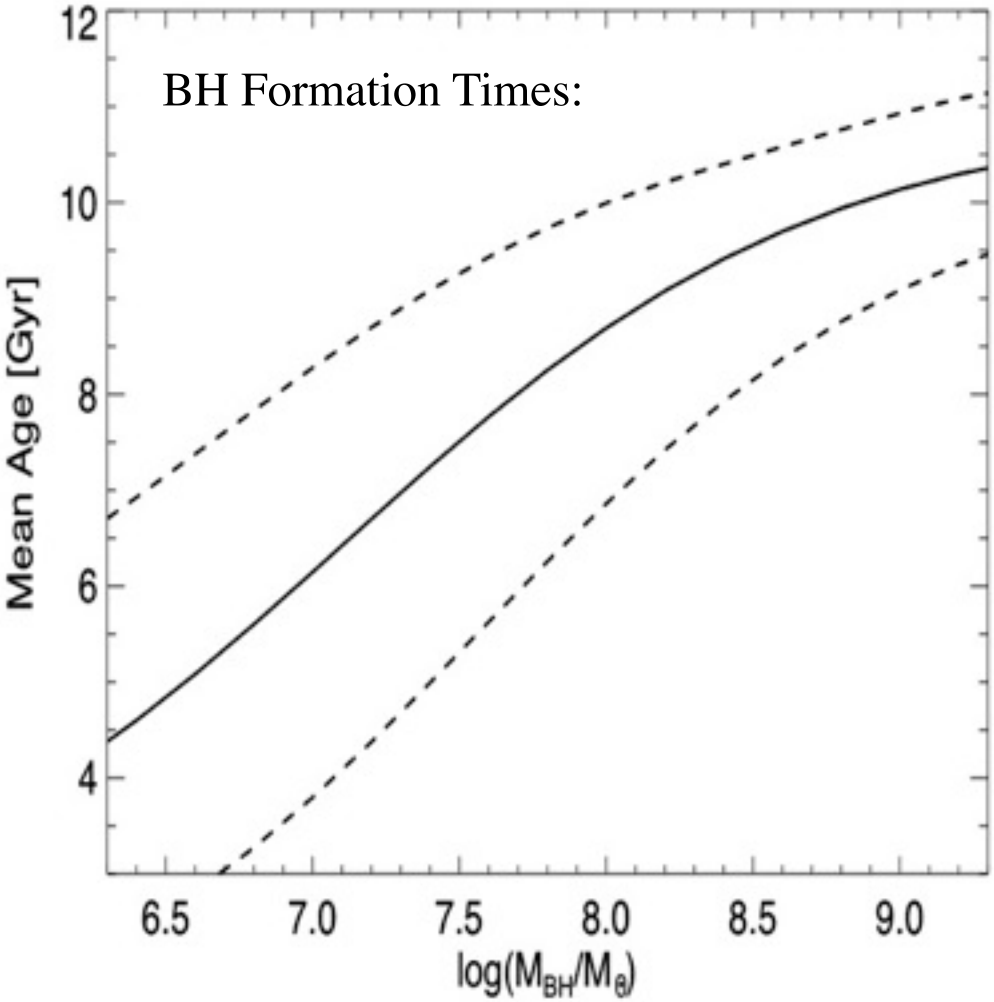
- It comes in many forms:
  - radio jets
  - winds (from the accretion disk)
  - radiation pressure/ galactic winds
  - Compton heating
  - ionization

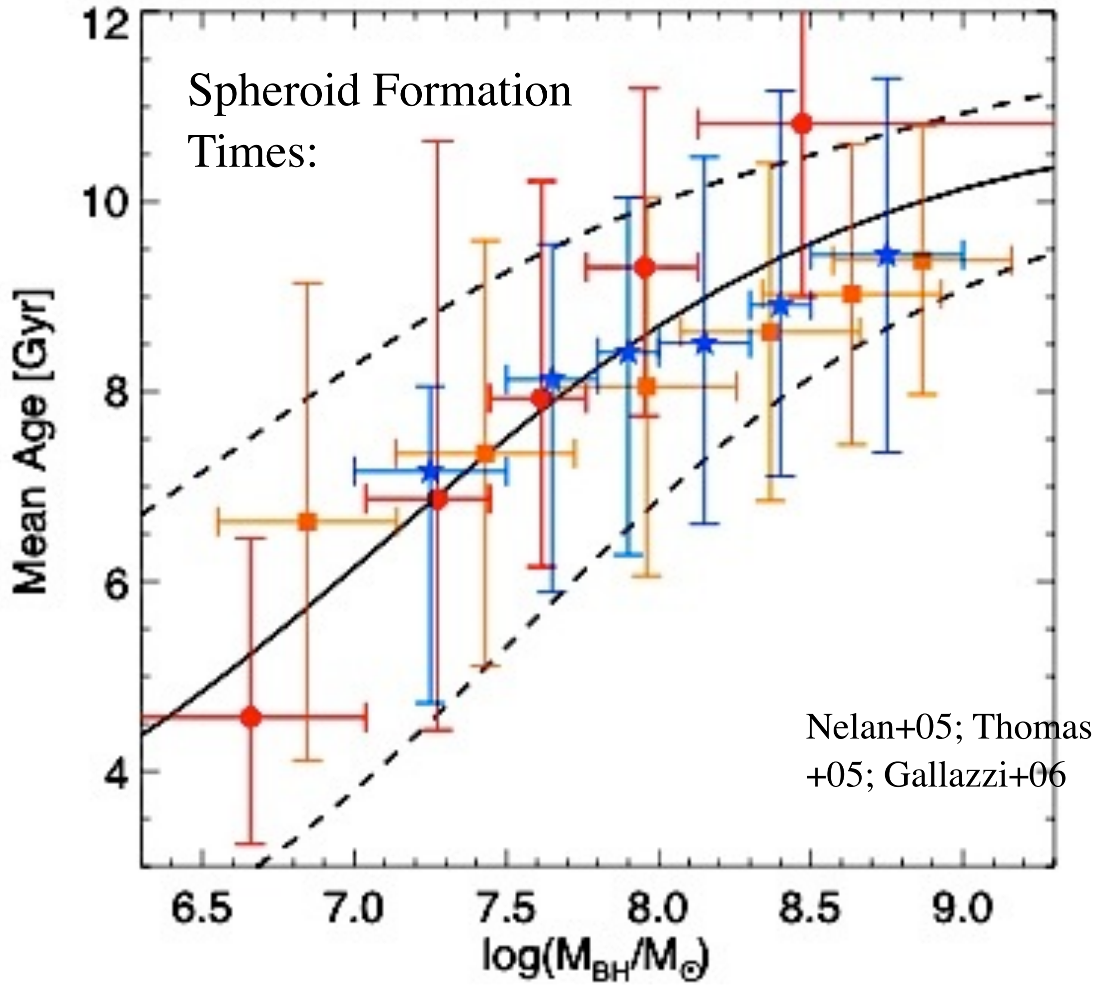


Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

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

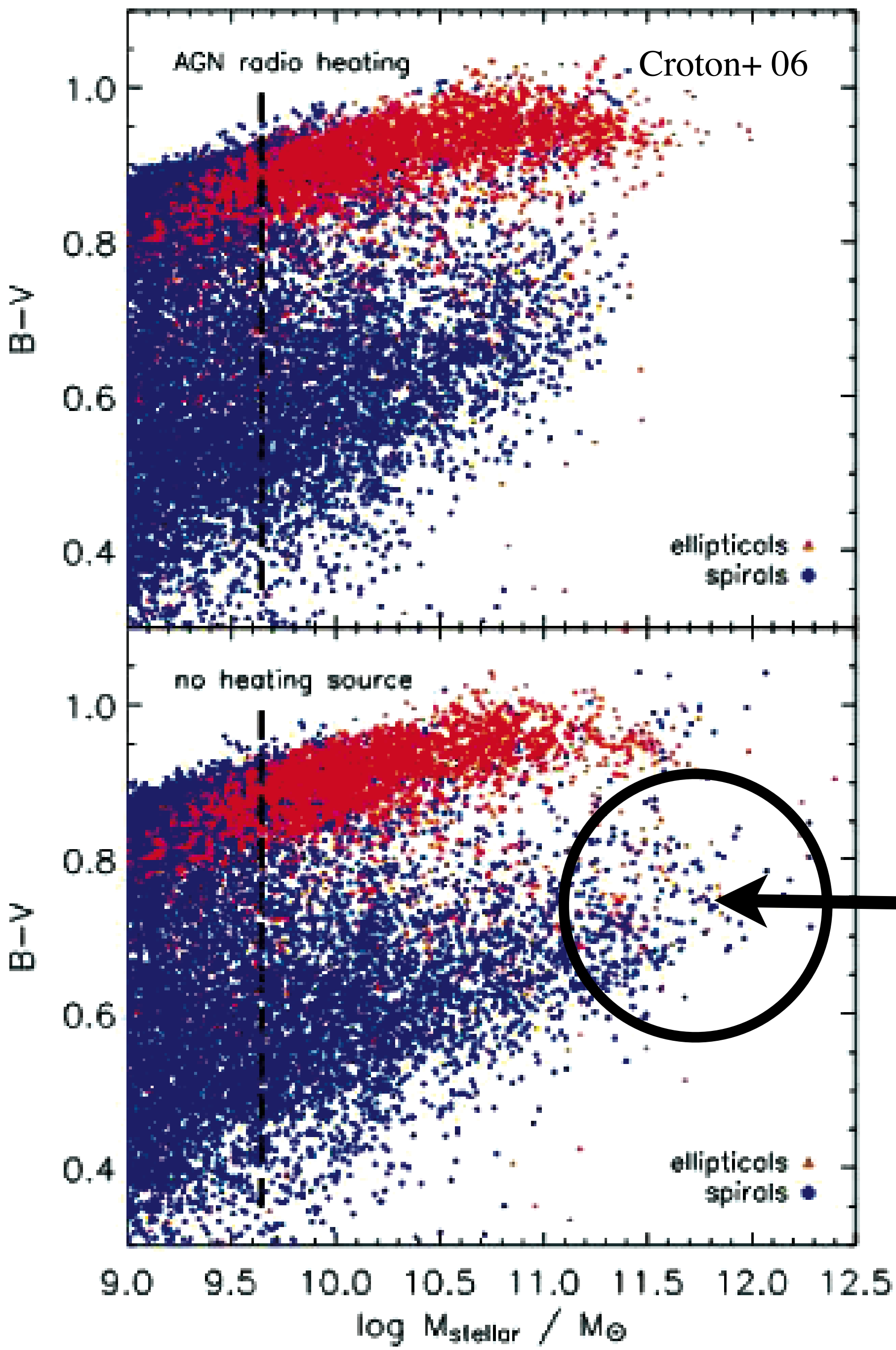




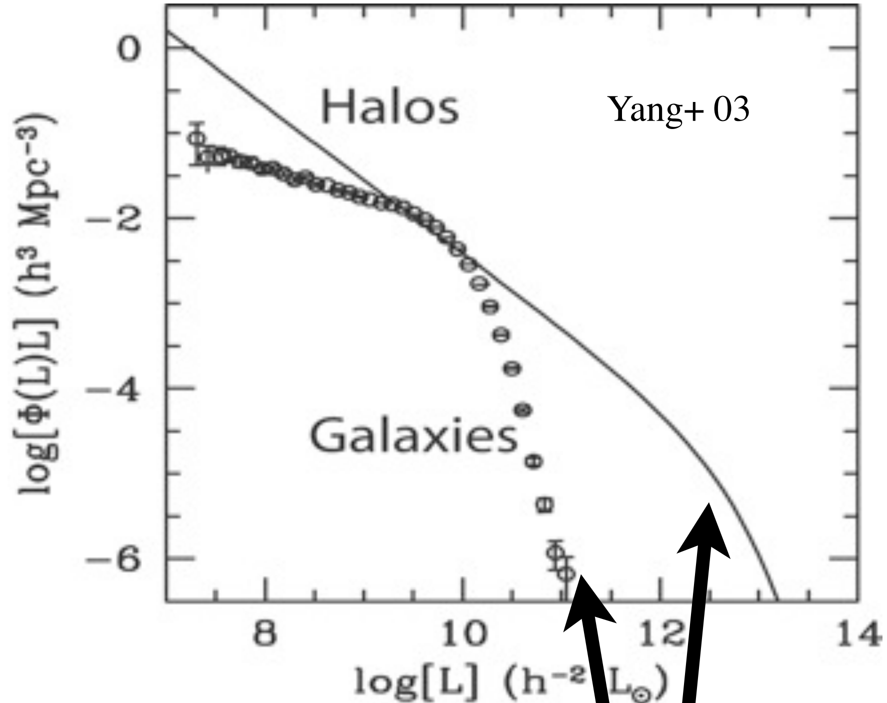
PFH, Lidz, Coil, Myers, et al. 2007

Motivation

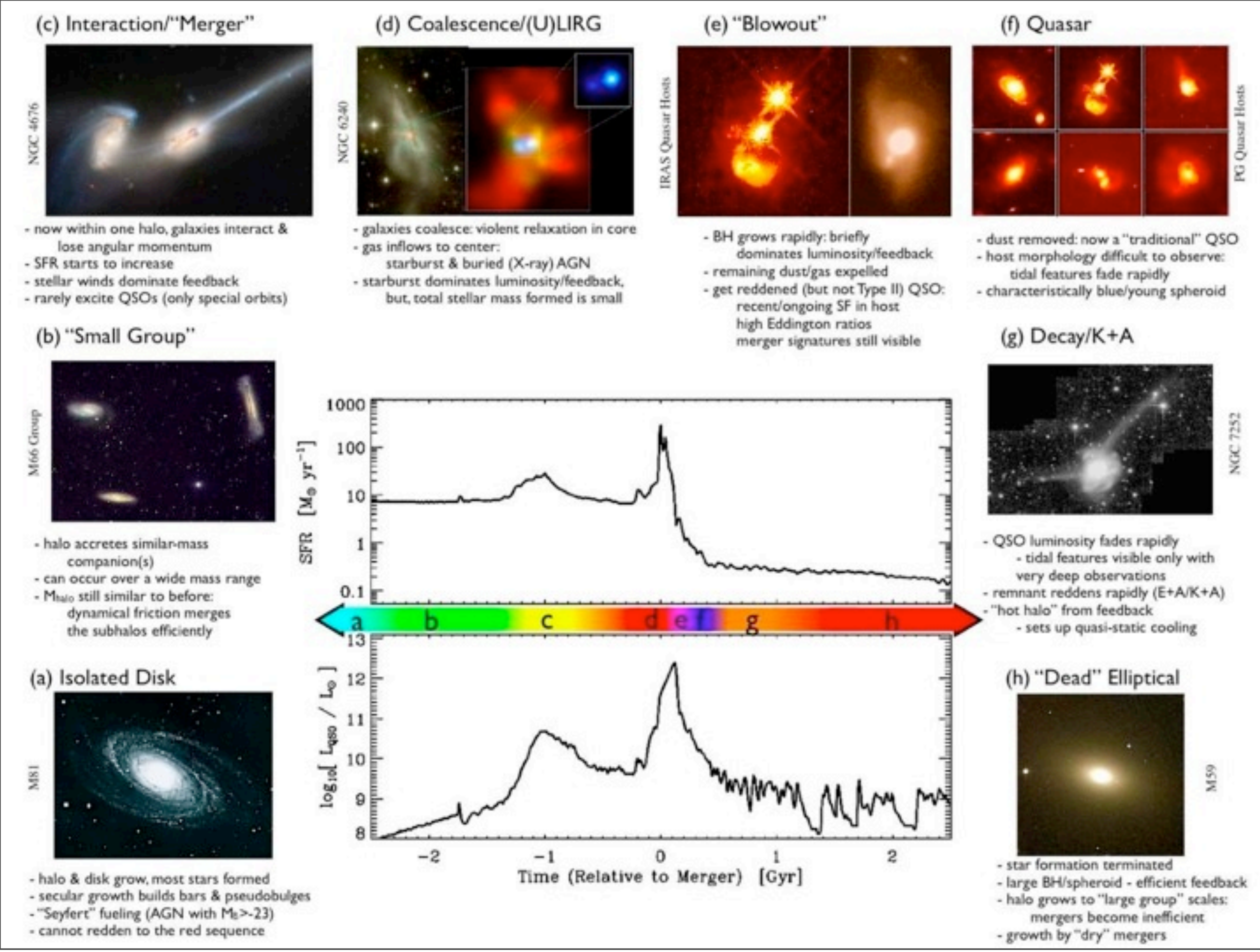
MAYBE THIS CAN EXPLAIN OTHER, LONG-STANDING PROBLEMS?



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



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



Tuesday, December 25, 12

Three Outstanding (Inseparable?) Questions:

Triggering

Lightcurves

Feedback

Three Outstanding (Inseparable?) Questions:

Triggering

How?
When?
Angular Momentum?
Self-suppression?

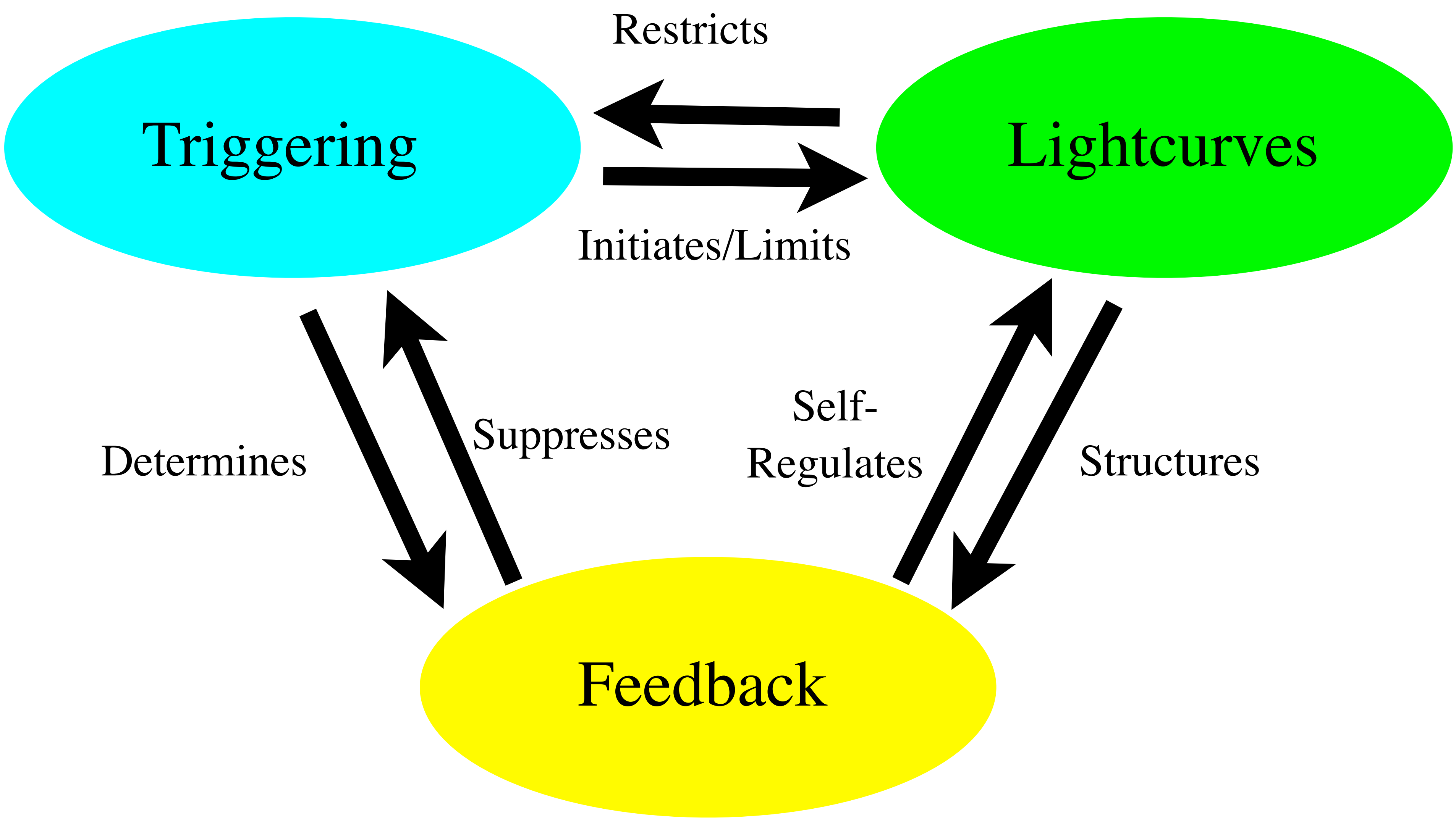
Lightcurves

Lifetimes?
Self-Regulation?
Variability?
Feedback?

Feedback

Coupling mechanisms?
"Quasar" vs. "Radio" mode?
Large-scale impact?

Three Outstanding (Inseparable?) Questions:

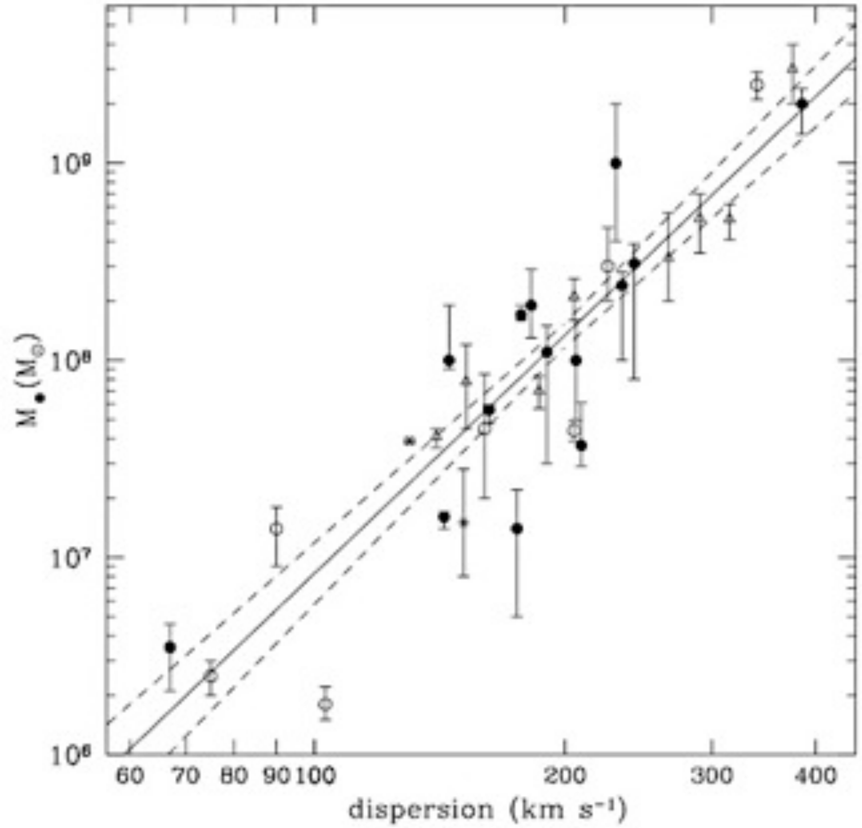


Triggering & Fueling: "Feeding the Monster"

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

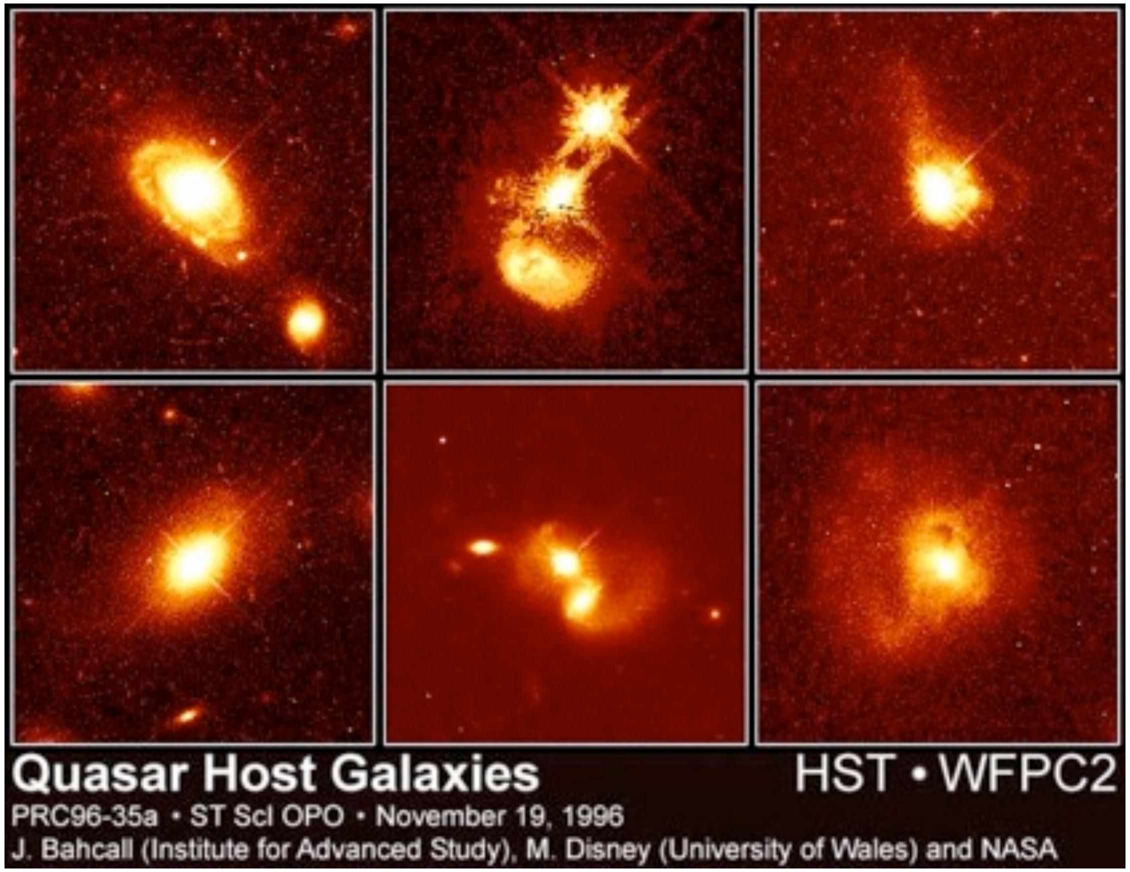
  → gas dynamics; rapid (~ few 10^7 years)

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

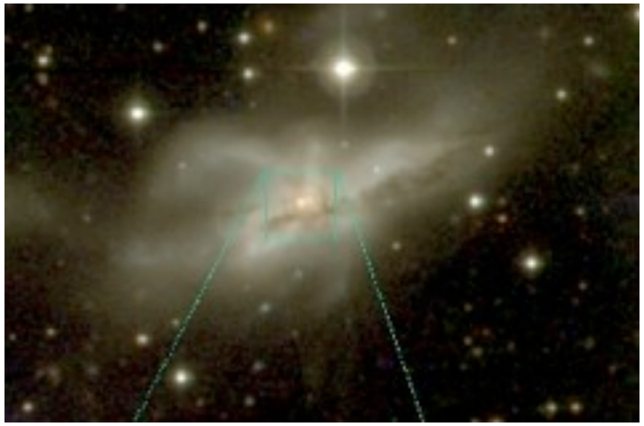
  → stellar dynamics; freefall timescale

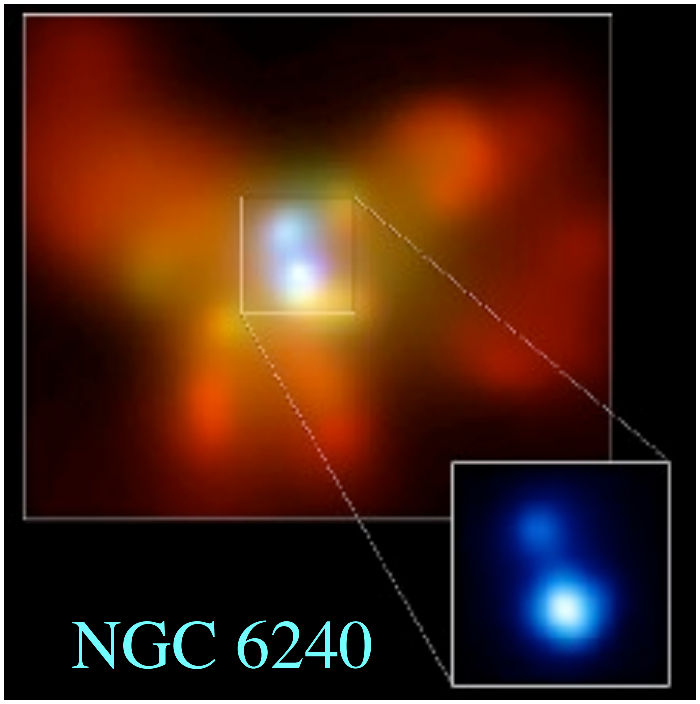
Candidate Process: Gas-Rich, Major Merger

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



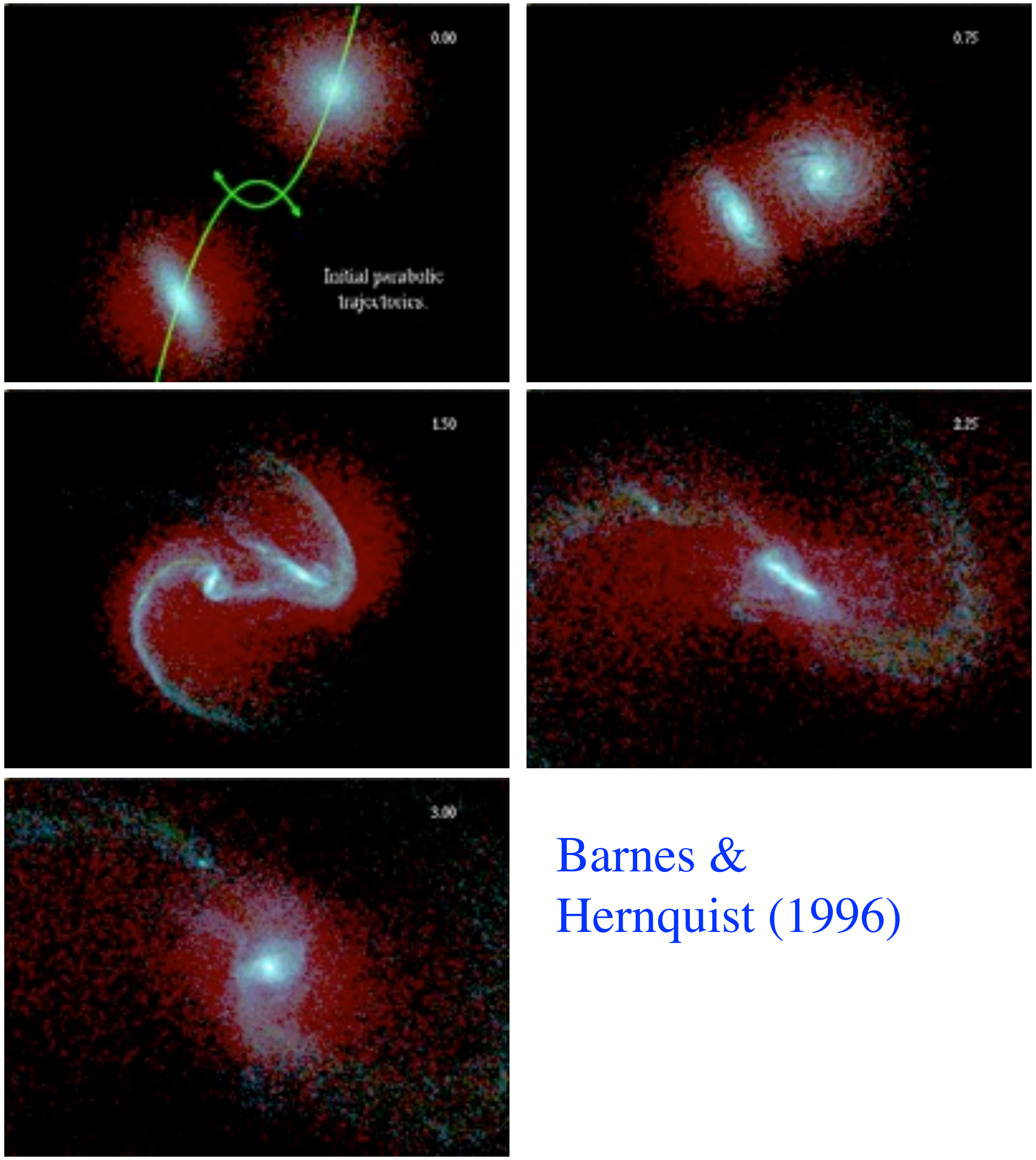
Komossa et al. (2003)





Plausible Physical Mechanism

- Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & LH 1991)
- Triggers starburst (e.g. Mihos & LH 1996)
- Feeds BH growth (e.g. Di Matteo et al. 2005)
- Merging stellar disks grow spheroid
- Requirements:
  - major merger
  - supply of cold gas ("cold" = rotationally supported)

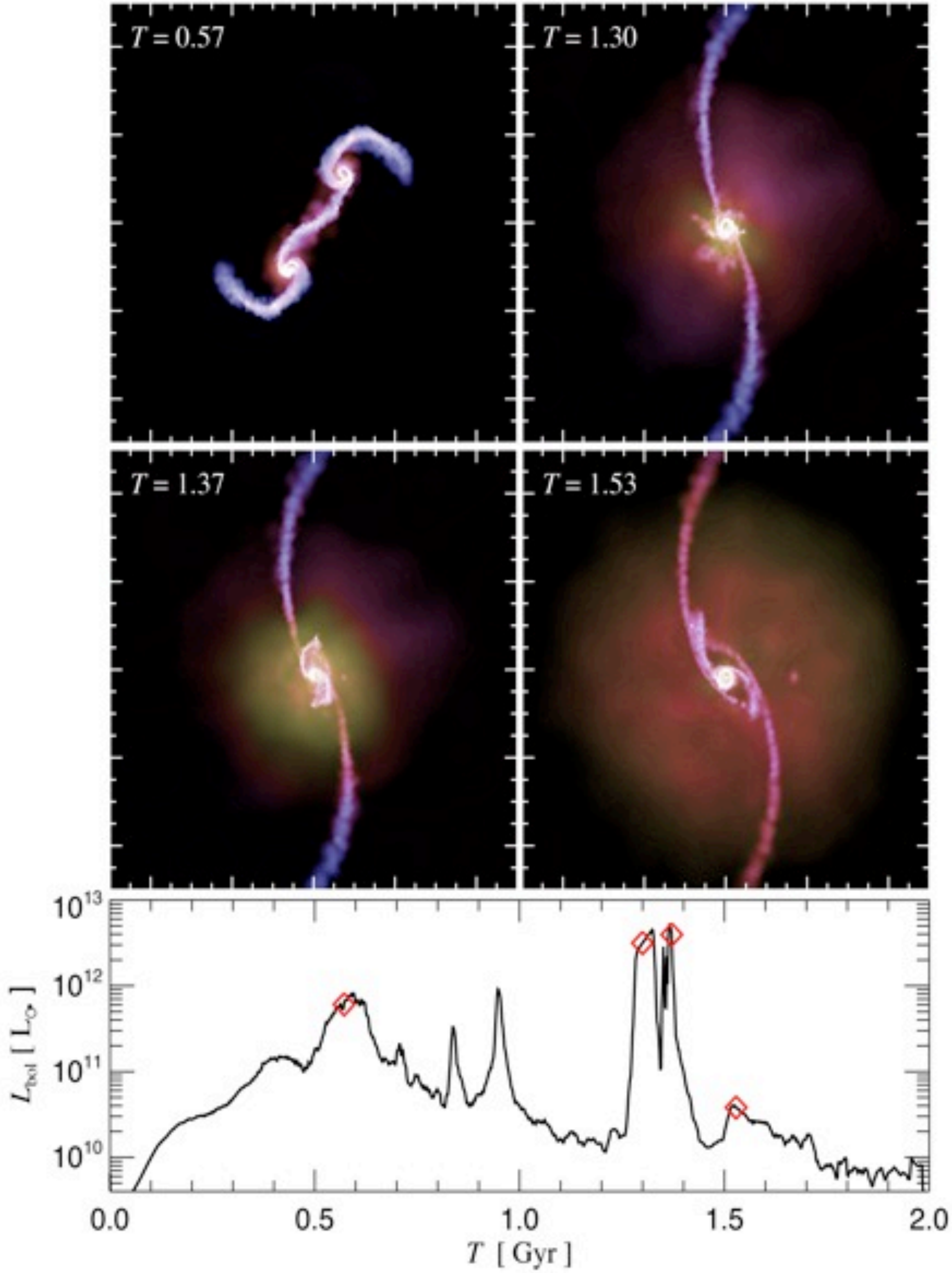


Barnes & Hernquist (1996)

The Simulations

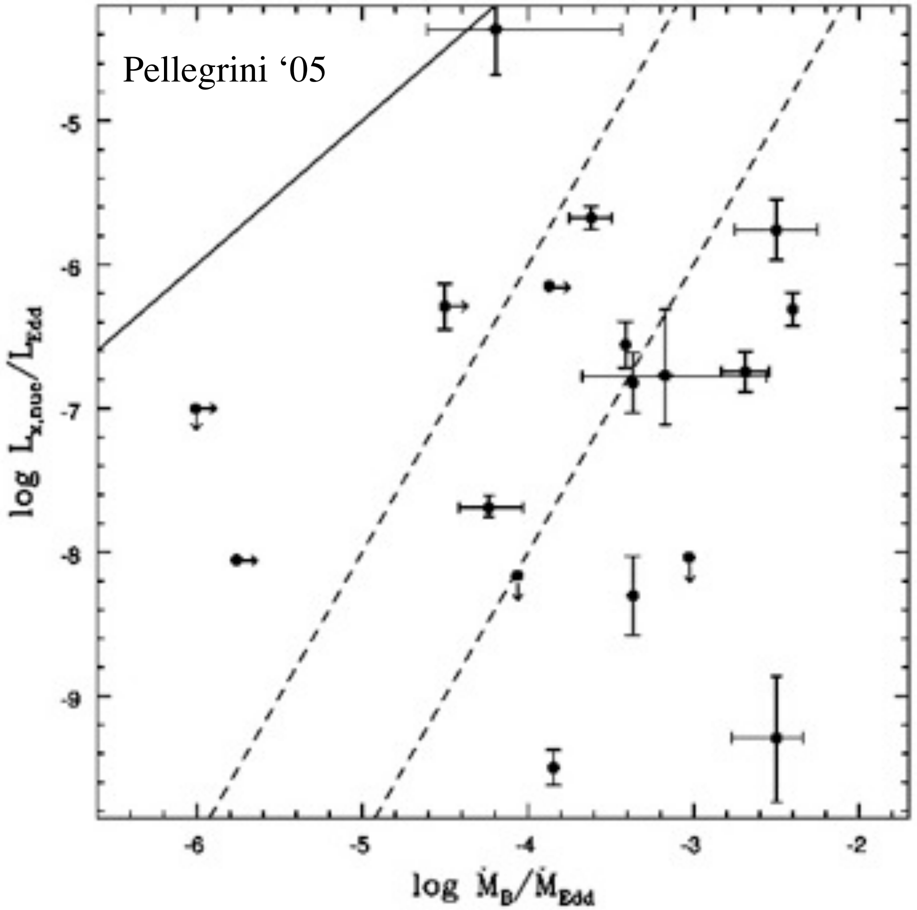
THE AGN...

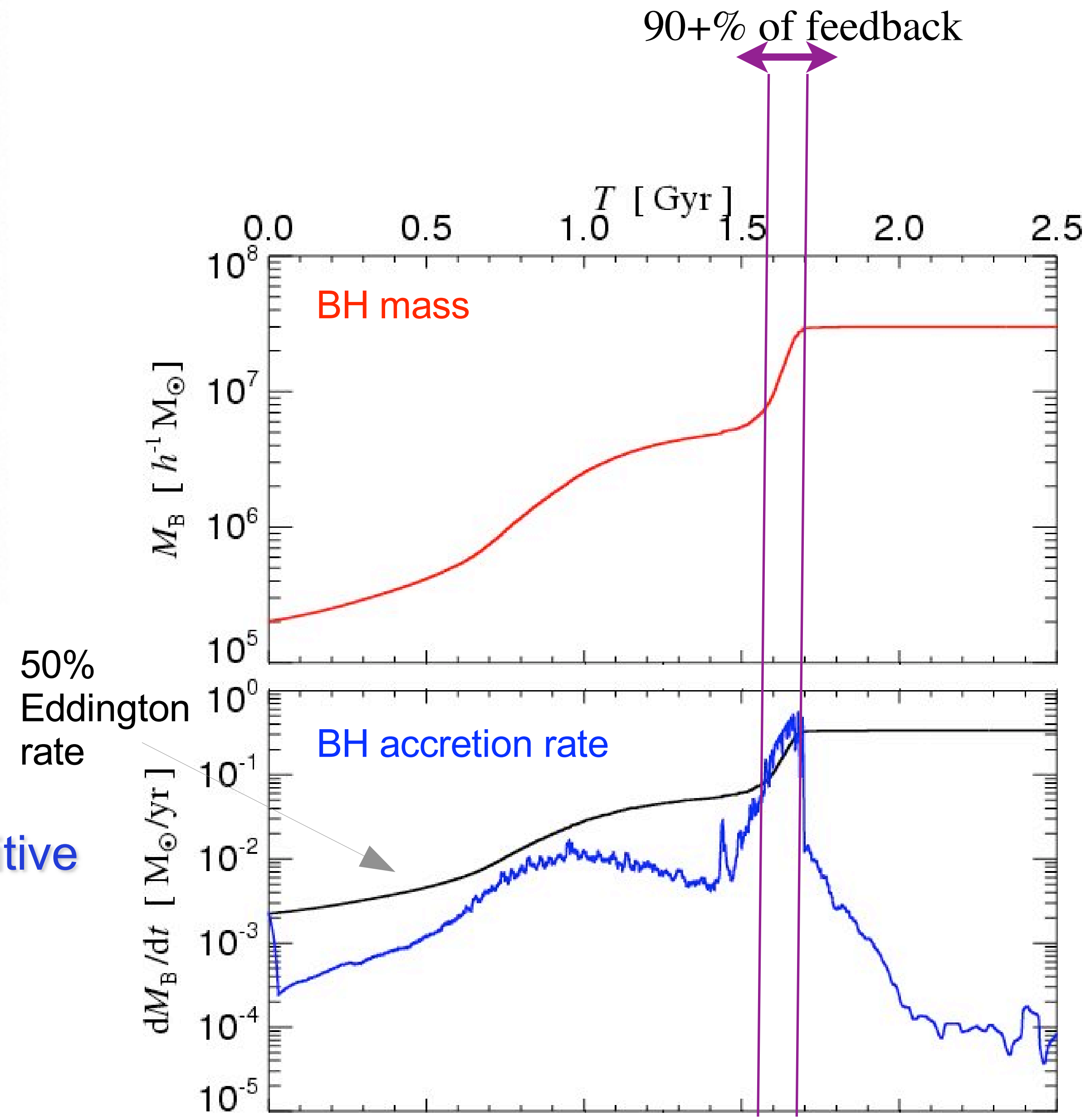
- R_{sch} ~ few AU ~
  10^{-6} x our resolution
- R_{Bondi} ~ 10 pc (typical)
  - Bondi-Hoyle accretion rate (max Eddington)
  - ~0.1 radiative efficiency (high-mdot)
  - ~5% couples to local gas (thermally)



The Simulations

A CAUTION...



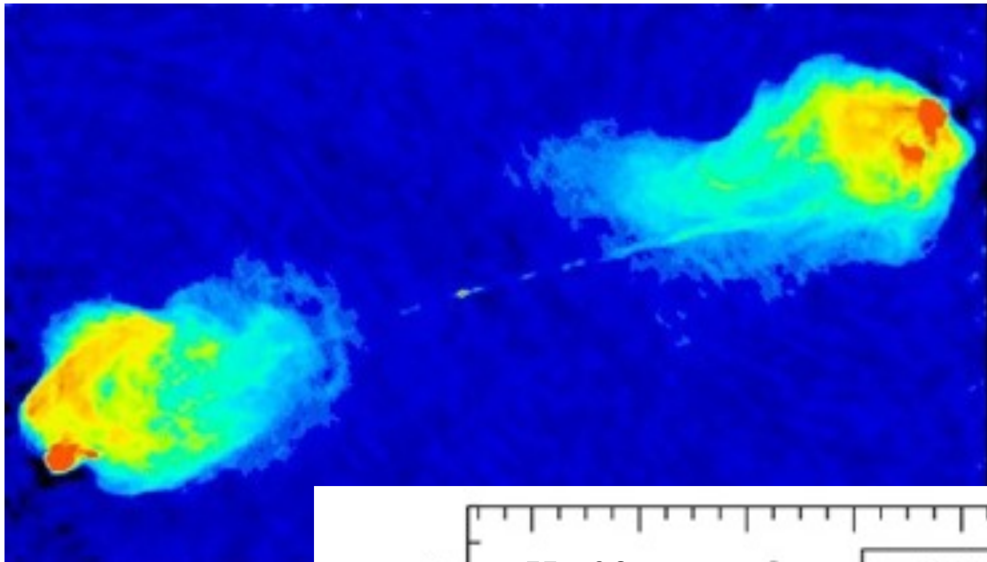


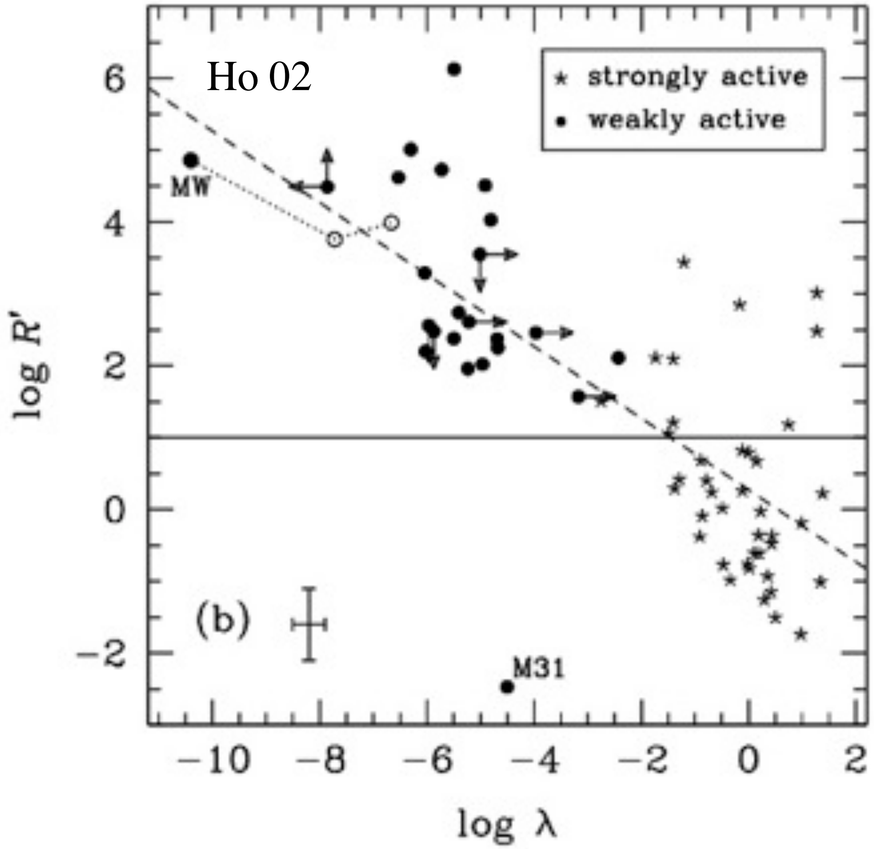
- But, feedback effects not sensitive to the accretion prescription!

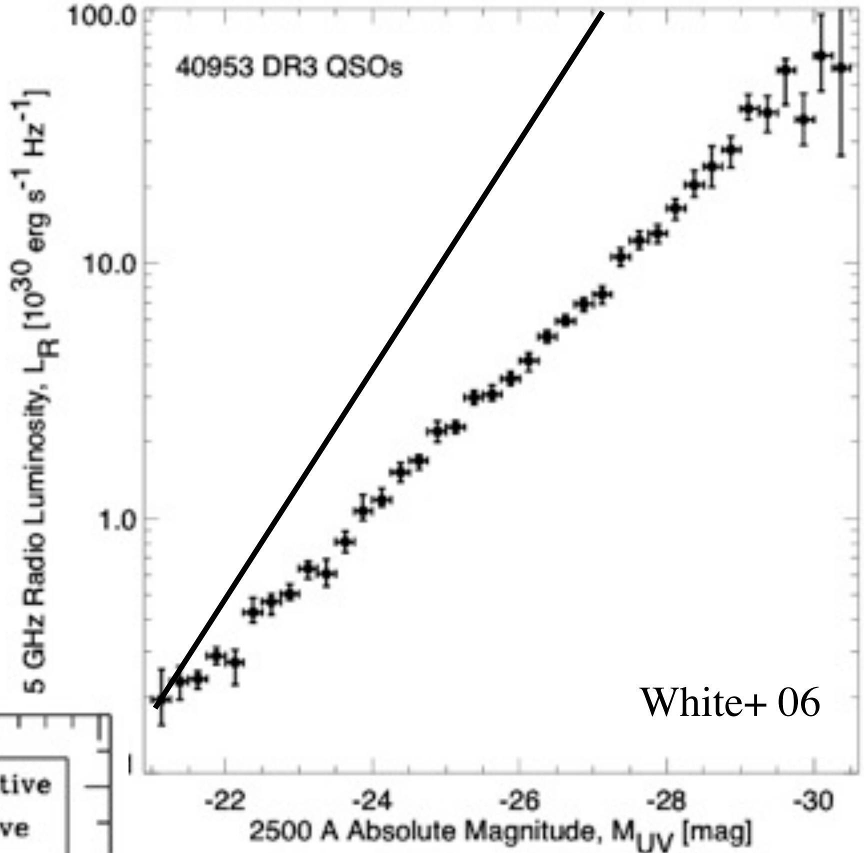
The Simulations

INITIAL, IMPULSIVE FEEDBACK VS. “MAINTENANCE”

We see today... but...





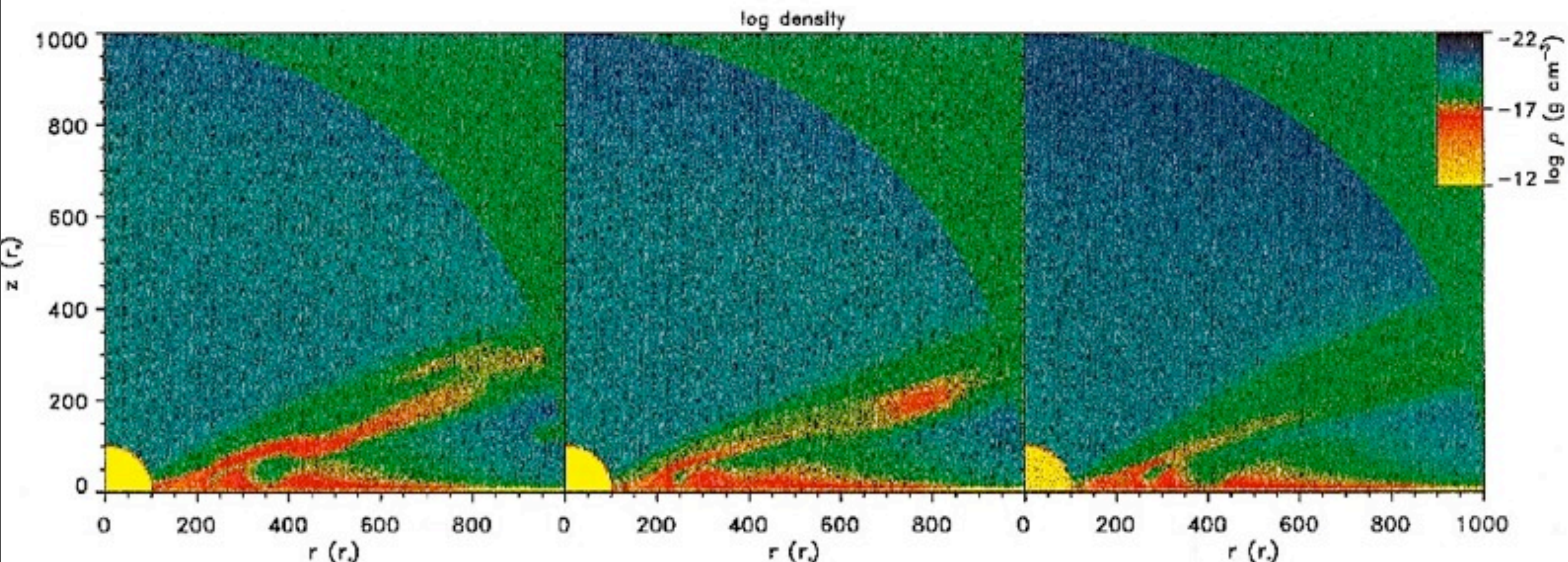


- Even with low ($<10^{-3}$) coupling efficiency, radio only important when
  $L << L_{edd}$ &
  $t \sim t_{Hubble}$

The Simulations

WHAT ABOUT THE FEEDBACK PRESCRIPTION?

- 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.)

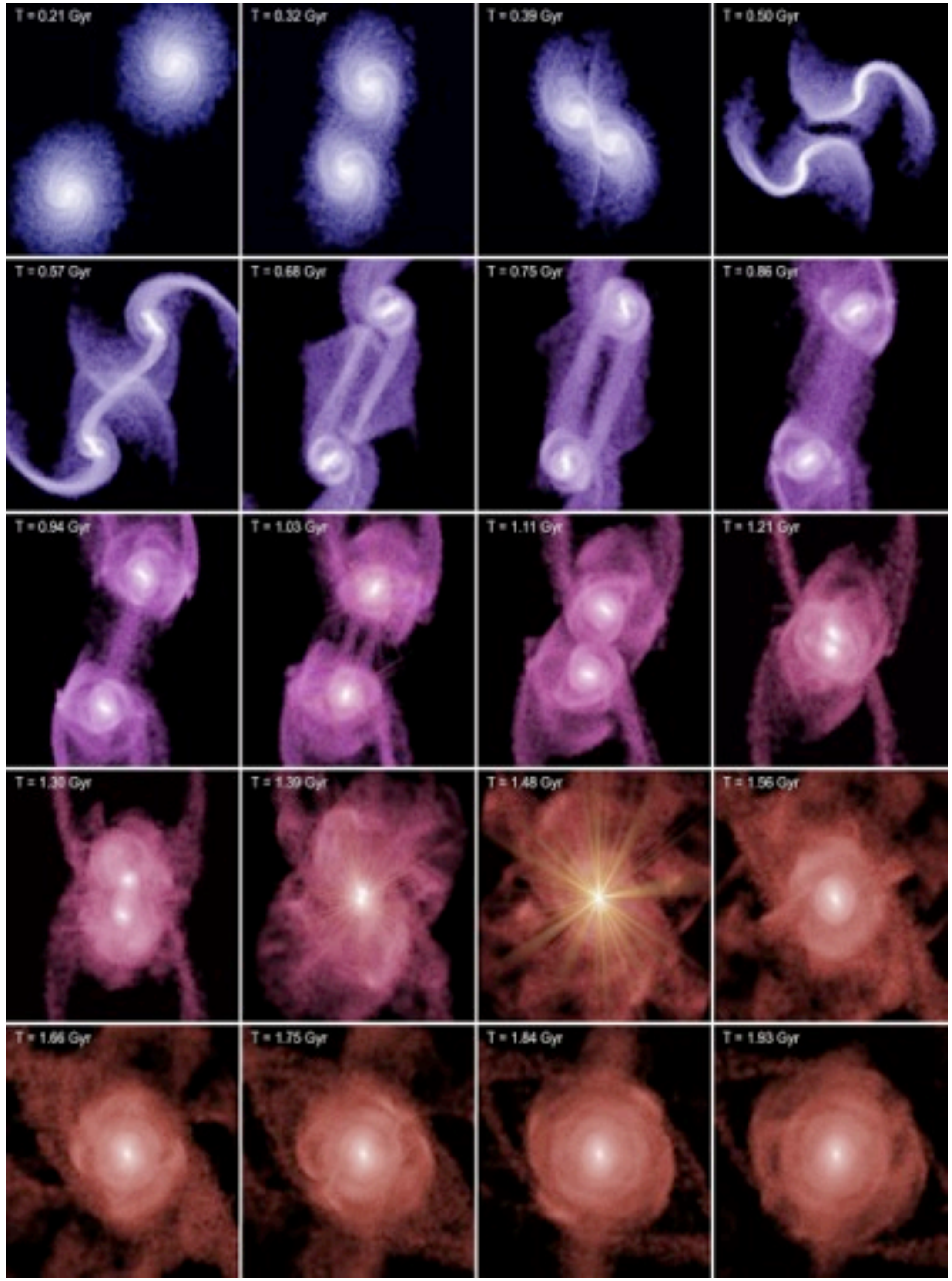


- Probably *not* radio jets

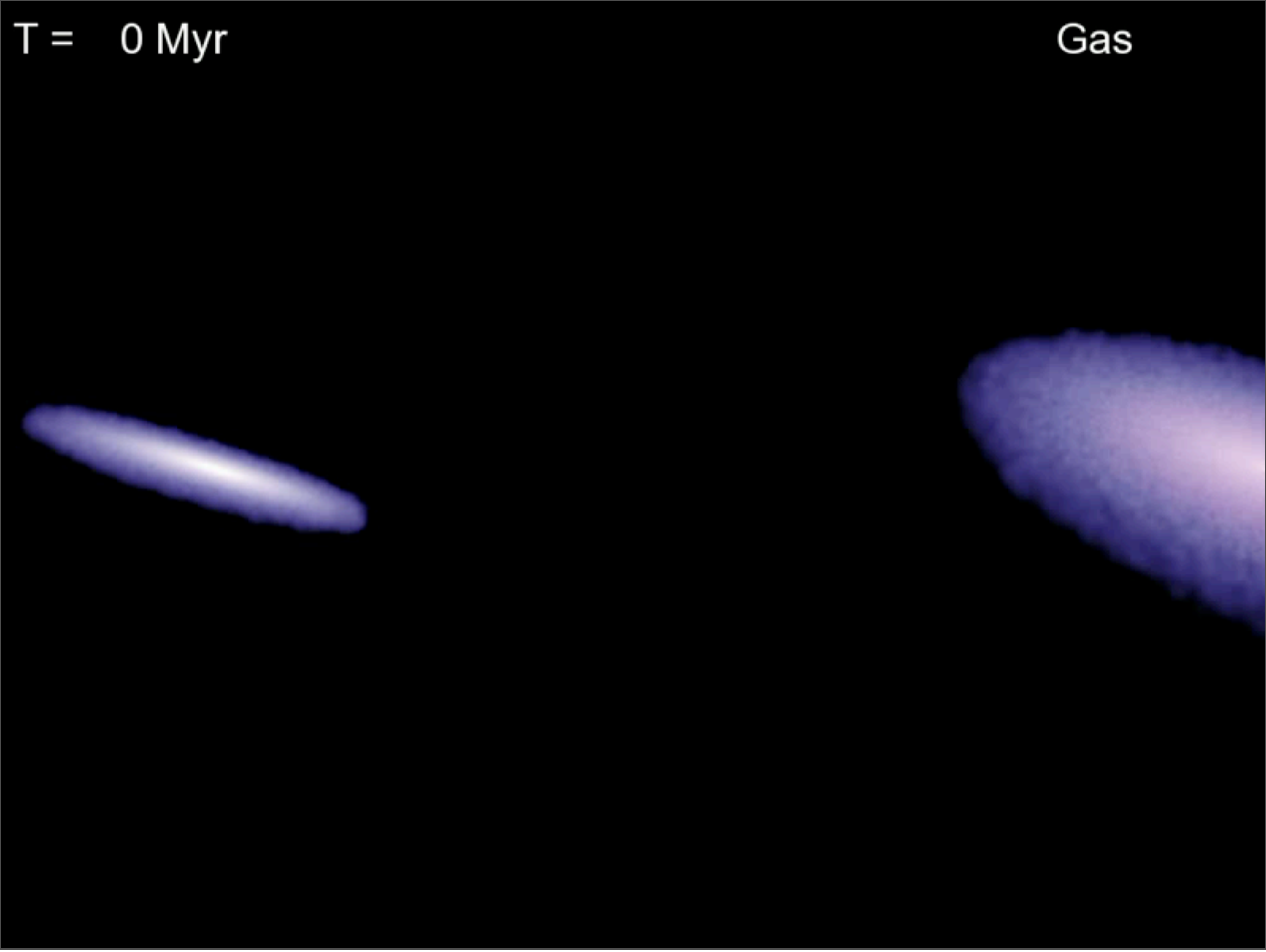
The Simulations

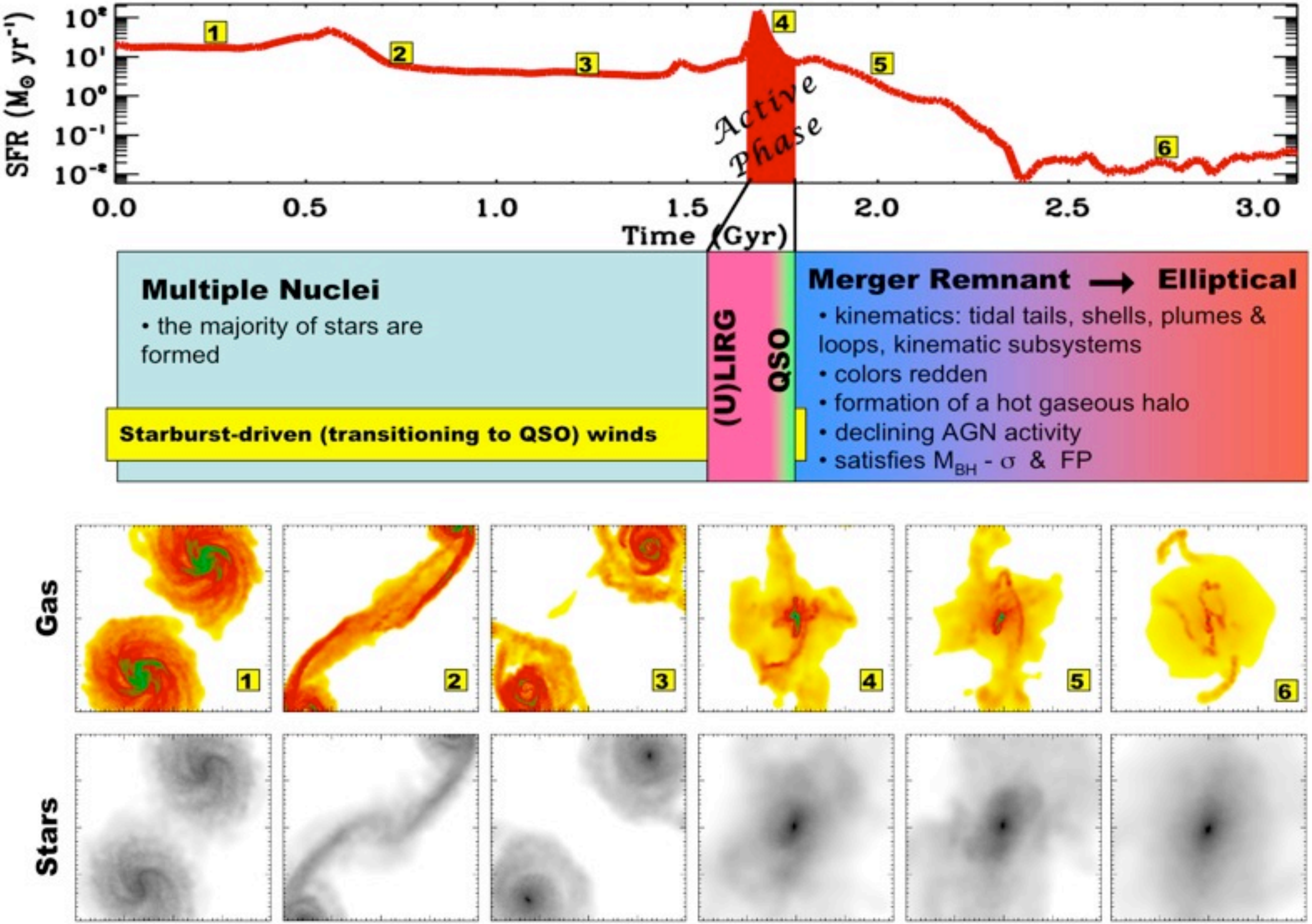
FINALLY, WHAT TO SIMULATE?

- Span the parameter space, varying:
  - Masses & mass ratios
  - Disk gas fractions
  - Redshift of formation & merger
  - Disk structural parameters
    - Bulge-to-disk ratio, concentration, scale lengths
  - ISM Feedback/Pressurization (isothermal > full multiphase)
  - BH accretion & feedback efficiency
  - Stellar winds : add/remove
    - Mass loading, energy-loading
  - Orbital parameters
    - Disk orientations
    - Angular momentum
    - Pericentric passage

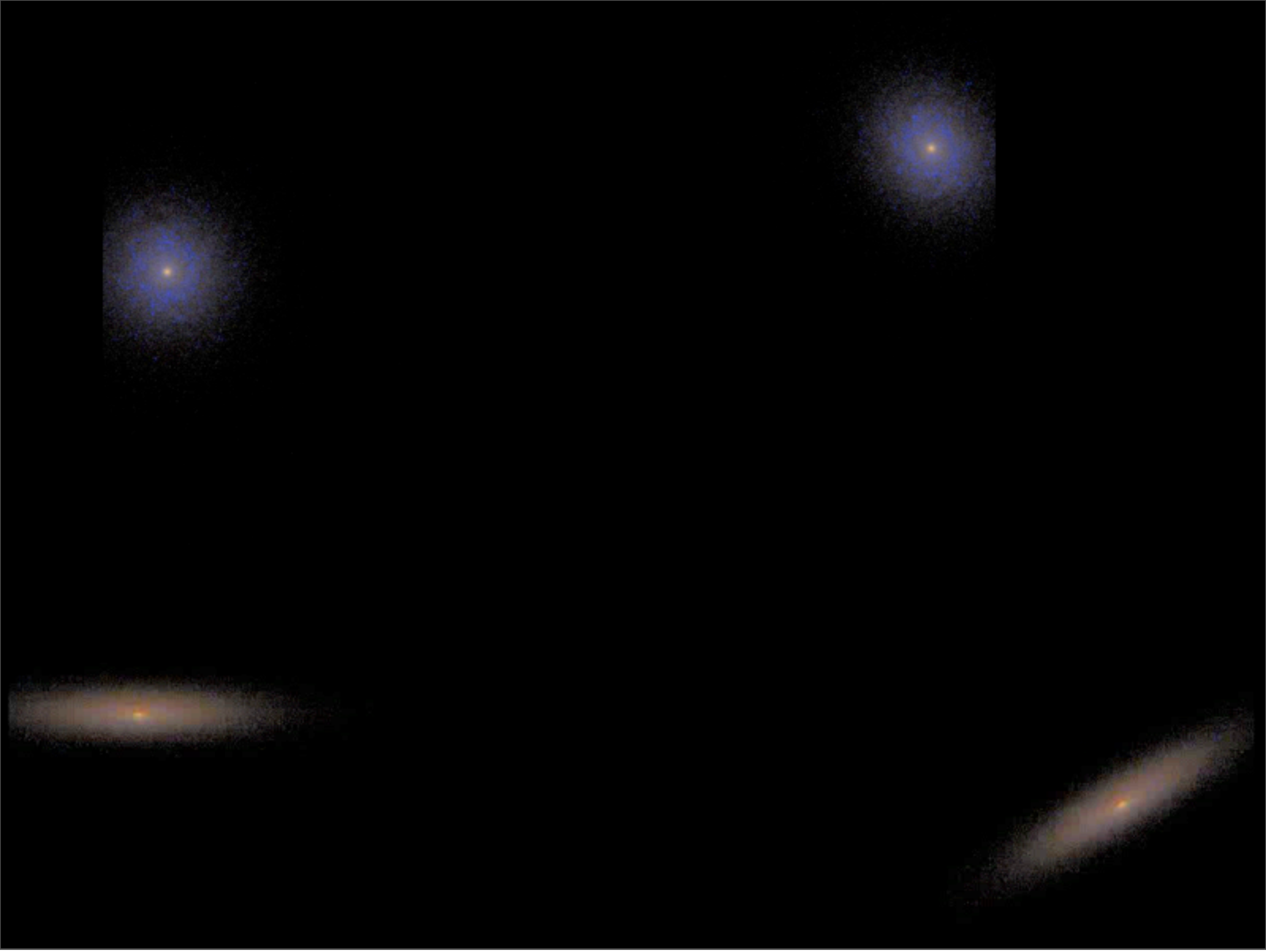


- ~500+ simulations and counting (Robertson et al. 2005; Cox et al. 2004)

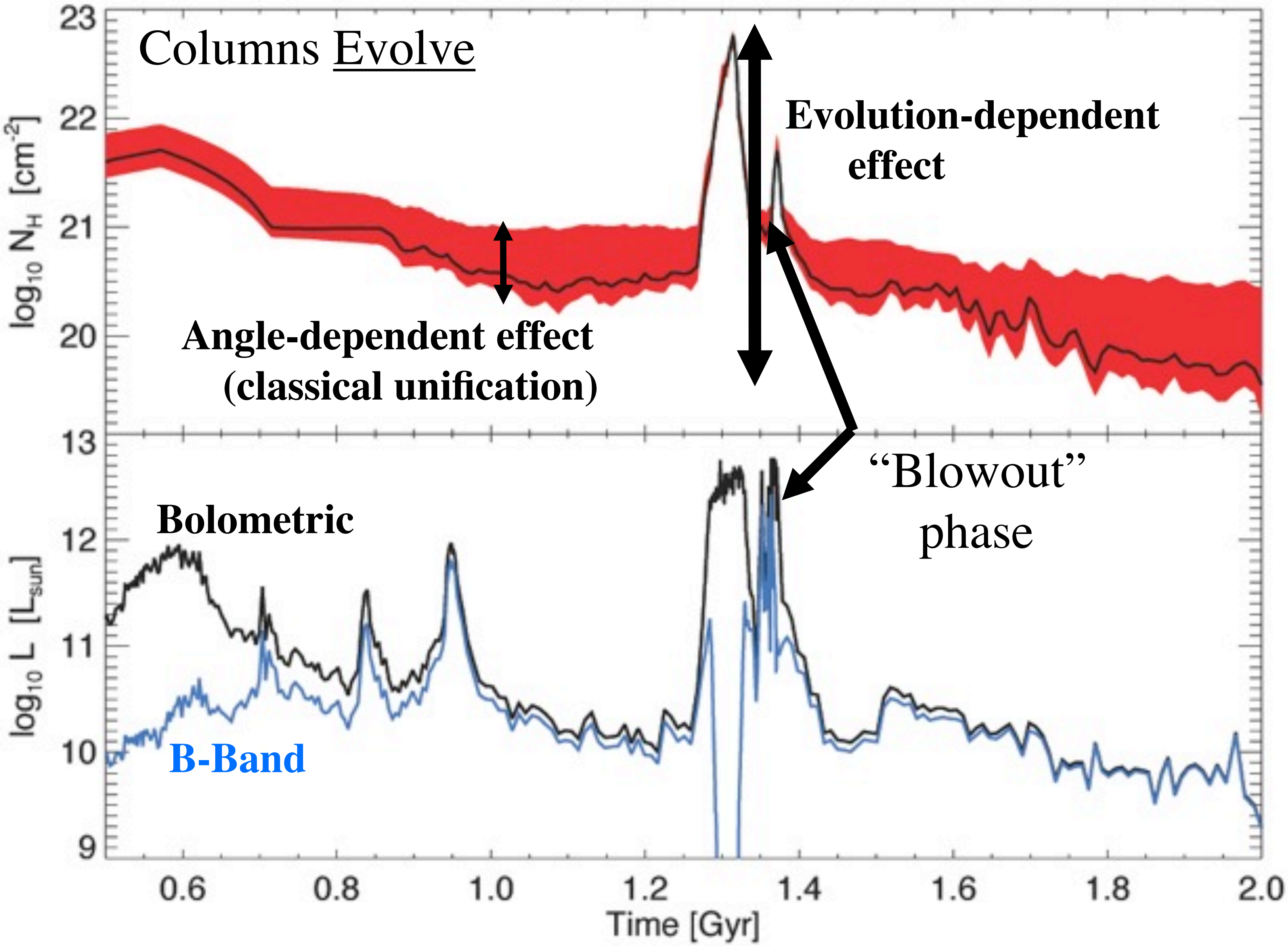

T = 0 Myr
Gas



SFR ($M_\odot$ yr^{-1})
Time (Gyr)
Active Phase
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



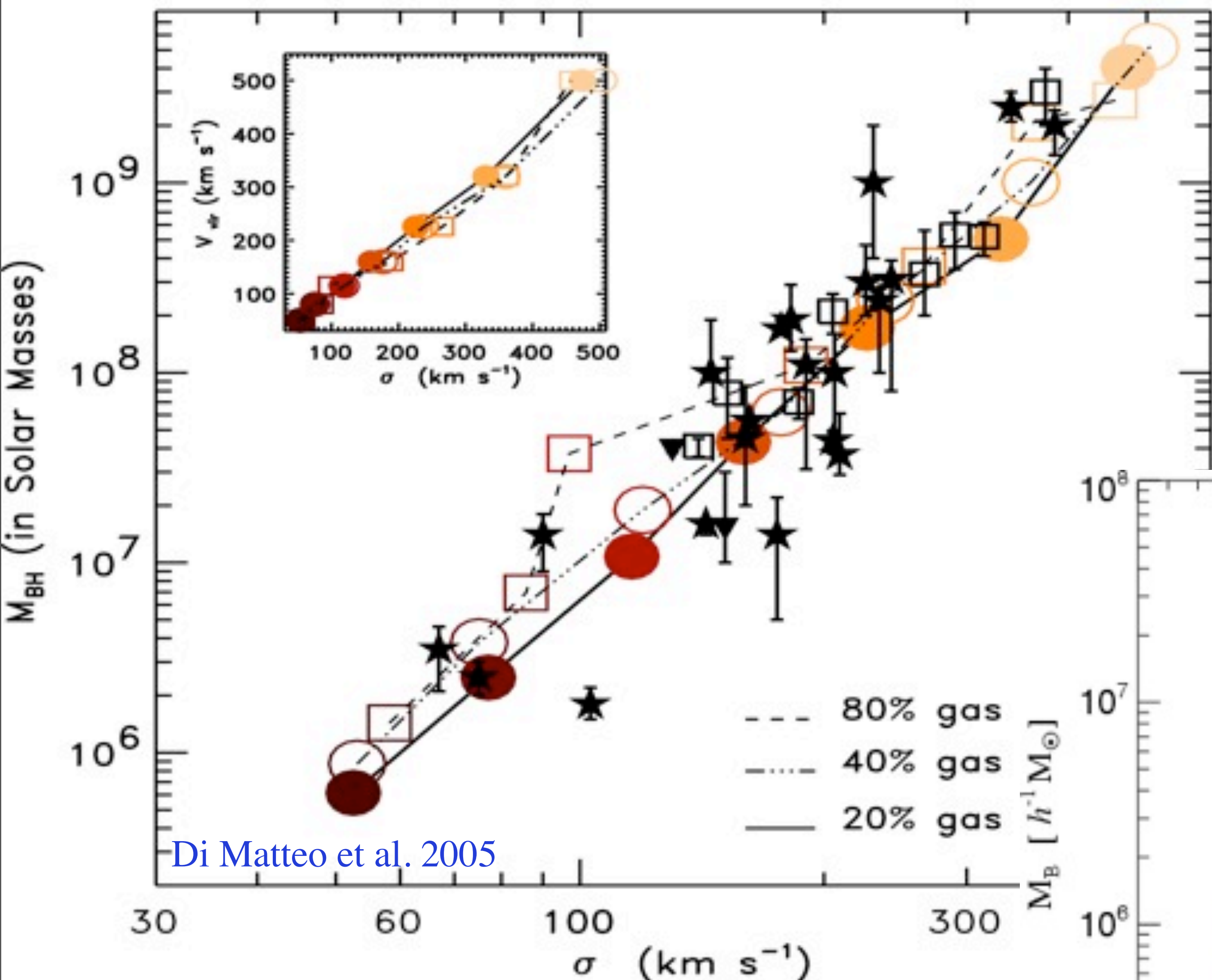
Quasar Lightcurves:

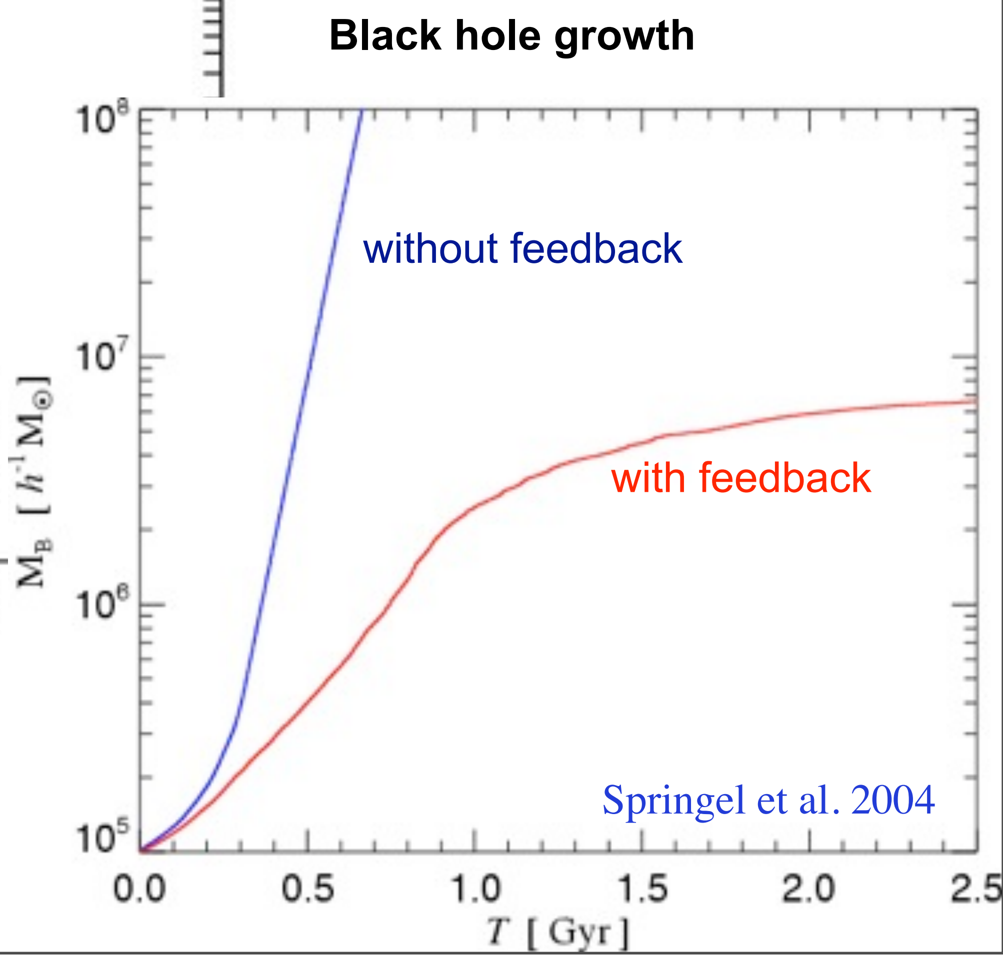


- Multi-phase ISM decomposition: gas+dust+metal columns

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

PREVENTS RUNAWAY BLACK HOLE GROWTH

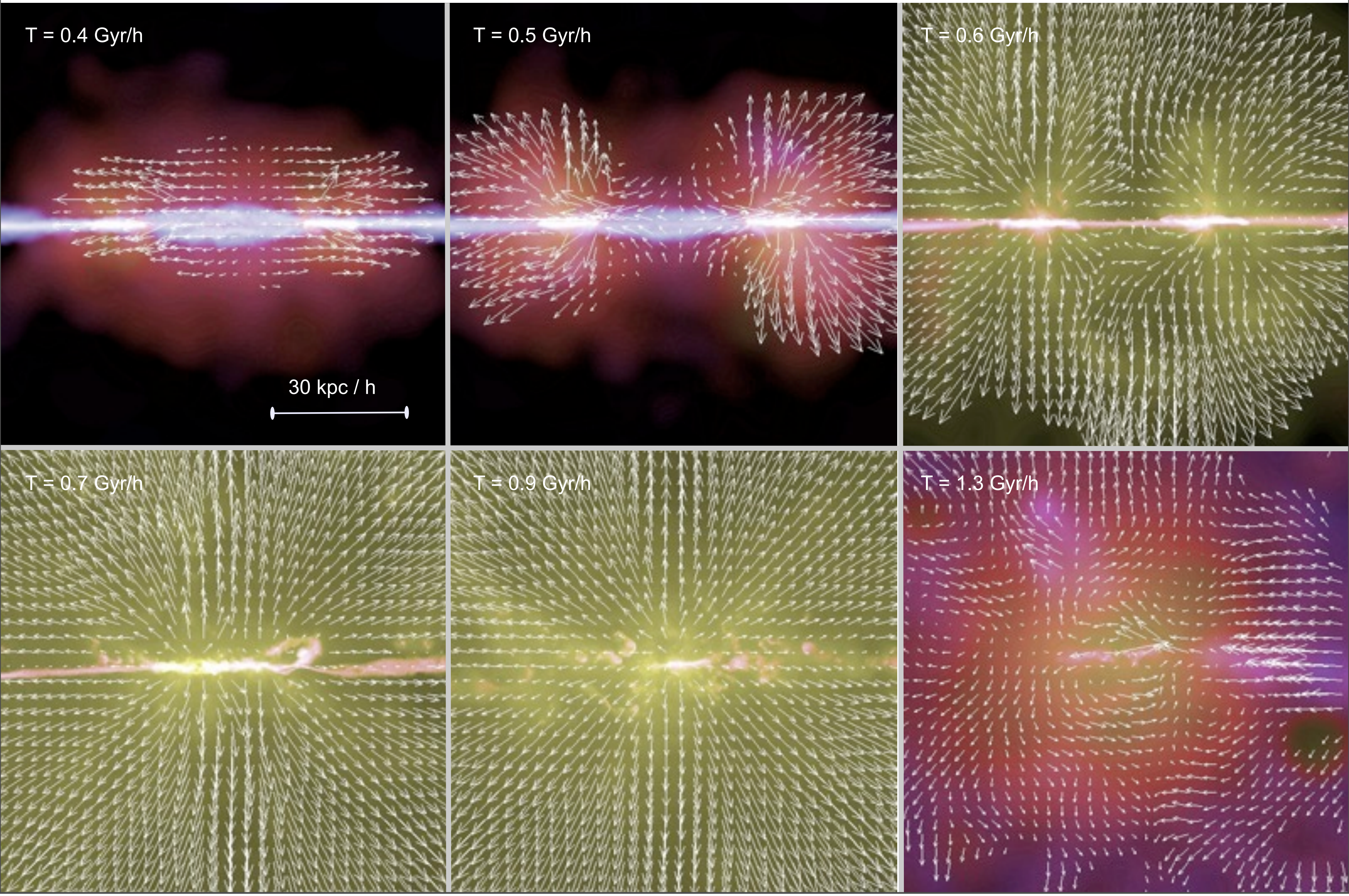




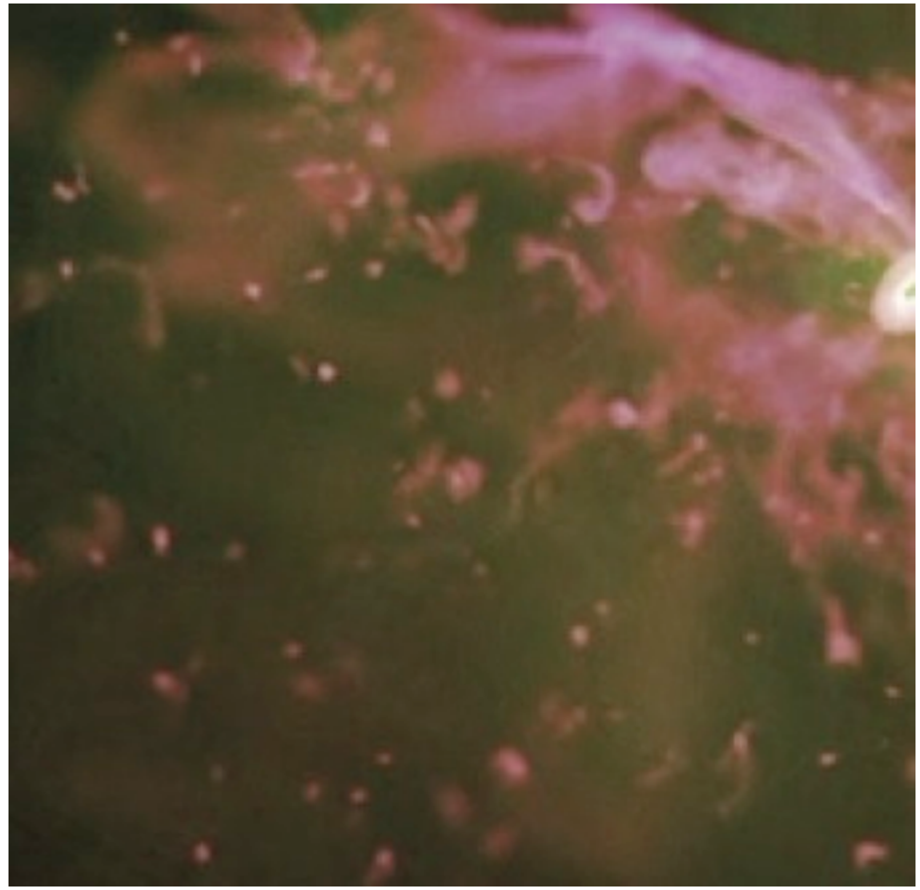
The feedback by the central black activity may drive a strong quasar wind

GAS OUTFLOW BY AGN FEEDBACK

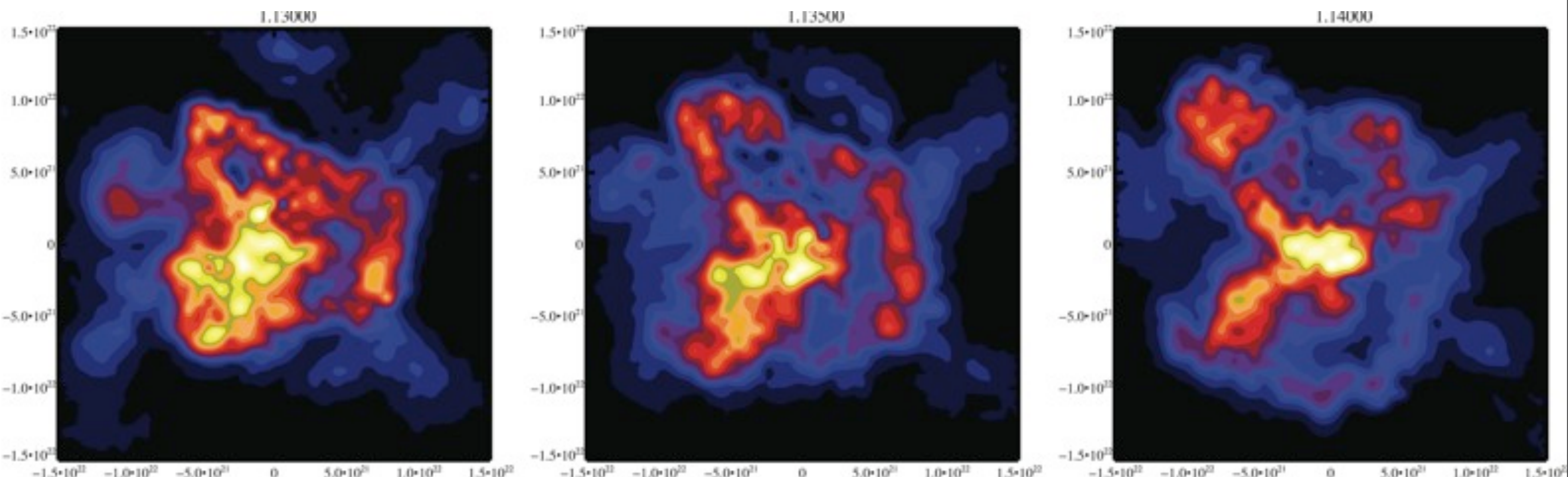
(outflow reaches speeds of up to ~1800 km/sec)



Outflows are Explosive and Clumpy

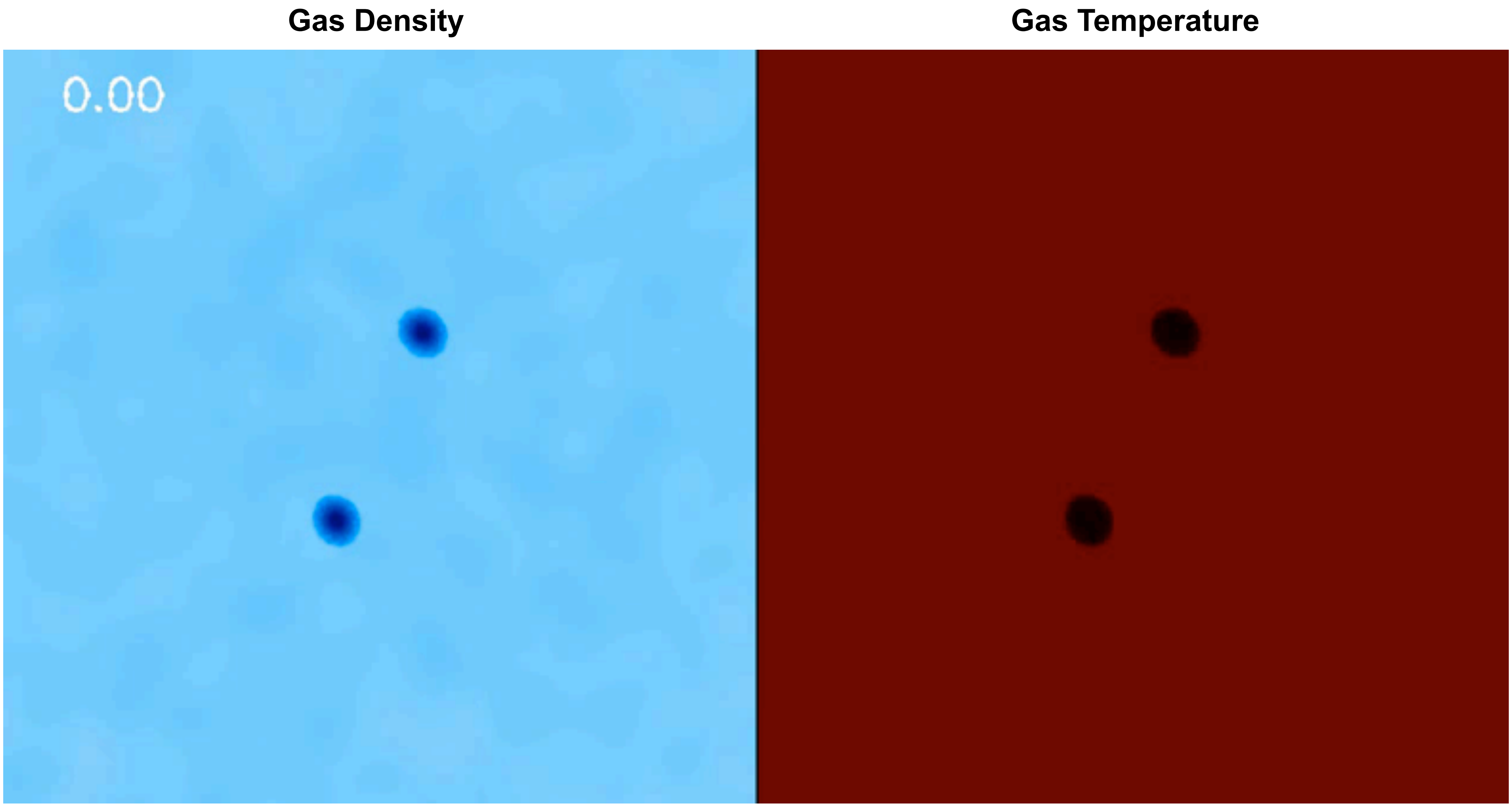


- Rapid BH growth => point-like injection
  - Explosion, independent of coupling
- Clumpy
  - ULIRG cold/warm transition (S. Chakrabarti)
  - CO outflows (D. Narayanan)



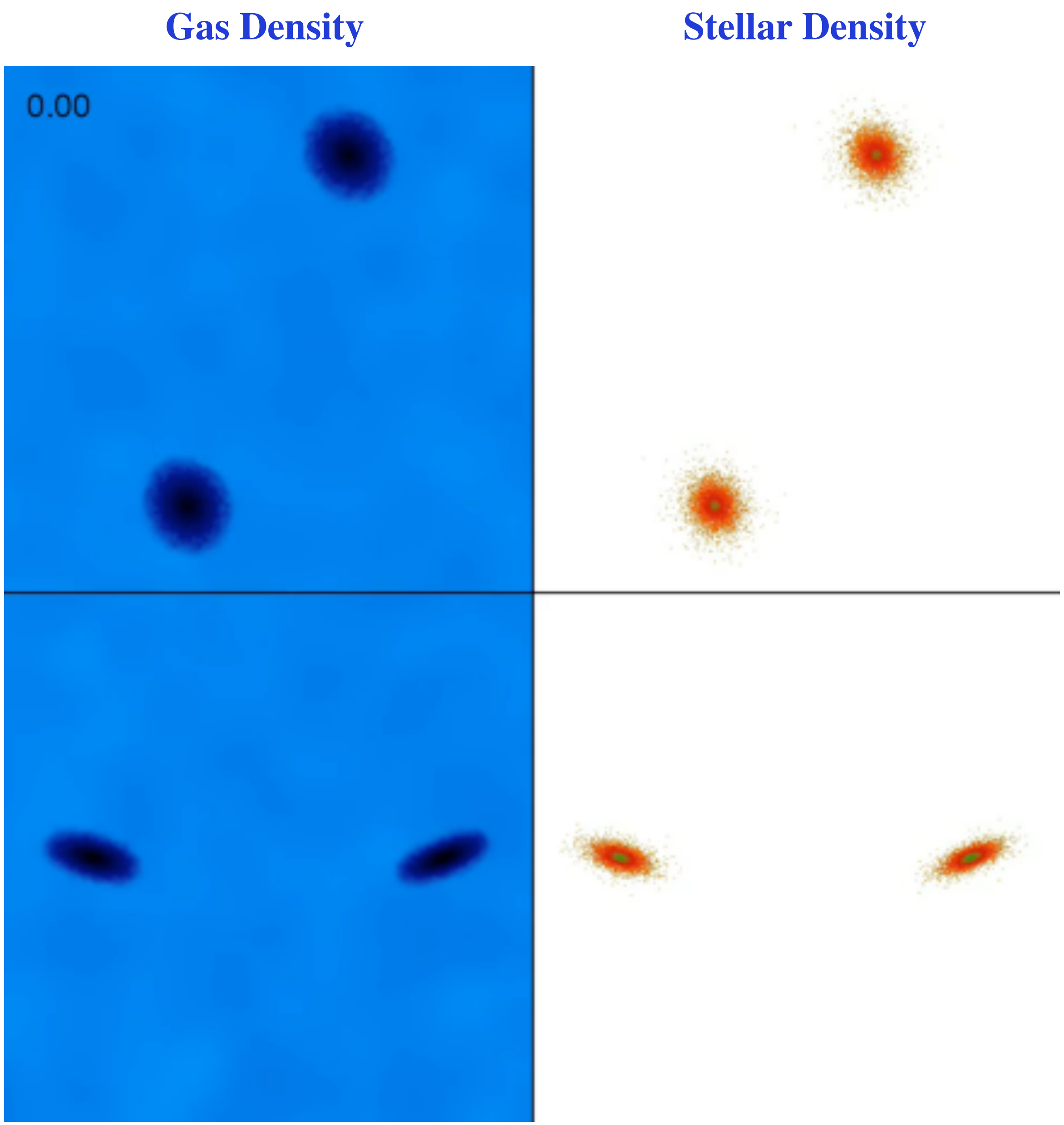
Quasar Outflows May Be Significant for the ICM & IGM

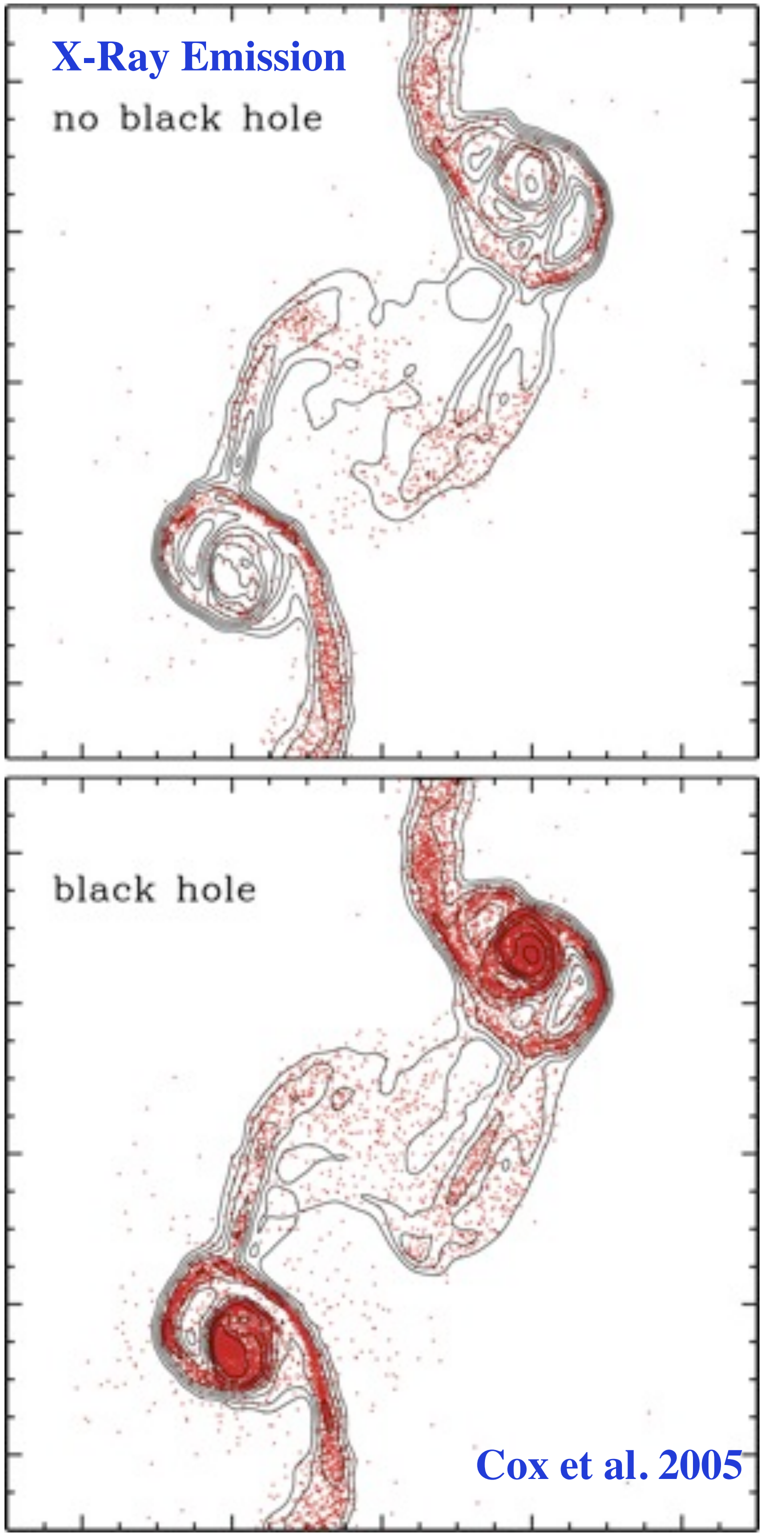
SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?



Feedback-Driven Winds

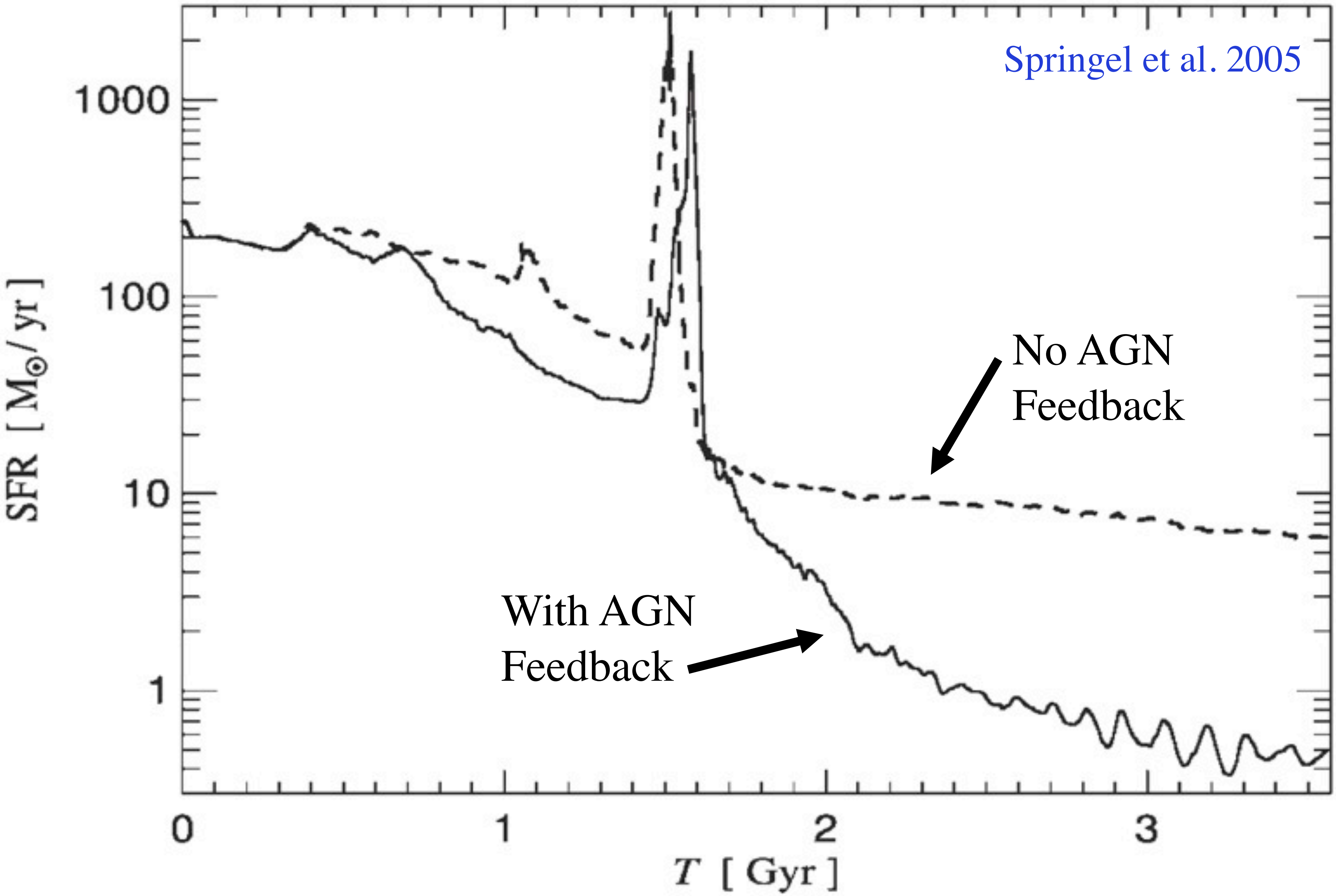
METAL ENRICHMENT & BUILDING THE X-RAY HALO





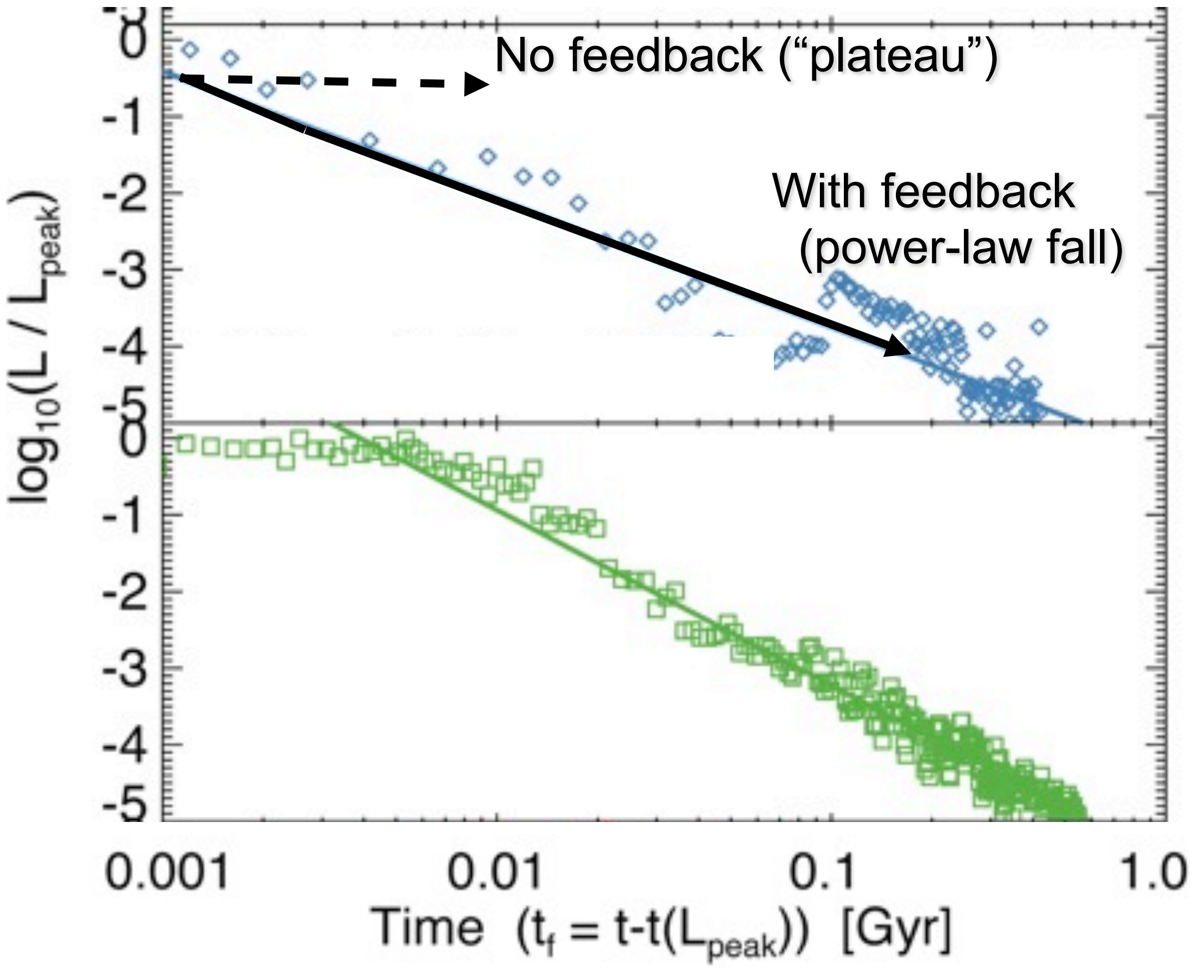
Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?



Quasar Light Curves & Lifetimes

- Feedback determines the decay of the quasar light curve:

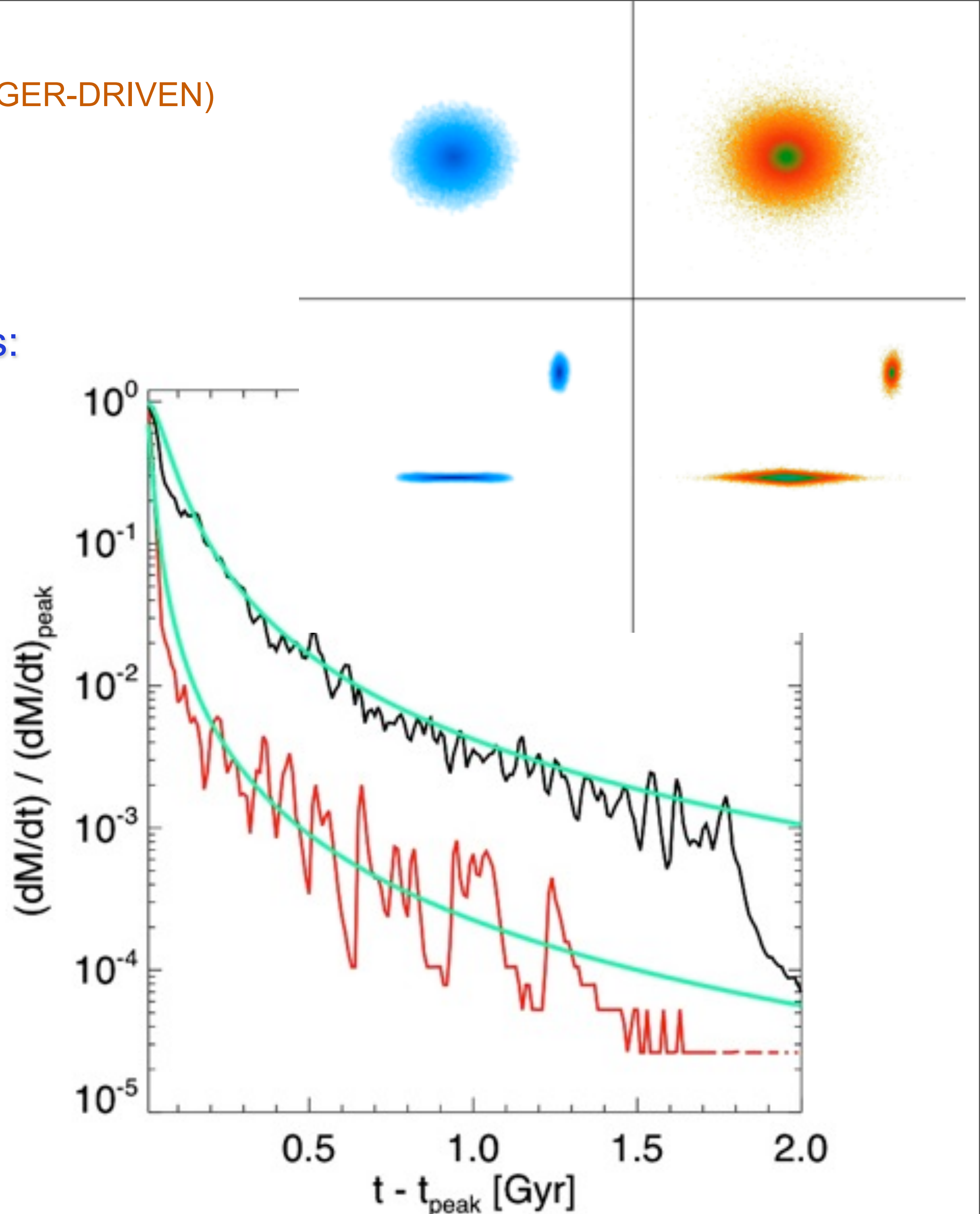


- Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)

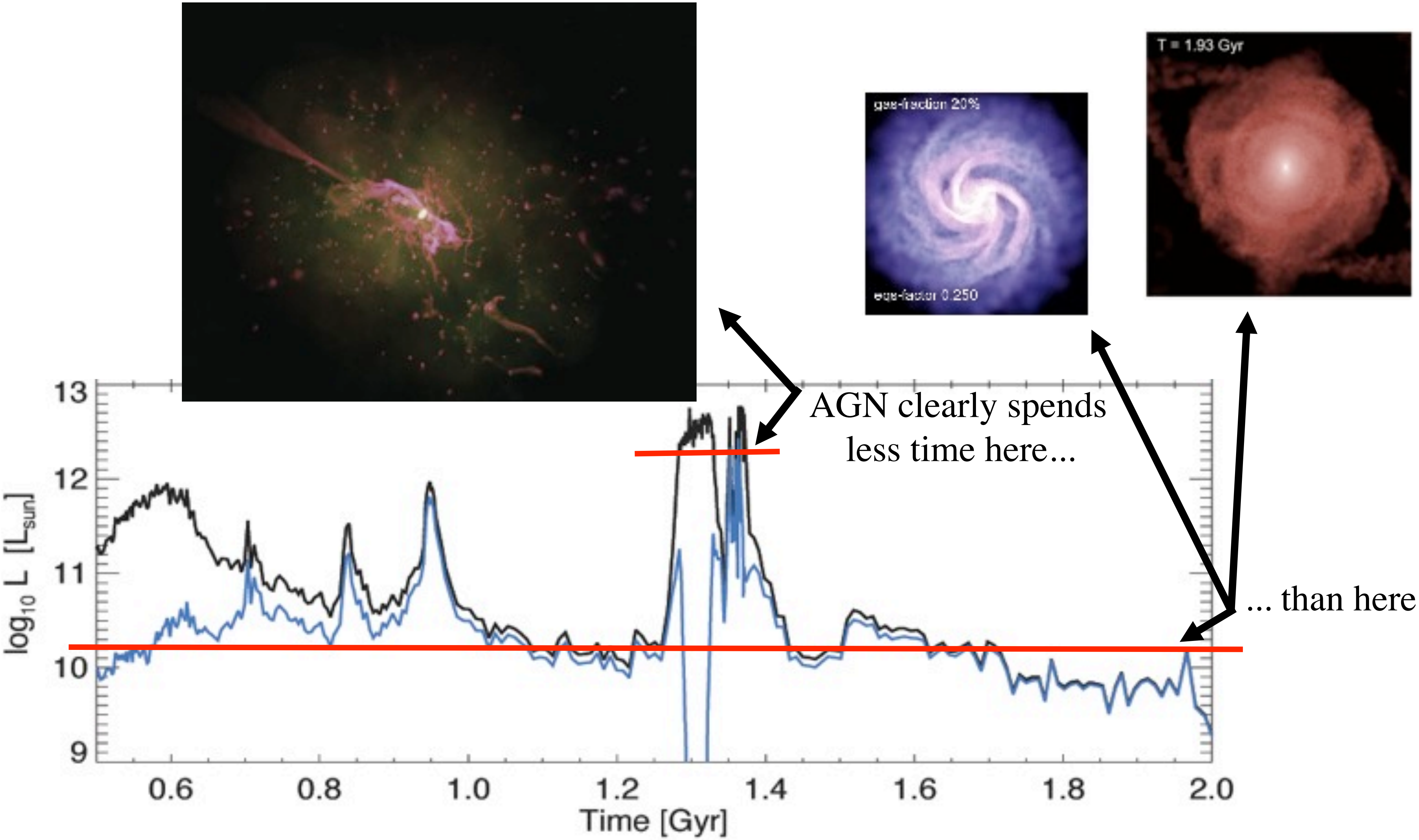
PFH et al. 2006a

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:
  - Agrees well with simulations!
- Generalize to "Seyferts"
  - Disk-dominated galaxies with bars
  - Minor mergers



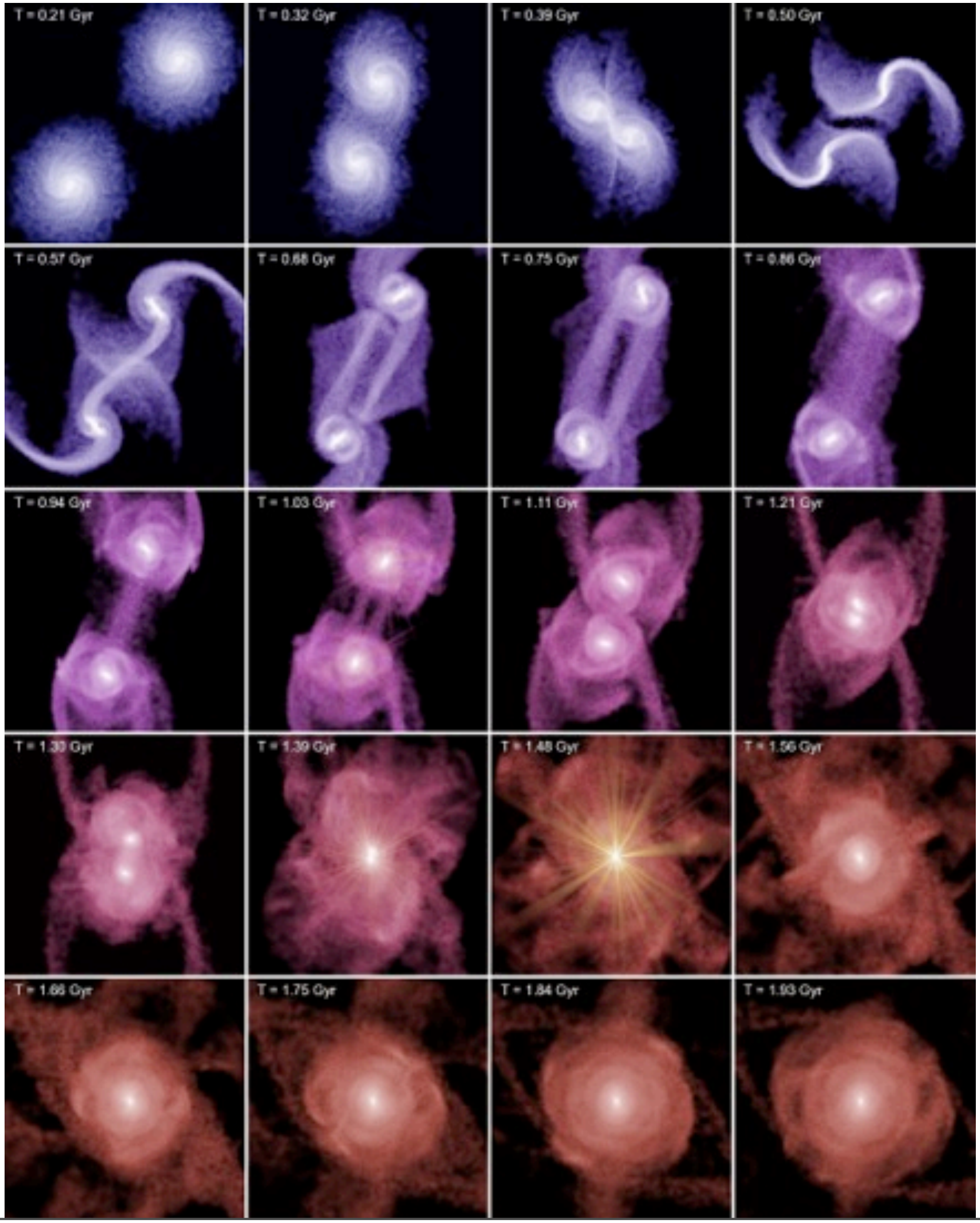
So What Is the “Quasar Lifetime”?



- “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

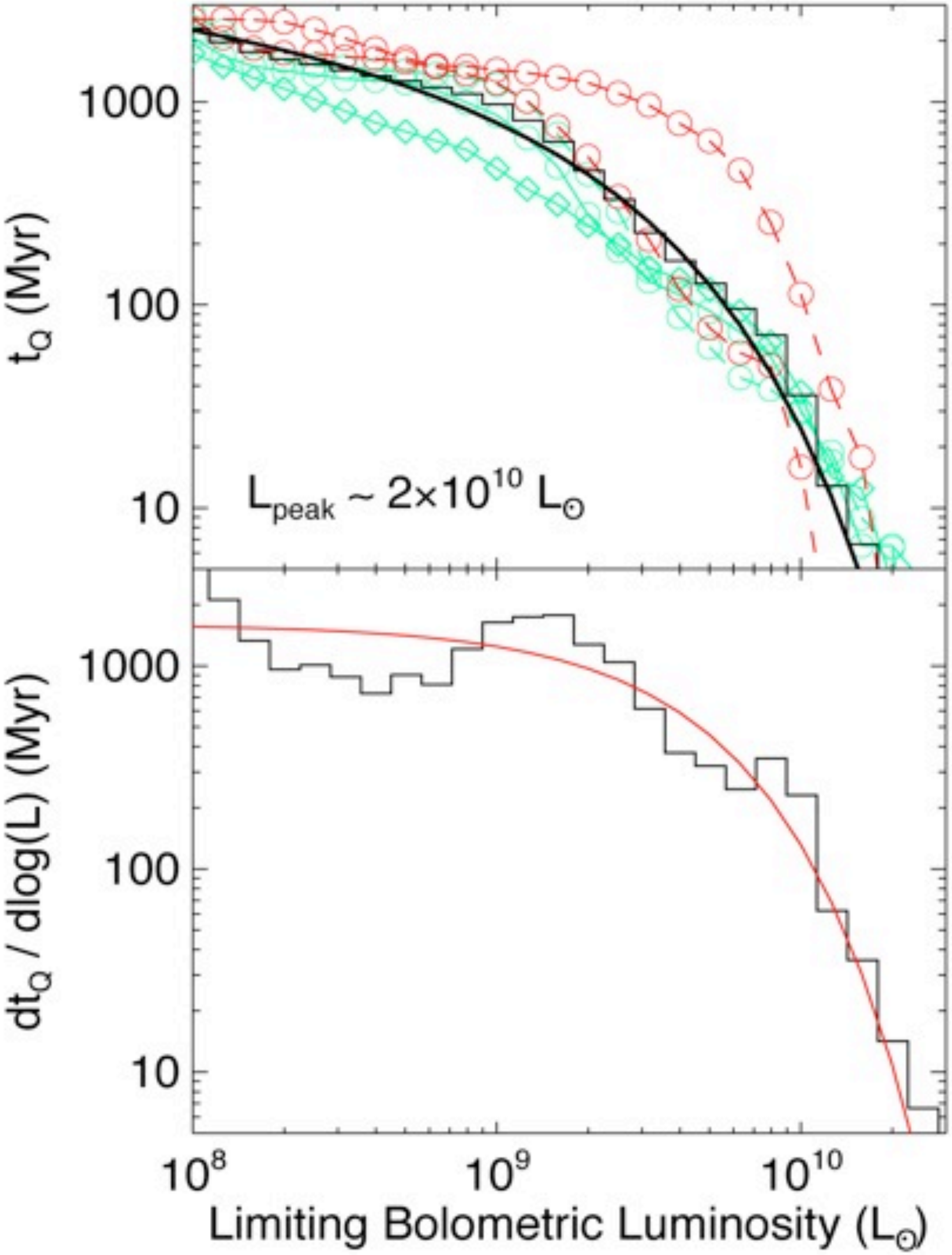


- "Quasar Lifetime": a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity

PFH et al. 2006b

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME



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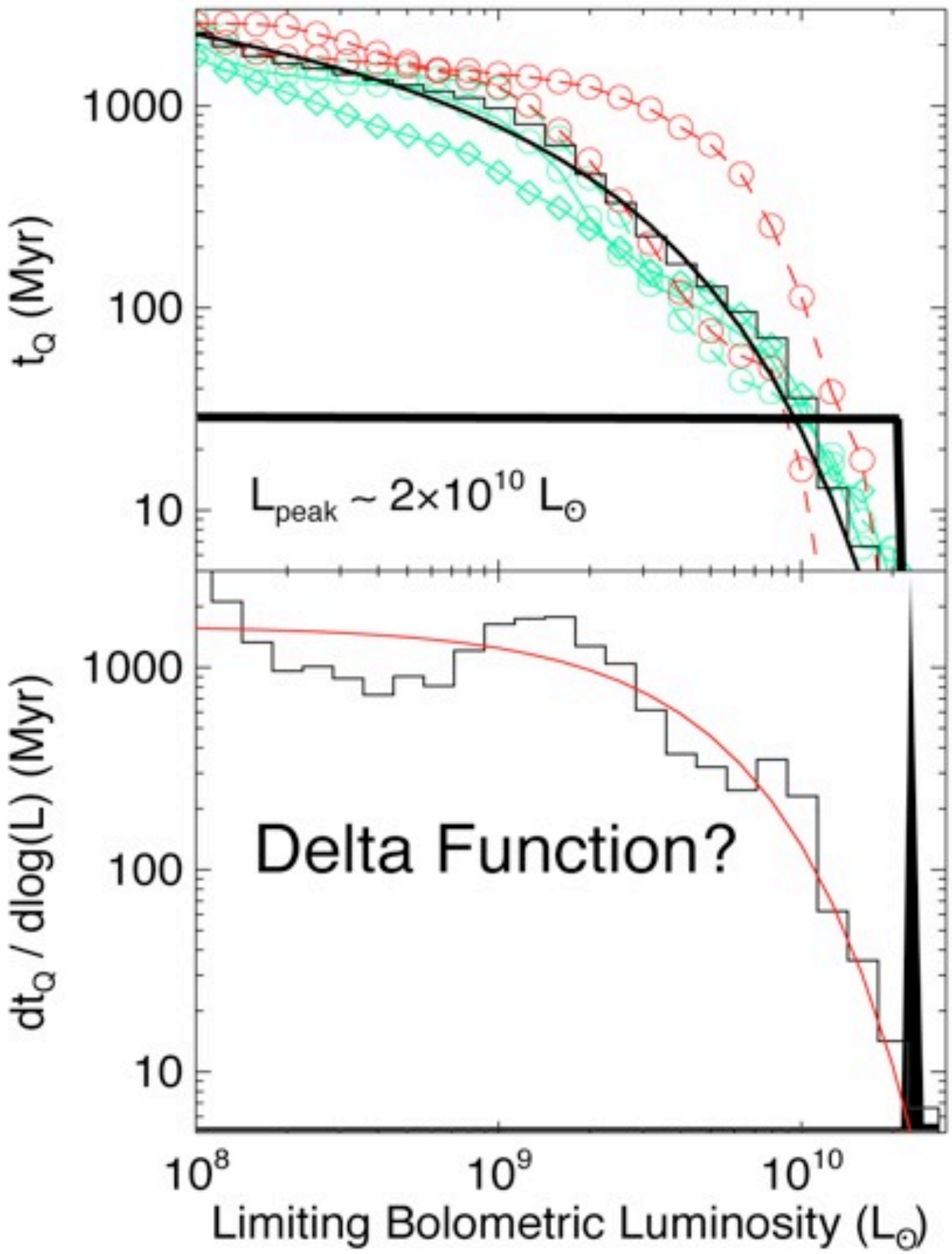

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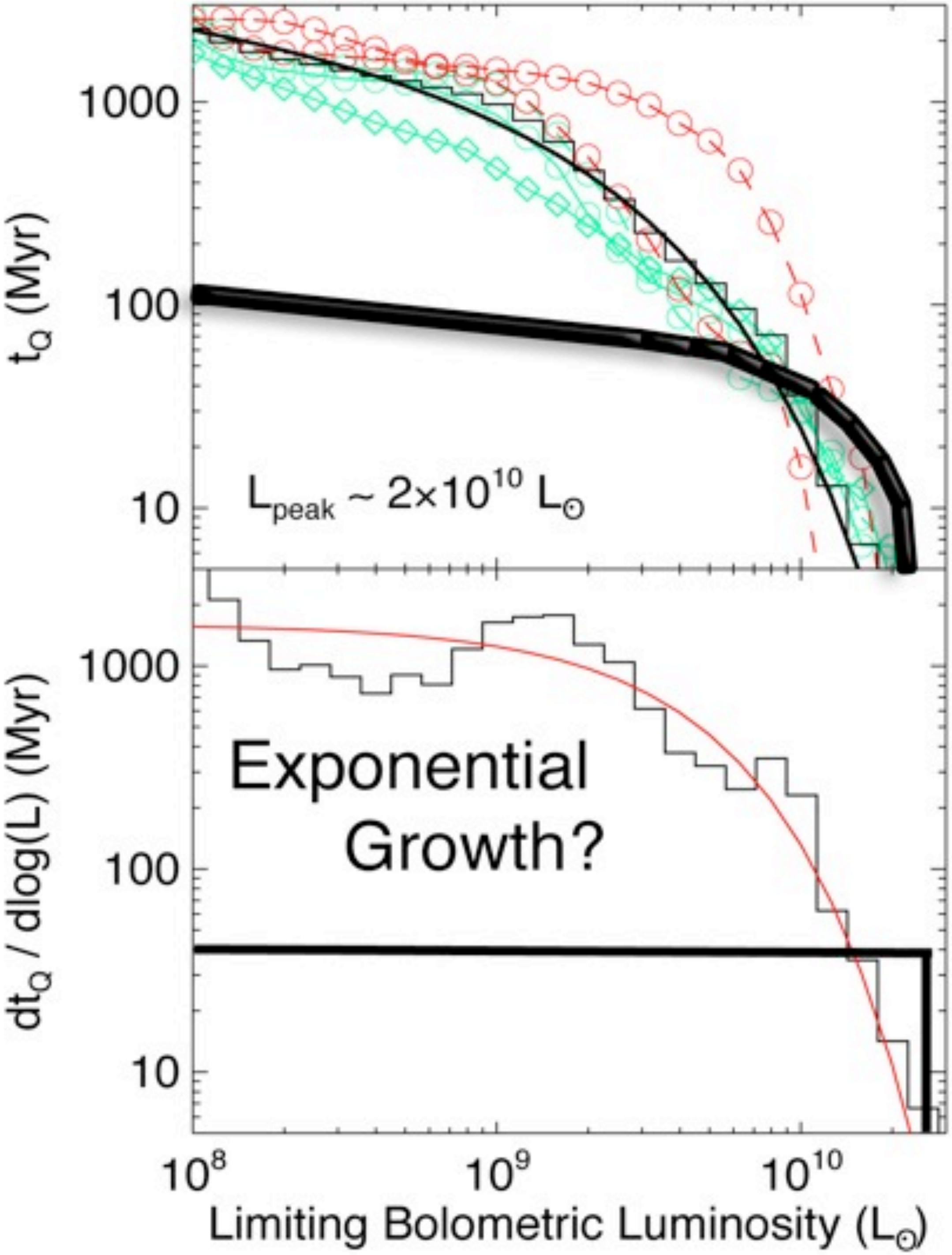
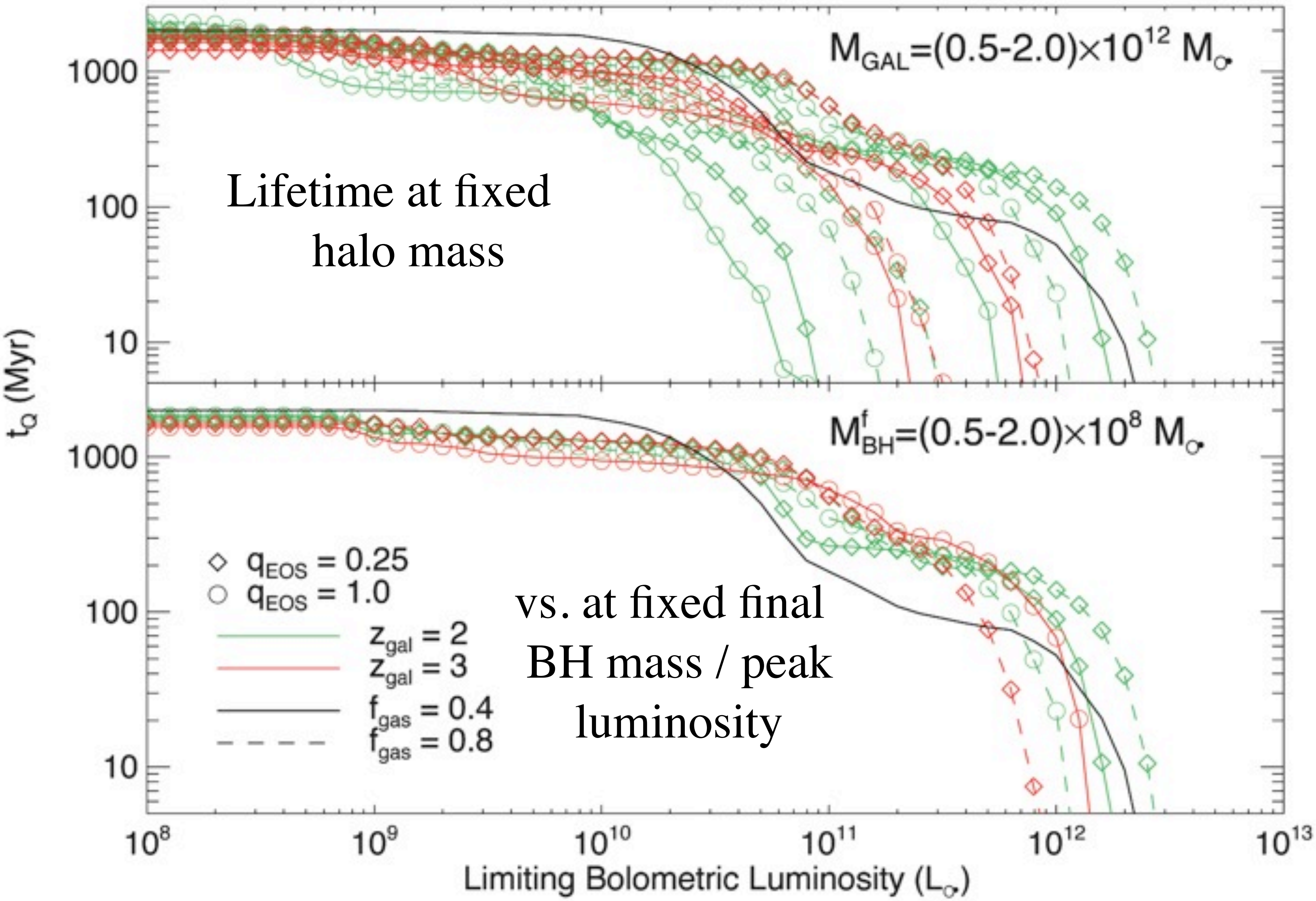


- "Quasar Lifetime": a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity

PFH et al. 2006b

Robustness of Quasar Lifetimes

LIFETIME DISTRIBUTION IS A FUNCTION OF JUST THE FINAL MASS/PEAK LUMINOSITY

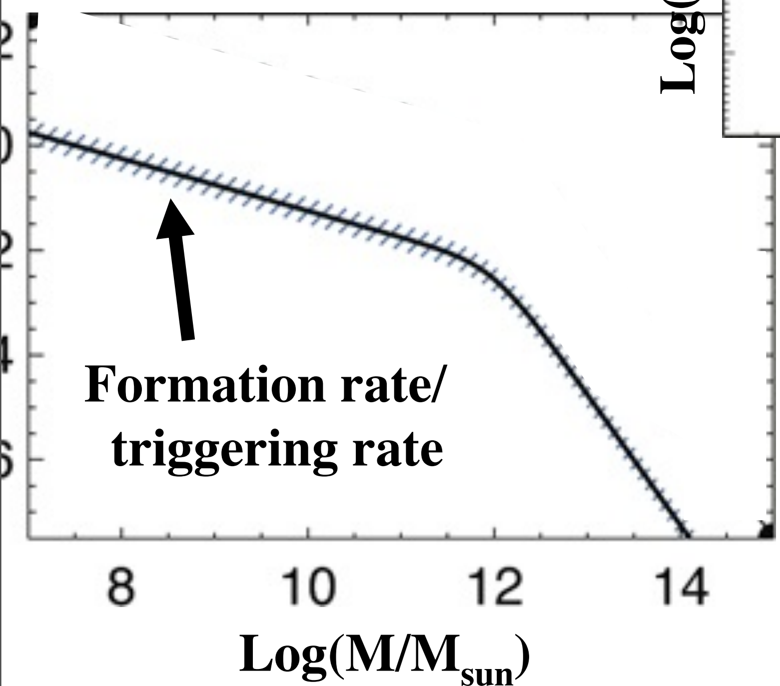


PFH et al. 2006b

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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

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



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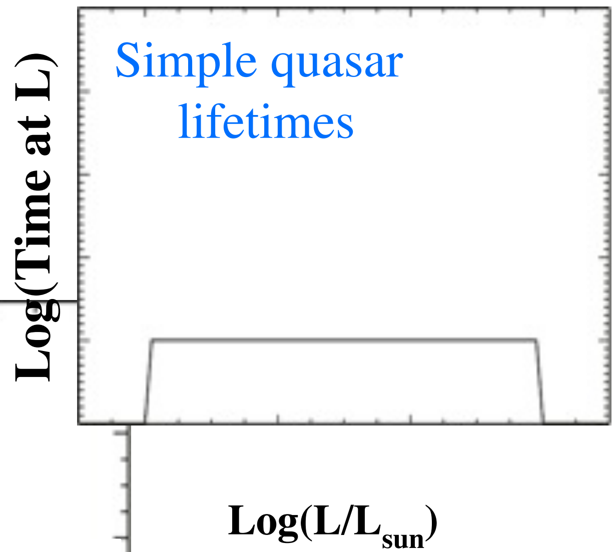

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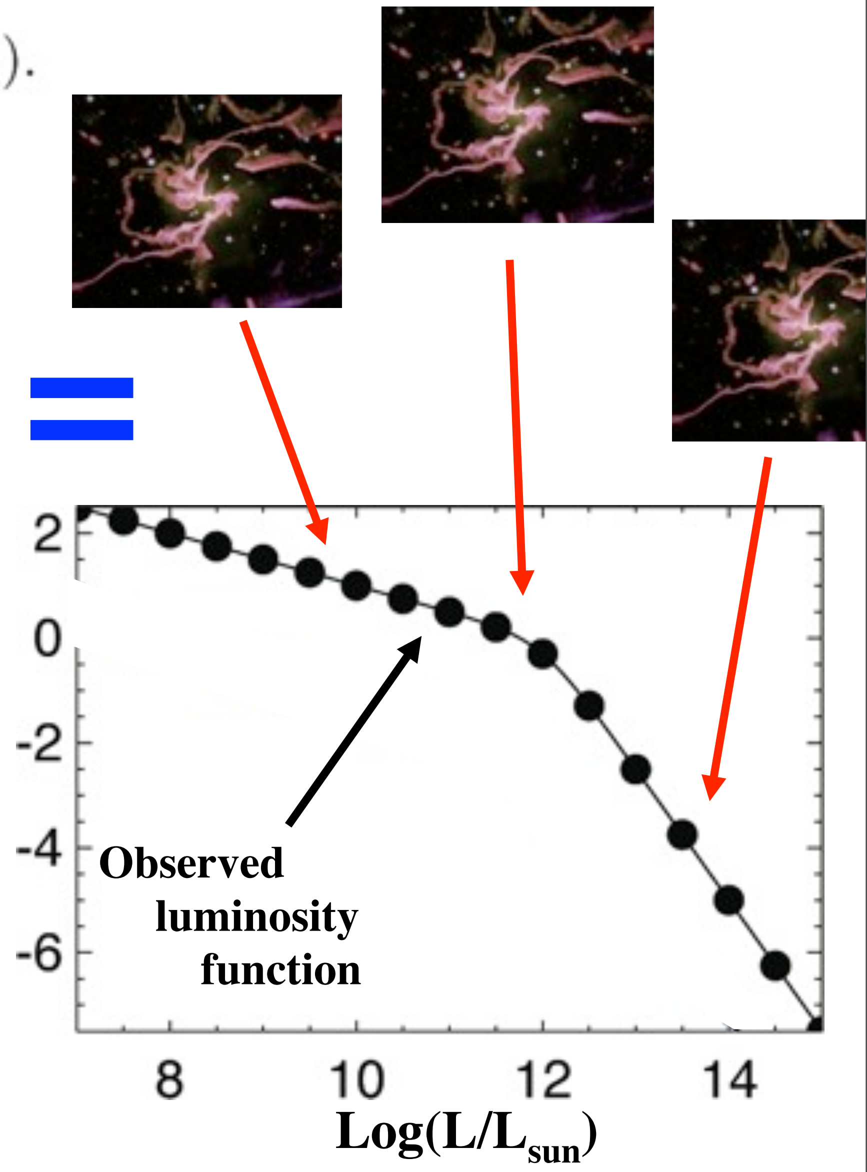
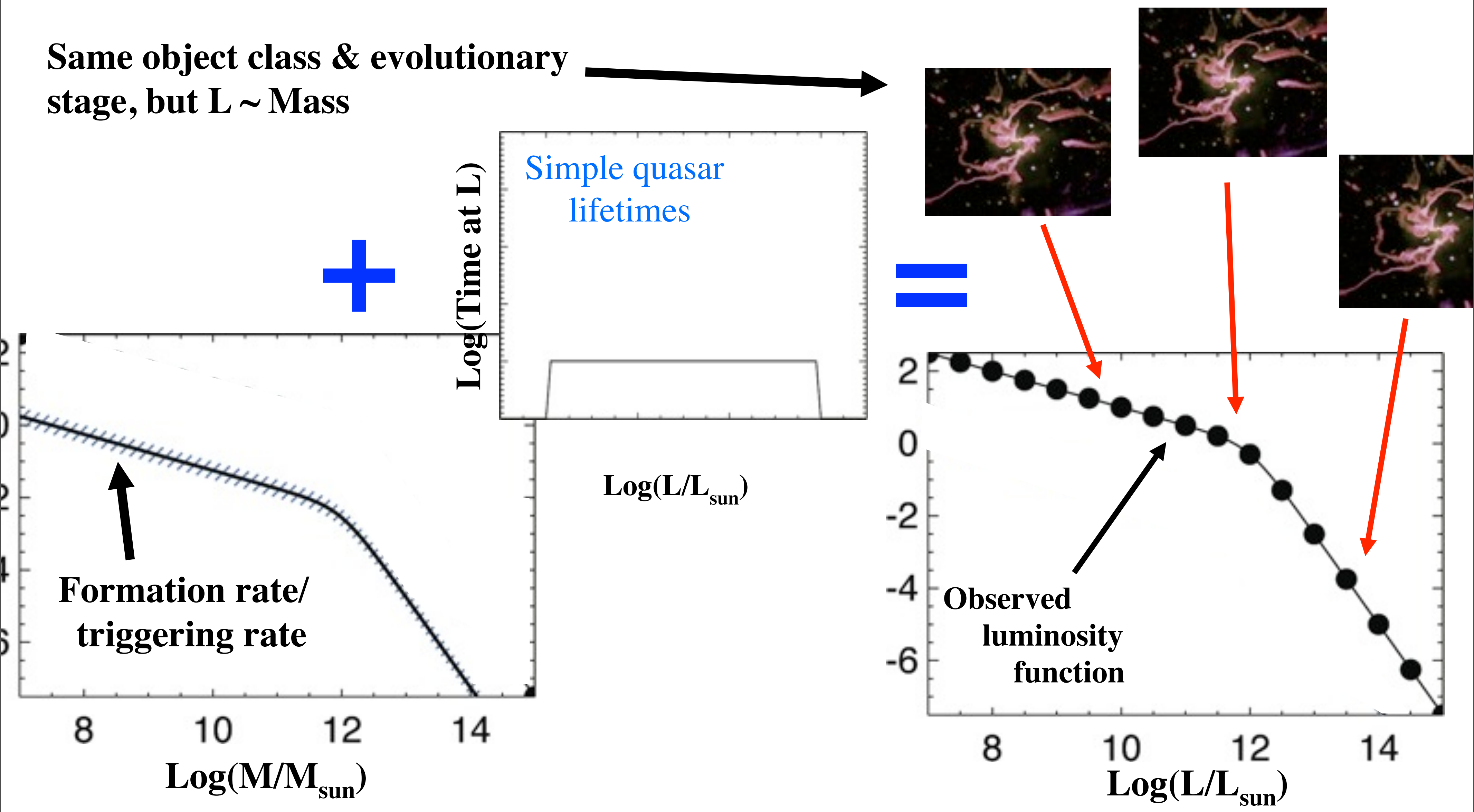


- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF

Given the Conditional Quasar Lifetime, De-Convolve the QLF

QUANTIFIED IN THIS MANNER, UNIQUELY DETERMINES THE RATE OF "TRIGGERING"



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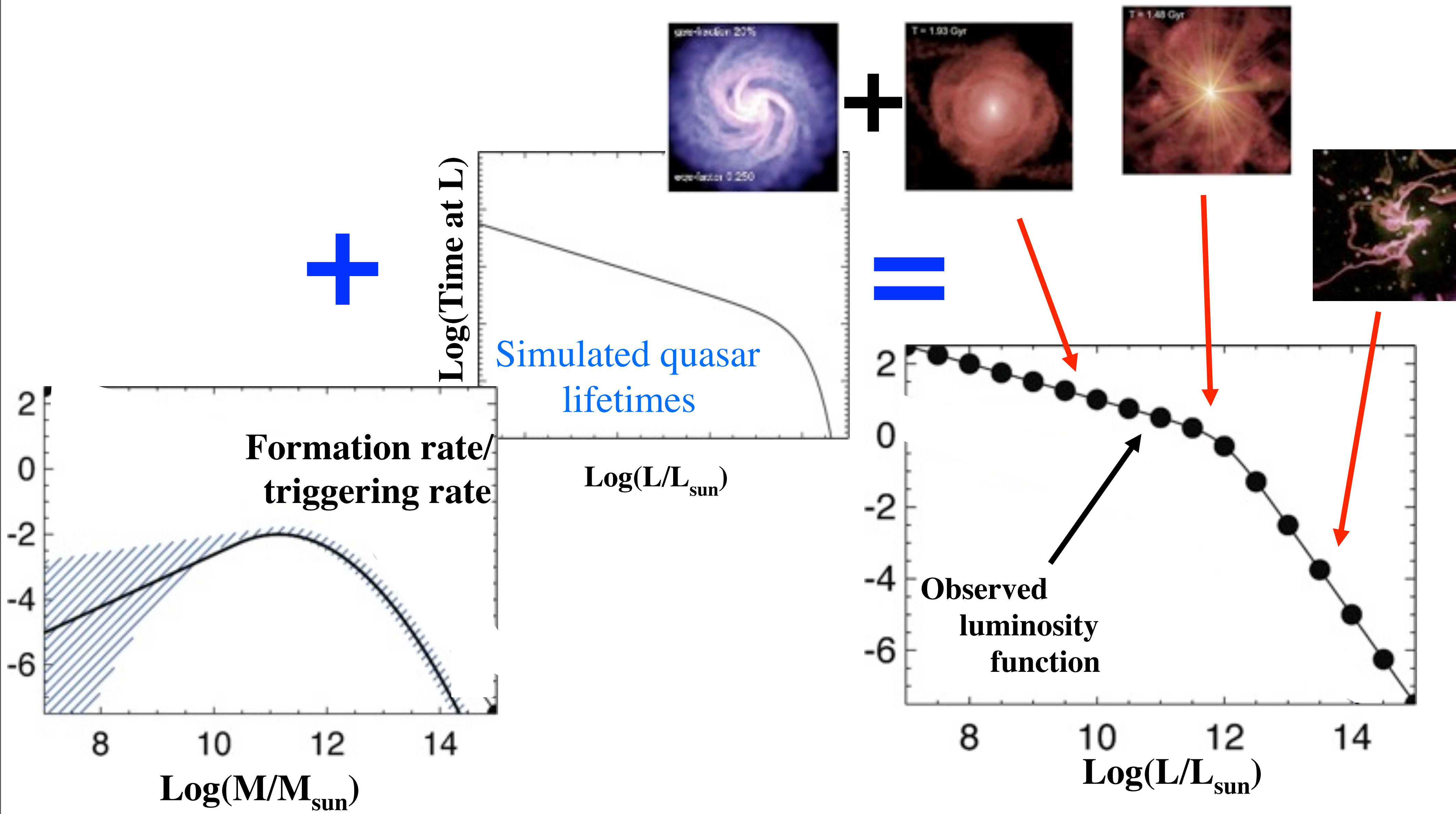
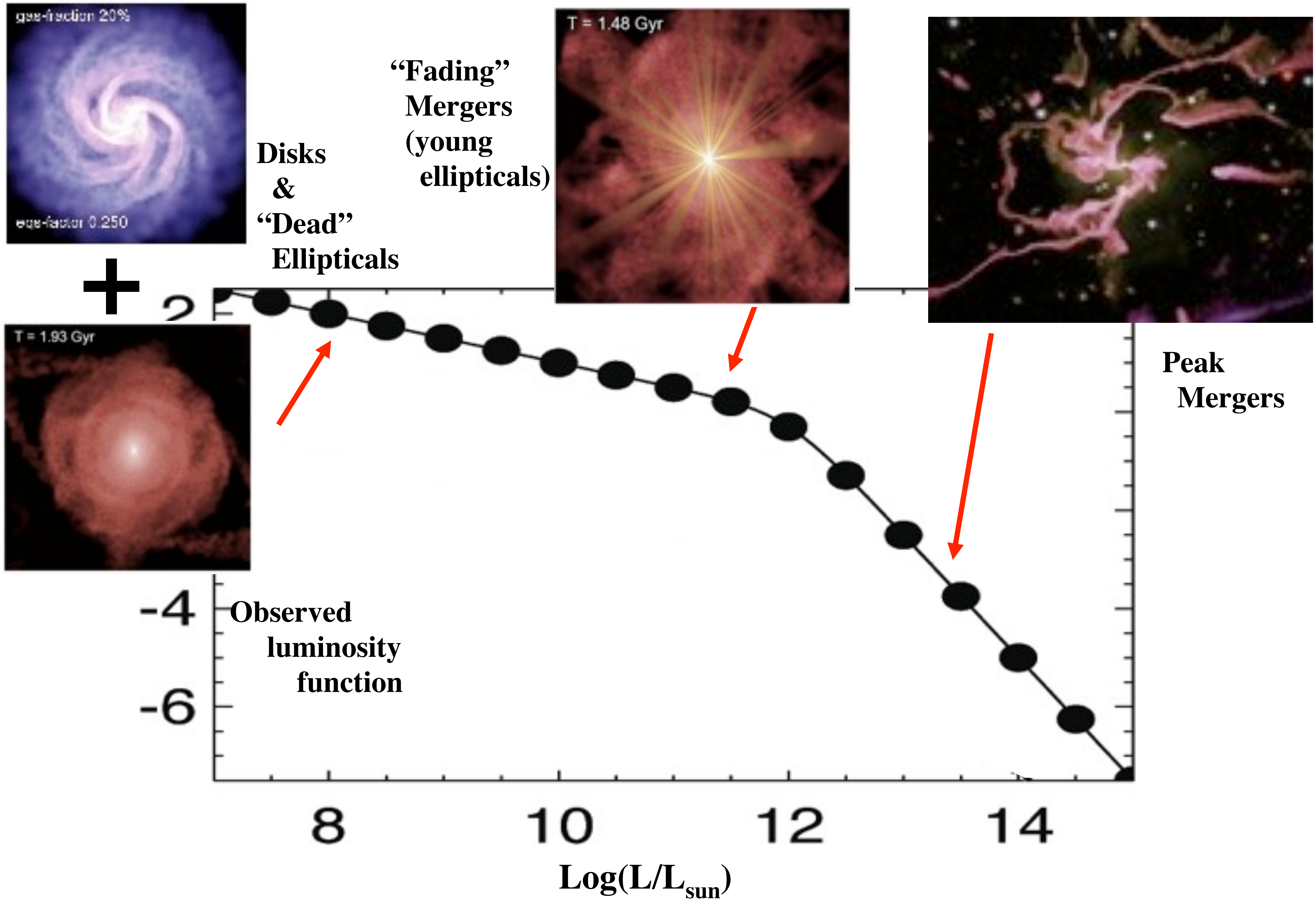


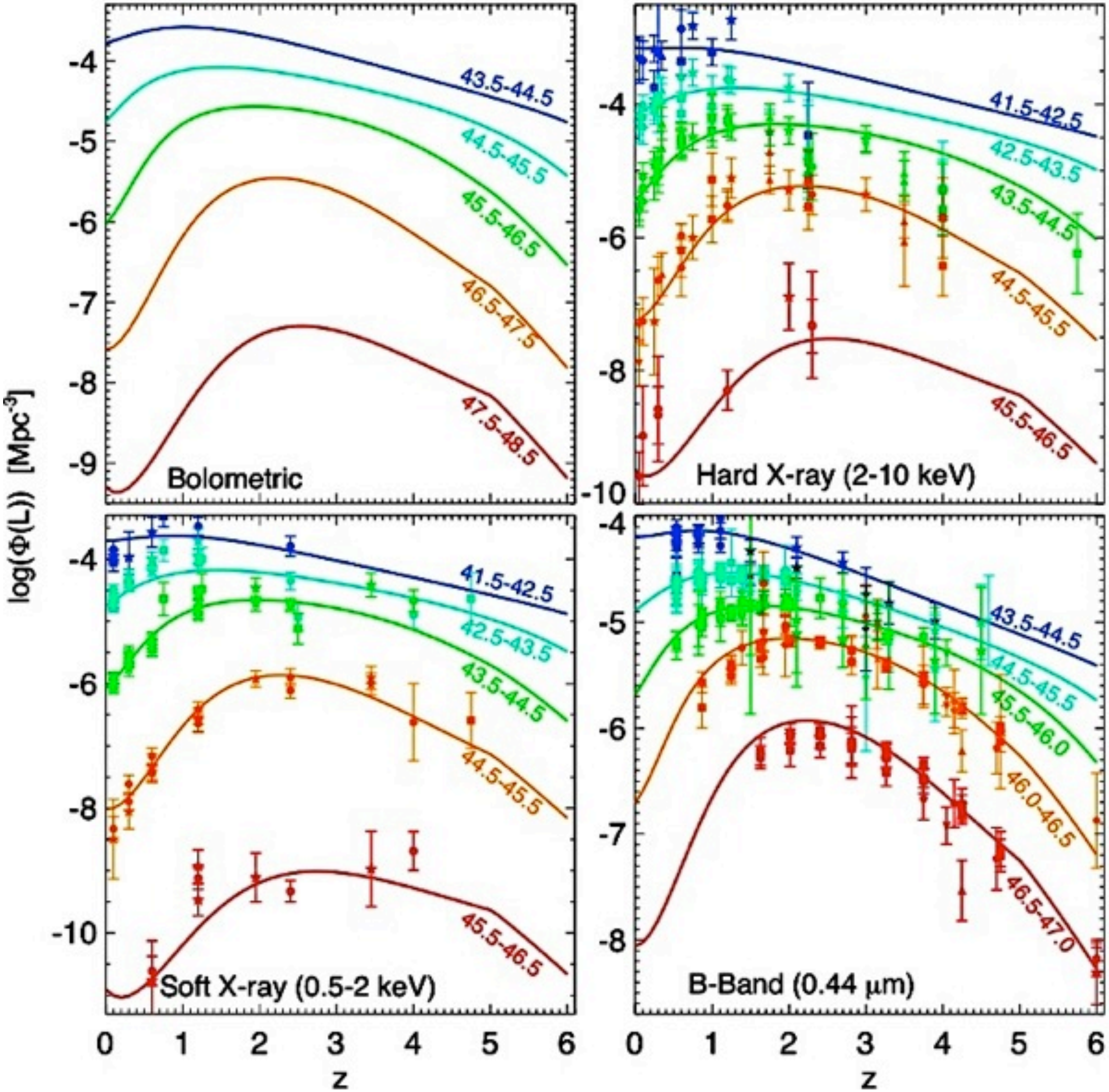
- *Different* shapes
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts



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

Luminosity-Dependent Density Evolution

"SECOND ORDER"

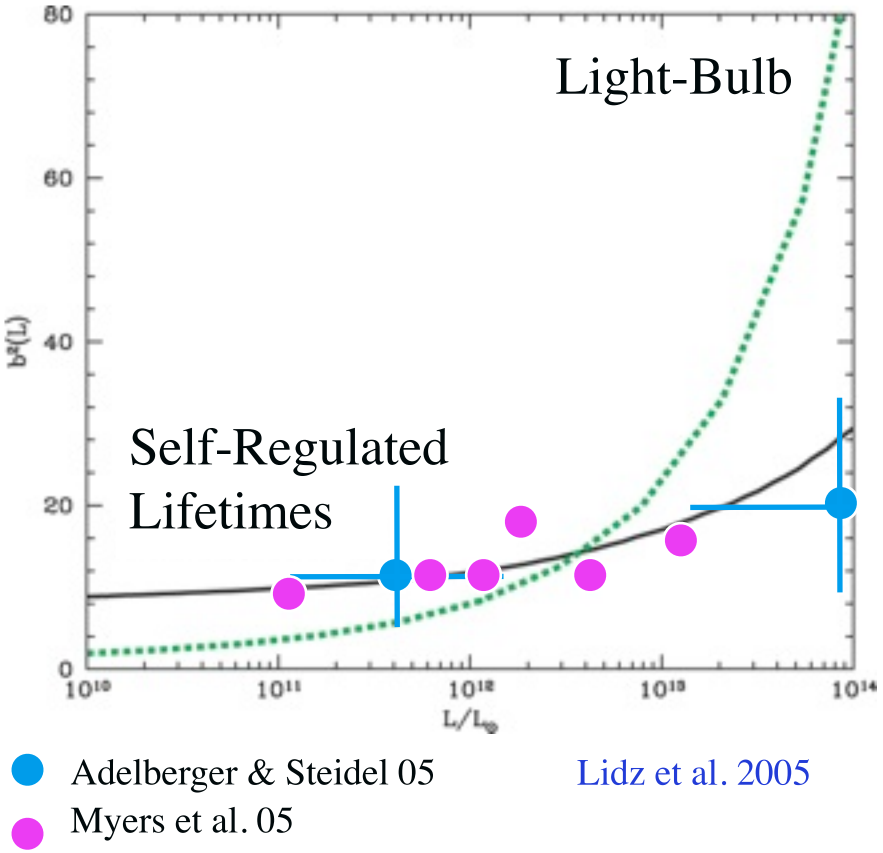


PFH, Richards, Hernquist

(also: Hasinger et al. 2007)

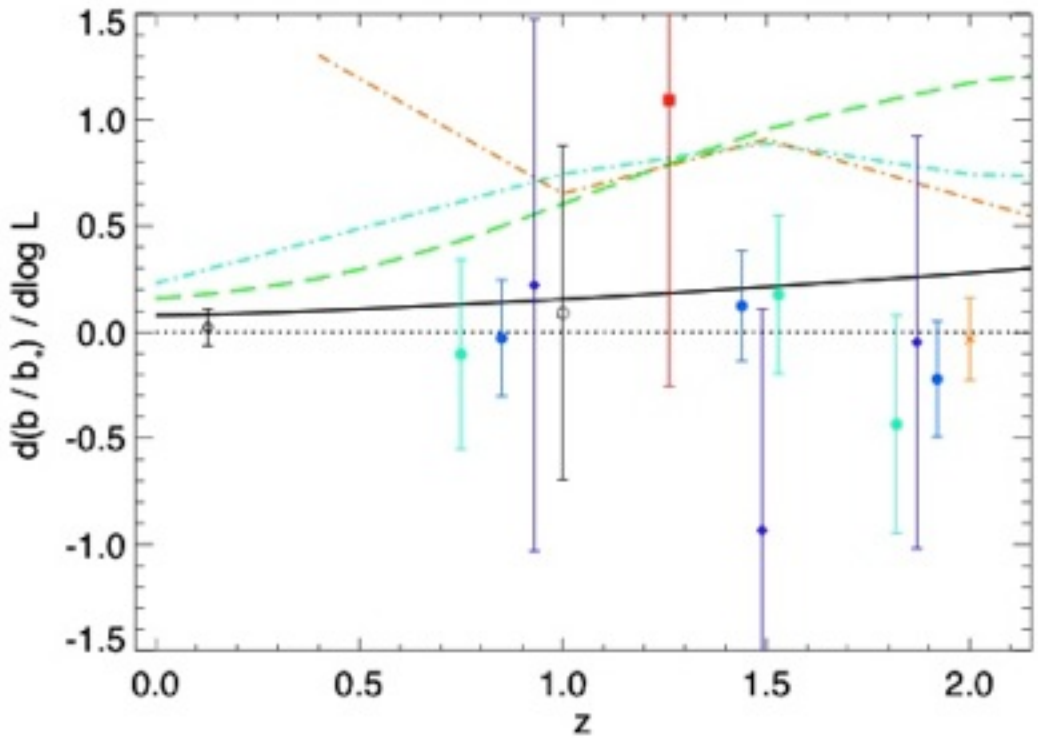
Quasar Clustering is a Strong Test of this Model

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



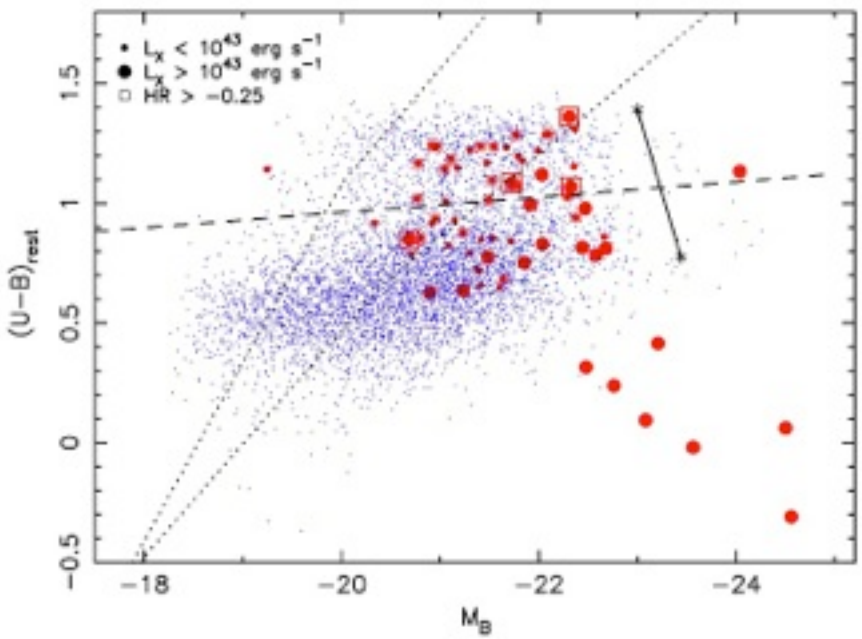
Lidz et al. 2005

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

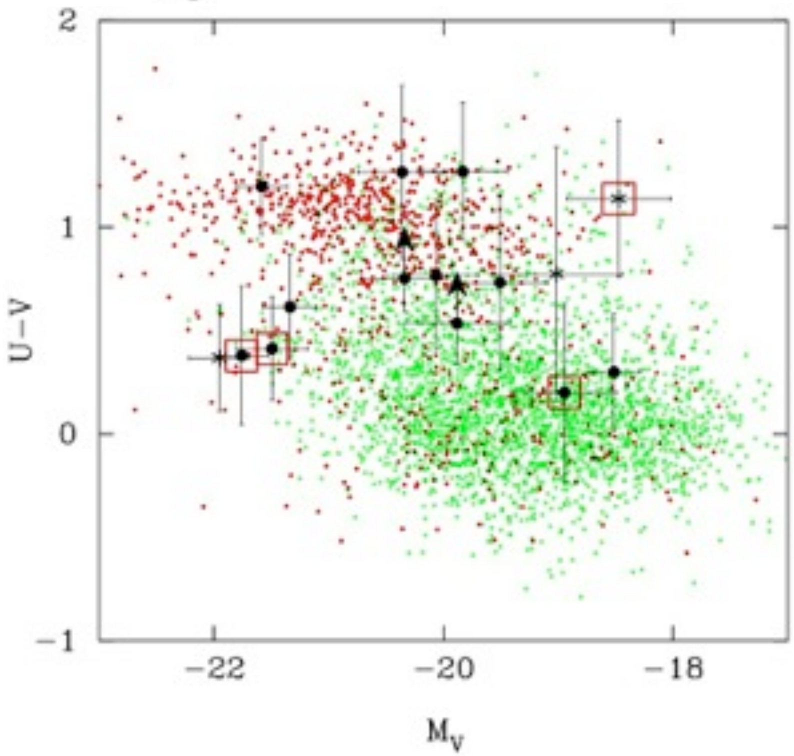


Hopkins, Lidz, Coil, Myers et al. 2007

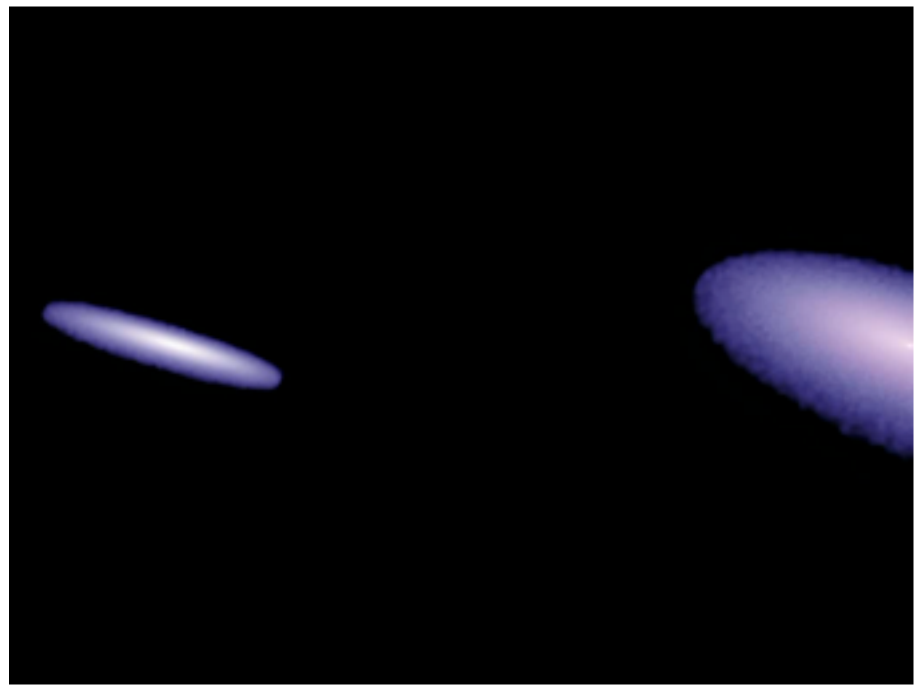
Color Evolution of Quasar Hosts



Nandra+ ‘06
DEEP2
0.7 < z < 1.4
X-ray QSOs

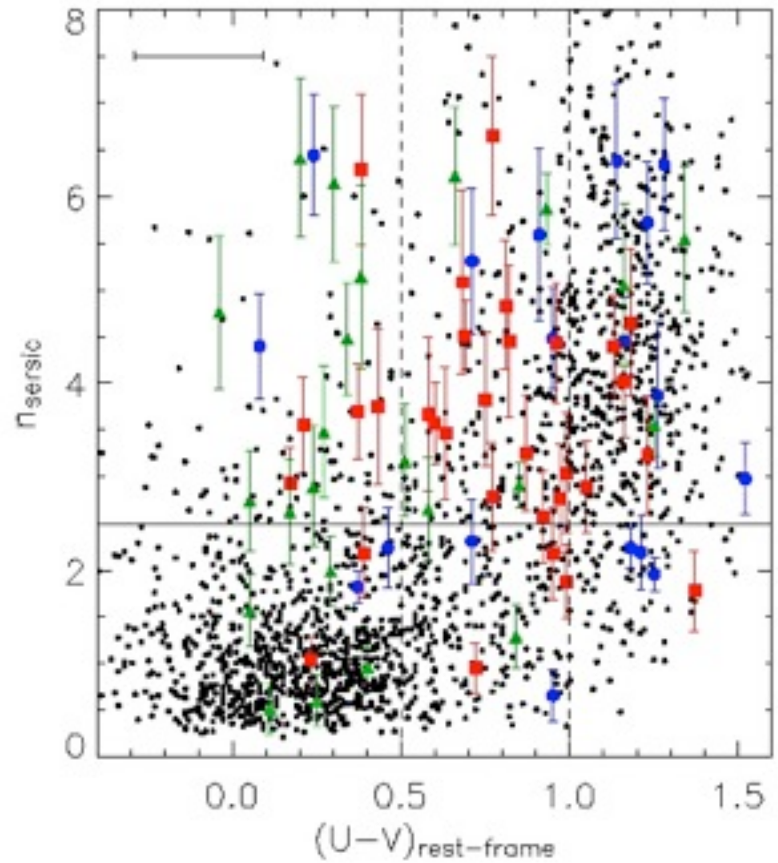


Sanchez+ ‘05
GEMS
0.5 < z < 1.1
Optical QSOs

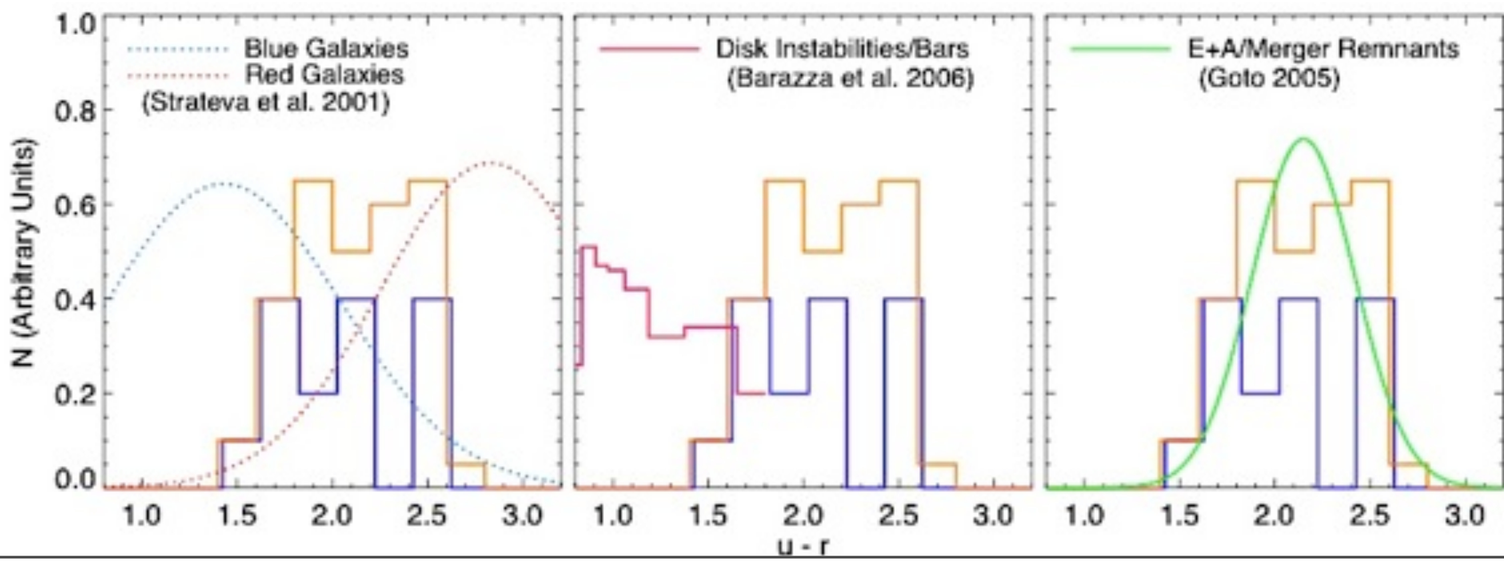


Color Evolution of Quasar Hosts

- Quasars live in *blue spheroids*
- Need to go to next level: full stellar populations - are these really post-SB?
- Examine the time/redshift dependence



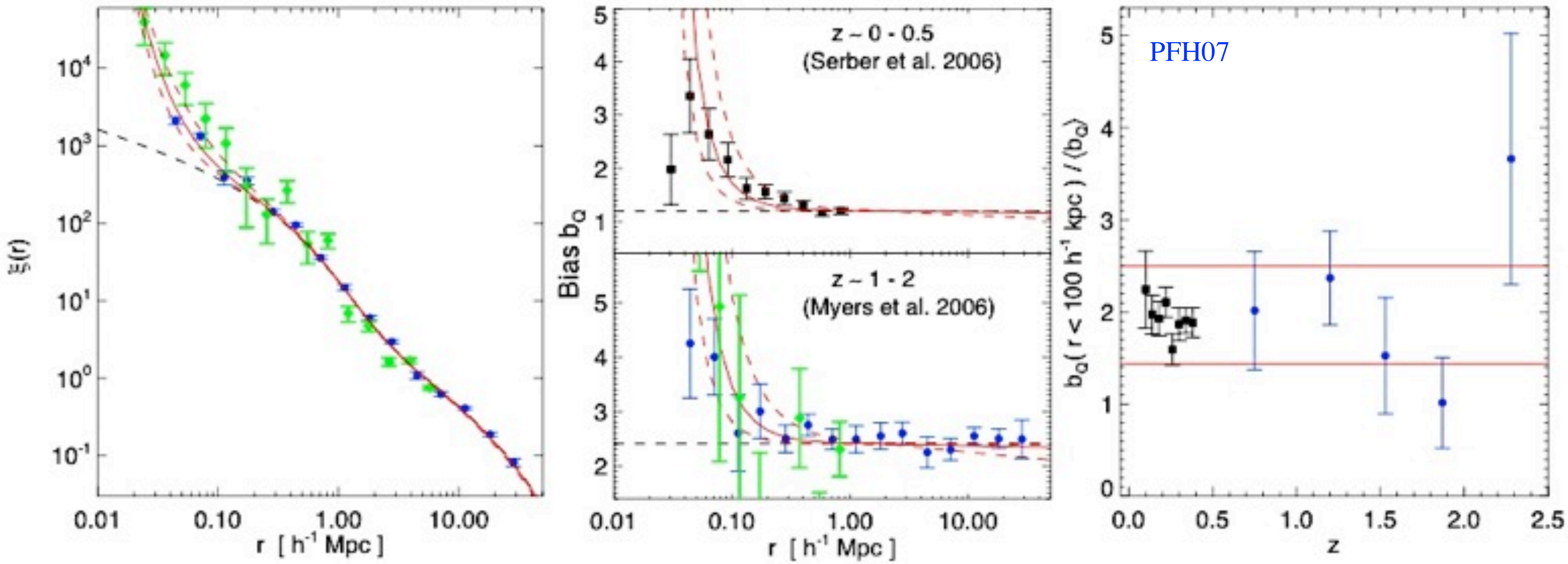
Silverman et al.



PH07

Where Quasars Are Born

- 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

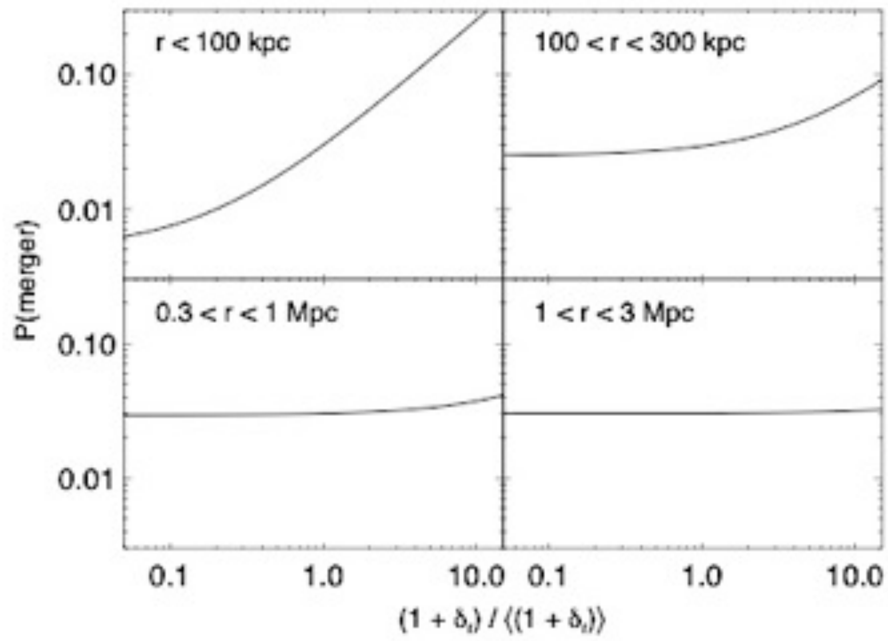


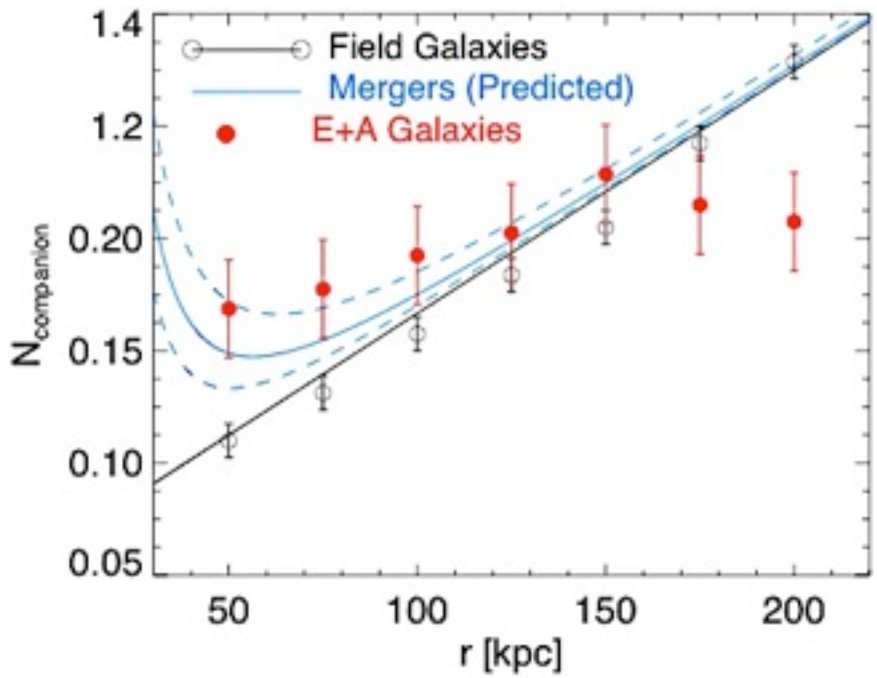
- Predicted by merger models (Thacker & Scannapieco et al., PFH)

Where Quasars Are Born

PFH07

- Small-Scale Excess:
  - Predicted in merger models
    - Mergers biased to regions with *small-scale* overdensities
    - Seen in cosmological simulations (Thacker et al.)
    - Seen in merger remnants! (Goto et al.; Hogg et al.)
  - *Not* expected in secular/instability, cooling flow, stellar mass loss, or other models





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

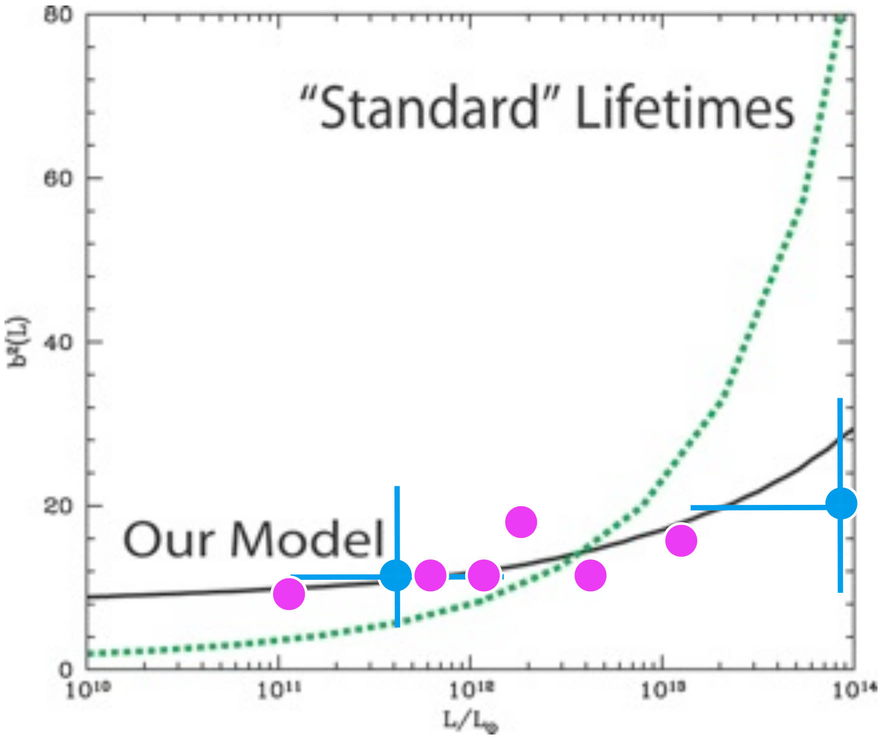
- "Are AGN mergers?" is the *wrong* question: we should ask:
  - "Where (as a function of L, z, d) do mergers vs. secular processes dominate the AGN population?"
    - Clustering vs. scale
    - Host galaxy colors/SFH
    - Host morphology/kinematics
      - Both "merger signatures" and e.g. disk vs. elliptical, pseudobulge vs. classical bulge

Thanks!

Galaxy Crash

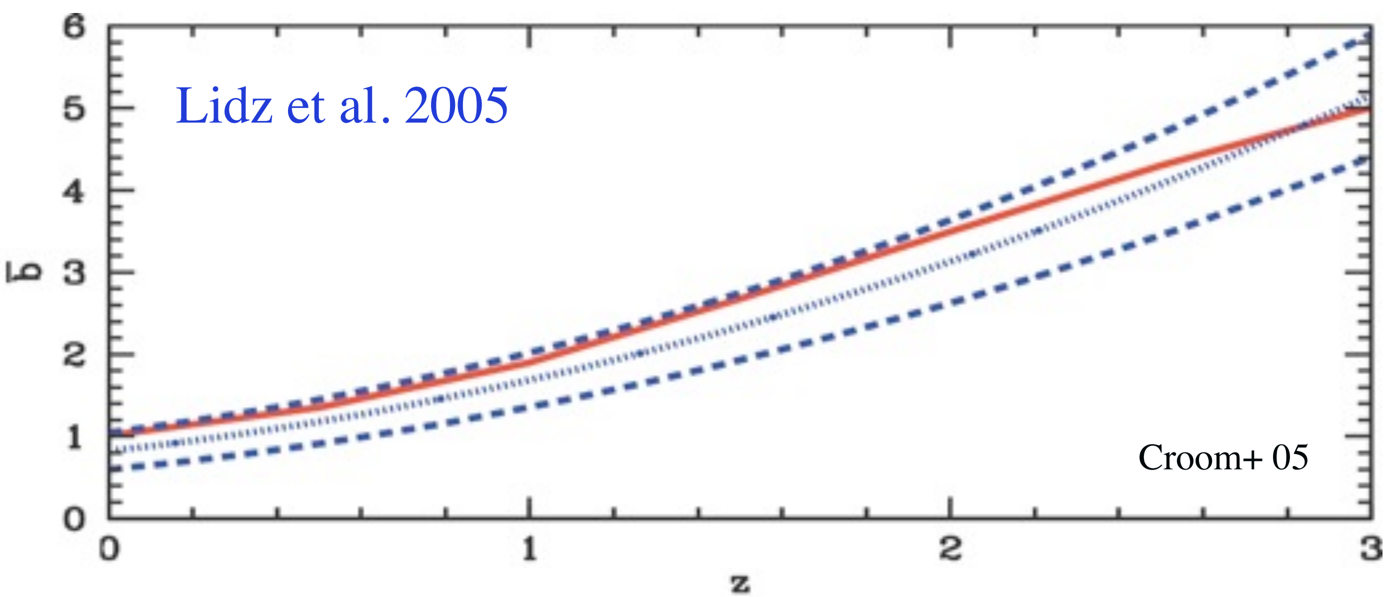
Quasar Clustering is a Strong Test of this Model

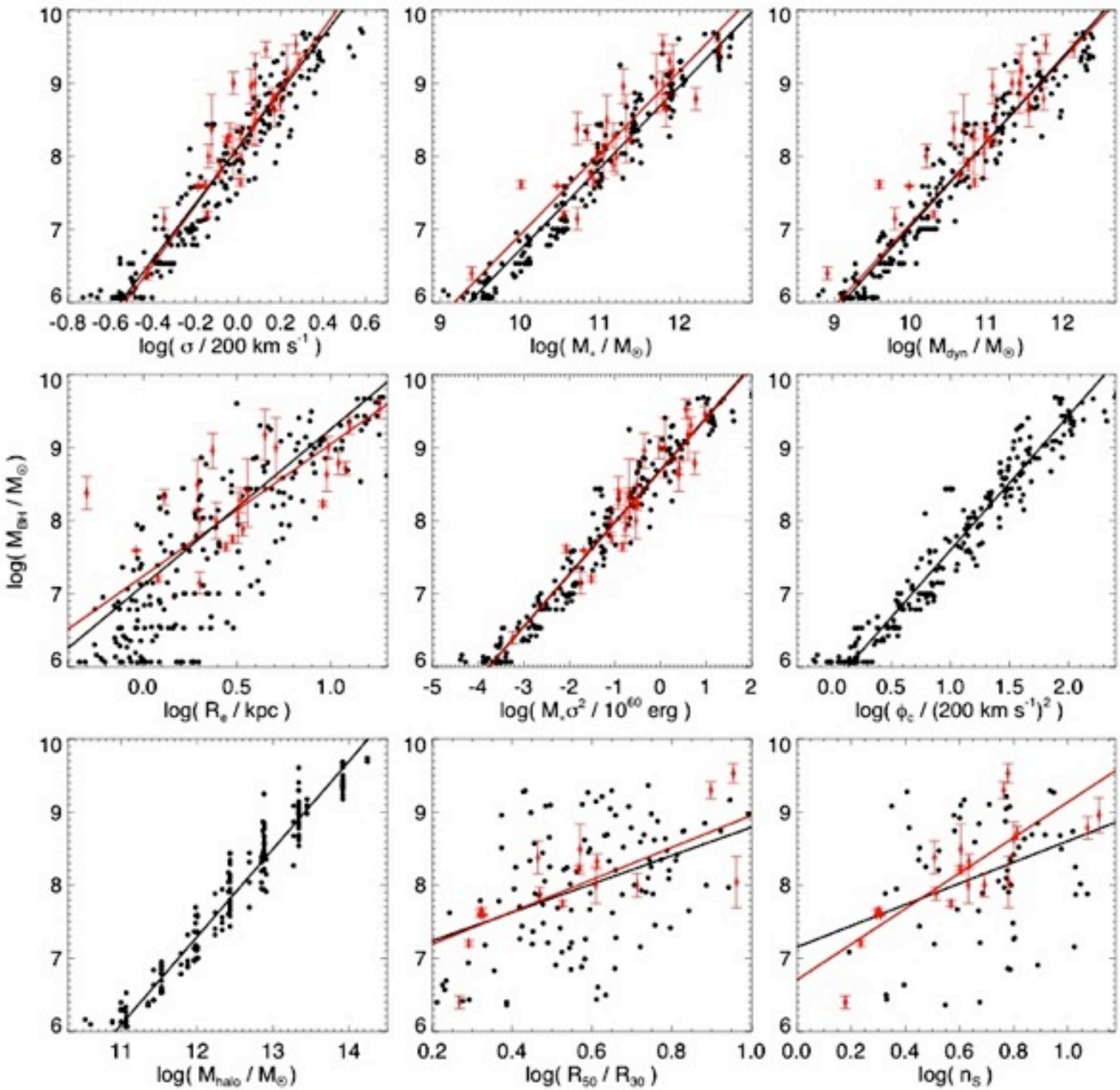
MOST FAINT QSOS ARE DECAYING BRIGHT QSOS - SHOULD BE IN SIMILAR HOSTS



- Adelberger & Steidel 05
- Myers et al. 05

- Weak dependence of clustering on observed luminosity
  - (Croom et al. 2005, Adelberger & Steidel 2005, Myers et al. 2005)
- Observed trends with redshift
  - (M_halo ~ 10^13 M_sun)



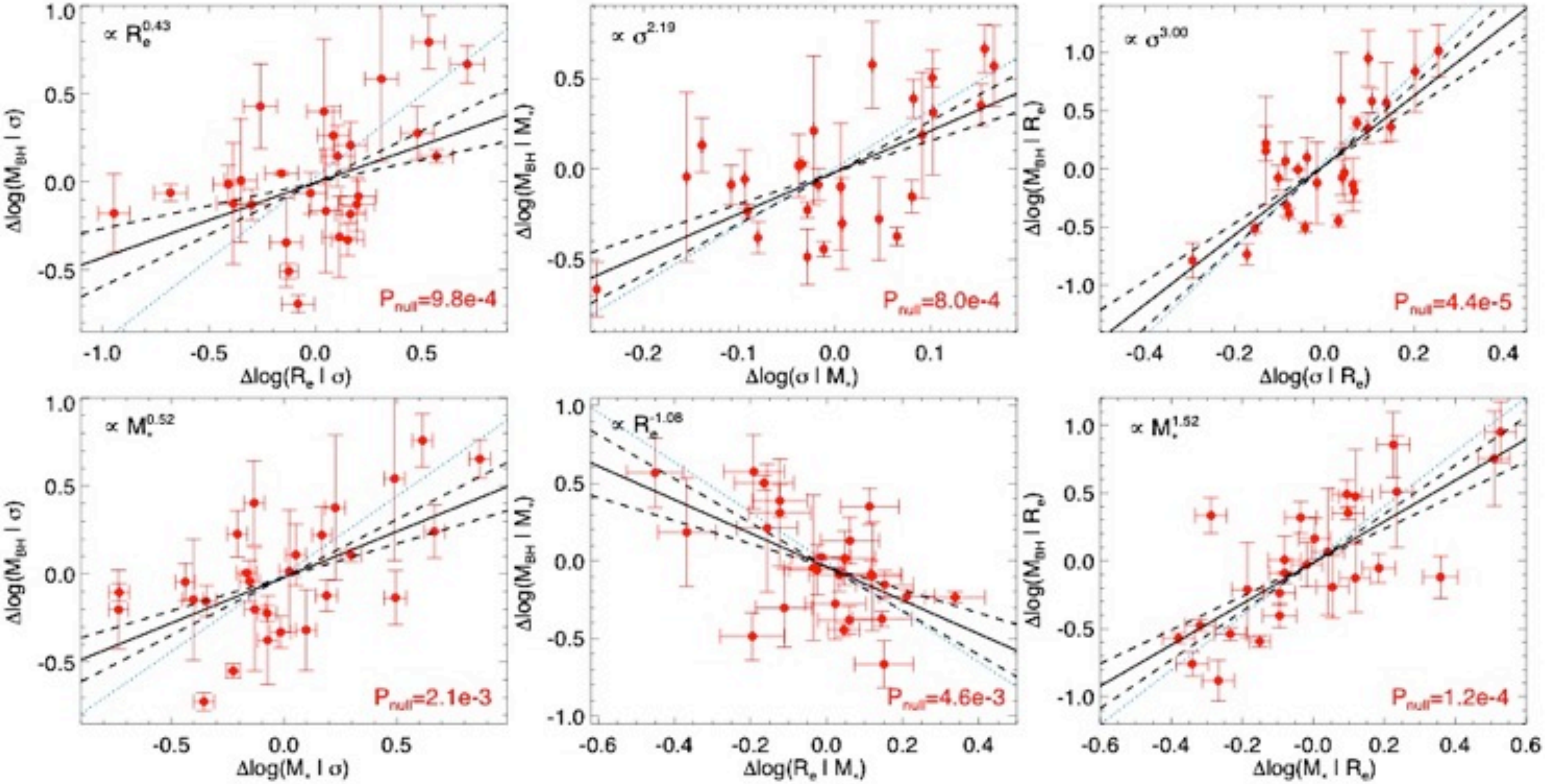


log(σ / 200 km s^-1)
log(M* / M⊙)
log(Mdyn / M⊙)
log(MBH / M⊙)
log(Re / kpc)
log(M*σ² / 10^60 erg)
log(φc / (200 km s^-1)²)
log(Mhalo / M⊙)
log(R50 / R90)
log(nS)

Which Correlation Is “Most Fundamental”?

COMPARE RESIDUALS

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



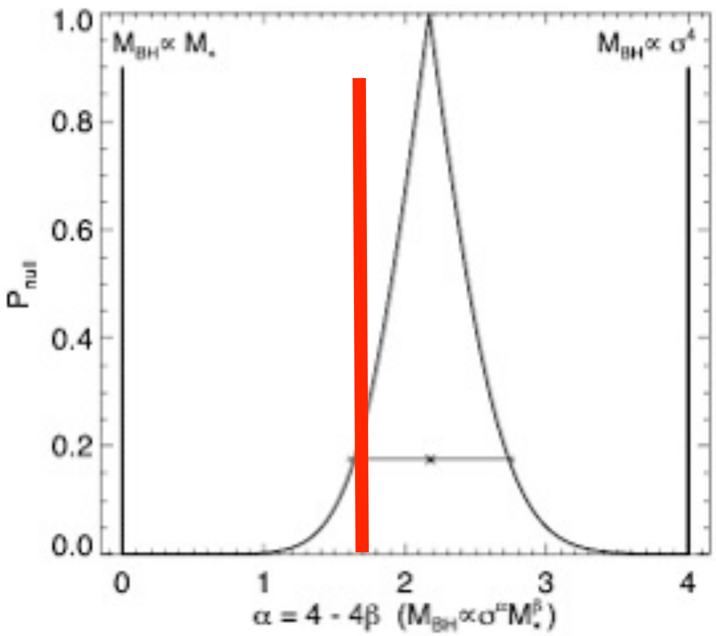
~3s significant residual trend with respect to ANY single variable correlation!

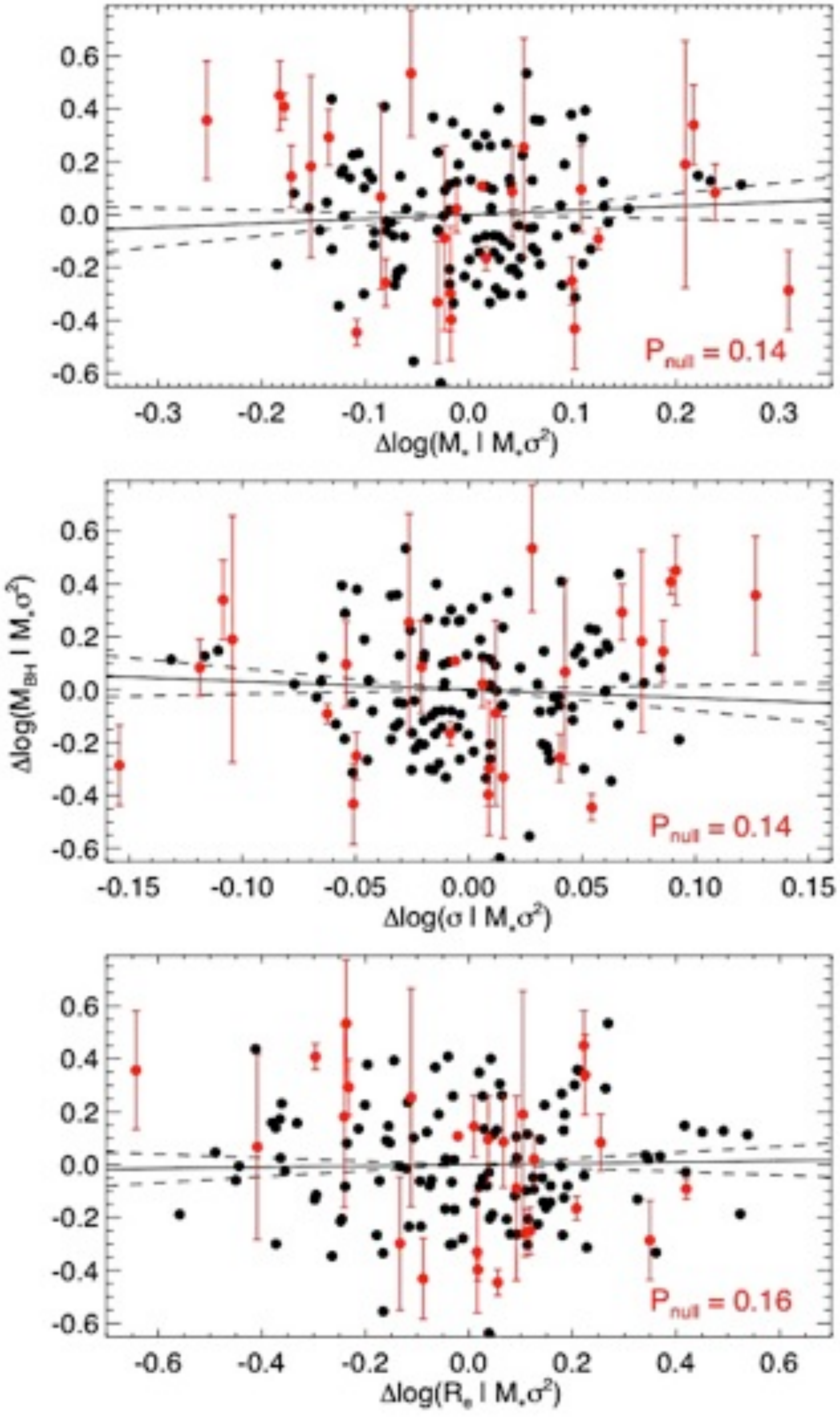
Which Correlation Is “Most Fundamental”?

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





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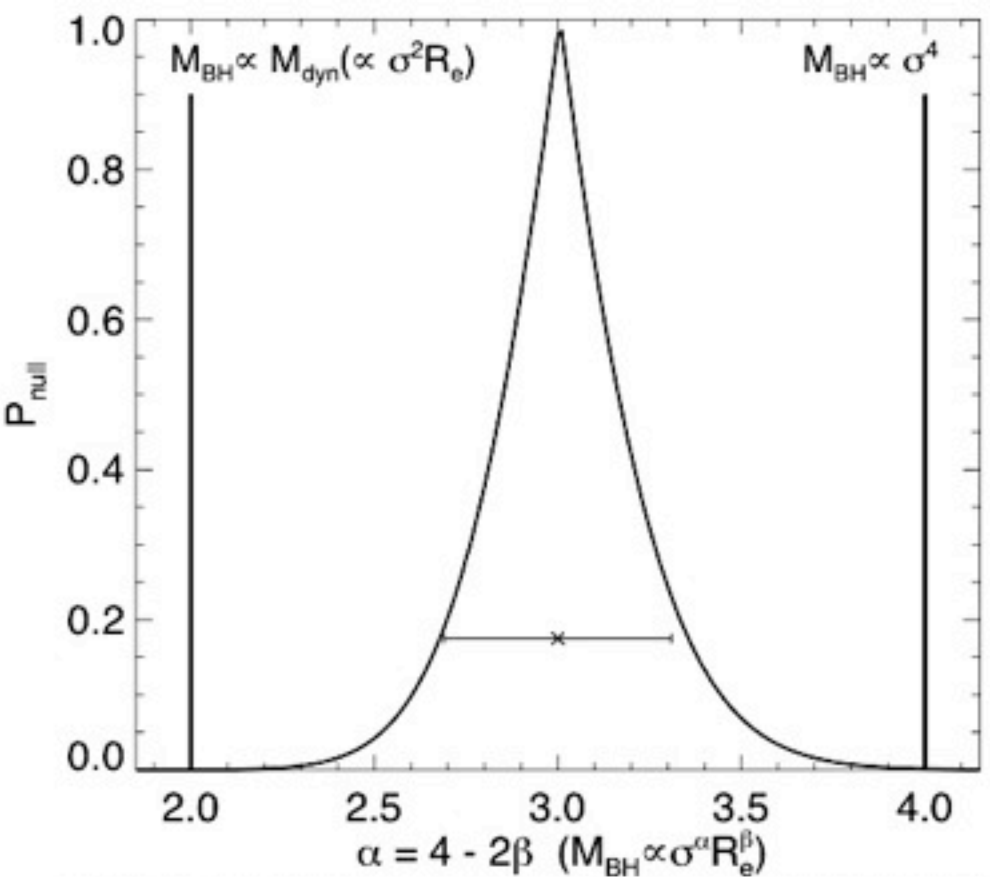
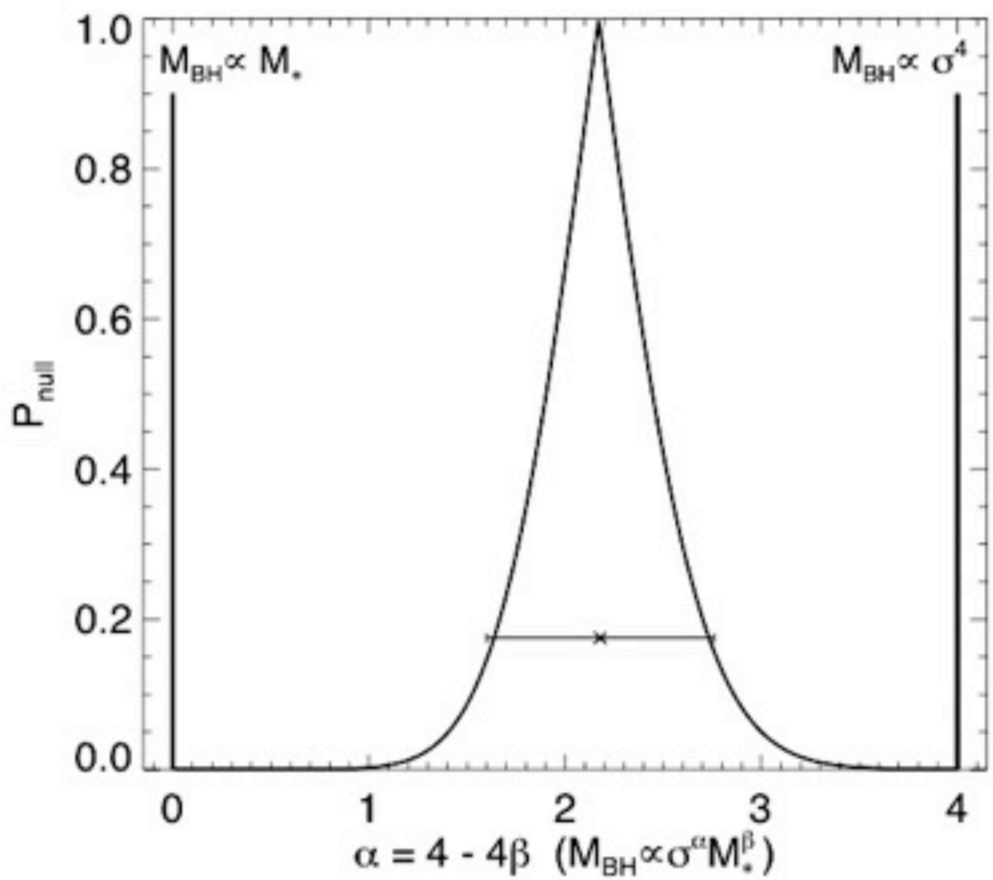
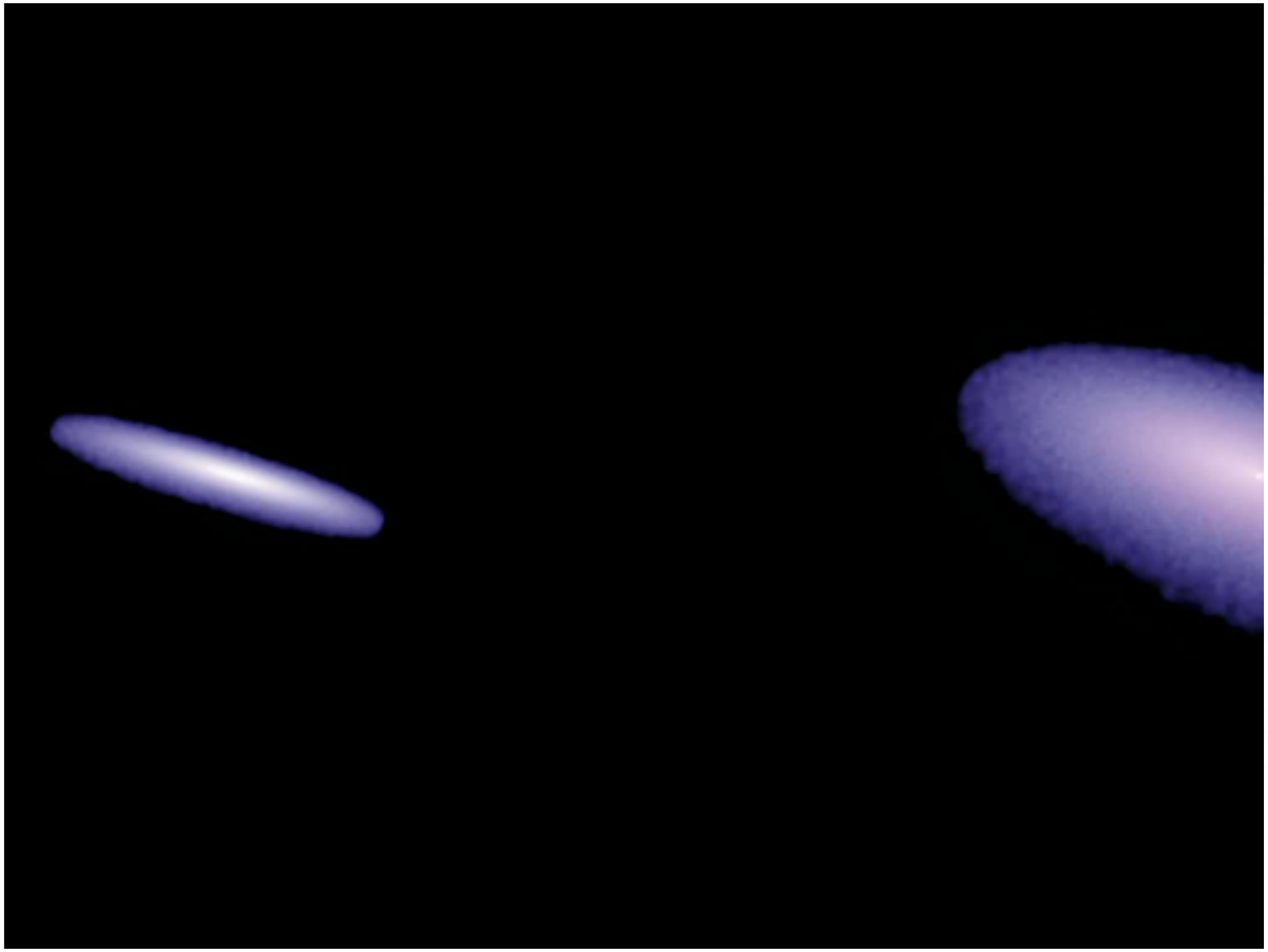
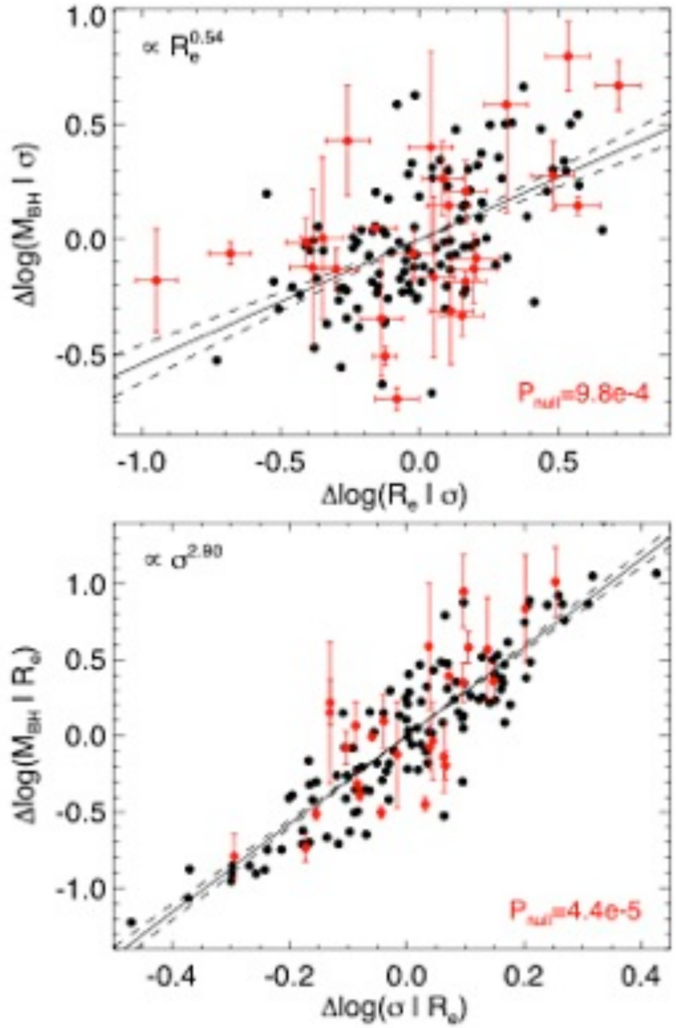




Do Feedback-Regulated Simulations Predict This?

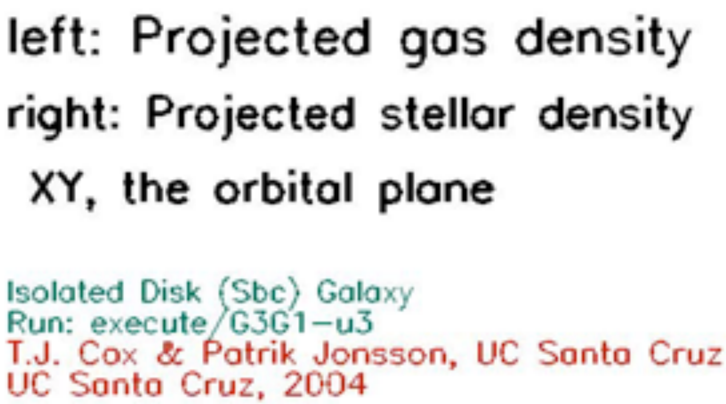
SIMPLE COUPLING OF BH RADIATED ENERGY TO SURROUNDING GAS IN A MERGER

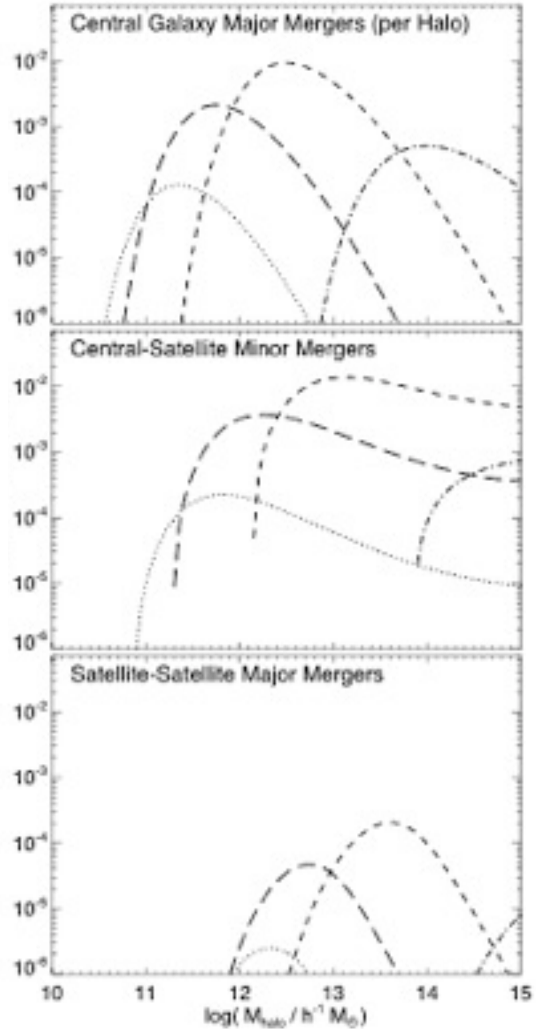


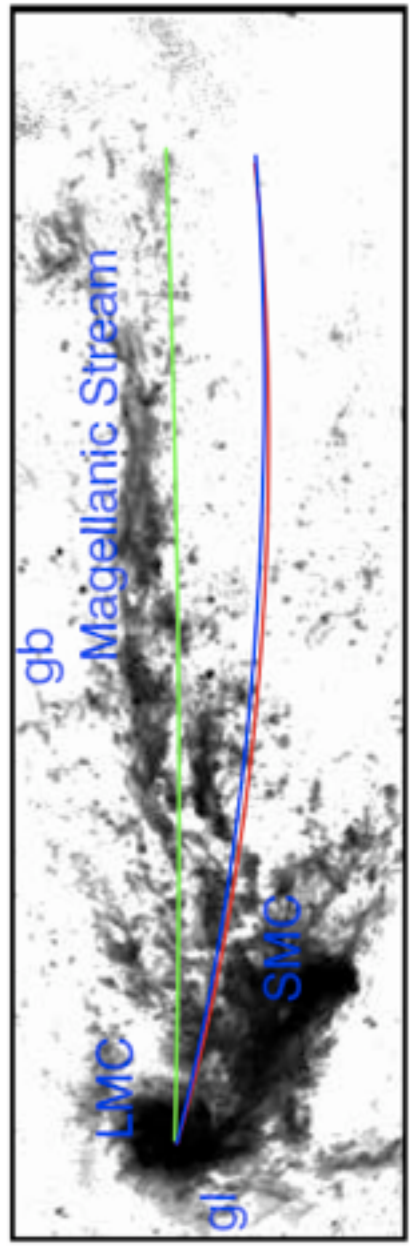


- Supports basic Silk & Rees ’98 argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential of material to be unbound

Other Fueling Mechanisms: Minor Mergers



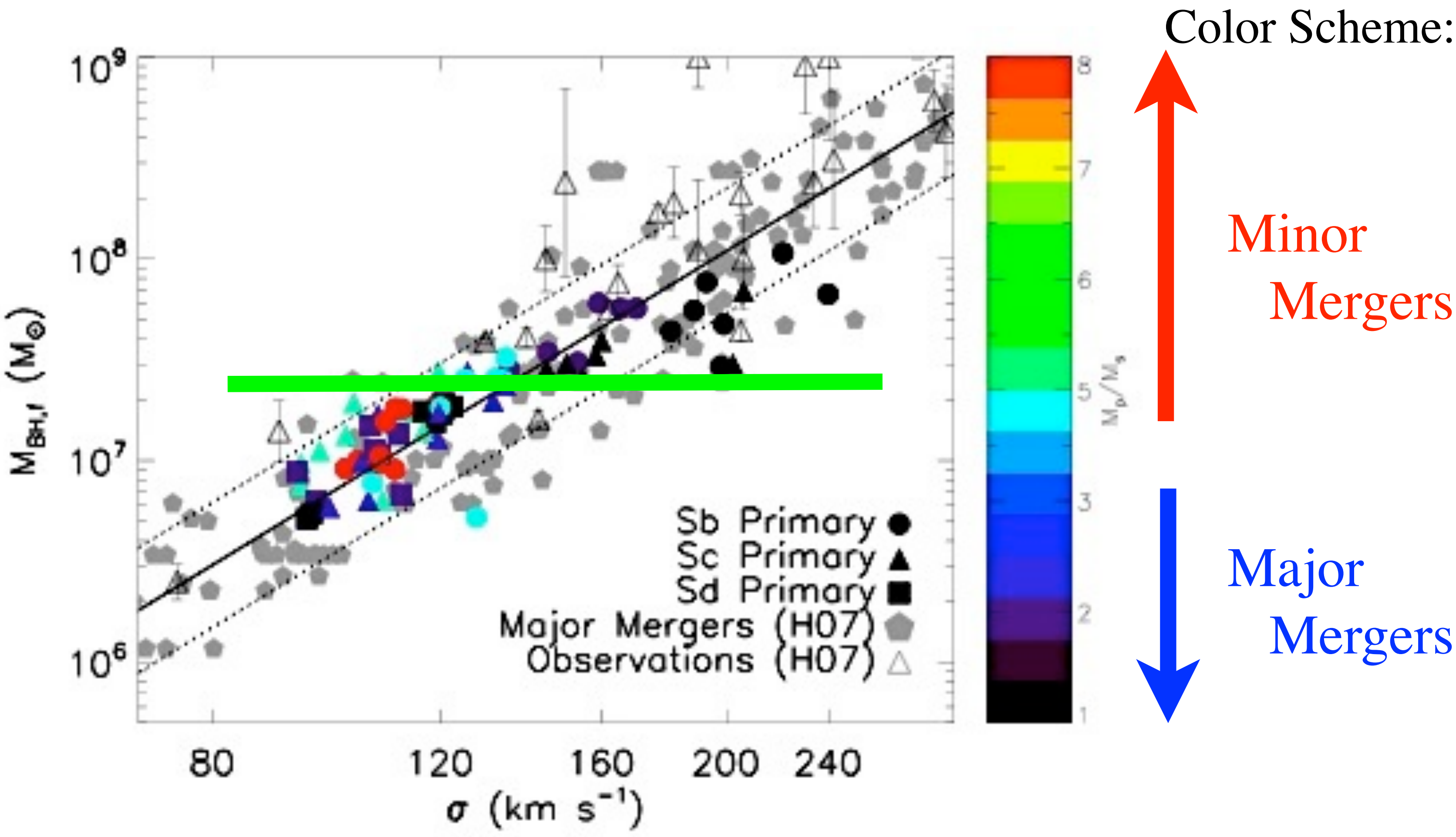




Besla et al. (2007)

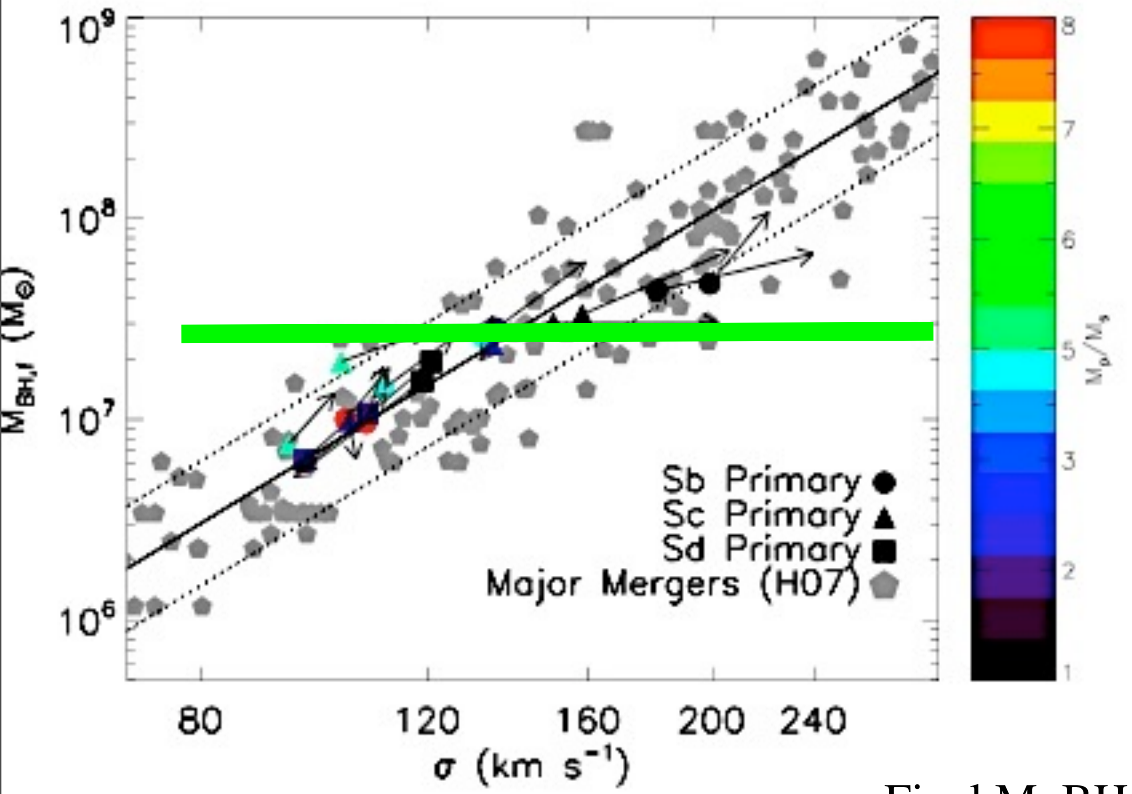
- Minor Mergers
  - Not so violent -probably don't dominate spheroid formation (LMC/SMC)
  - Not very efficient: even if growth ~ M_secondary/M_primary, major mergers "win"

Other Fueling Mechanisms: Minor Mergers



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

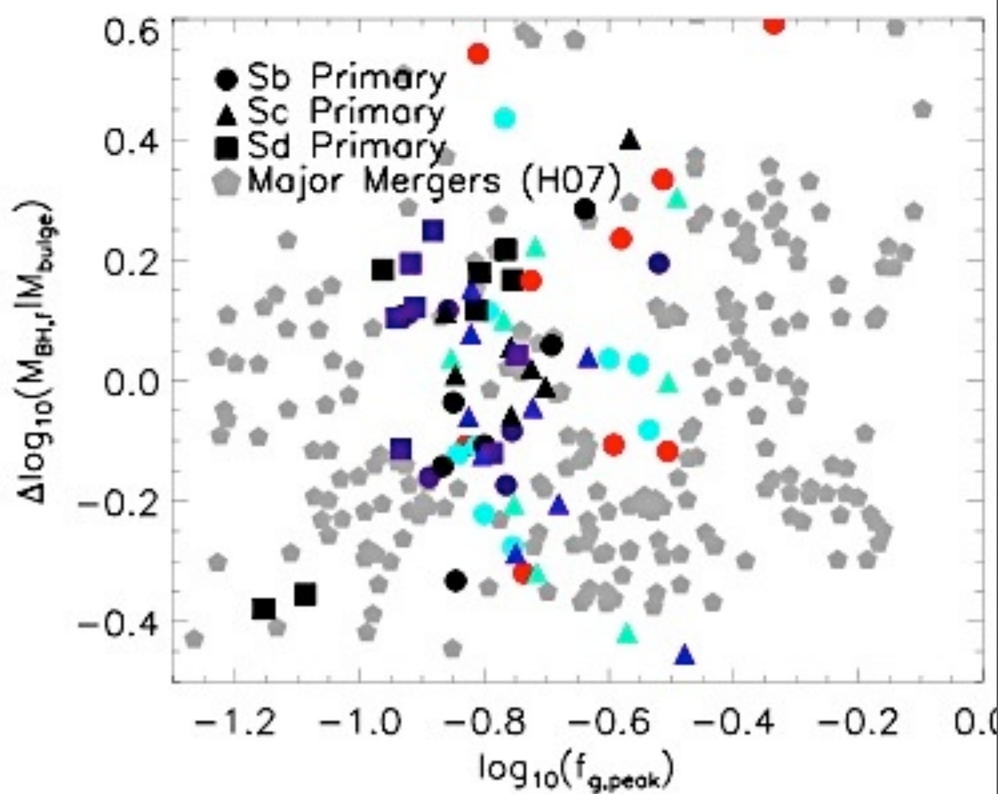
Other Fueling Mechanisms: Minor Mergers



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

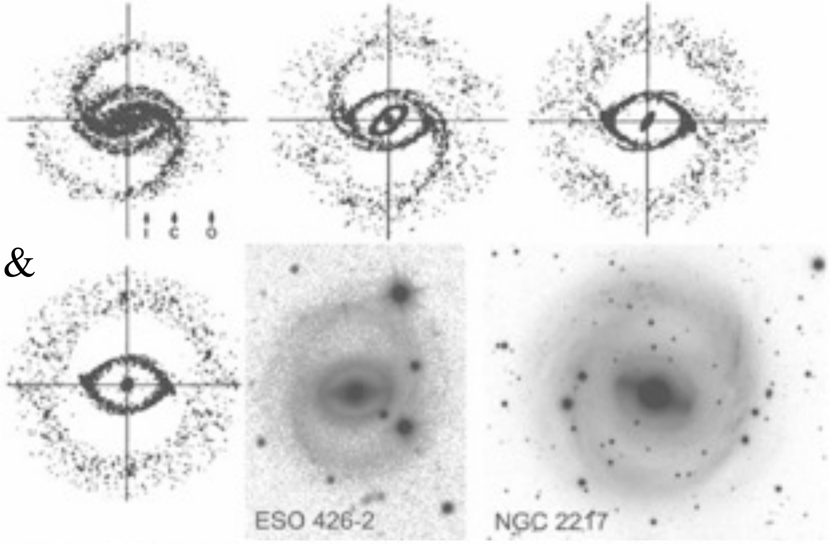
- BH doesn't care how much gas you give it:: building the potential depth is the hard part -- the BH will easily "catch up"

Final M_BH relative to mean

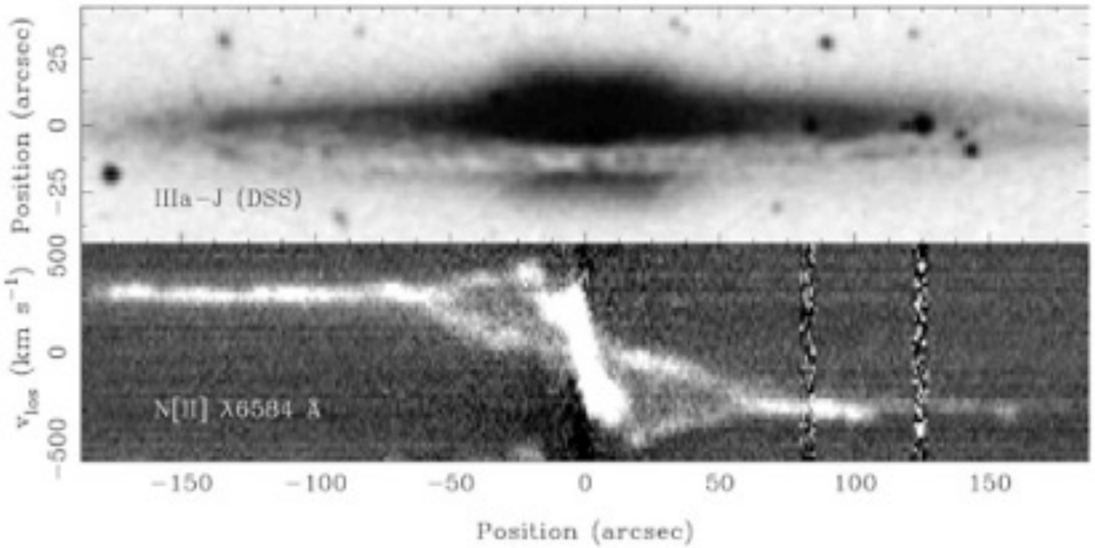


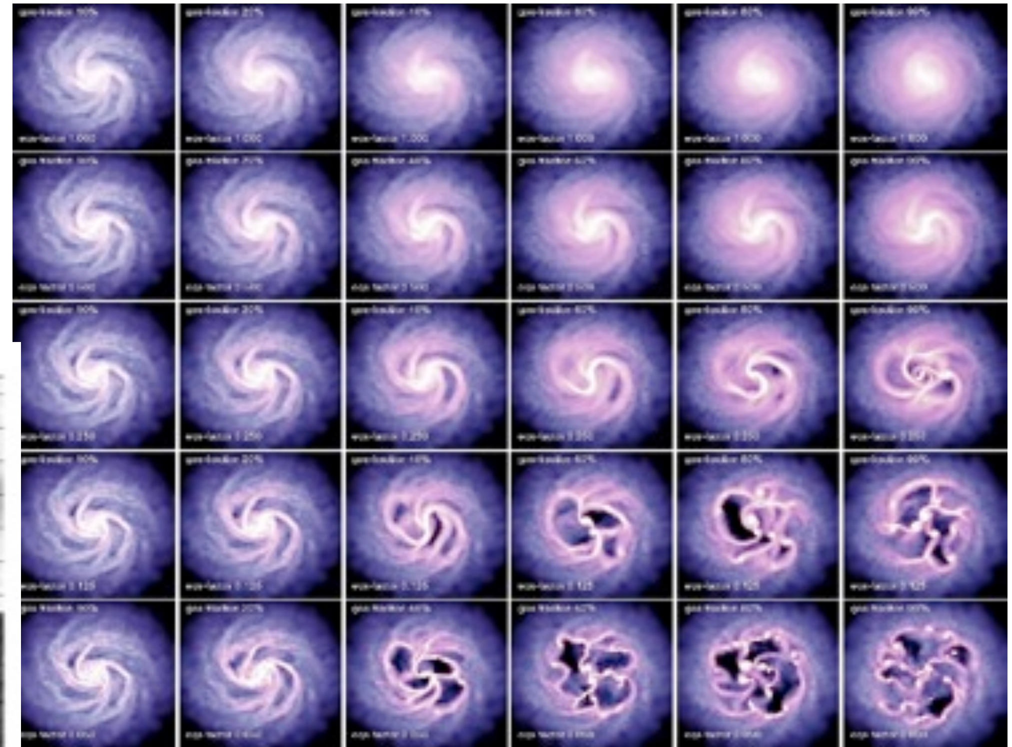
Mass of gas supplied to BH

Other Fueling Mechanisms: Disk/Bar Instabilities



Kormendy & Kennicutt



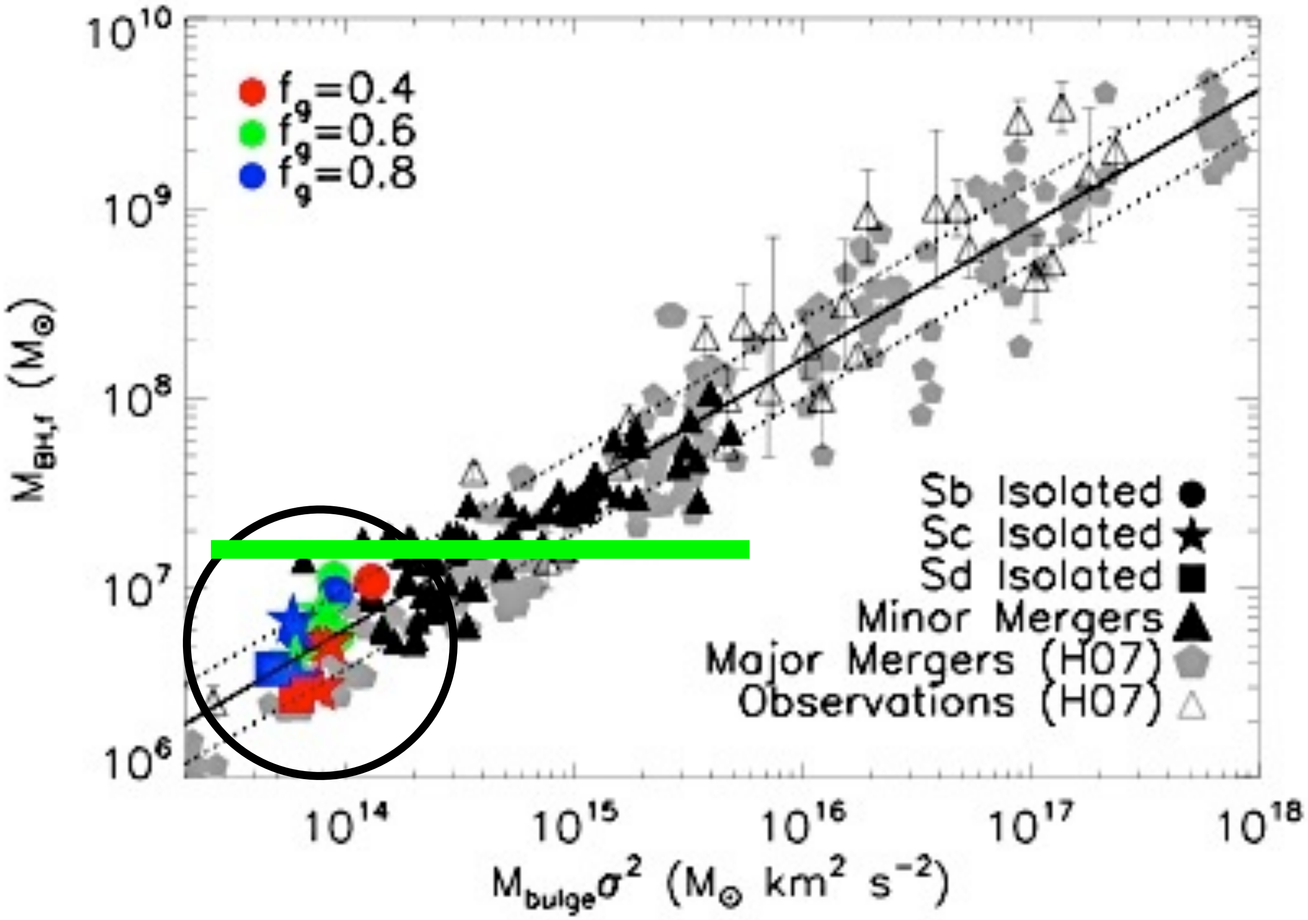


Springel et al. (2005)

- 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.)

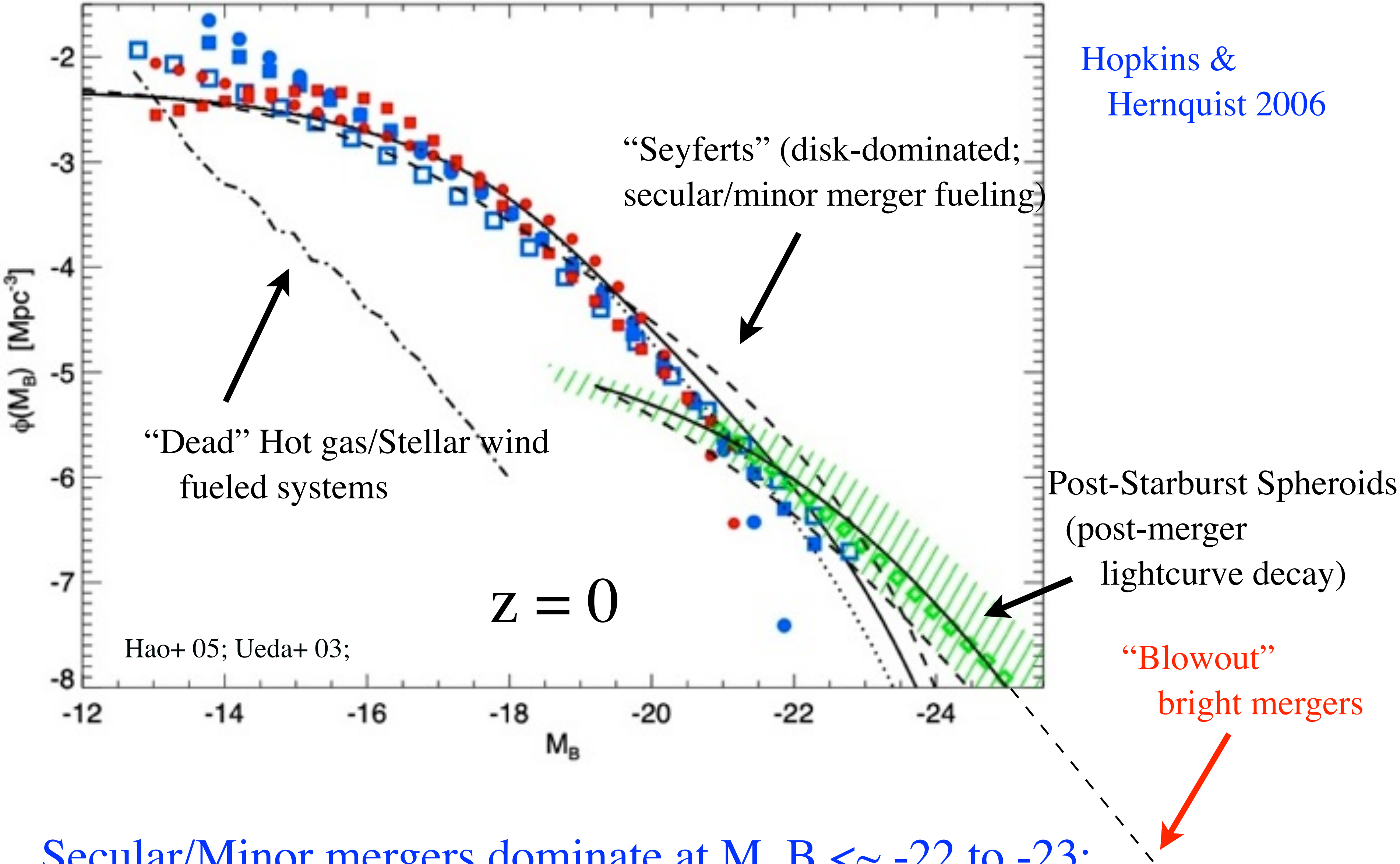
Other Fueling Mechanisms: Disk/Bar Instabilities

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!

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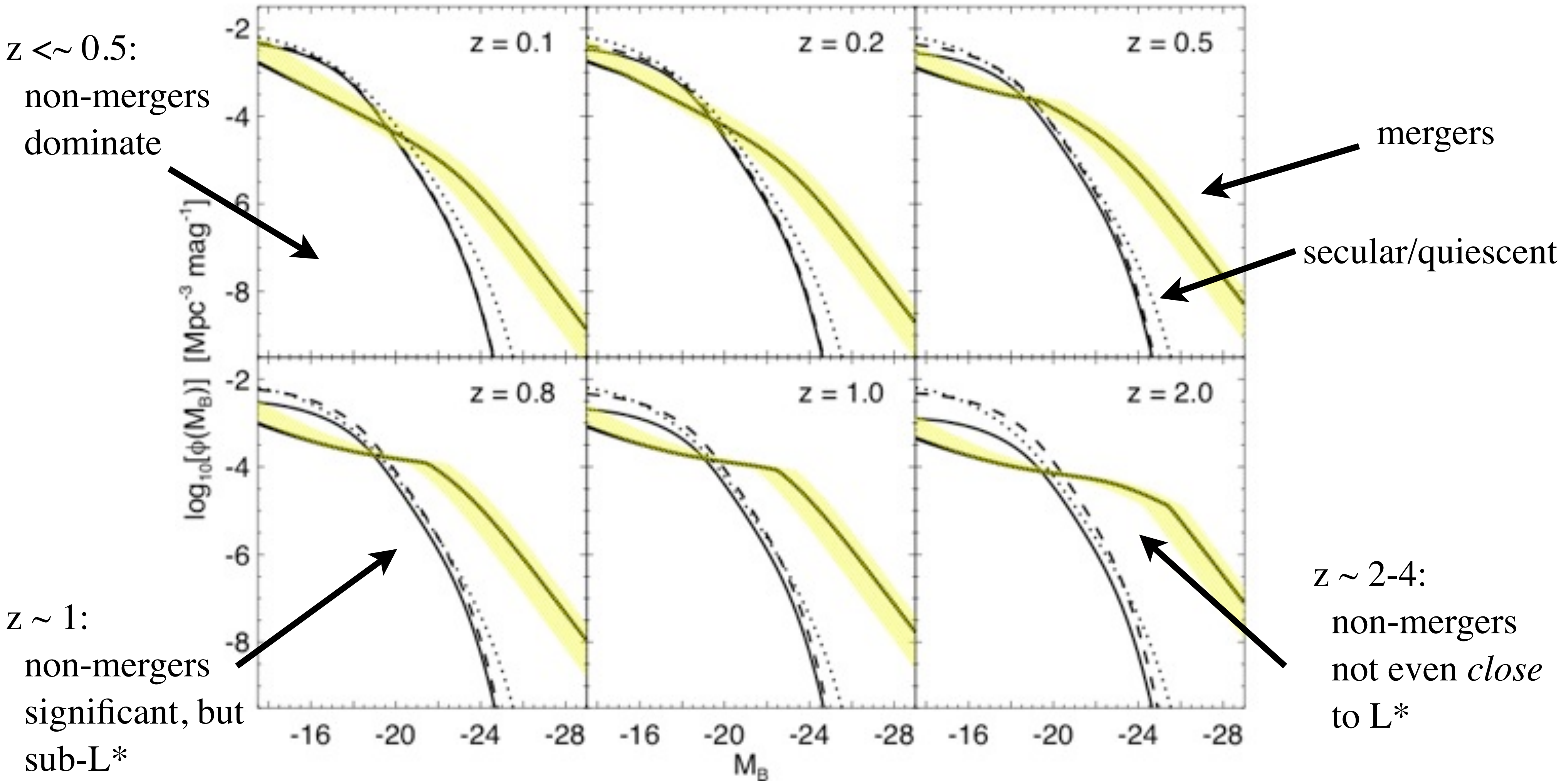


- Secular/Minor mergers dominate at M_B <~ -22 to -23:
  (L_x <~ a few 10^43)
  - Seyfert-Quasar divide is a good proxy
  - If true: they are significant (~10-20%), but not dominant contributor to total accretion density/BH mass density

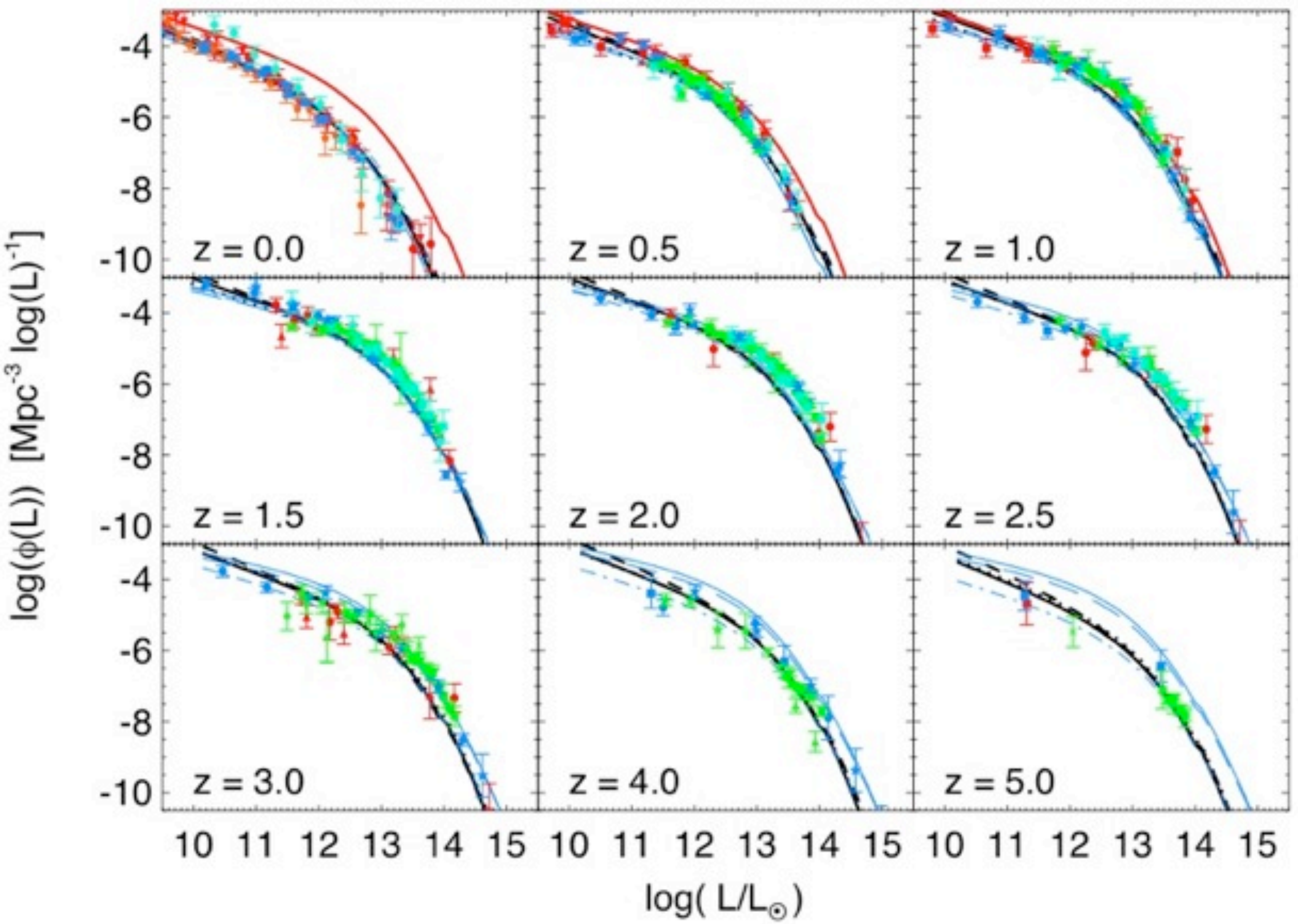
Some Basic Checks:

- Construct generic model of merger-driven quasar activity (PH et al. 2007; astro-ph/0706.1243)

  - Populate halo+subhalo MFs (from cosmological simulations) with "initial" galaxies (according to HODs/ empirical constraints)
  - Let them grow (star formation & accretion)
  - Let them merge
  - Assume major, gas-rich merger > BH/bulge
  - "Paint on" detailed simulations where necessary

Predictions

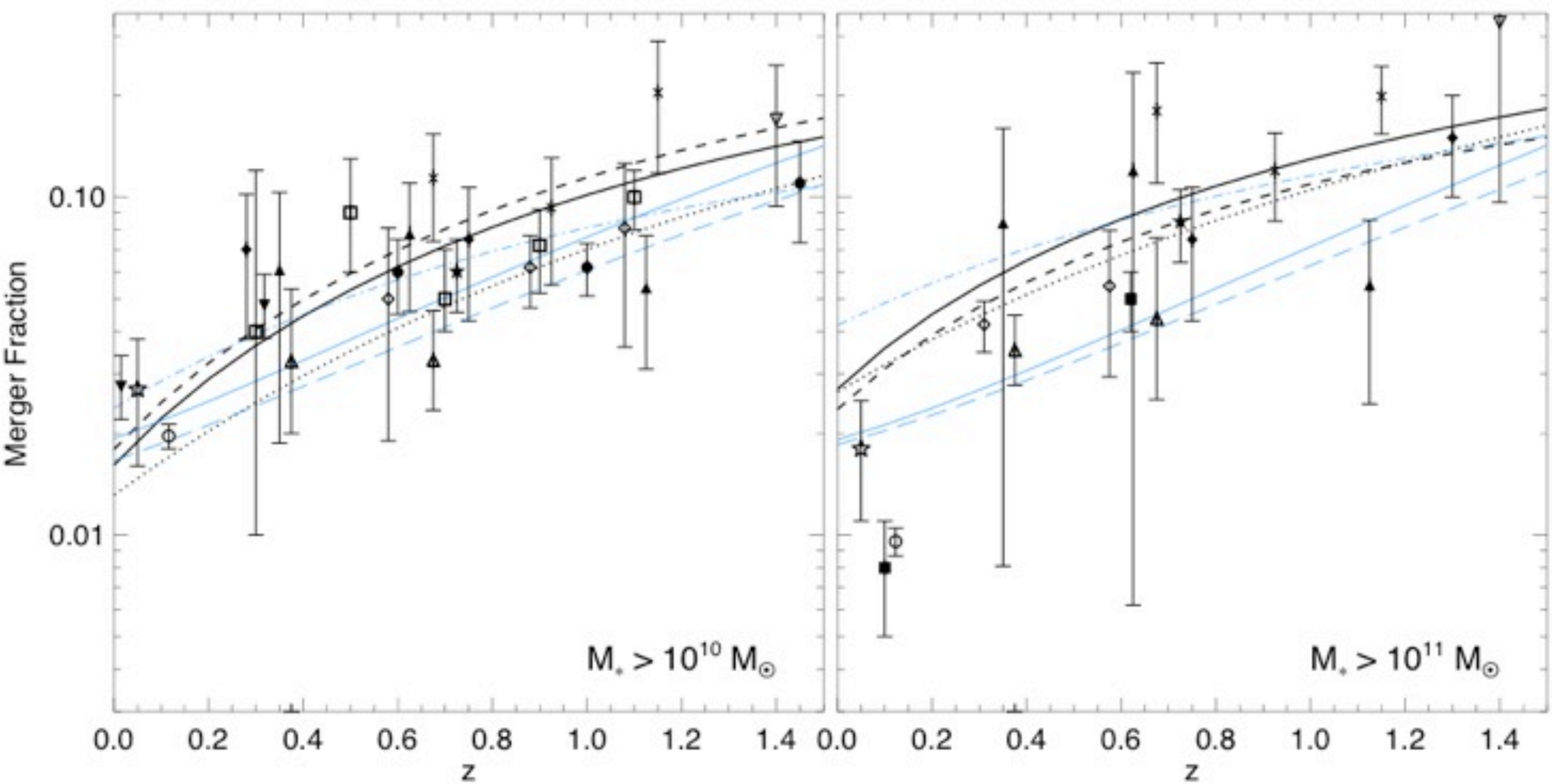
- Predicts the QLF vs. redshift, luminosity, wavelength



PH07

Predictions

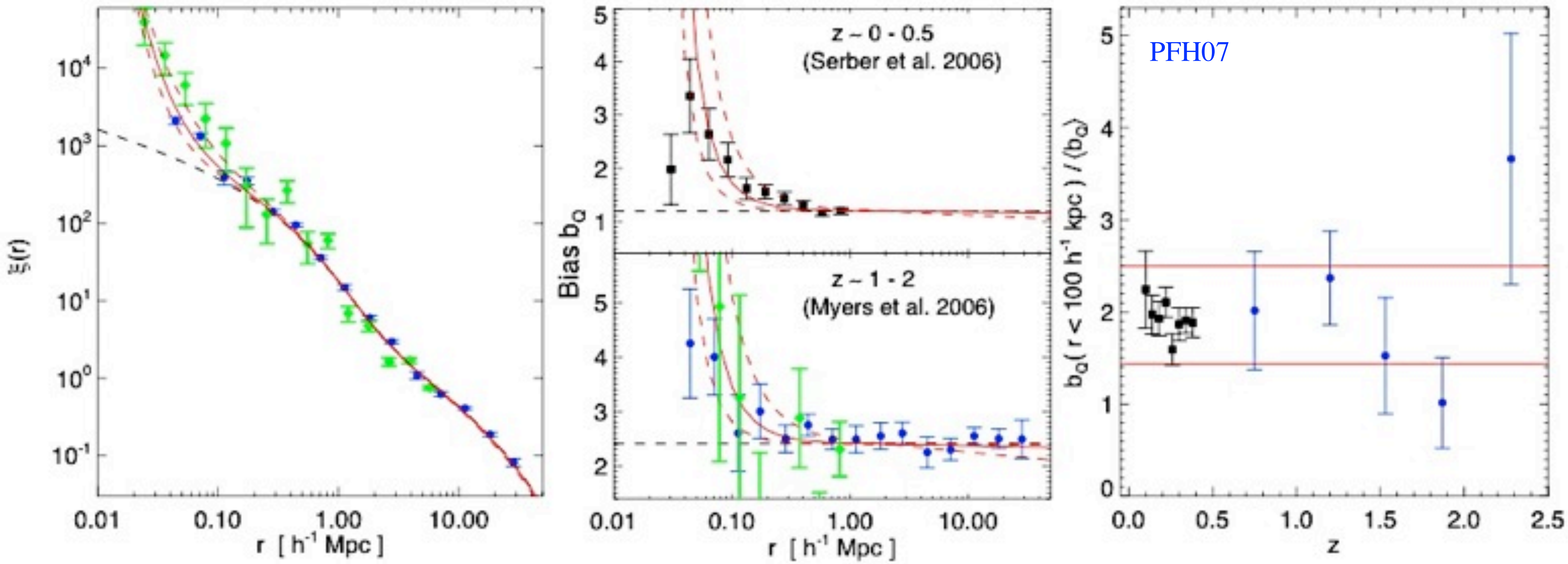
- Predicts the QLF vs. redshift, luminosity, wavelength
- There are "enough" mergers!



PH07

Where Quasars Are Born

- 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)

Where Quasars Are Born

PFH07

- Small-Scale Excess:
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    - Mergers biased to regions with *small-scale* overdensities
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    - Seen in merger remnants! (Goto et al.; Hogg et al.)
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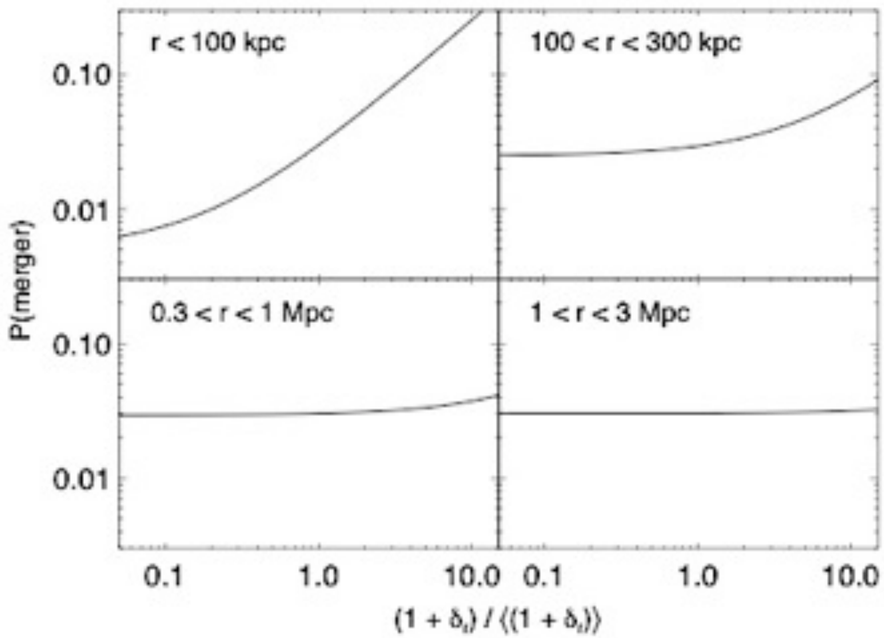
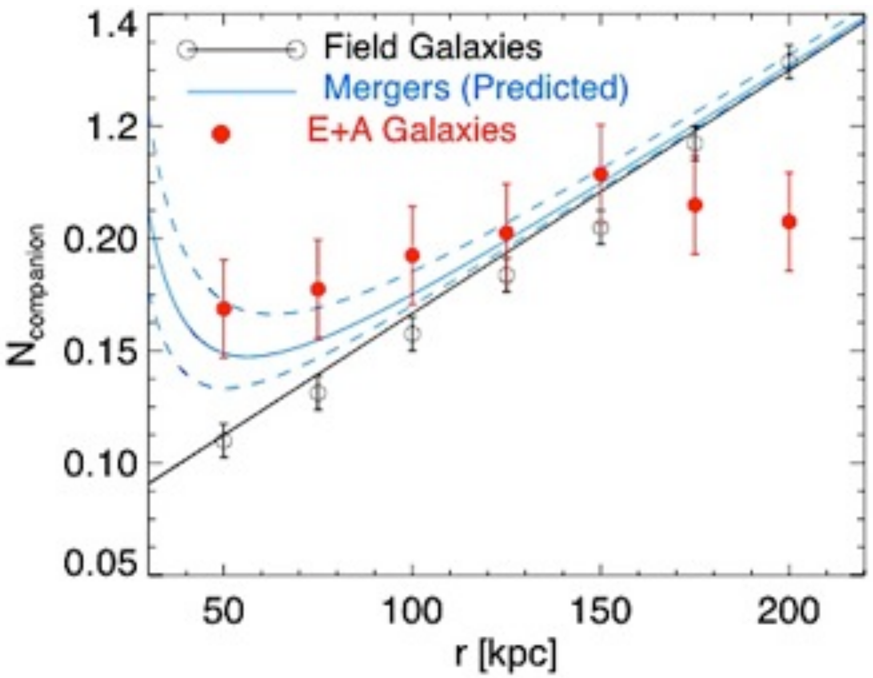
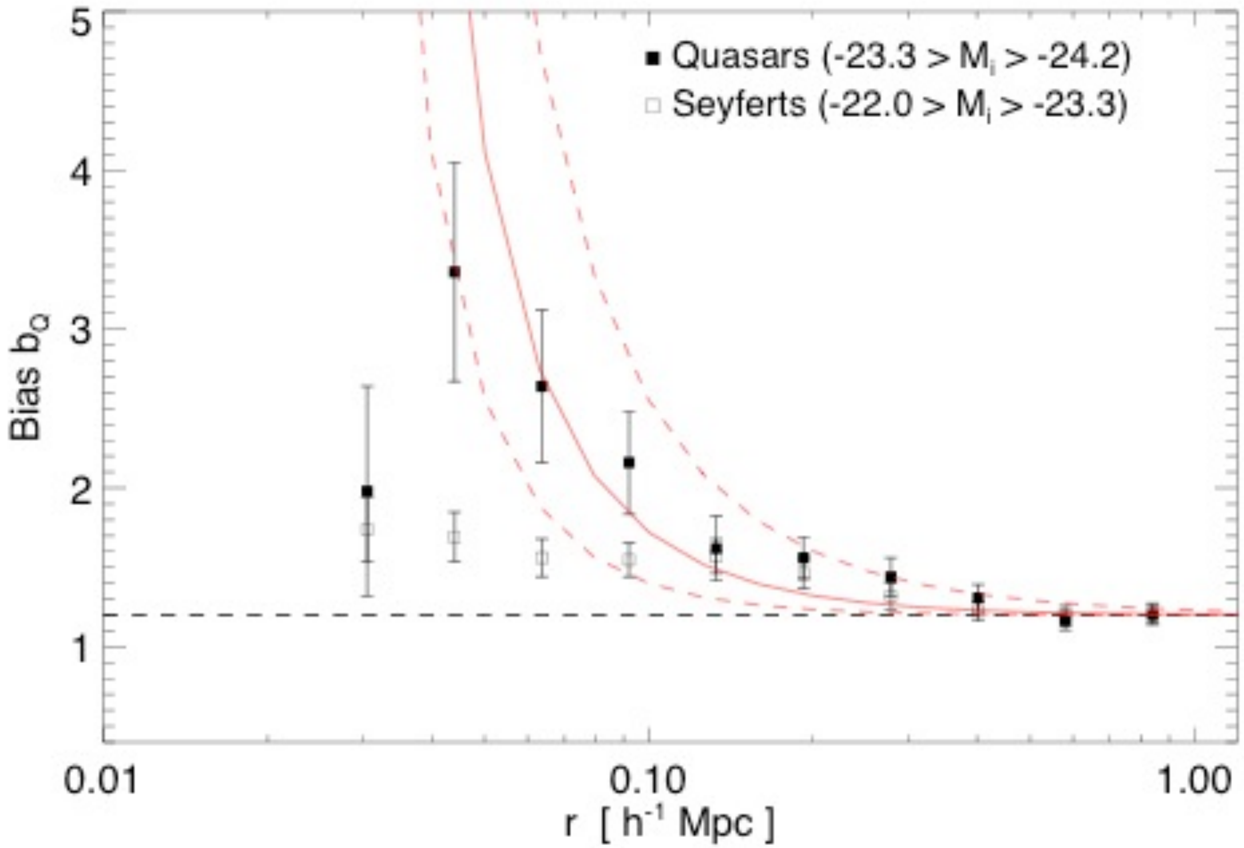




Where Quasars Are Born

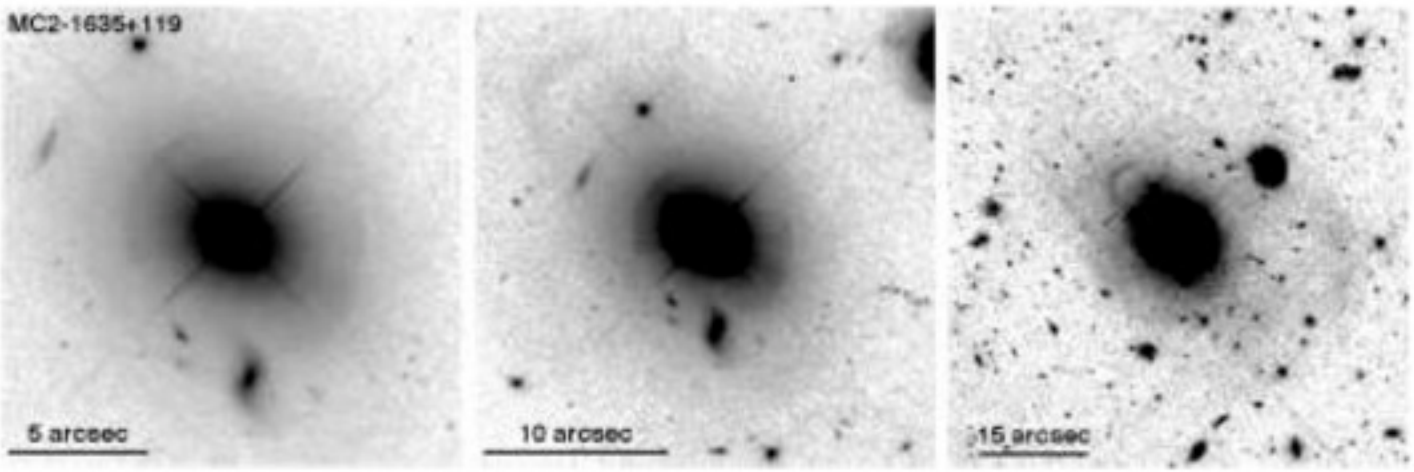
- Small-Scale Excess:
  - Not seen in Seyferts:
    - Suggests different processes dominate fueling below M_B ~ -23 (M_bh ~ 10^7)?



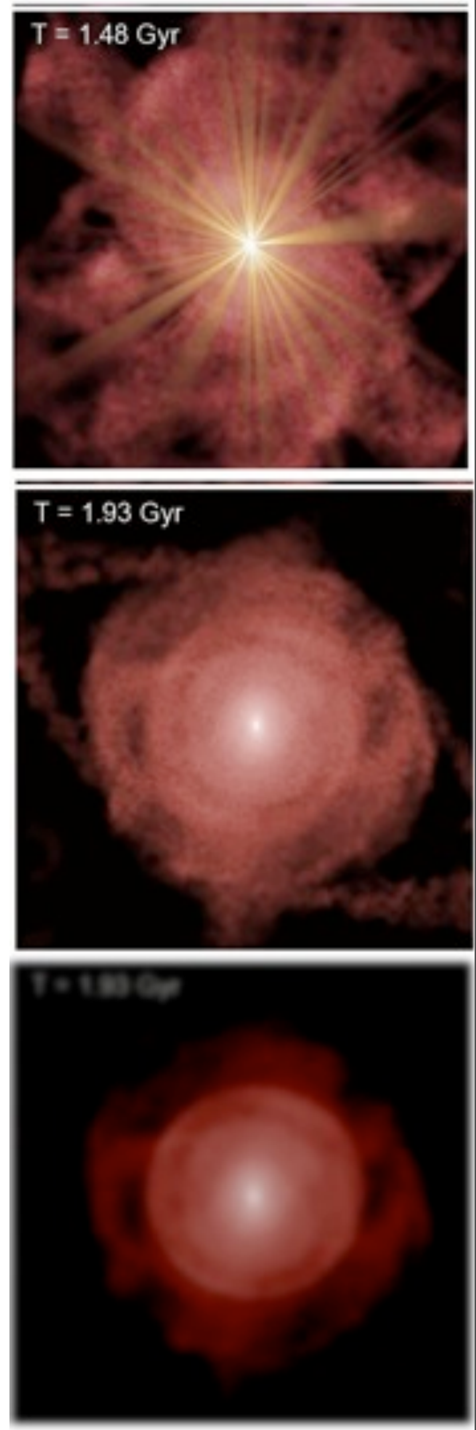
Serber et al. 2006

The Difficulty

- 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)



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



QSO = 1000xHost

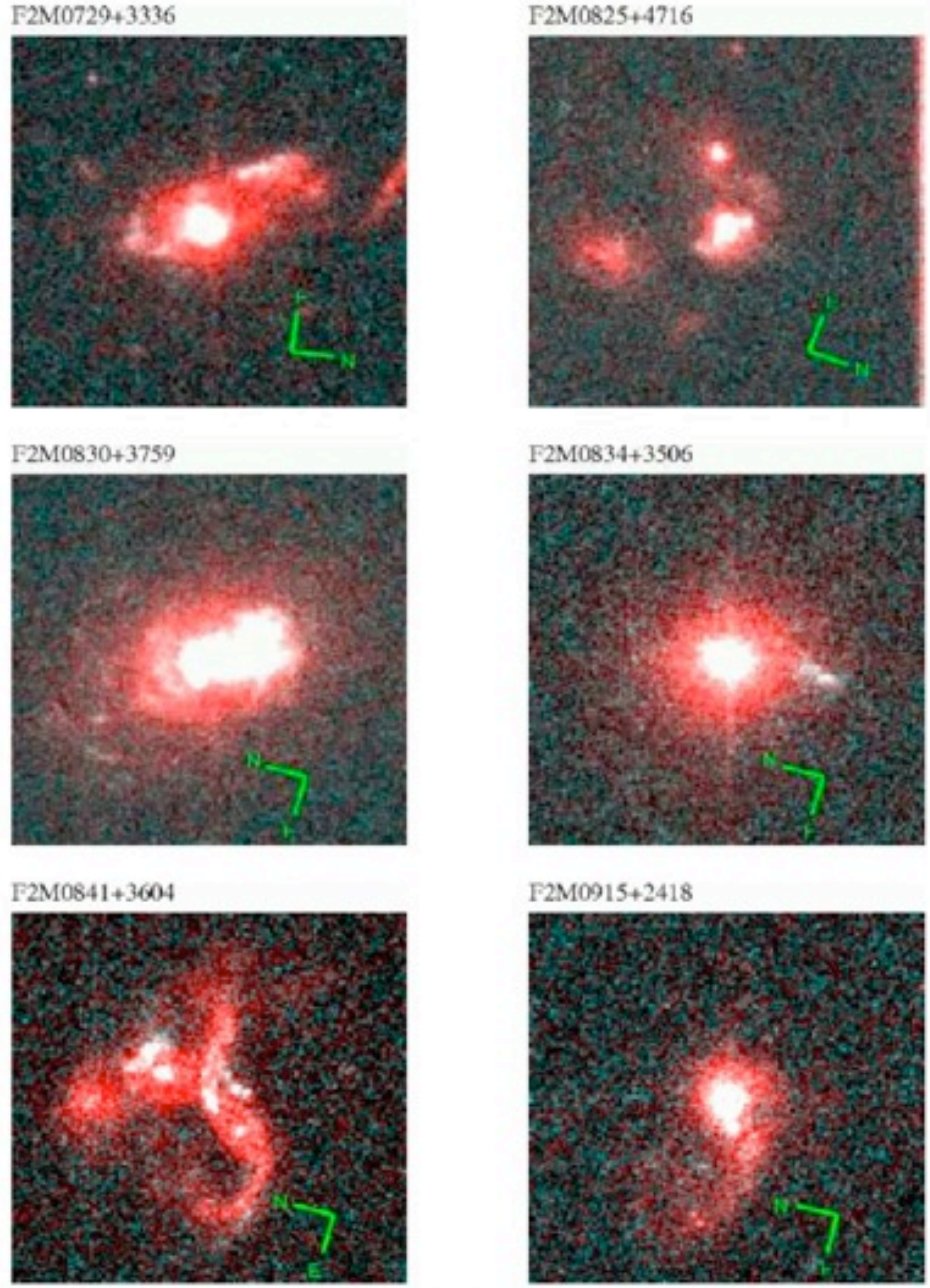
QSO = Host

QSO = 0.1xHost

The Difficulty

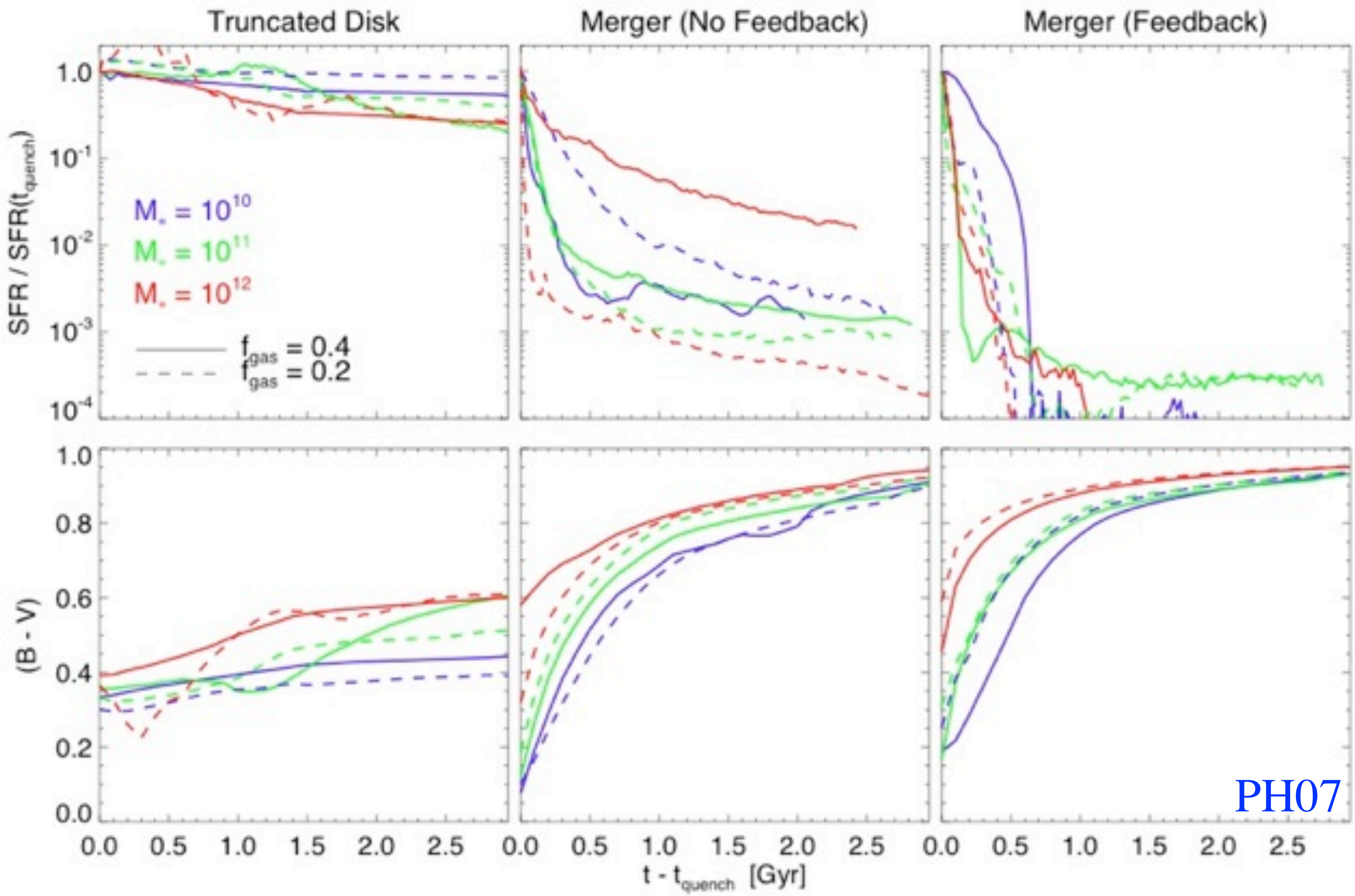
Red or IR-bright QSOs:

- Nearly ~100% mergers
  (Hutchings et al., Guyon et al., Urrutia)
- Need to prove they will turn into
  their bluer "cousins"



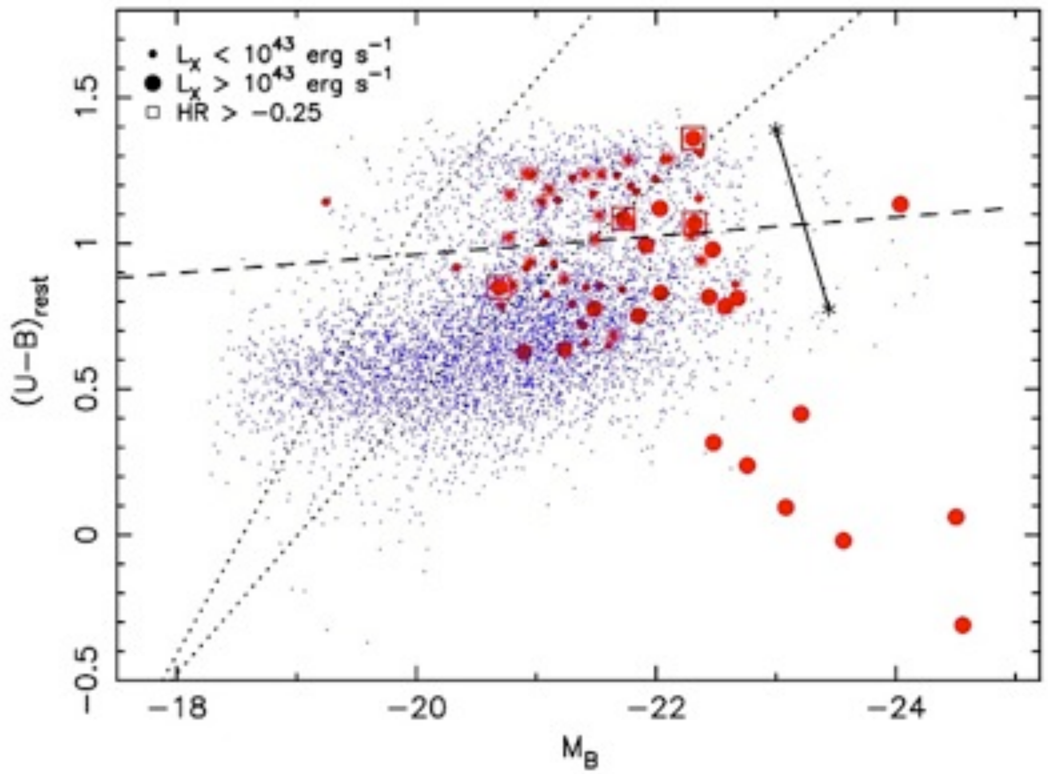
Uses of Color & Morphology Information

- Merger efficiently exhausts gas; feedback can expel what remains > remnant rapidly reddens

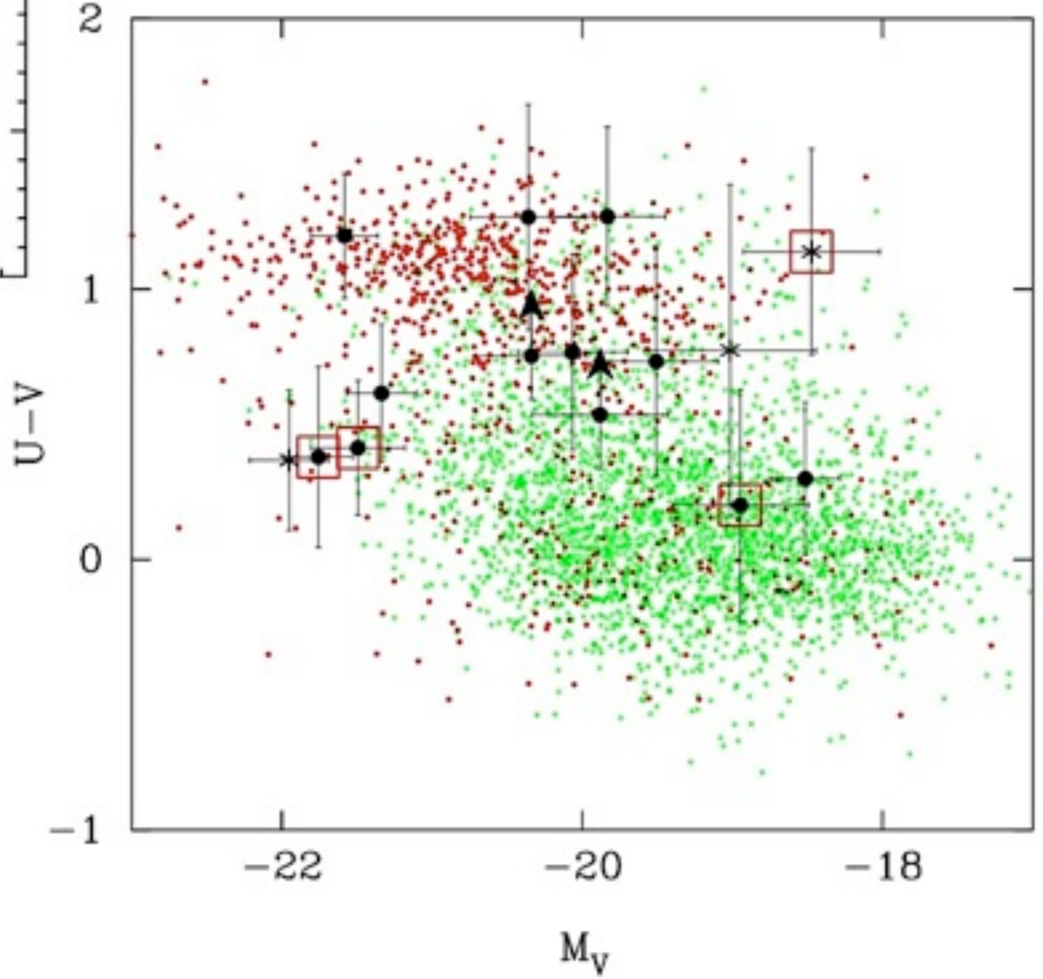


- Not true of secular evolution/pseudobulges (Kormendy, Balcells et al.)

Colors of Quasar Hosts



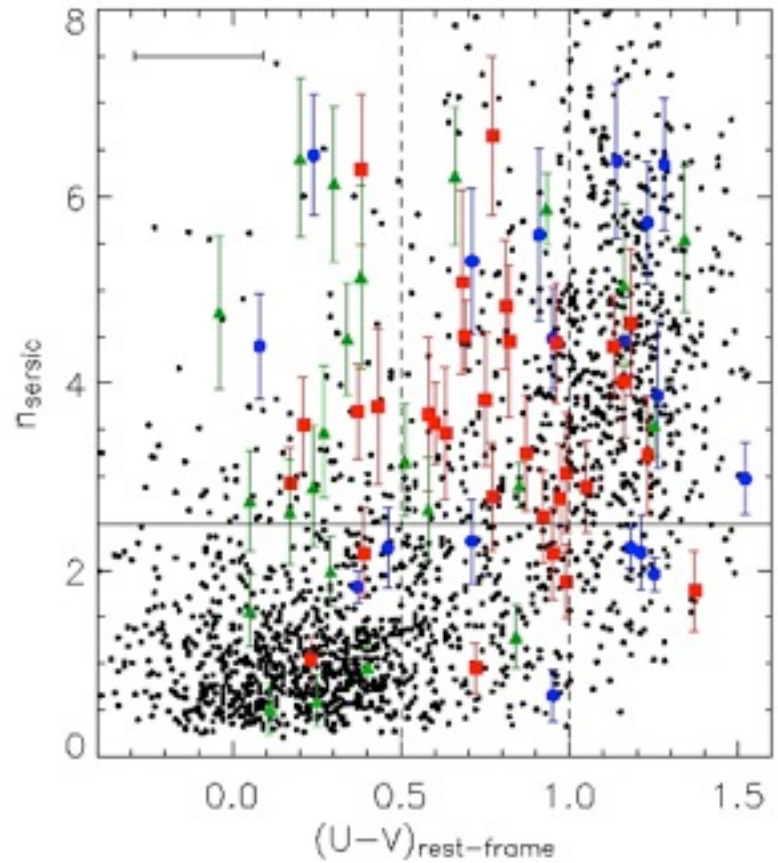
Nandra+ '06
DEEP2
$0.7 < z < 1.4$
X-ray QSOs



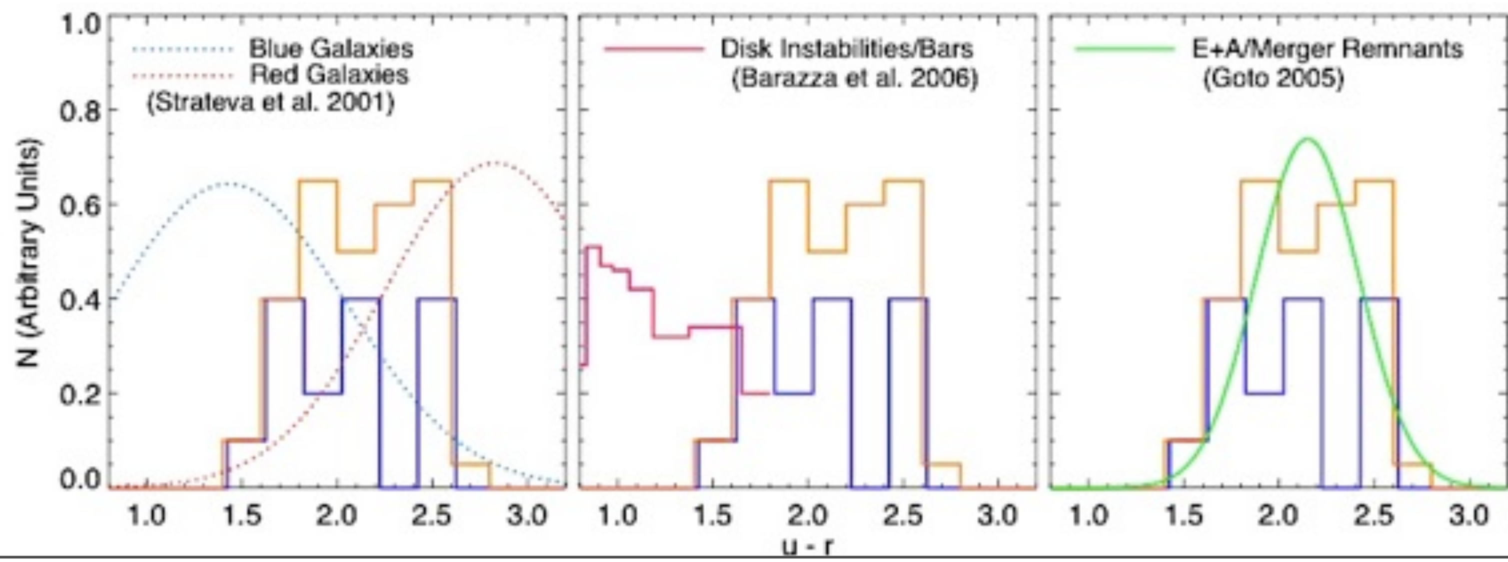
Sanchez+ '05
GEMS
$0.5 < z < 1.1$
Optical QSOs

Color & Morphology of Quasar Hosts

- Quasars live in *blue spheroids*
- Need to go to next level: full stellar populations - are these really post-SB?
- Examine the time/redshift dependence



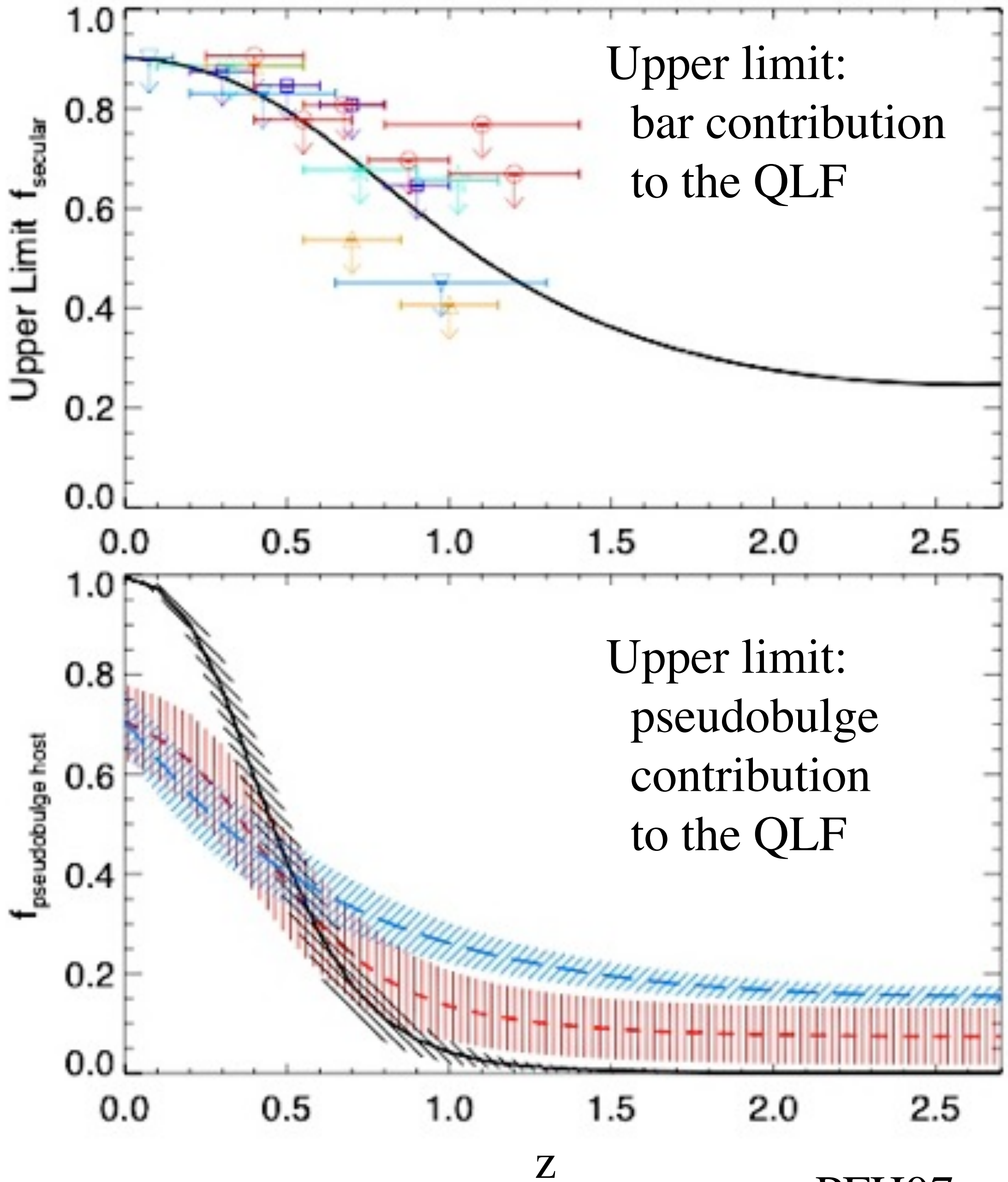
Silverman et al.



PH07

Morphology of Quasar Hosts

- Mergers form "classical" bulges; secular evolution forms "pseudobulges"
- Pseudobulges important only in relatively late-type galaxies; small M_bh
- Bar fraction & pseudobulge fraction ~constant to z~1-2



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