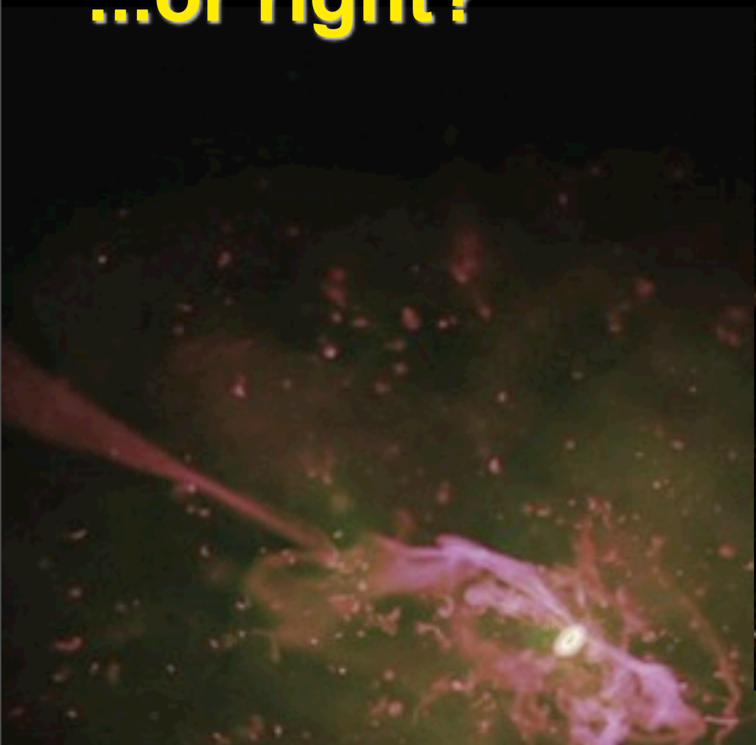
The Starburst-AGN Connection: What Models Say and How Observations Can Show them Wrong

...or right?



Philip Hopkins

10/30/08

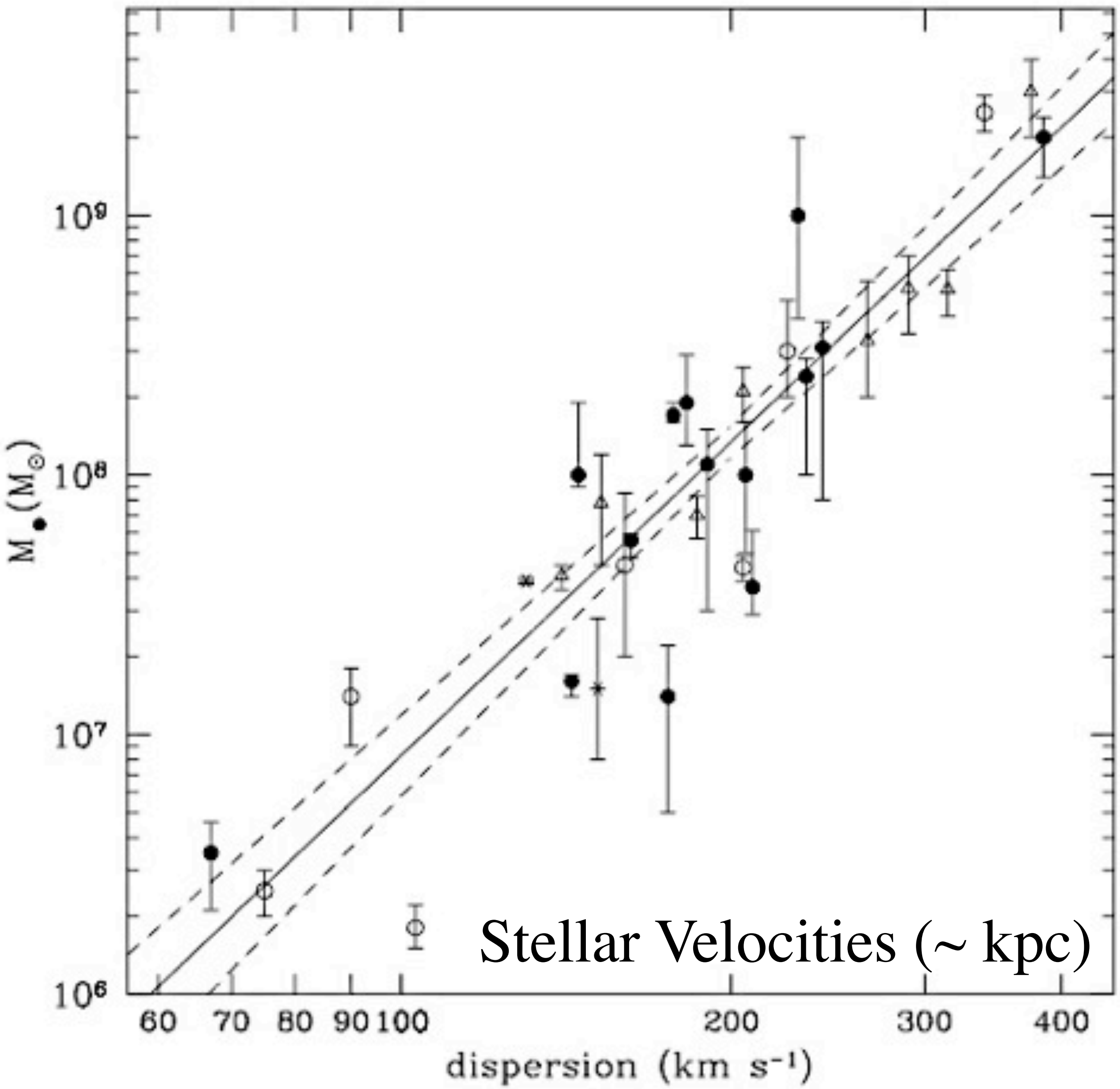
Lars Hernquist, T. J. Cox, Dusan Keres, Josh Younger, Desika Narayanan, Volker Springel, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Gordon Richards, Alison Coil, Kevin Bundy, Adam Myers, and many more

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

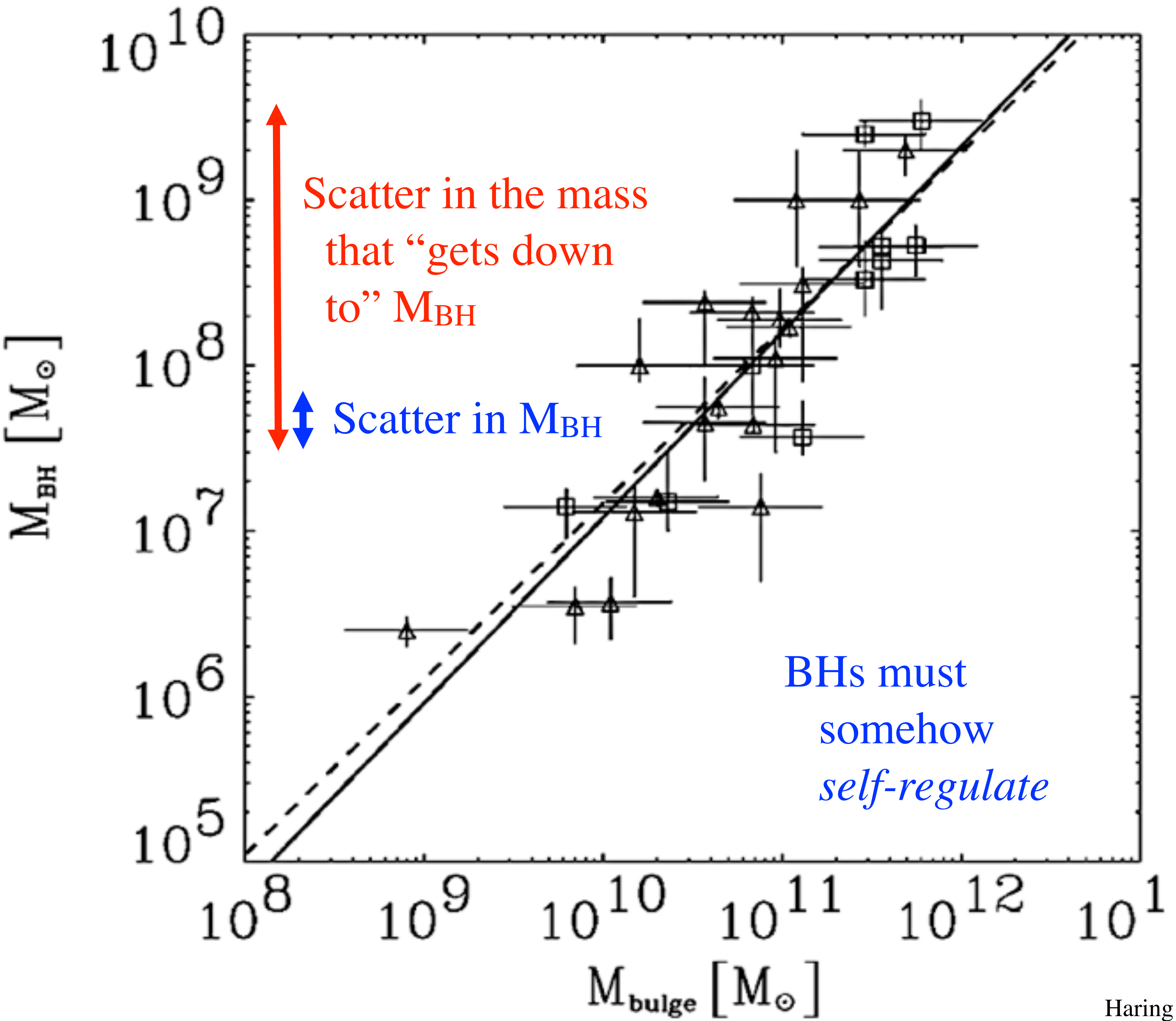
- Black holes are somehow sensitive to their host galaxies (bulges):

BH Mass (~ AU!)



Stellar Velocities (~ kpc)

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



Haring & Rix '04

Simplest Idea:

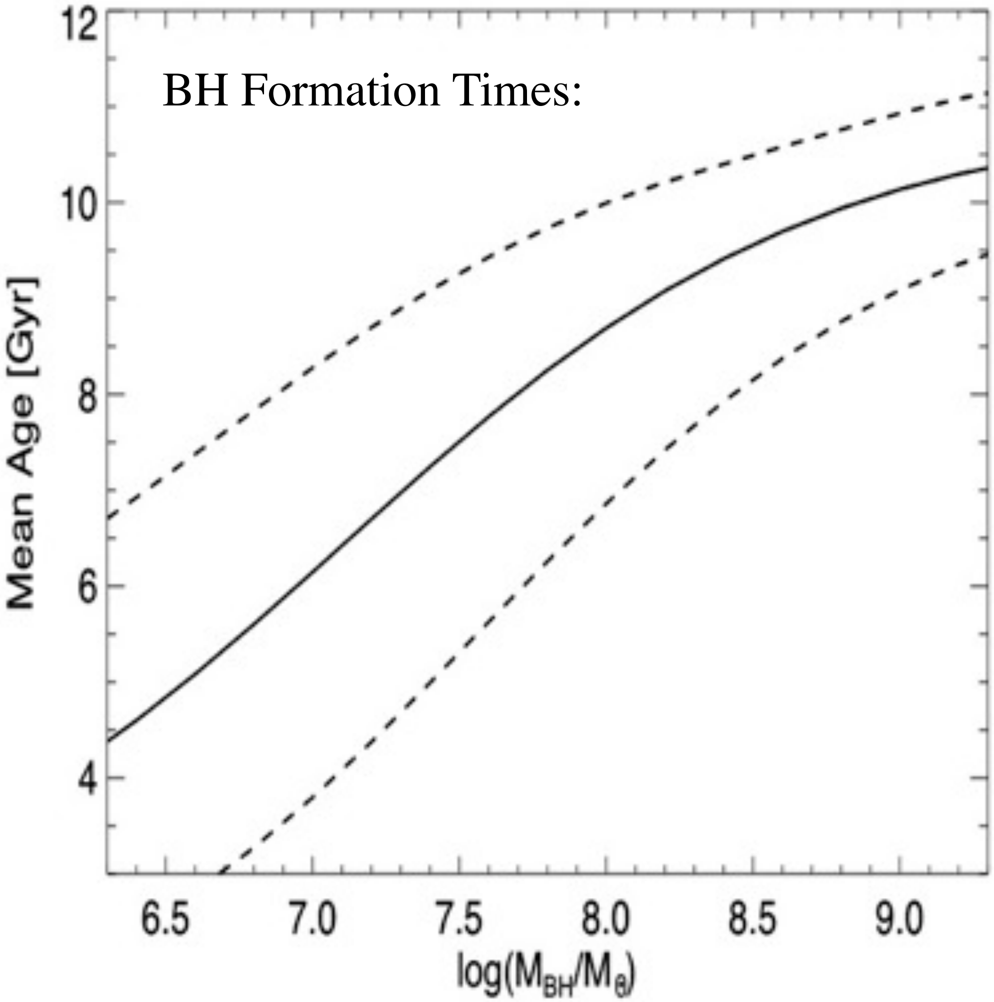
FEEDBACK ENERGY/MOMENTUM BALANCE (SILK & REES '98)

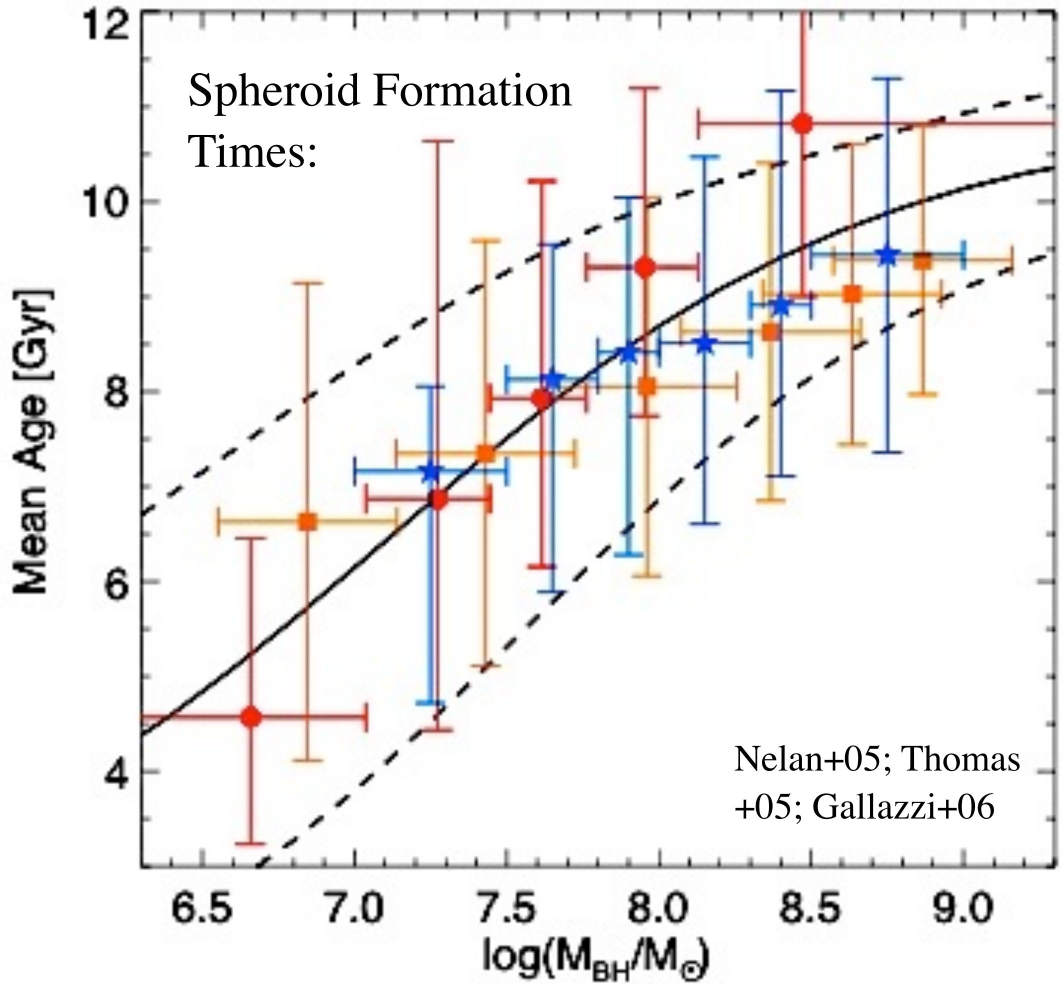
- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r (dM_{BH}/dt)\ c^2$ ($e_r \sim 0.1$)
- Total energy radiated:
  - $\sim 0.1\ M_{BH}\ c^2 \sim 10^{61}$ ergs in a typical $\sim 10^8\ M_{sun}$ system
- Compare this to the gravitational binding energy of the galaxy:
  -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

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



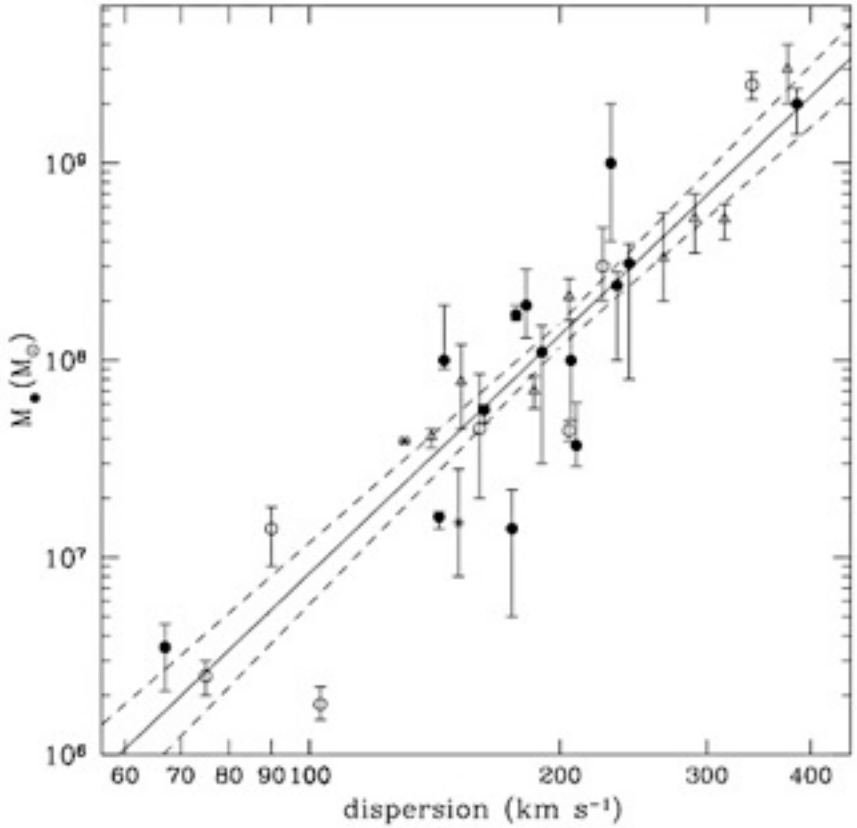


PFH, Lidz, Coil, Myers, et al. 2007

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

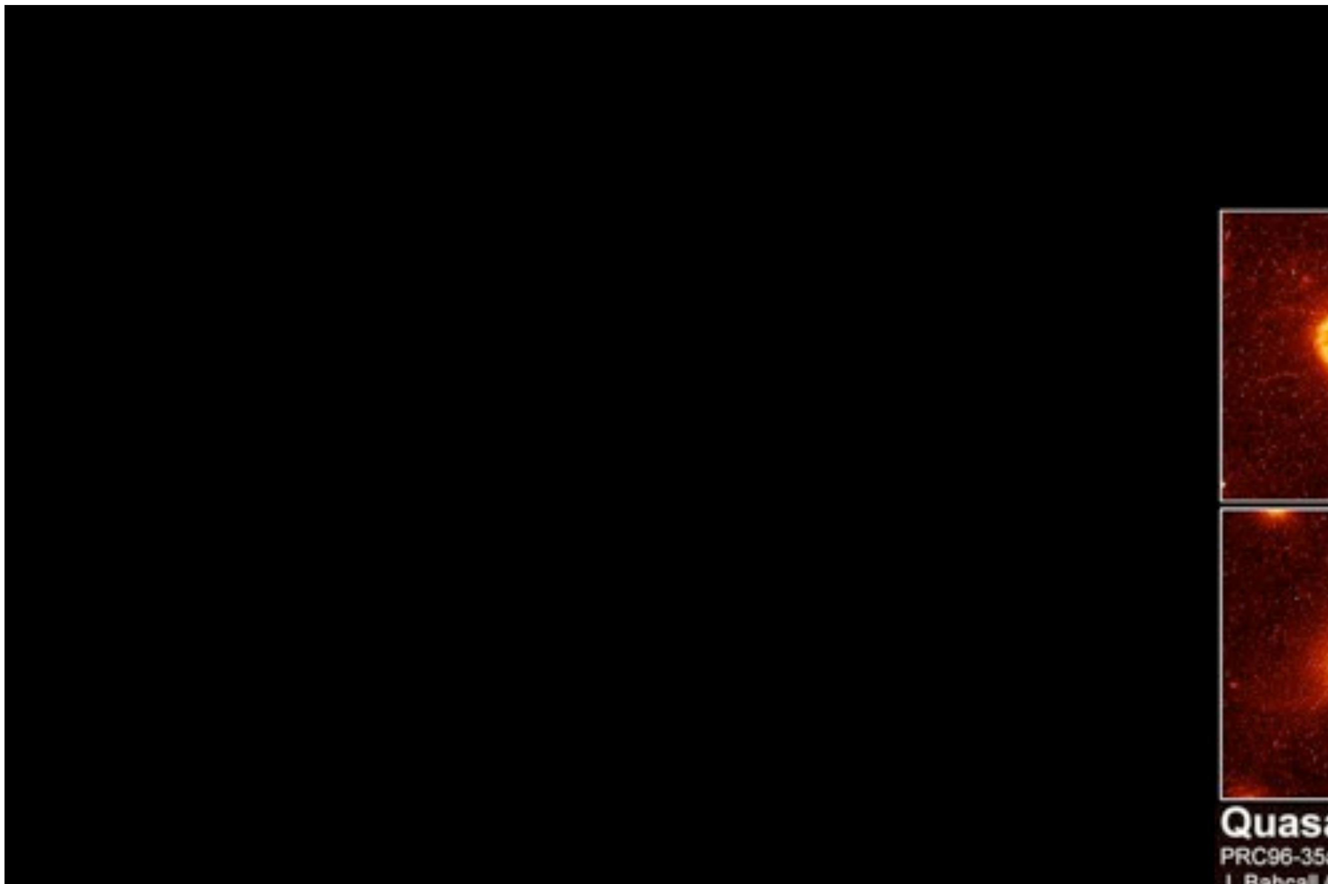
→ stellar dynamics; freefall timescale

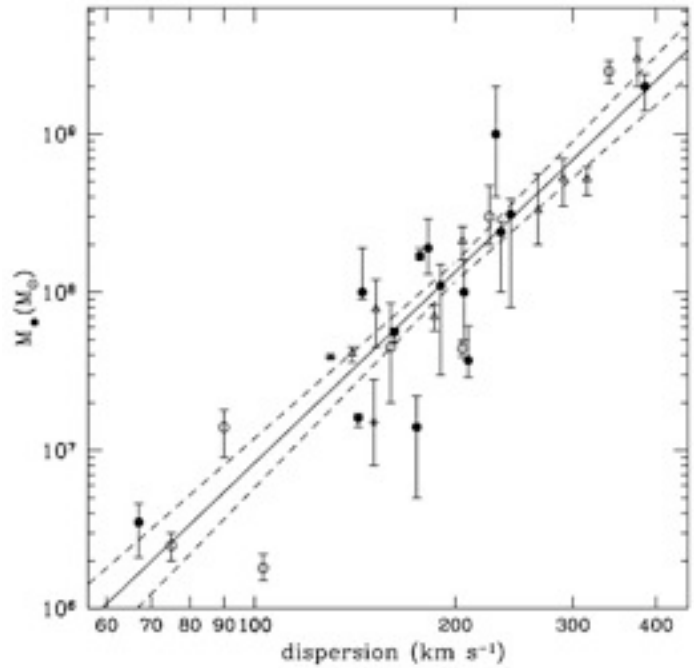
Triggering & Fueling: “Feeding the Monster”

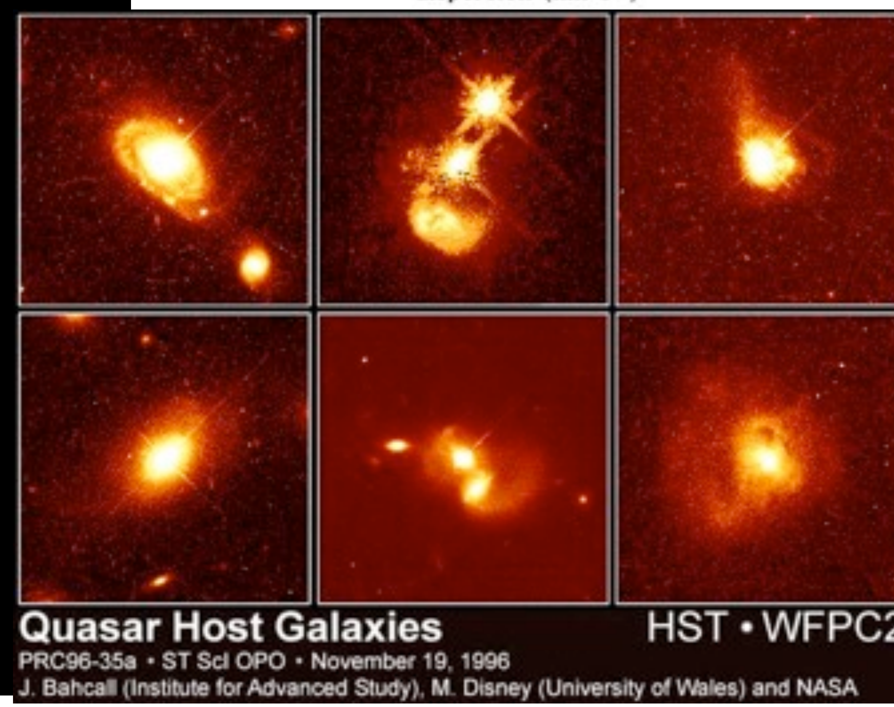
WHAT CAN BREAK DEGENERACIES IN DIFFERENT FUELING MODELS?

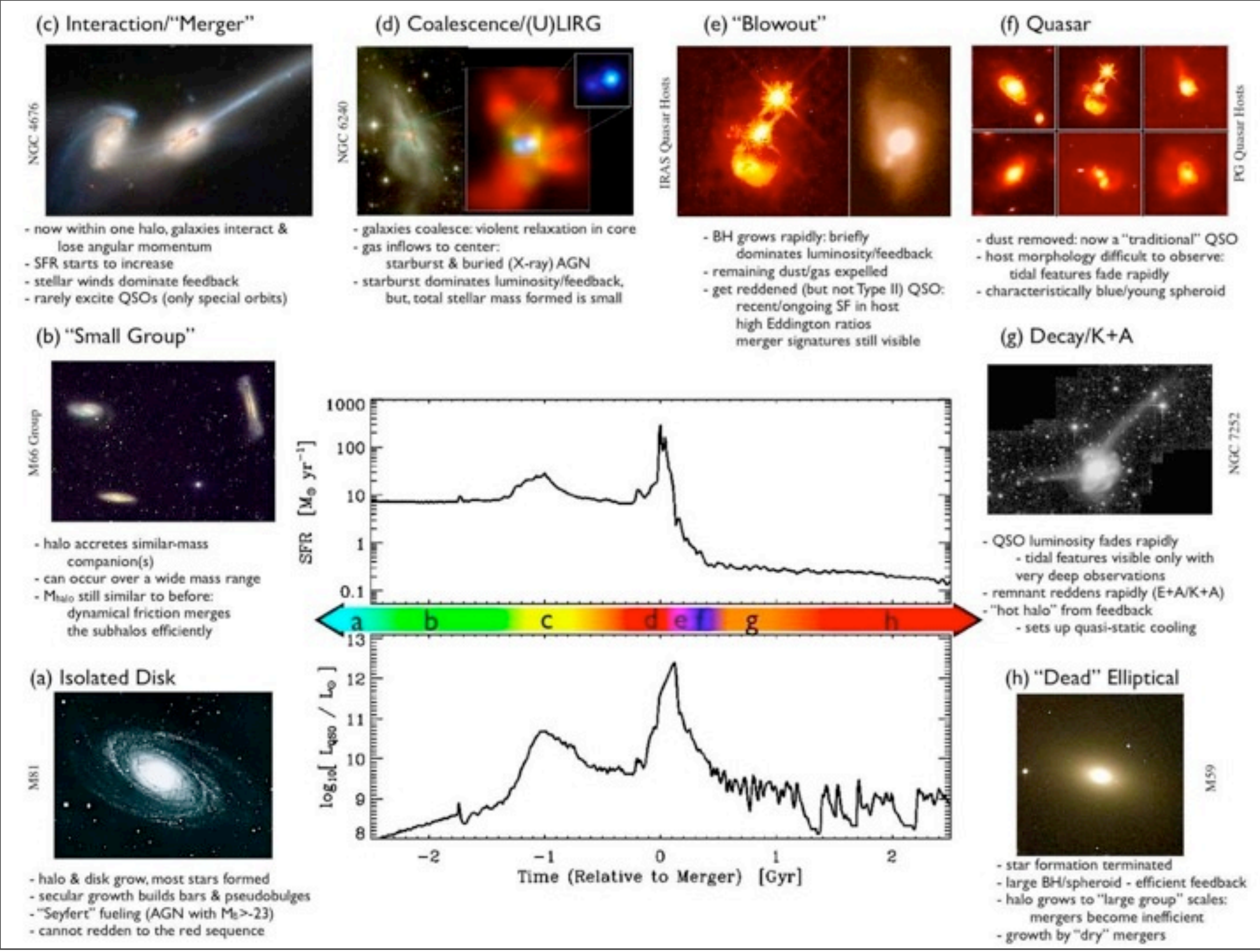
- If BHs trace spheroids, then
  most mass added in mergers

NGC 6240 Komossa et al. (2003)





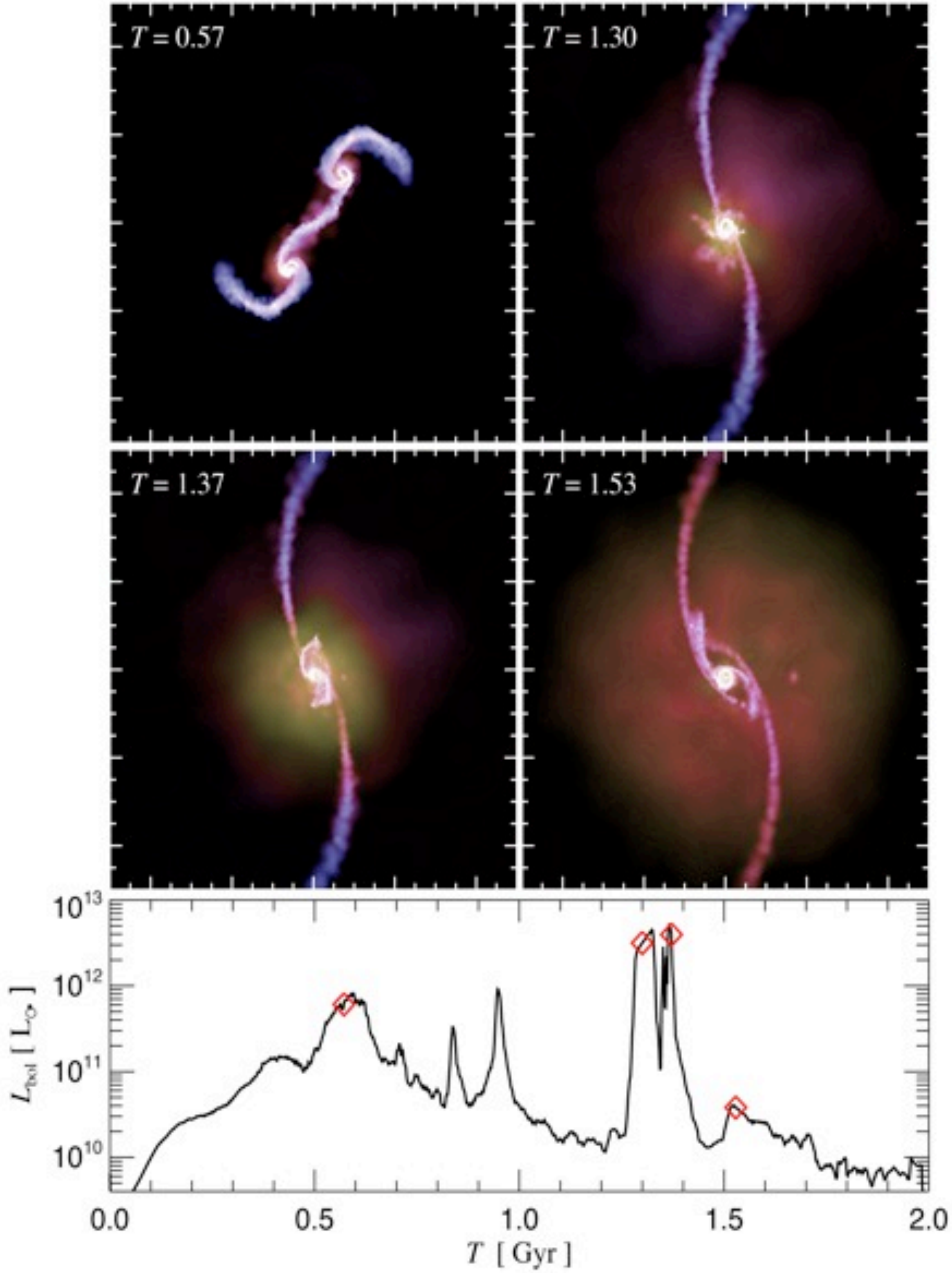


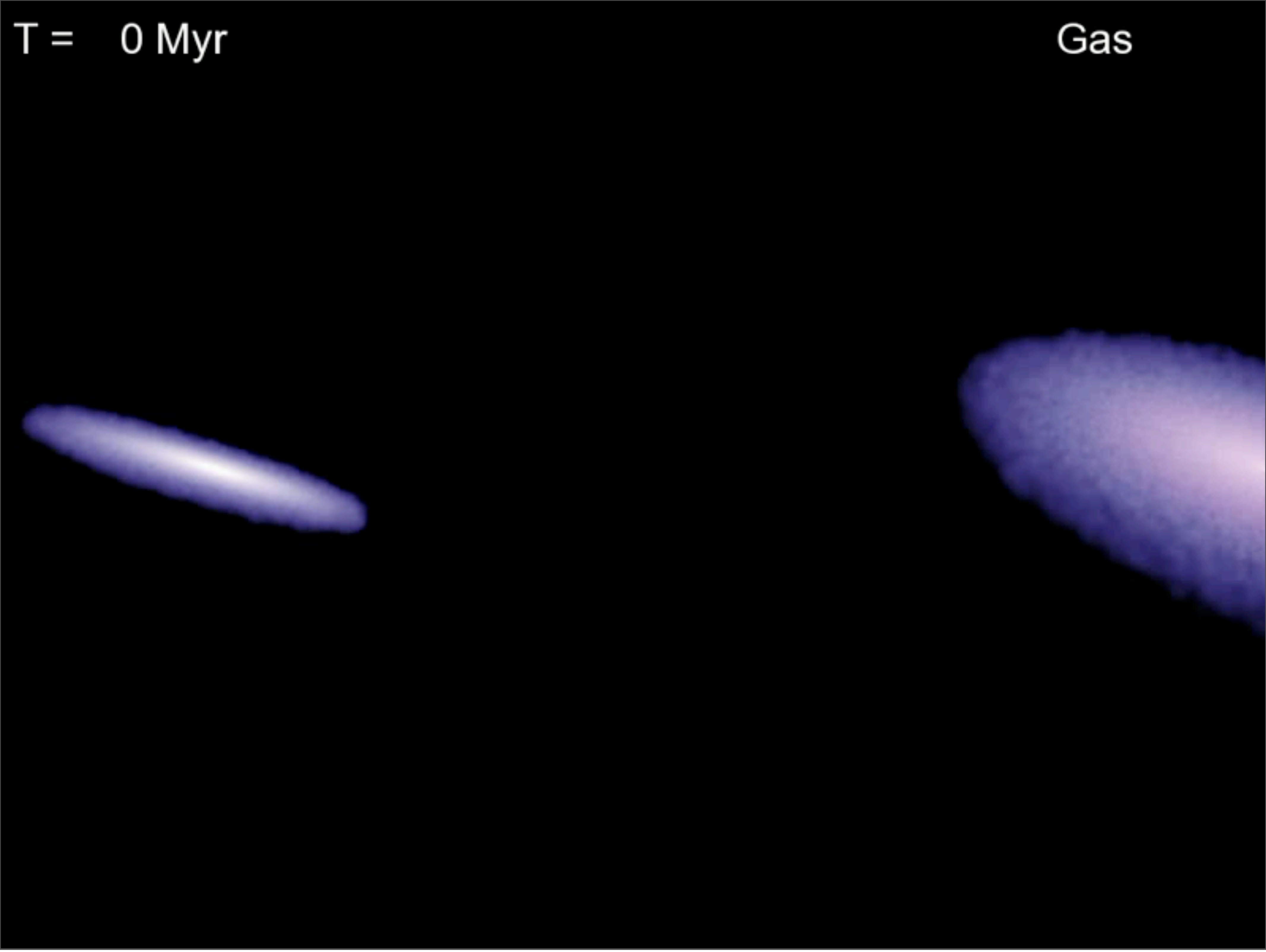

(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center: 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

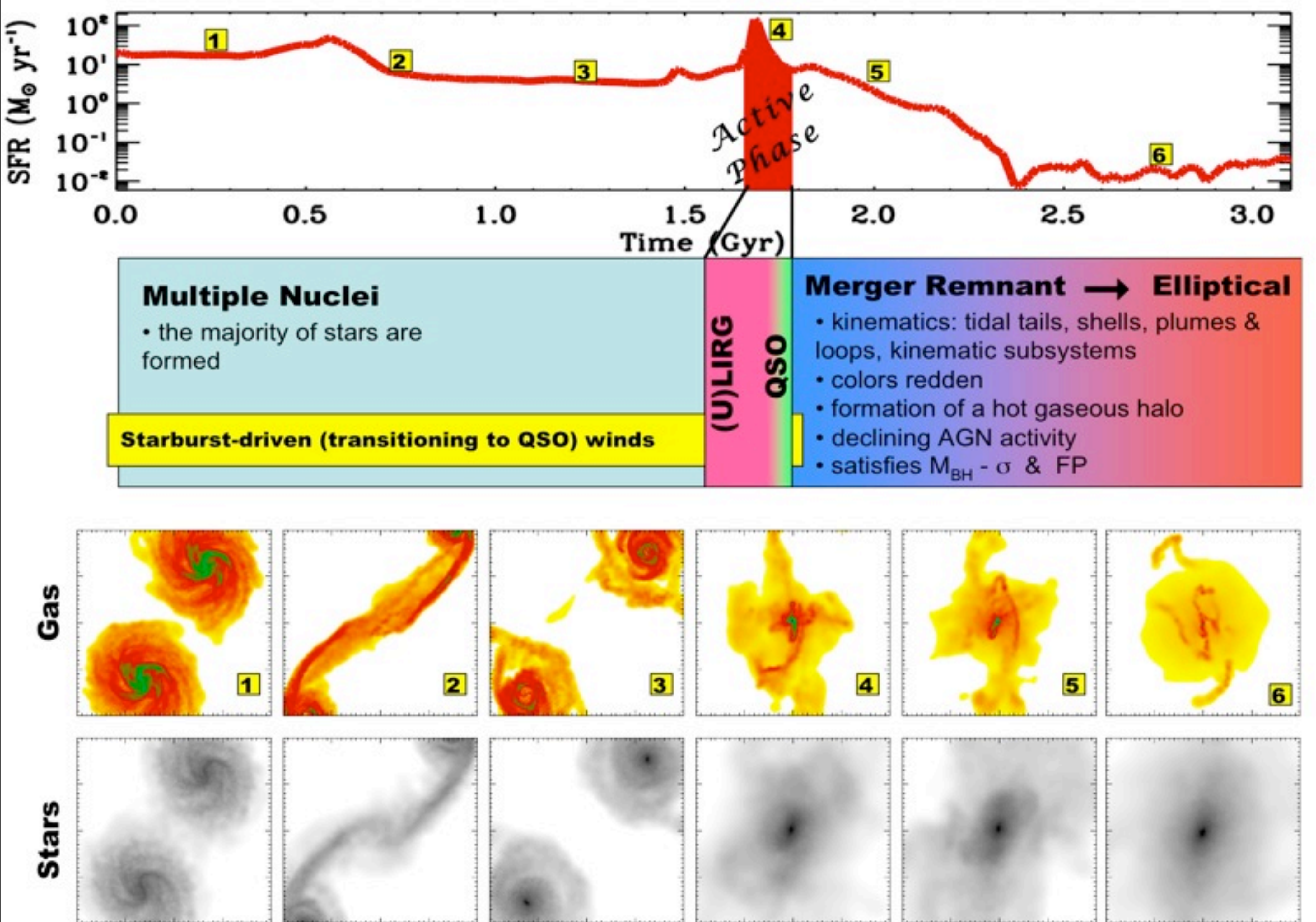
Let's Try It!

THE AGN...

- Merge two galaxies
- 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)



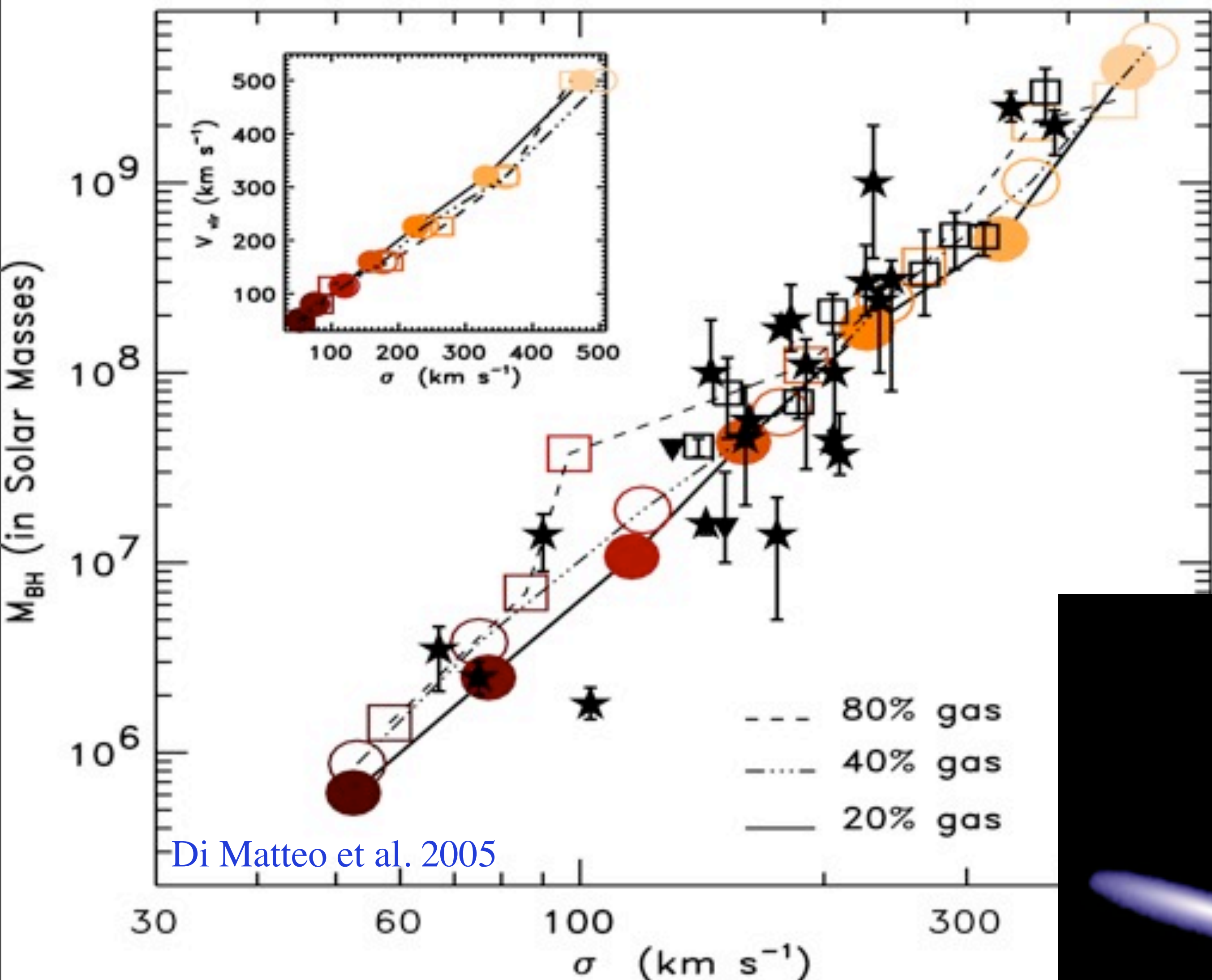

T = 0 Myr
Gas

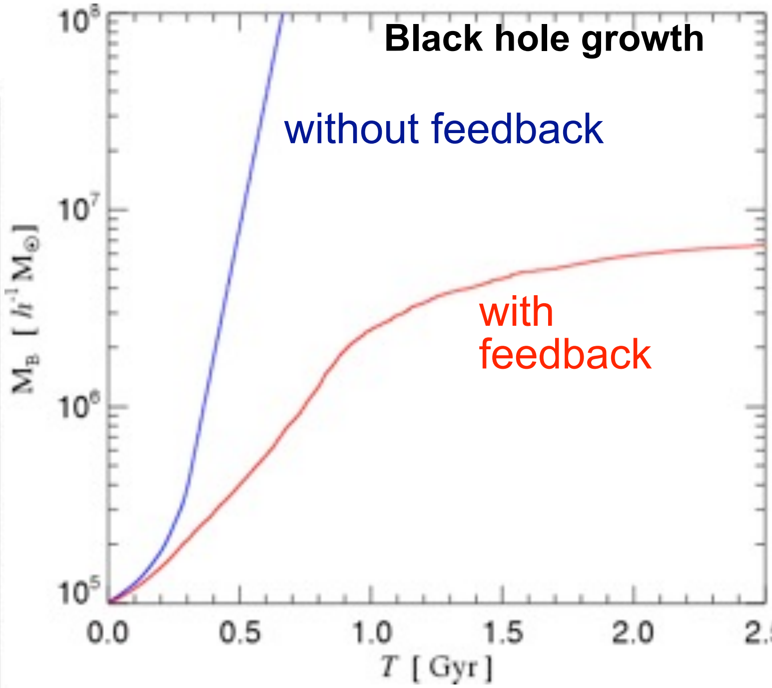


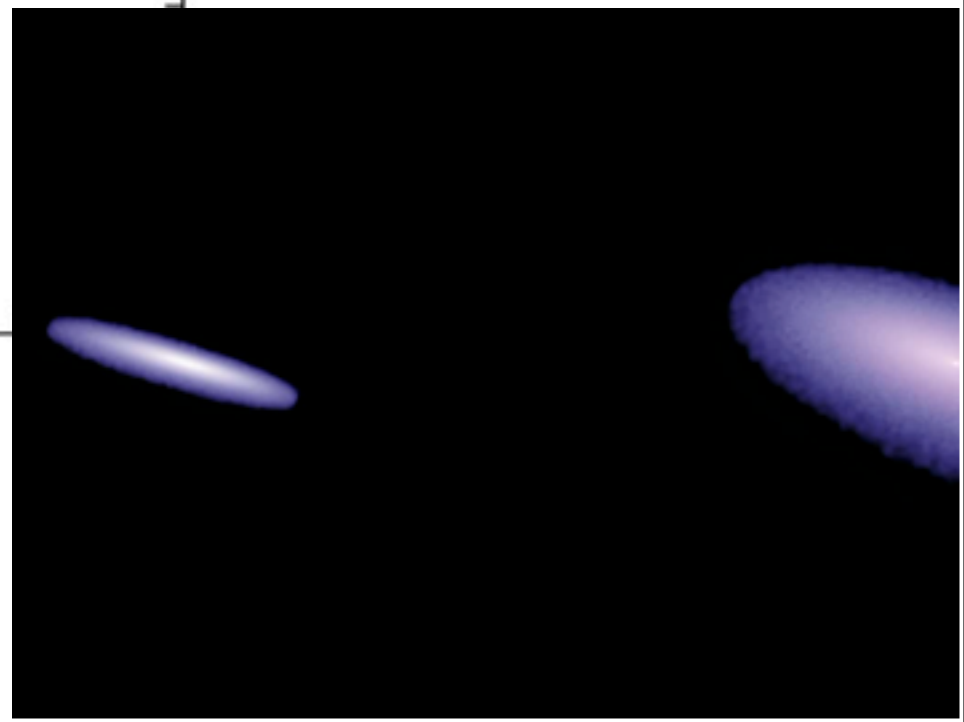
SFR ($M_\odot$ yr^{-1})
Time (Gyr)
1
2
3
4
5
6
Active Phase
Multiple Nuclei
• the majority of stars are formed
Starburst-driven (transitioning to QSO) winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
• colors redden
• formation of a hot gaseous halo
• declining AGN activity
• satisfies M_{BH} - σ & FP
Gas
Stars

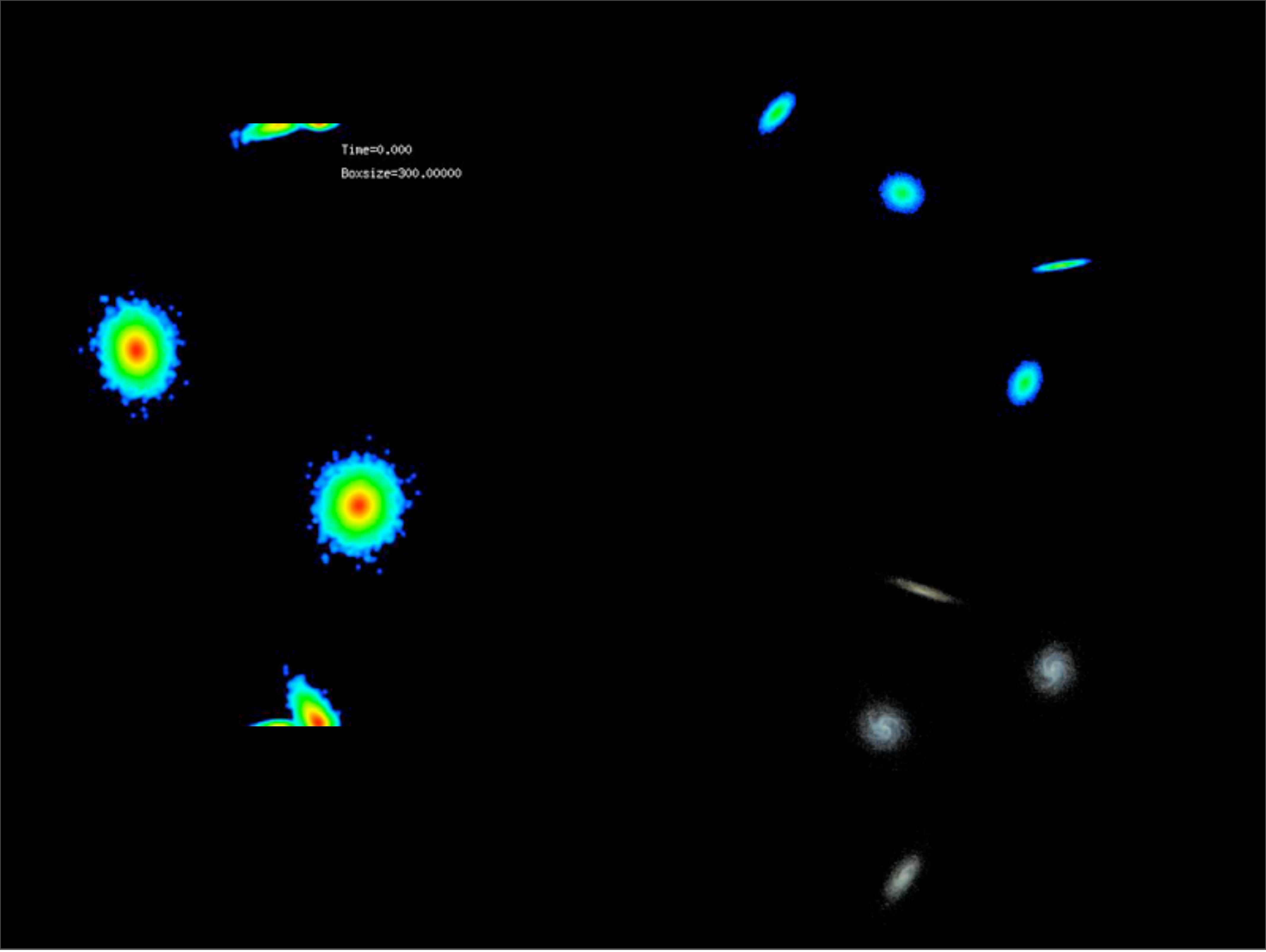
M-sigma Relation Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH





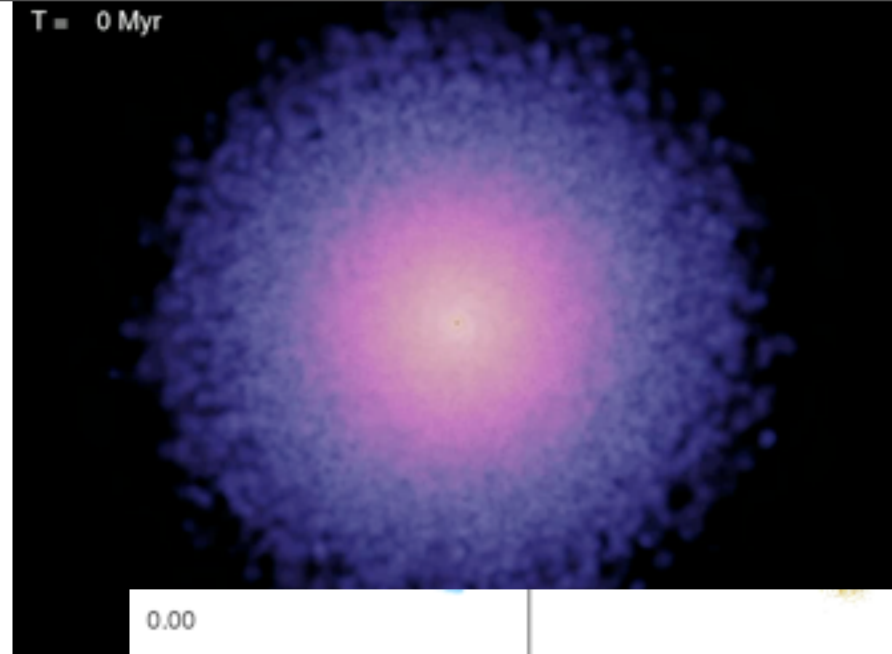


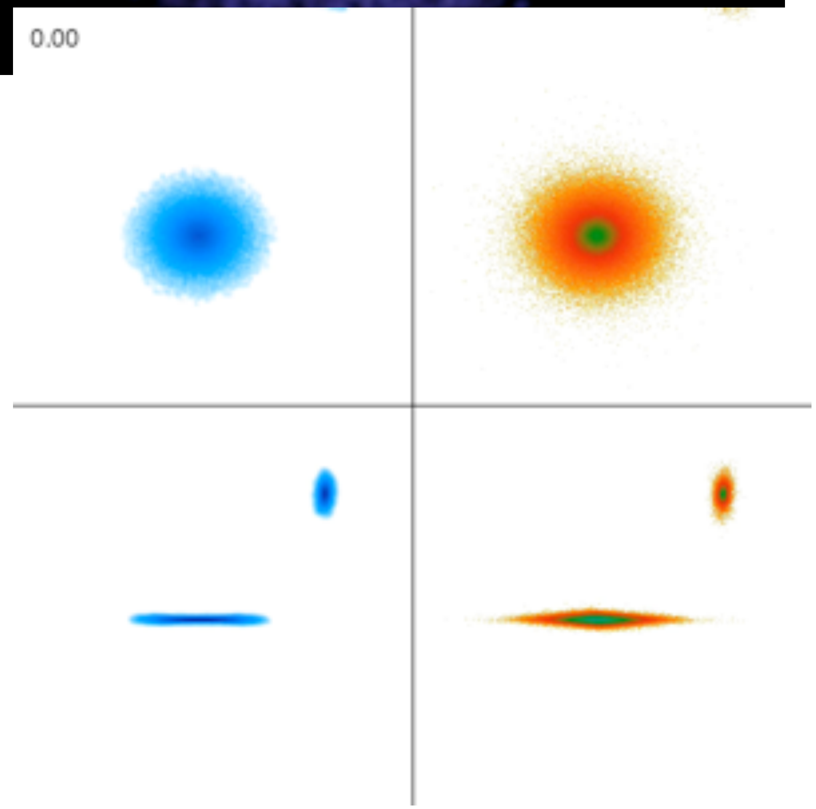

Time=0.000
Boxsize=300.00000

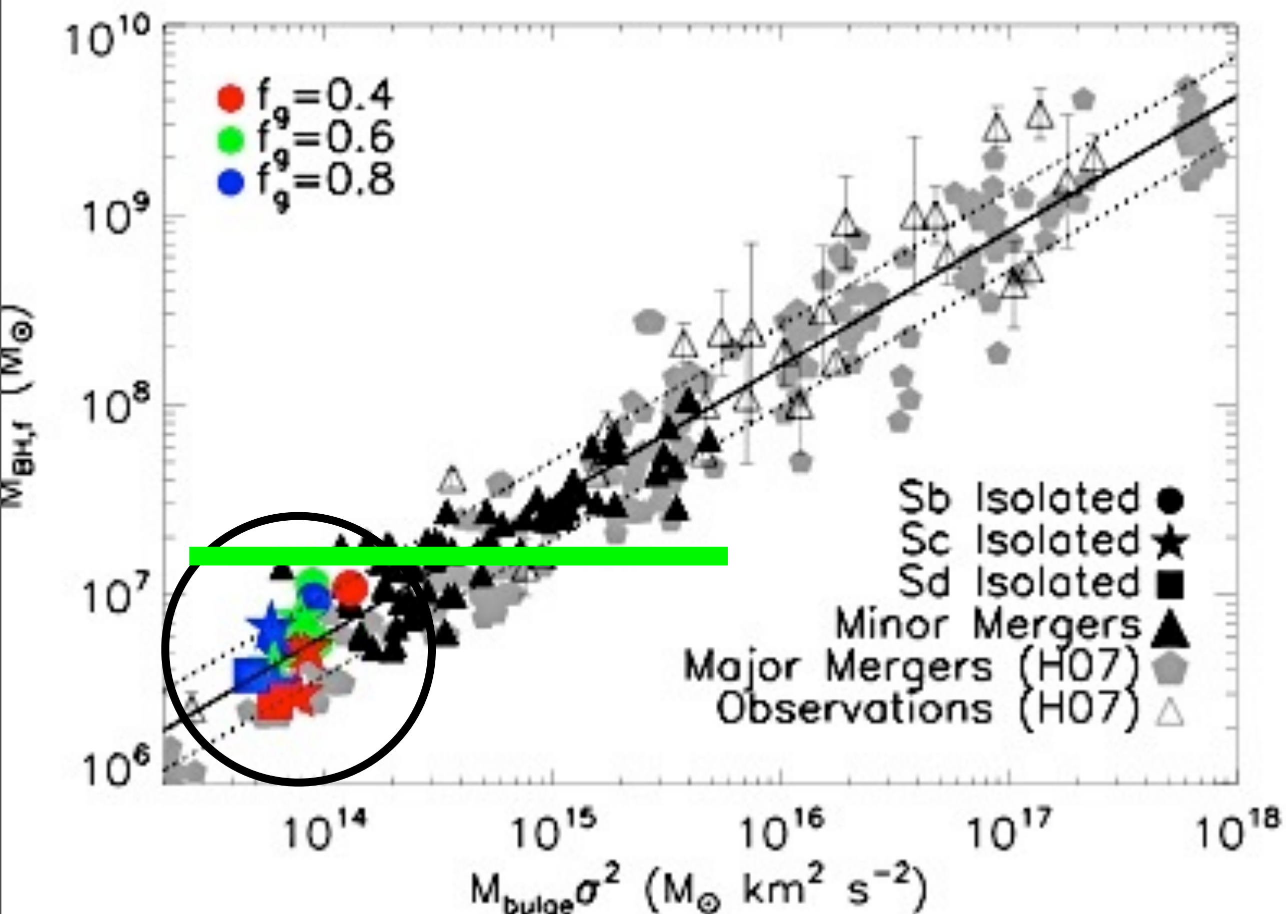
Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

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

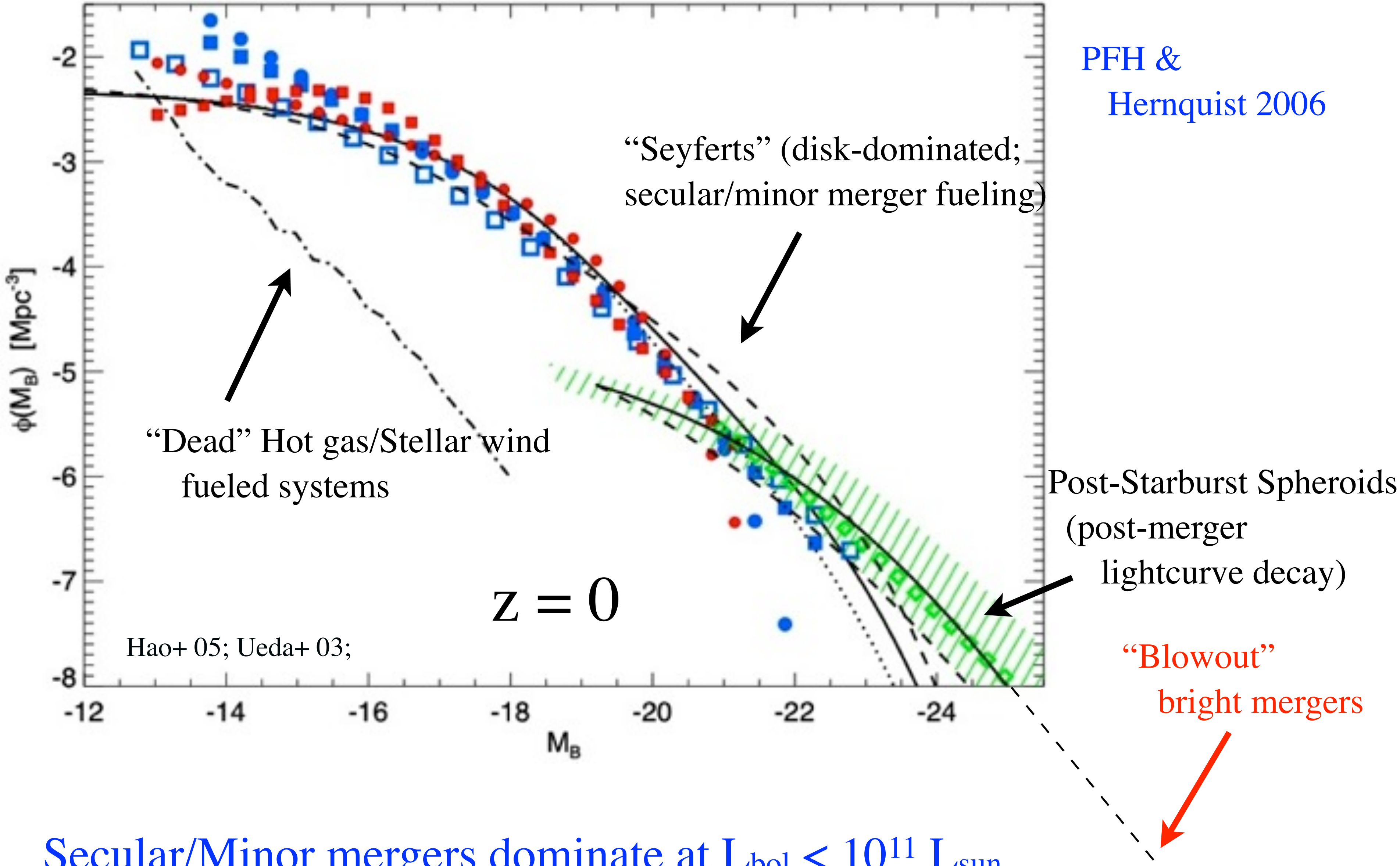






- If you don't build massive bulges, doesn't matter if you can get the gas in!

Emergent Picture:

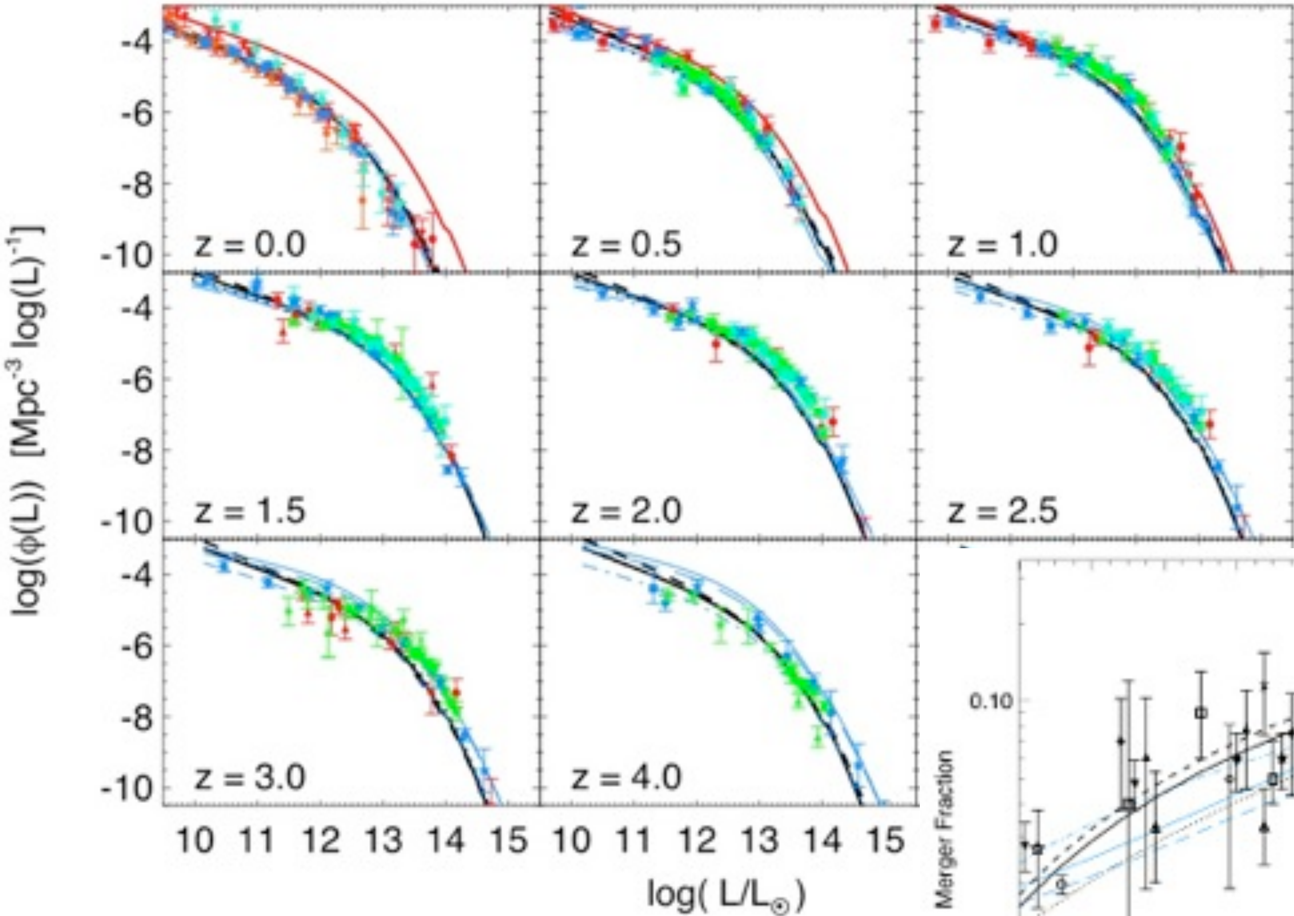


- Secular/Minor mergers dominate at $L_{bol} < 10^{11}\ L_{sun}$
  – Seyfert-Quasar divide is a good proxy!

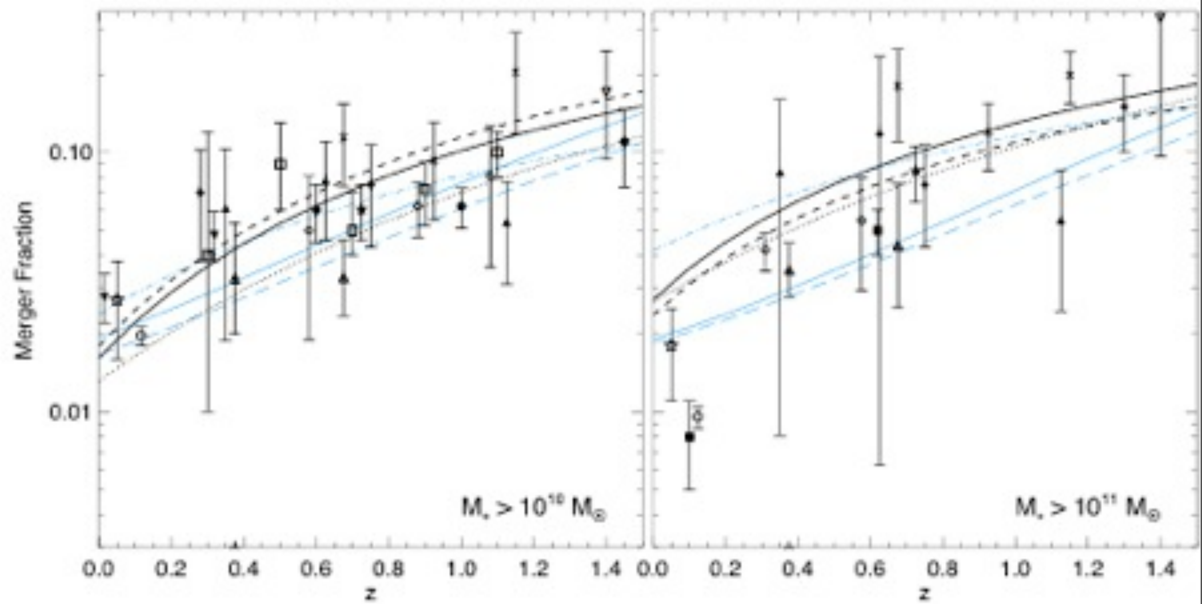
Testing the models:

NECESSARY CHECKS:

- Predicts the QLF vs. redshift, luminosity, wavelength



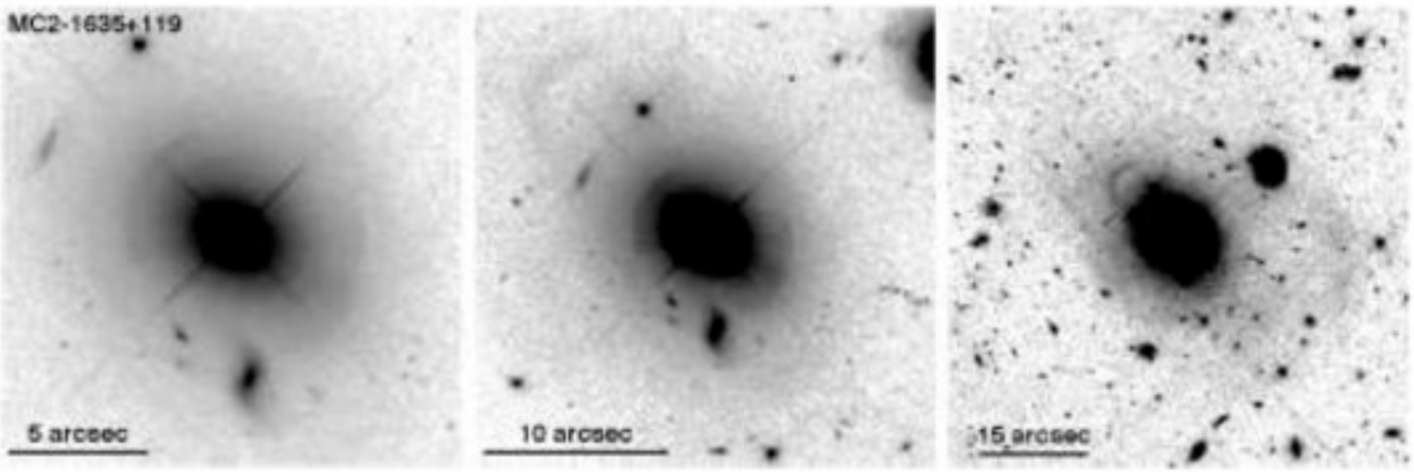
- There are “enough” mergers



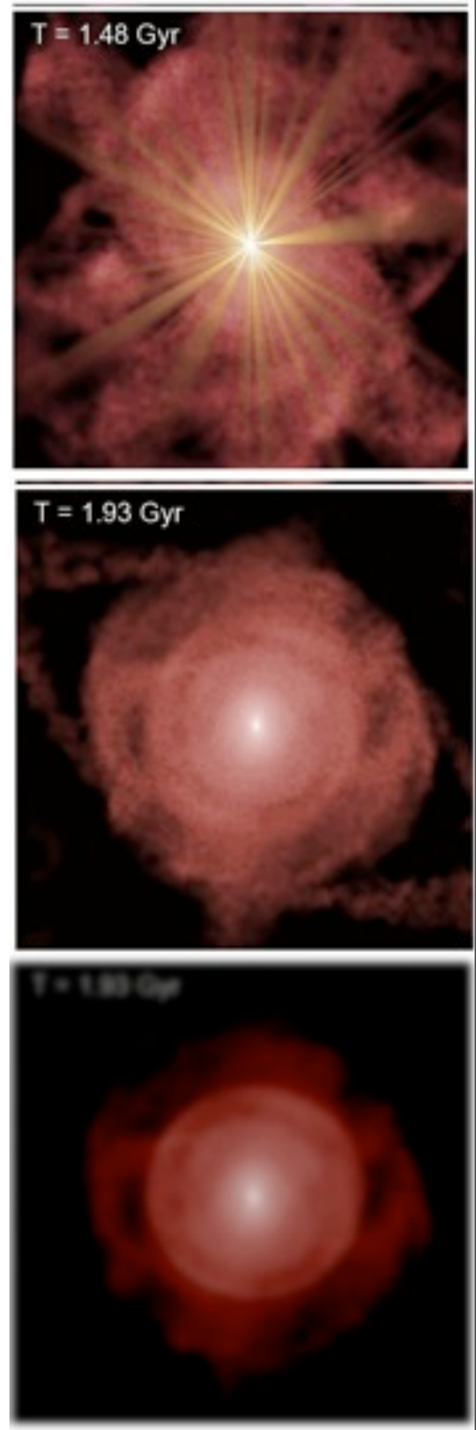
Testing the models:

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)



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



QSO = 1000xHost

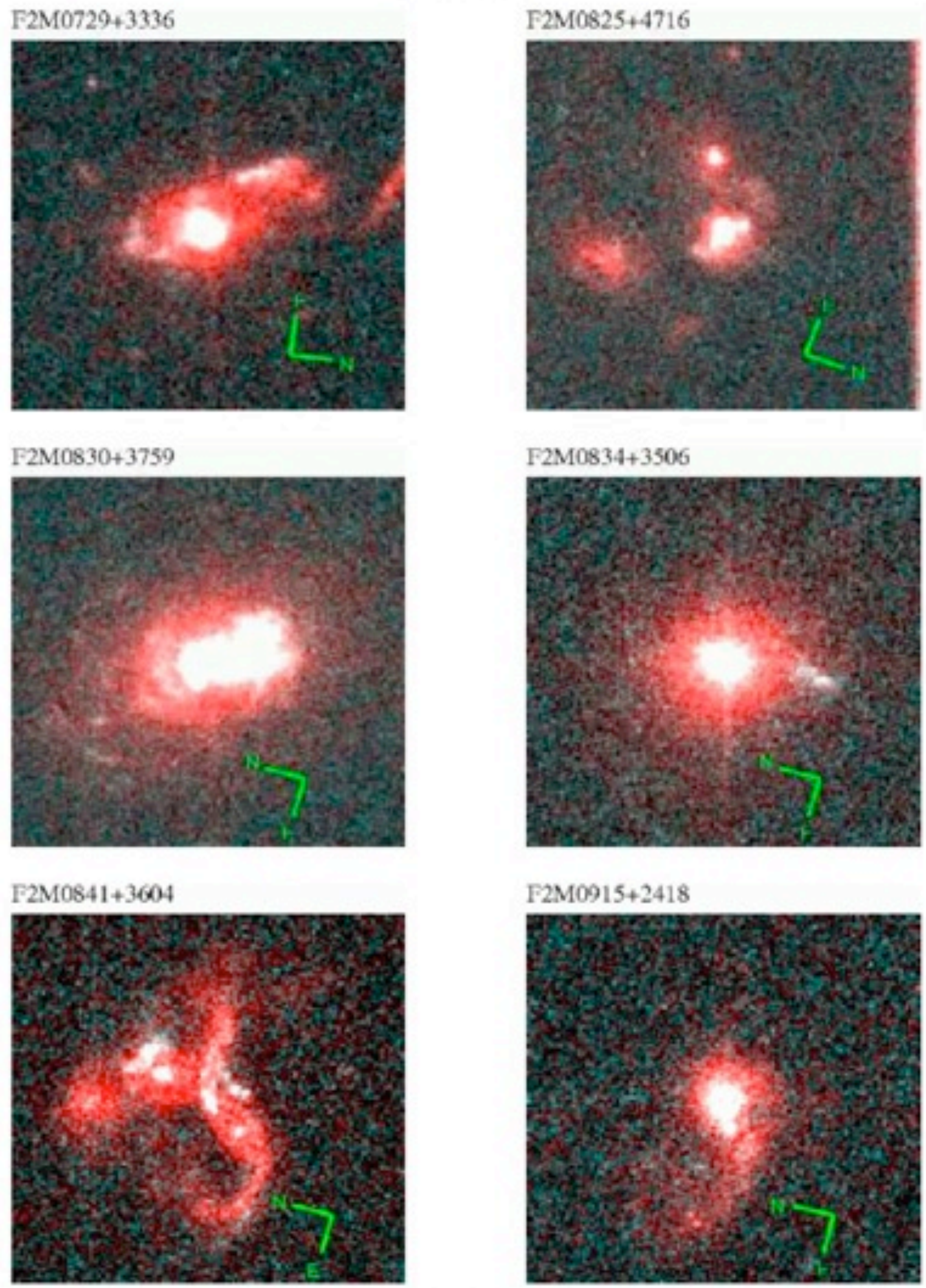
QSO = Host

QSO = 0.1xHost

Testing the models:

MORPHOLOGY:

- Red or Post-SB QSOs:
  - Nearly ~100% mergers (Urrutia, Shang)
  - Need to prove they will turn into their bluer "cousins"

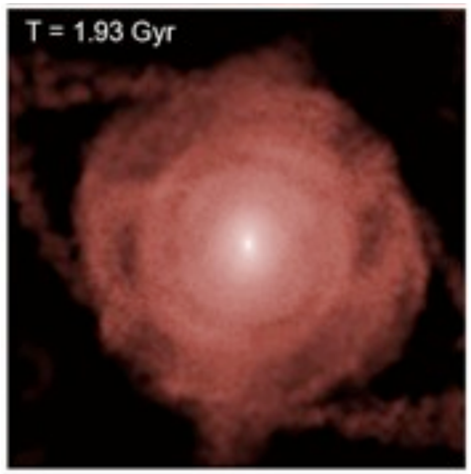


Testing the models:

MORPHOLOGY:

- BUT....

$\neq$

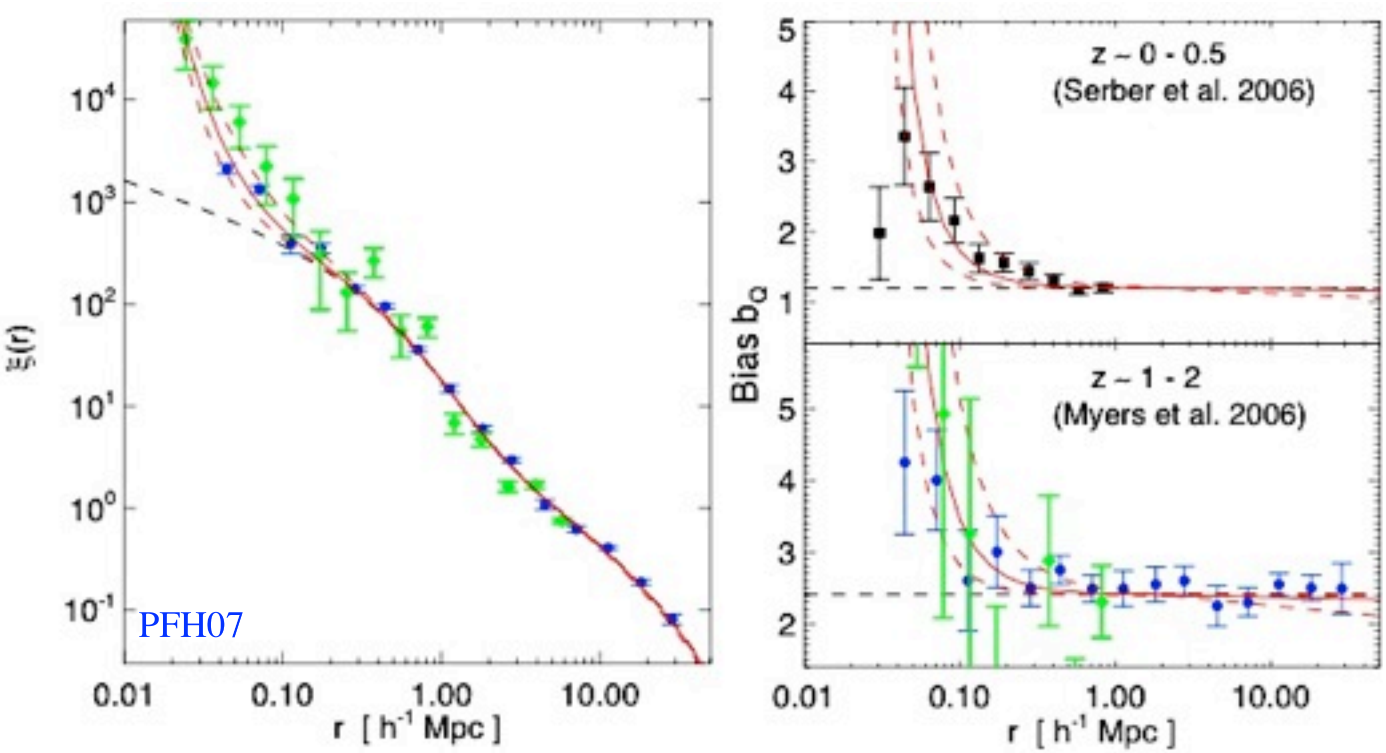


- Transition from “random” host galaxies to preference for elliptical host galaxies around $L_{bol} \sim 10^{12}\ L_{sun}$
    - Dunlop et al. (PG QSOs)
    - Rigby et al. (z~0.6 X-Ray QSOs)
    - Zakamska et al. 2008 (z~0.5 SDSS Type IIs)

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

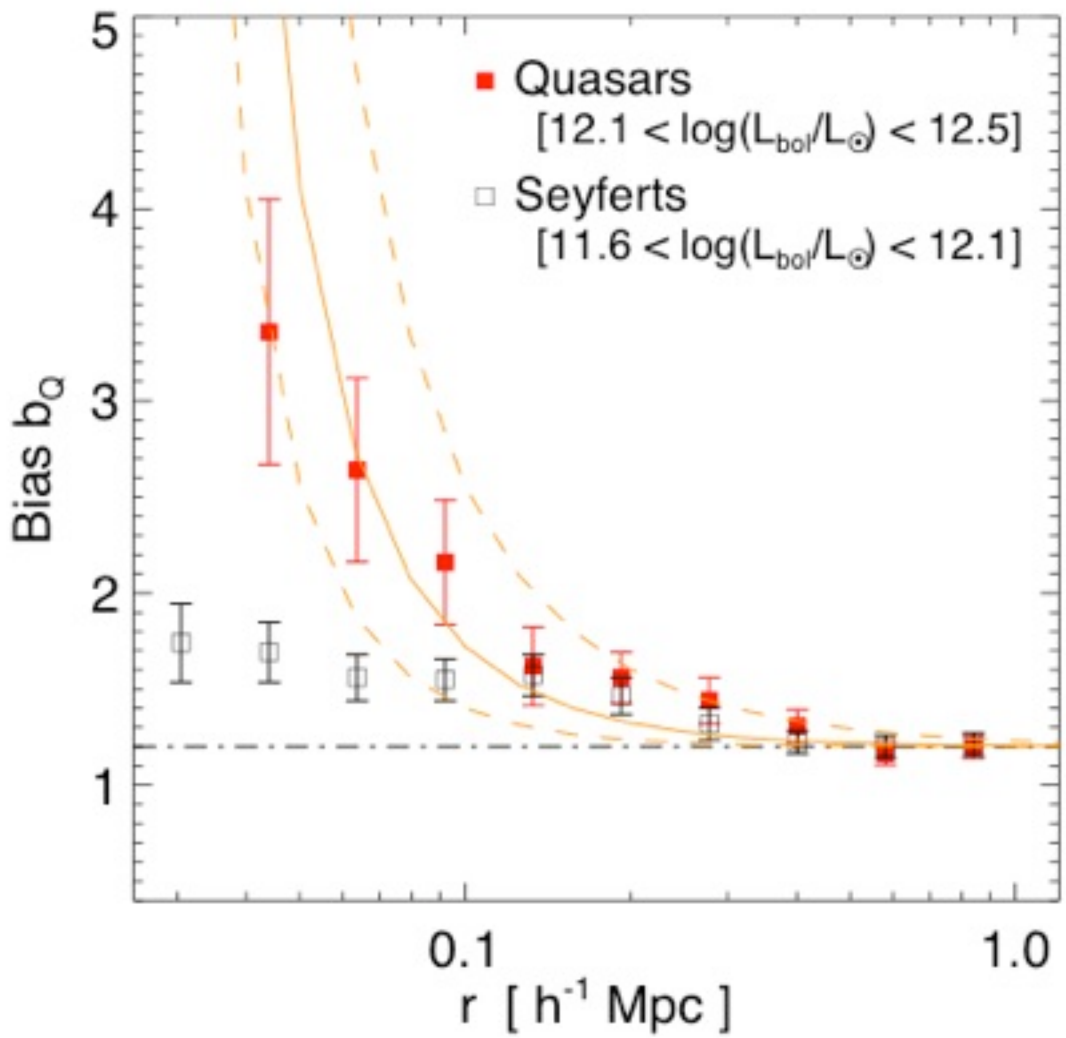


- Expected for mergers (Thacker & Scannapieco et al., PFH)
- Seen in Post-SB Galaxies (Goto et al., Hogg et al., Kauffmann et al.)

Testing the models:

CLUSTERING & ENVIRONMENT:

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

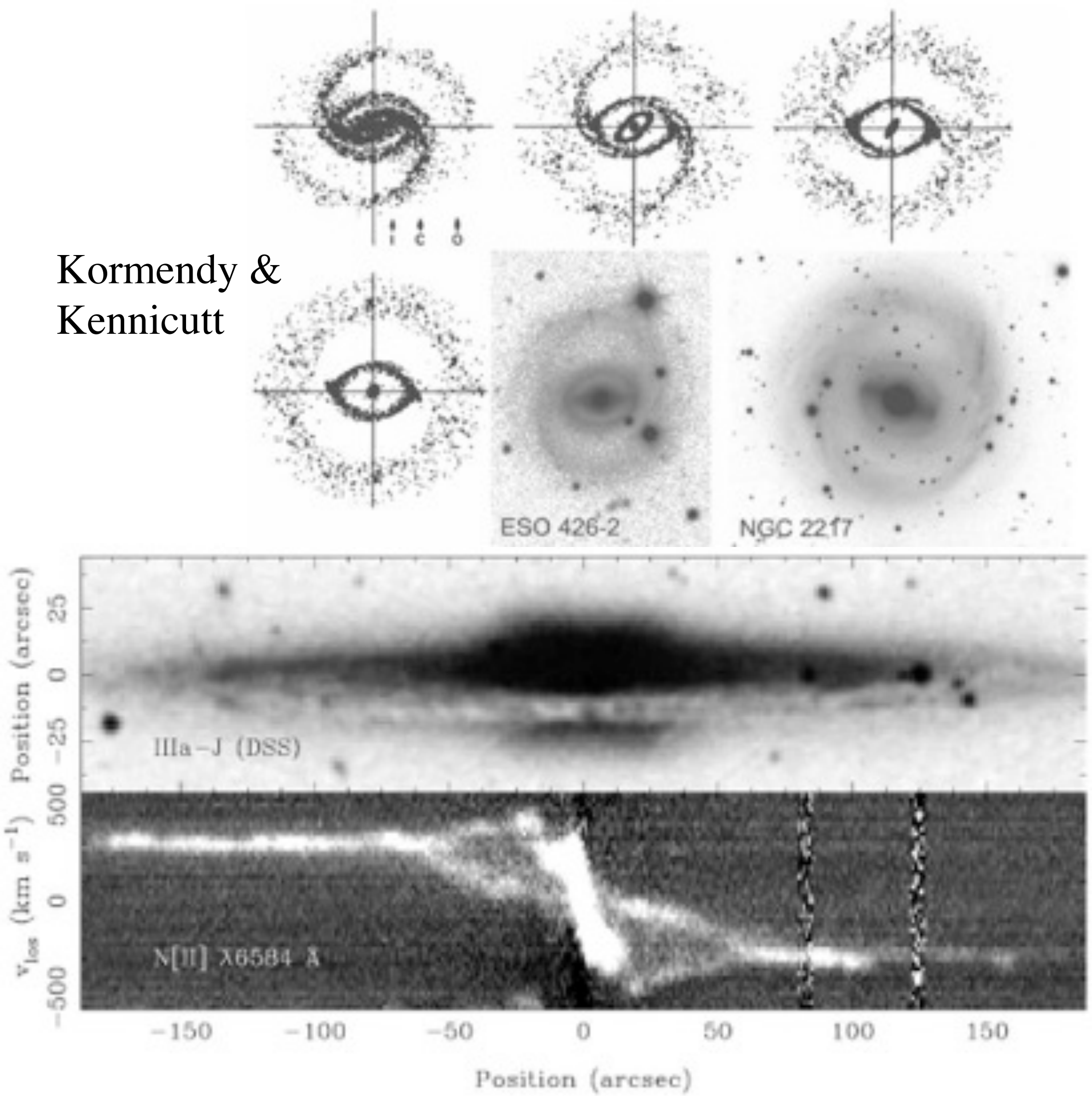


Serber et al. 2006

Testing the models:

REMNANT MORPHOLOGY:

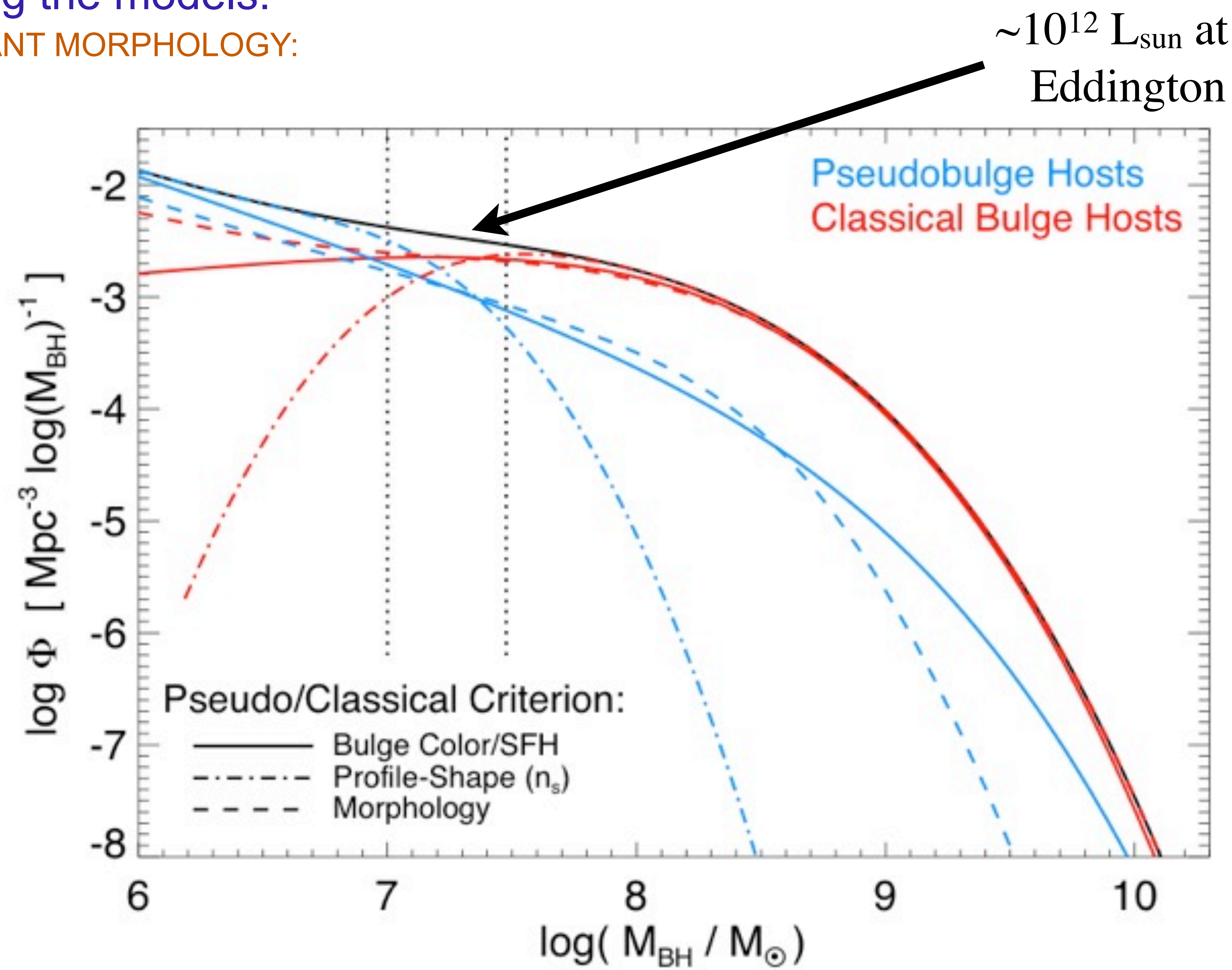
Kormendy & Kennicutt



- 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:

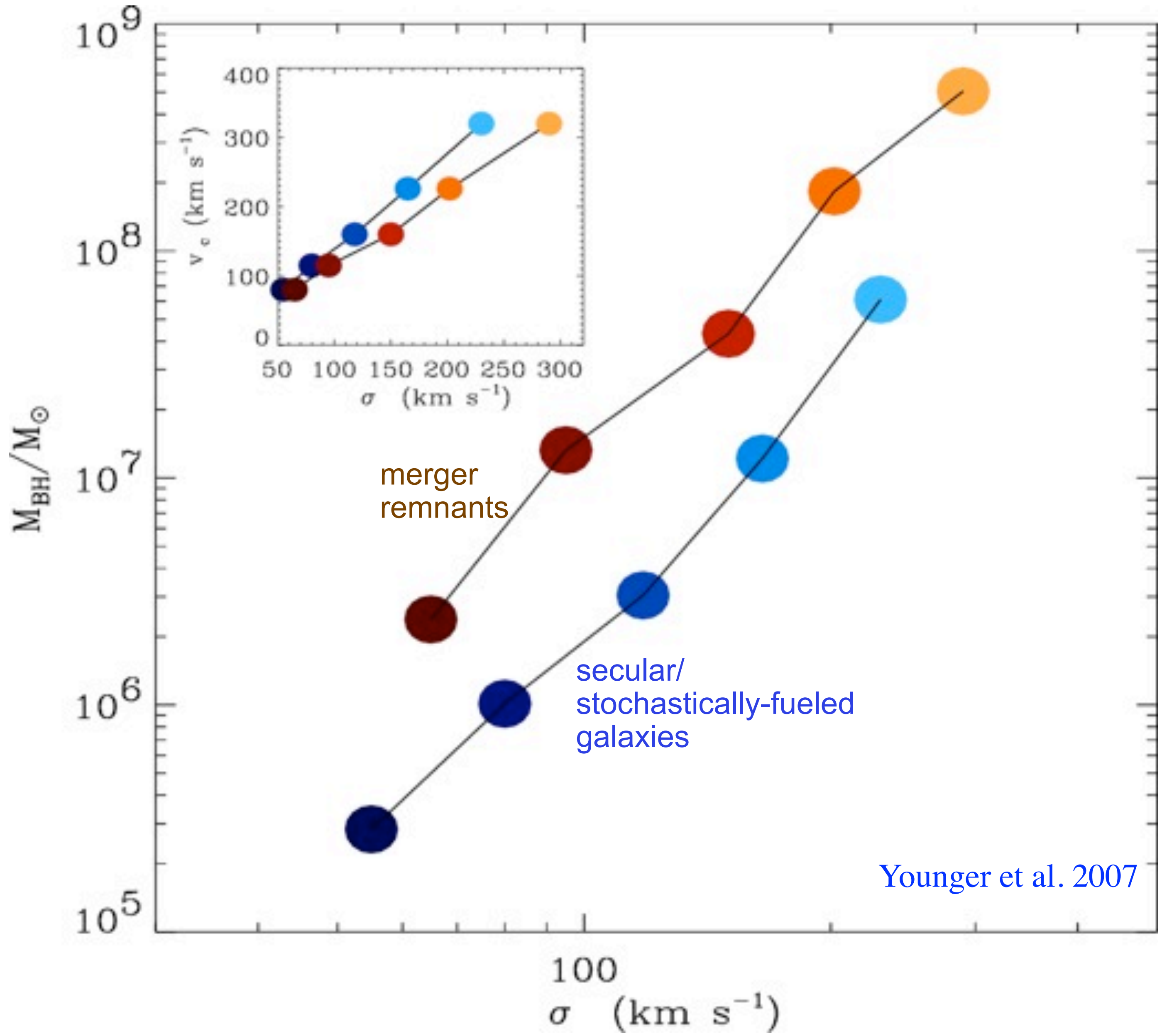
REMNANT MORPHOLOGY:



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

Testing the models:

REMNANT MORPHOLOGY: CORRELARY



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

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

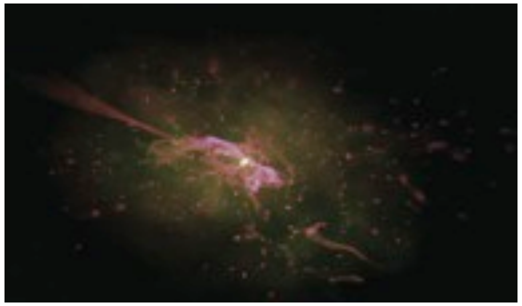
- "Are AGN mergers?" is the *wrong* question: we should ask:
  - "Where (as a function of L, z, d) do mergers vs. secular processes dominate the AGN population?"
    - Clustering vs. scale
    - Host galaxy colors/SFH
    - Host morphology/kinematics
      - Both "merger signatures" and e.g. disk vs.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

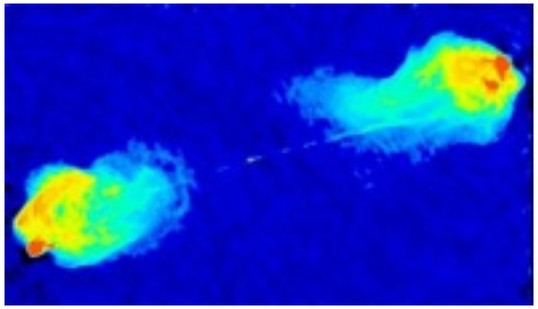
Clarifications & Caveats

- Most SF in extended ("disk") mode: only ~10% in <kpc bursts
  - M_{BH} tracks M_{gal} on average: "synched" by disk disruption events
- SF primarily shuts *itself* down (gas exhaustion)
  - BH just "sweeps up" ~ few - few 10s x M_{BH} (not ~M_{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_{bh}-M_{gal} evolution expected: doesn't mean BH grows "before" spheroid

"Transition" vs. "Maintenance"

"Transition"	"Maintenance"
Move mass from Blue to Red	Keep it Red
Rapid	Long-lived (~Hubble time)
Small scales	Large (~halo) scales
"Quasar" mode (high mdot)	"Radio" mode (low mdot)
Morphological Transformation	Subtle morphological change
Gas-rich/Dissipational Mergers	"Dry"/Dissipationless Mergers



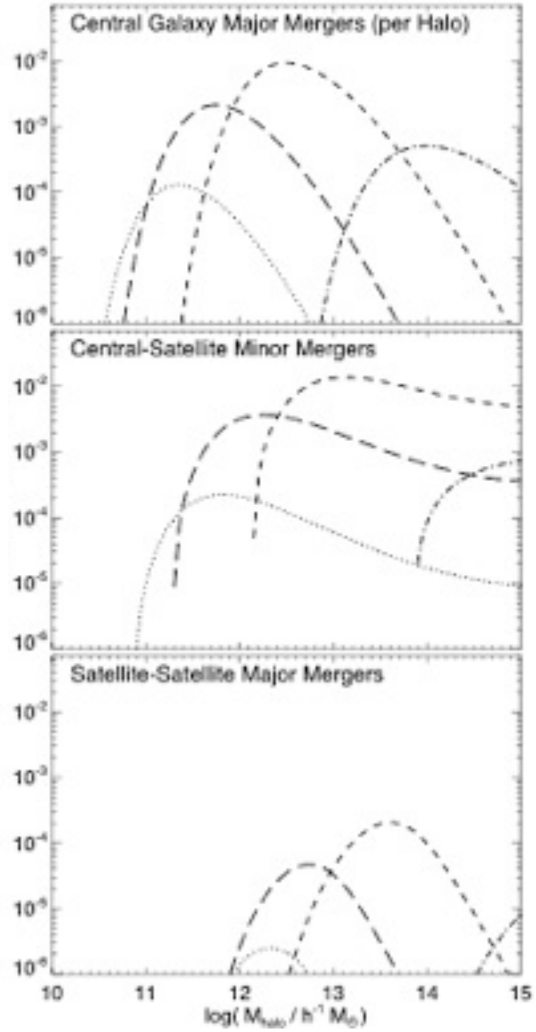


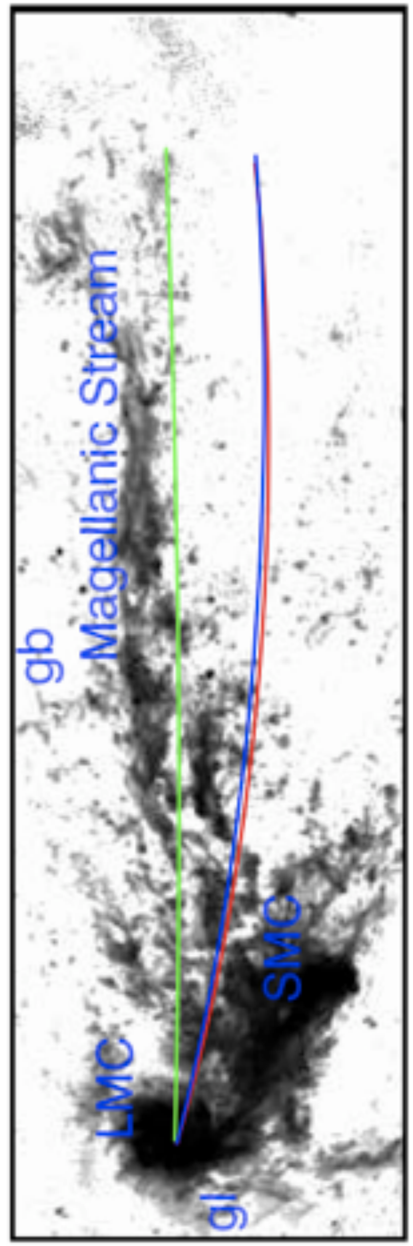
No reason these should be the same mechanisms... what connections?

Other Fueling Mechanisms: Minor Mergers

left: Projected gas density
right: Projected stellar density
XY, the orbital plane

Isolated Disk (Sbc) Galaxy
Run: execute/G3G1−u3
T.J. Cox & Patrik Jonsson, UC Santa Cruz
UC Santa Cruz, 2004

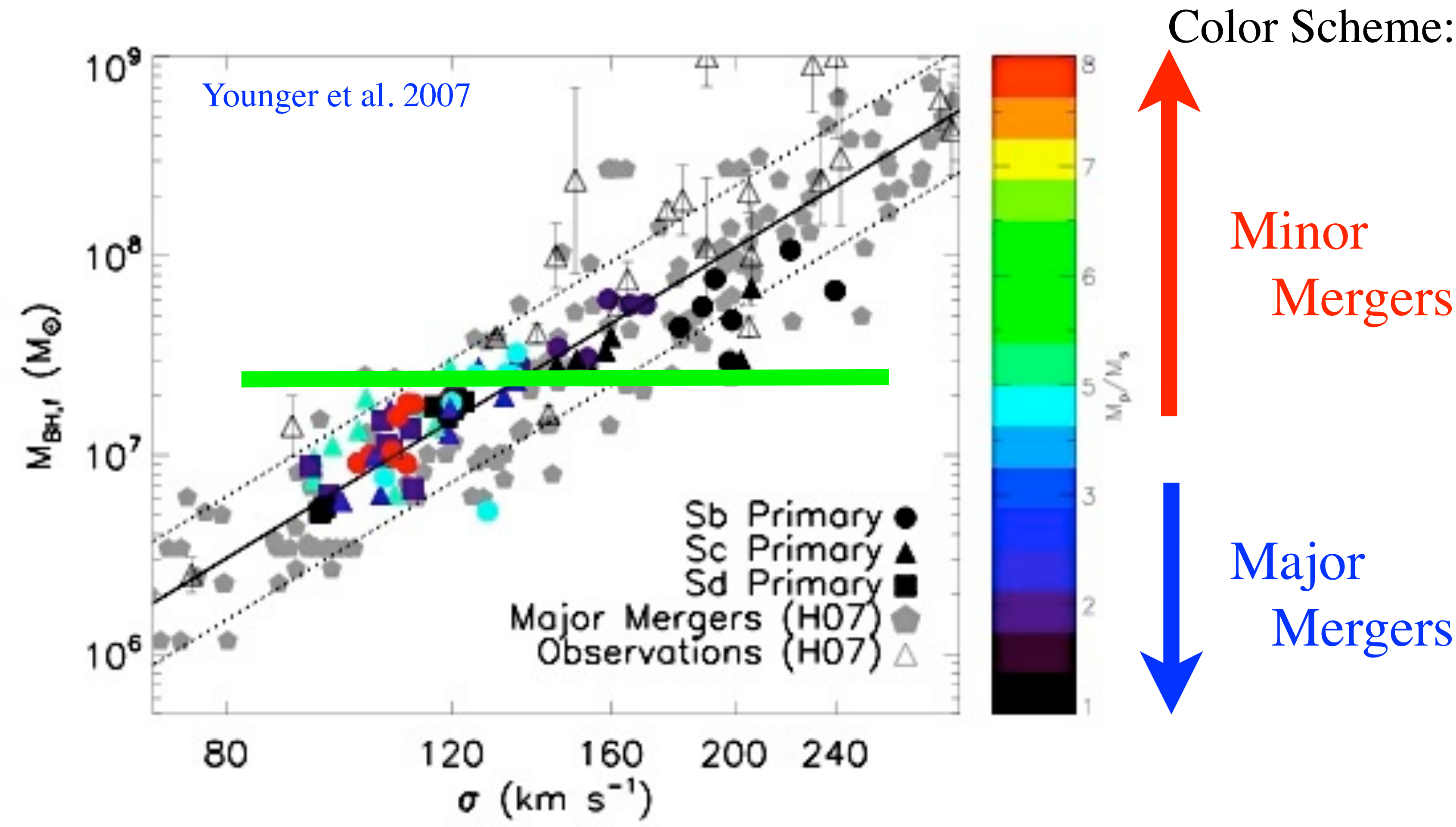




Besla et al. (2007)

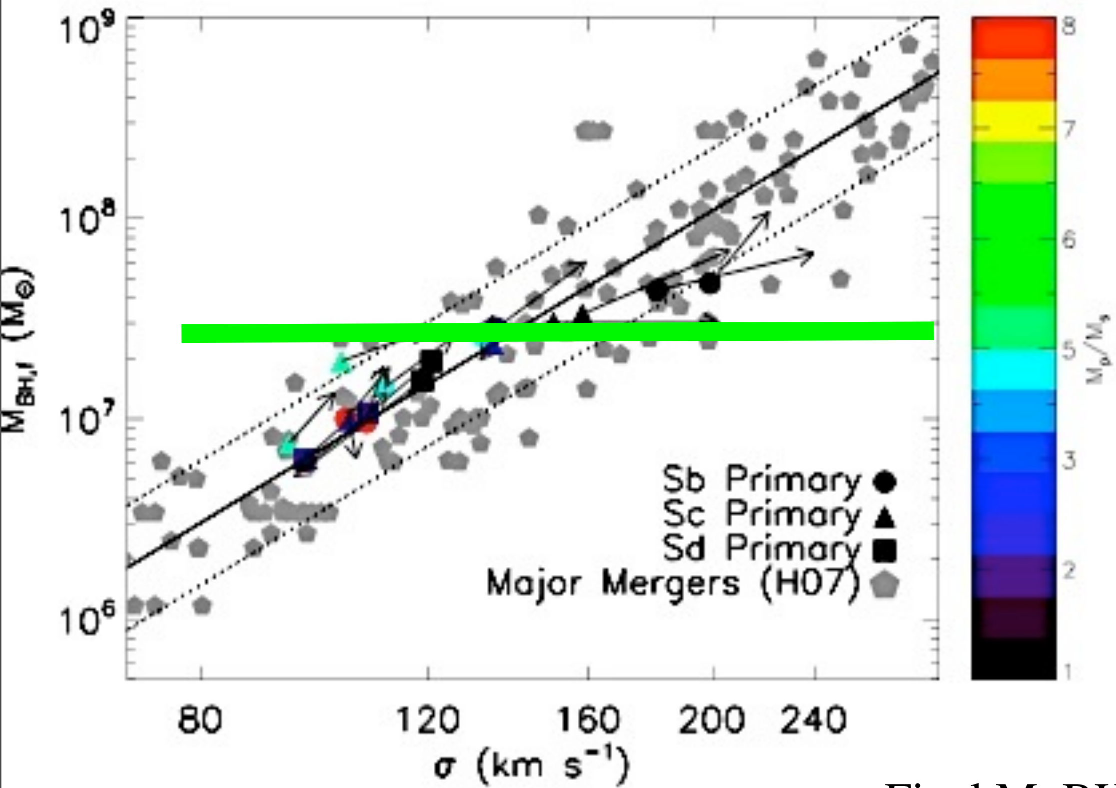
- Minor Mergers
  - Not so violent -probably don't dominate spheroid formation (LMC/SMC)
  - Not very efficient: even if growth ~ M_secondary/M_primary, major mergers "win"

Other Fueling Mechanisms: Minor Mergers



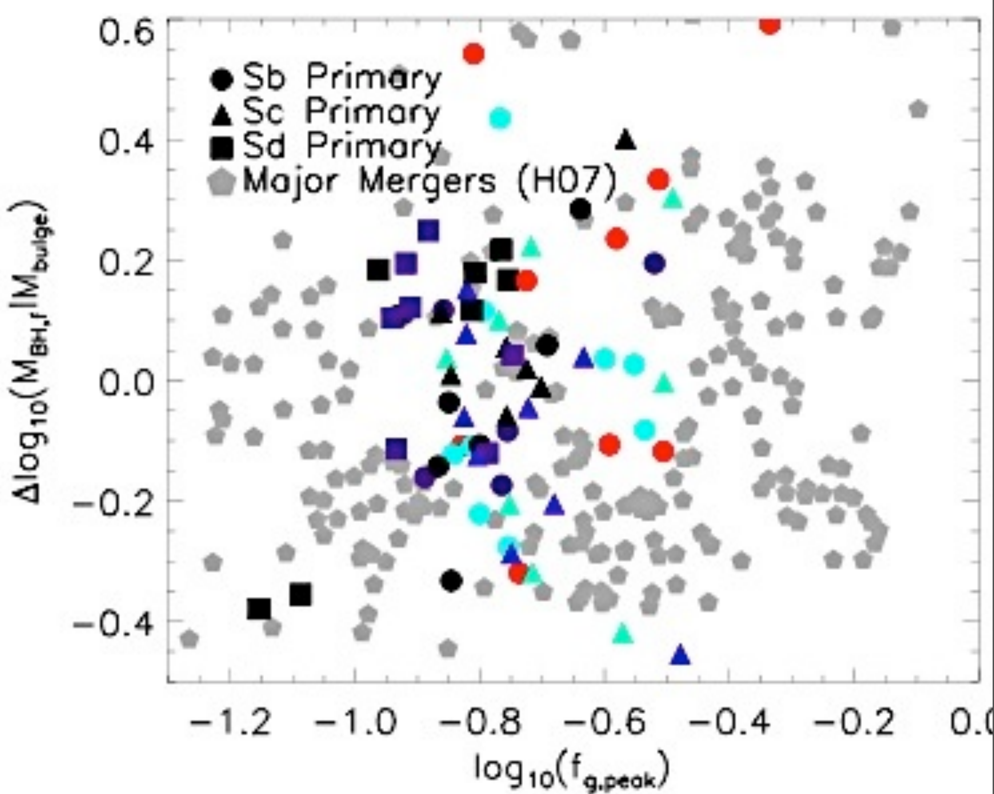
- Minor Mergers
  - Can get to ~1-2 10^7 M_sun ::: *very* hard to push beyond this

Other Fueling Mechanisms: Minor Mergers



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

Final M_BH relative to mean

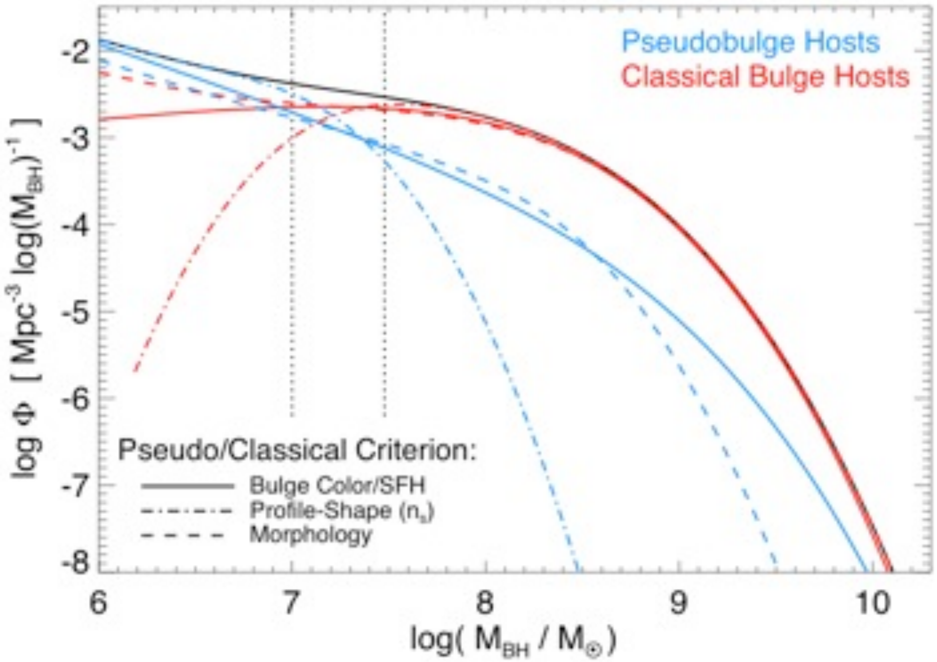


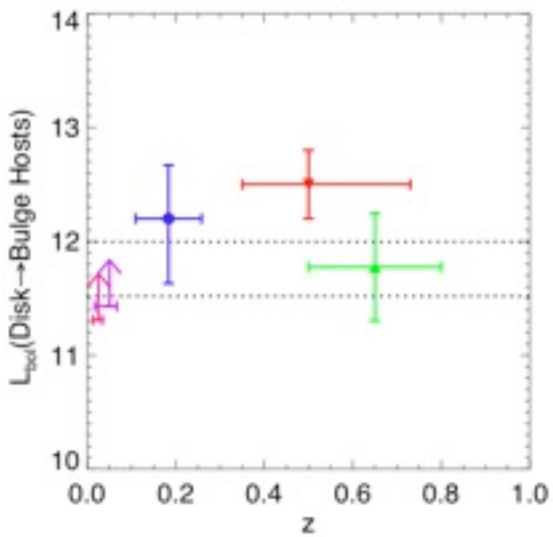
Mass of gas supplied to BH

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

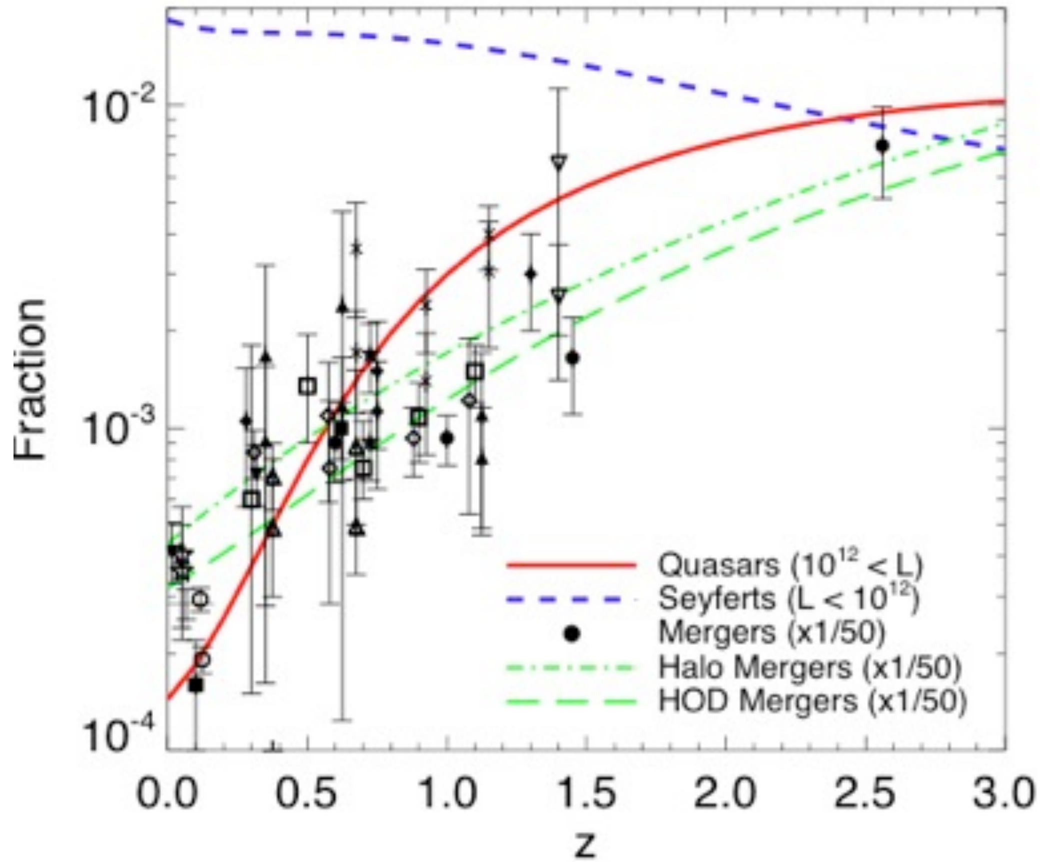
Does that picture hold up?

Appears to be true for hosts...



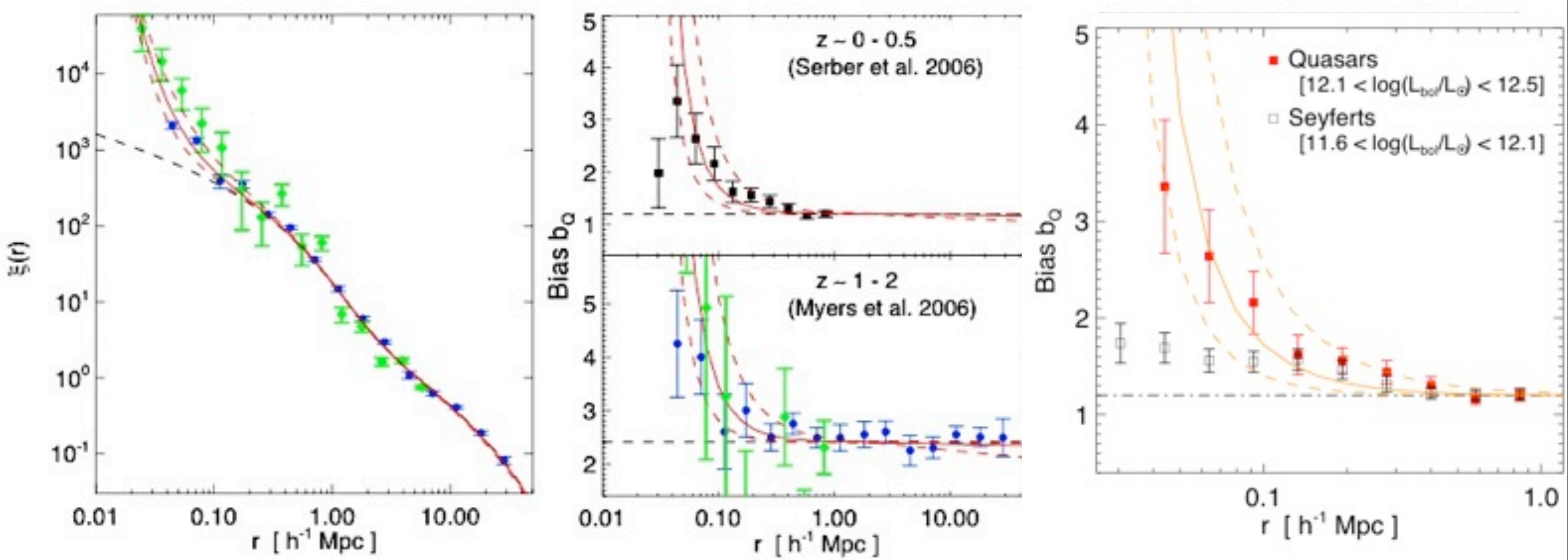


And may explain "downsizing" of AGN populations



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

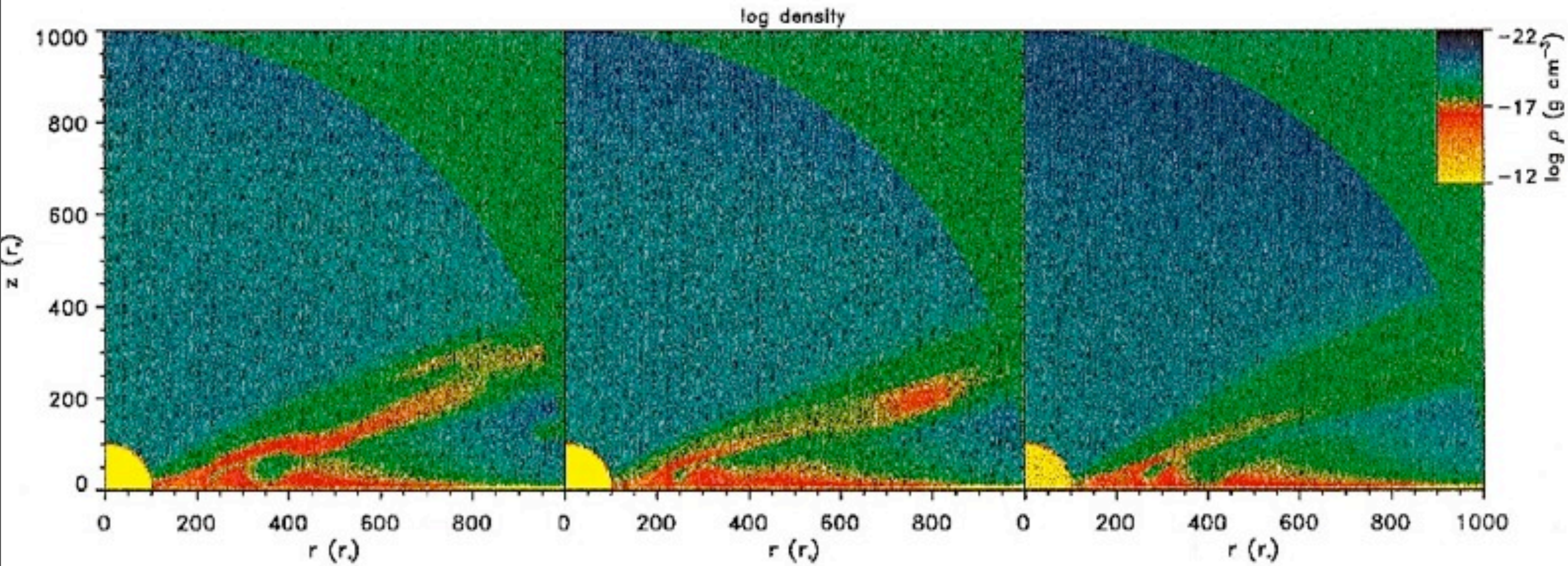


- Predicted by merger models (Thacker & Scannapieco et al., PFH)

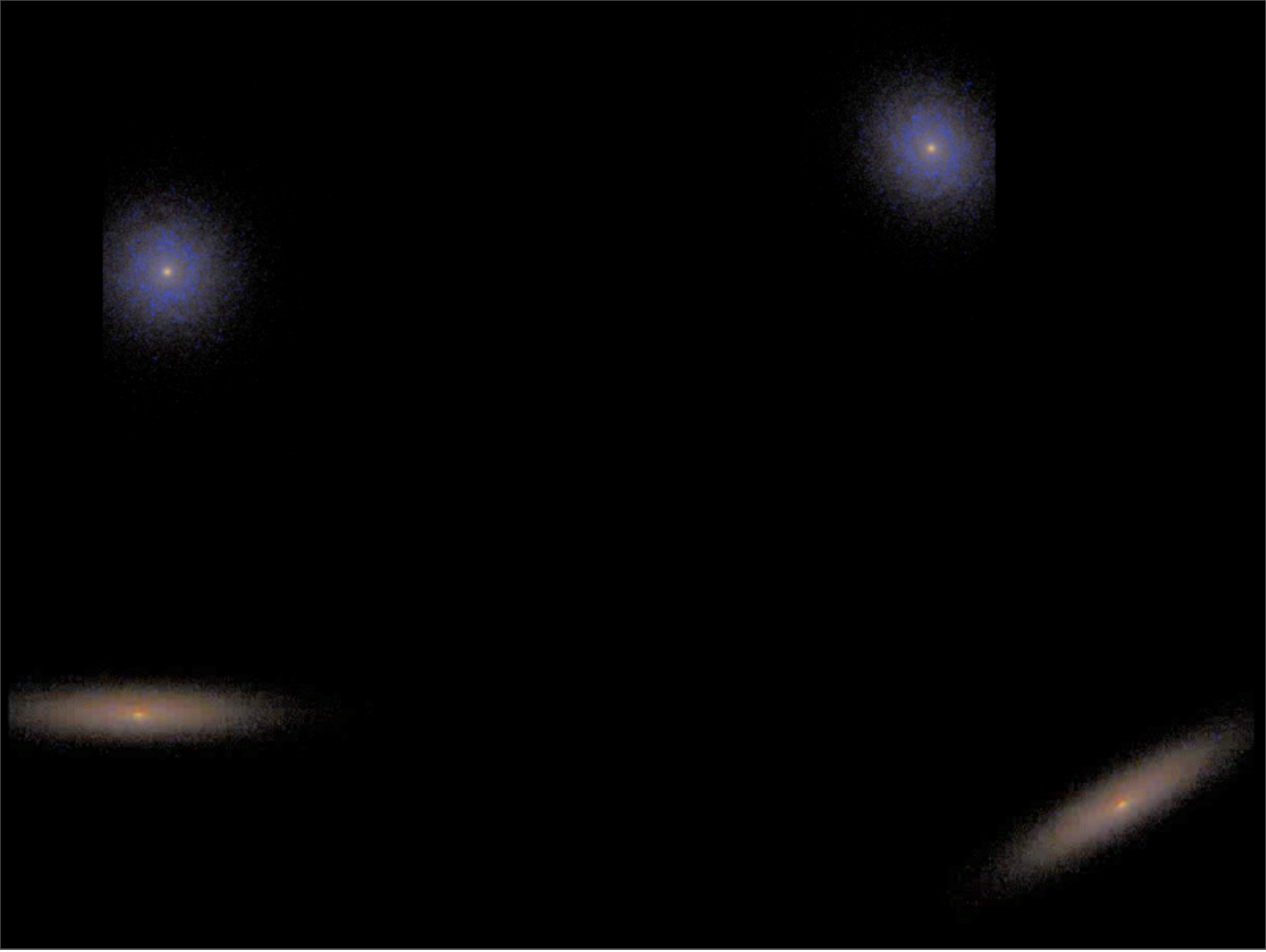
So let's (for now) consider mergers & bright quasars:

CAN WE MODEL IT?

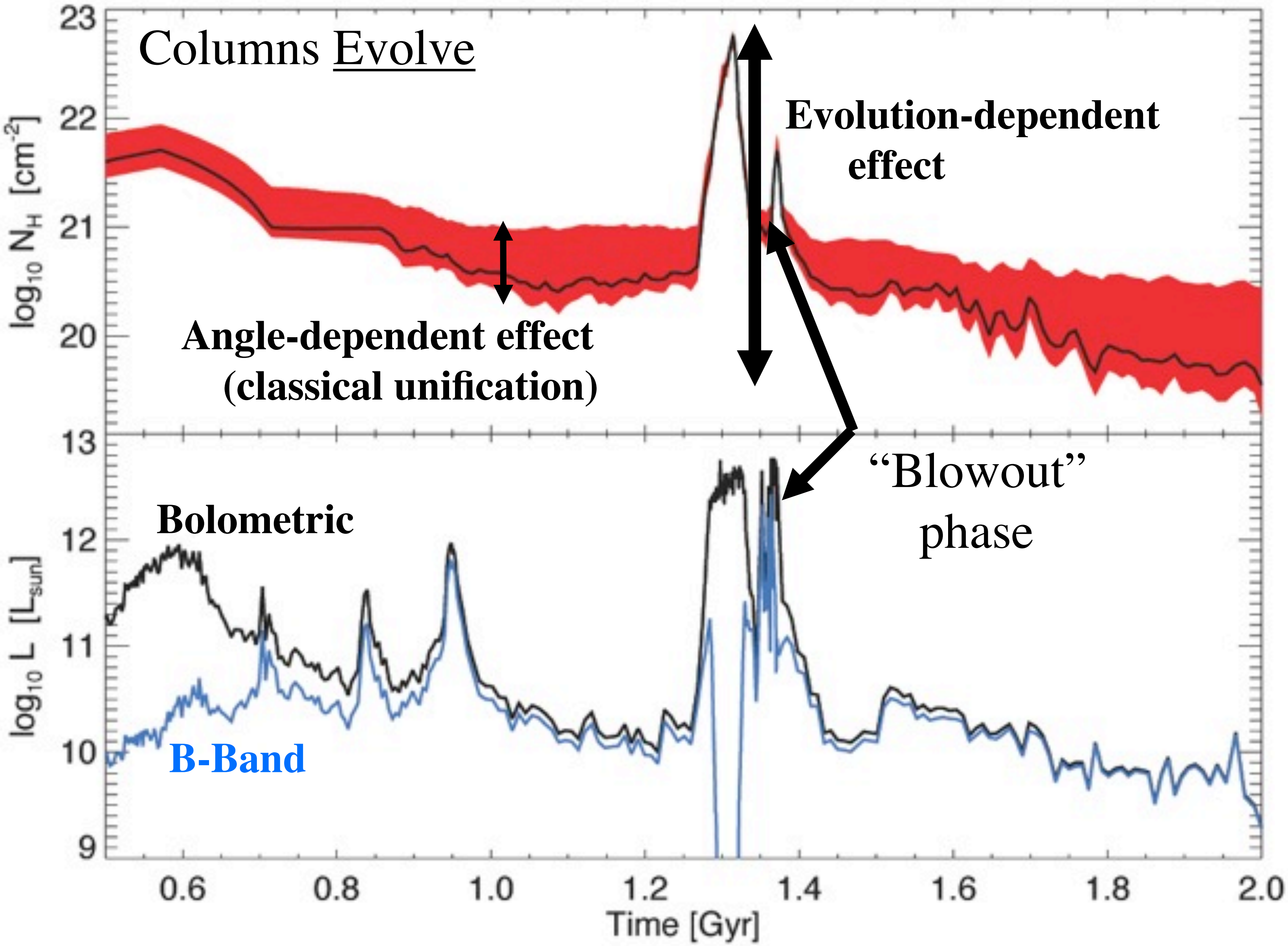
- Modeling "Quasar" Feedback
- ~5% to match observed M-sigma normalization (Silk & Rees '98)
  - Line opacities + AGN spectrum (Sazonov et al.)
  - Momentum driven winds (Murray et al.)
  - Disk wind simulations (Proga et al.)



- Probably *not* radio jets



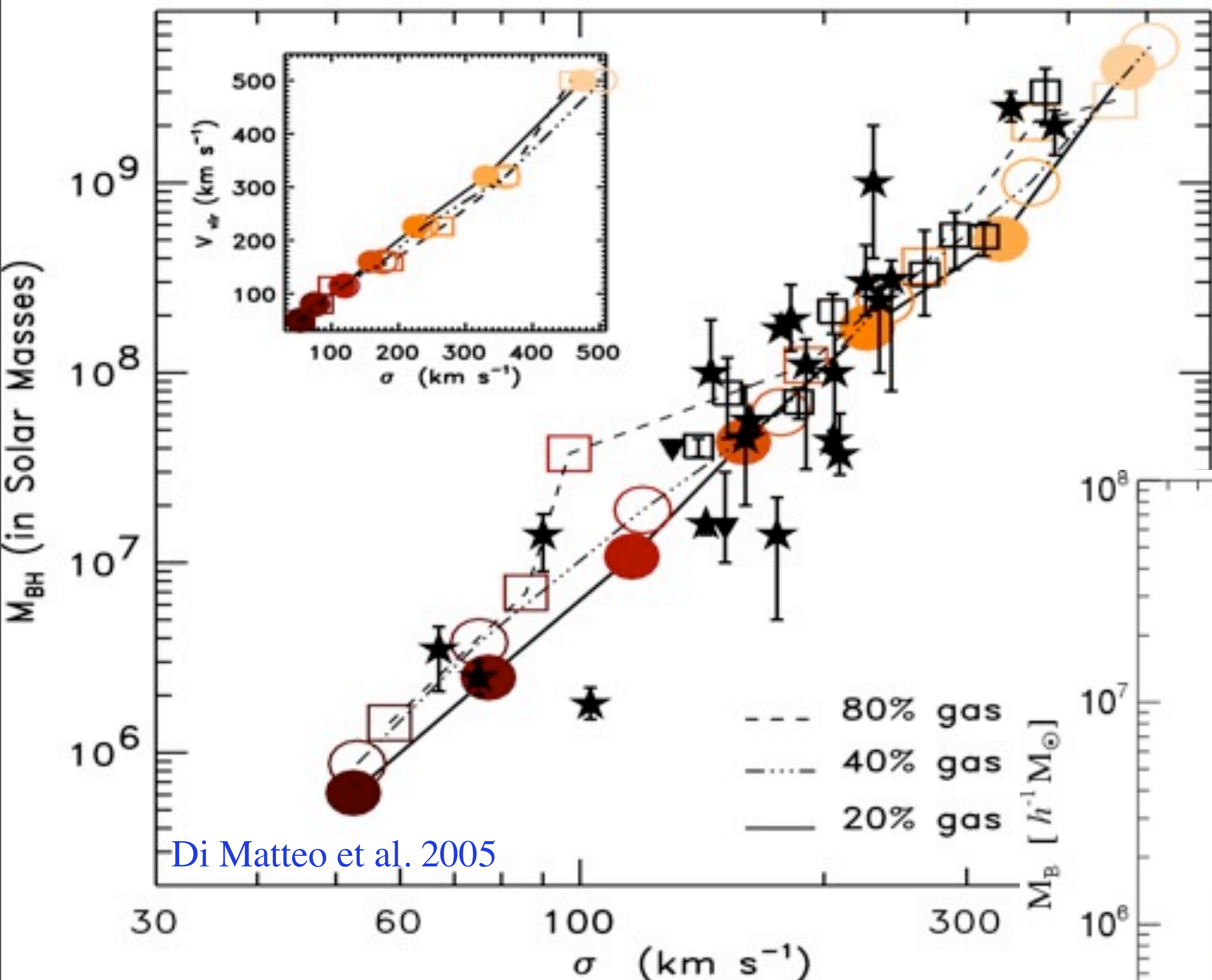
Quasar Lightcurves:



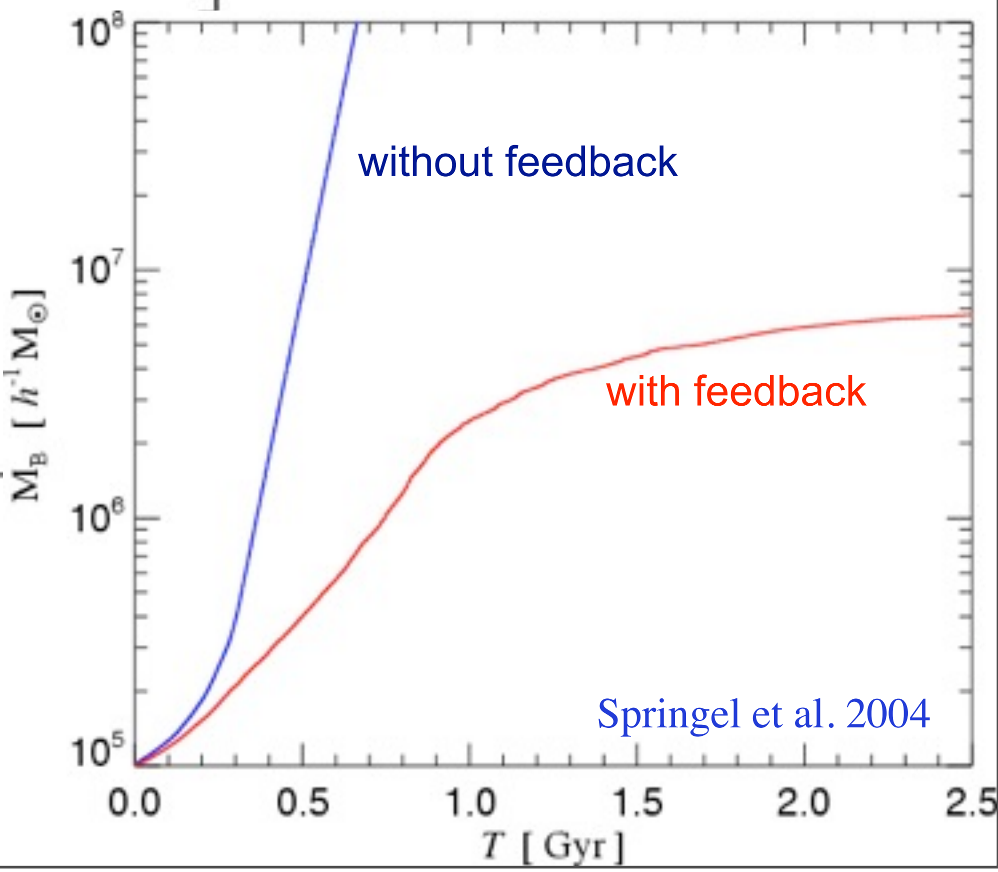
- Multi-phase ISM decomposition: gas+dust+metal columns

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

PREVENTS RUNAWAY BLACK HOLE GROWTH

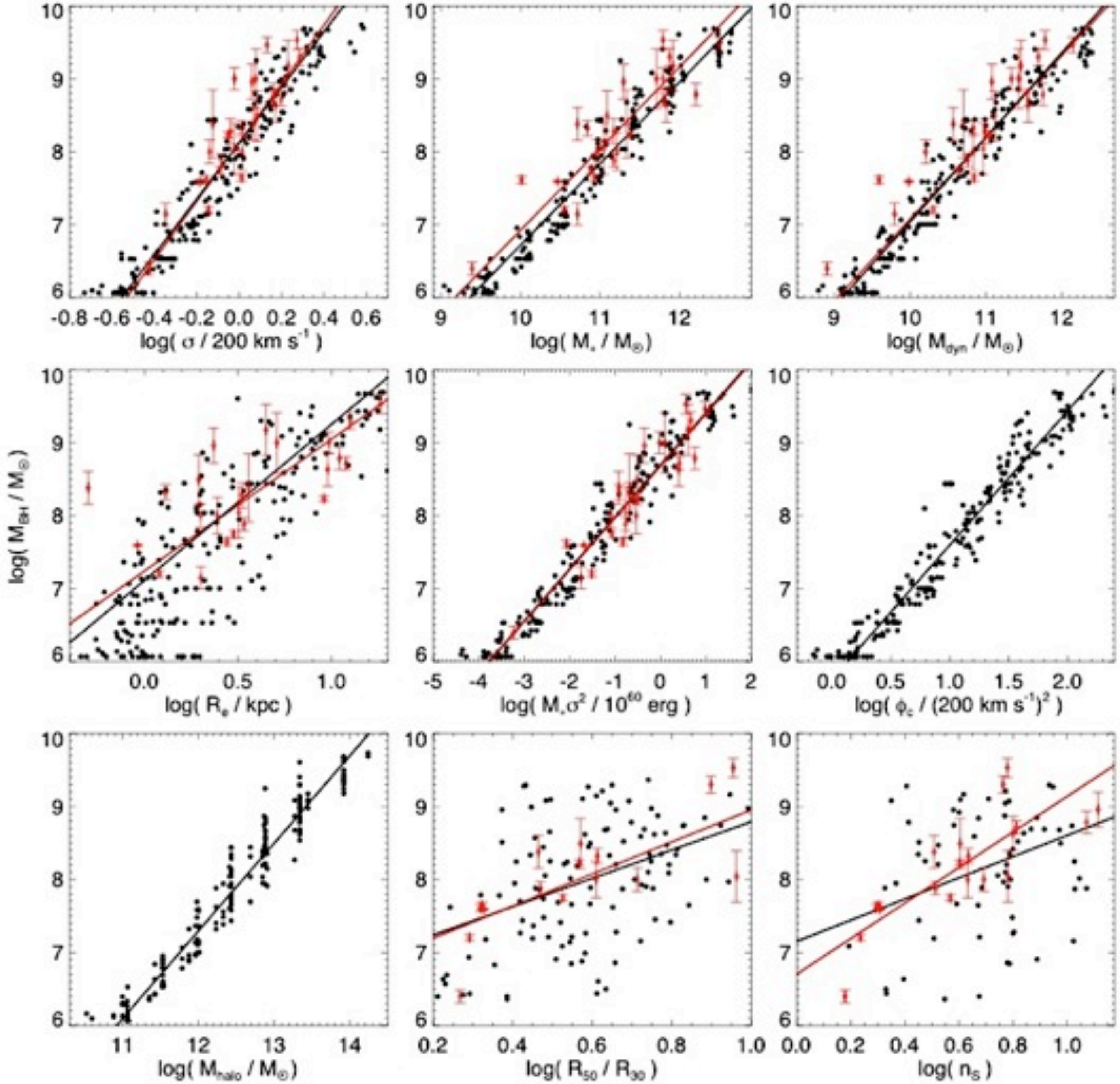


Black hole growth



Explains all the observed BH-Host Correlations

BUT WHAT IS THE "FUNDAMENTAL" CORRELATION?



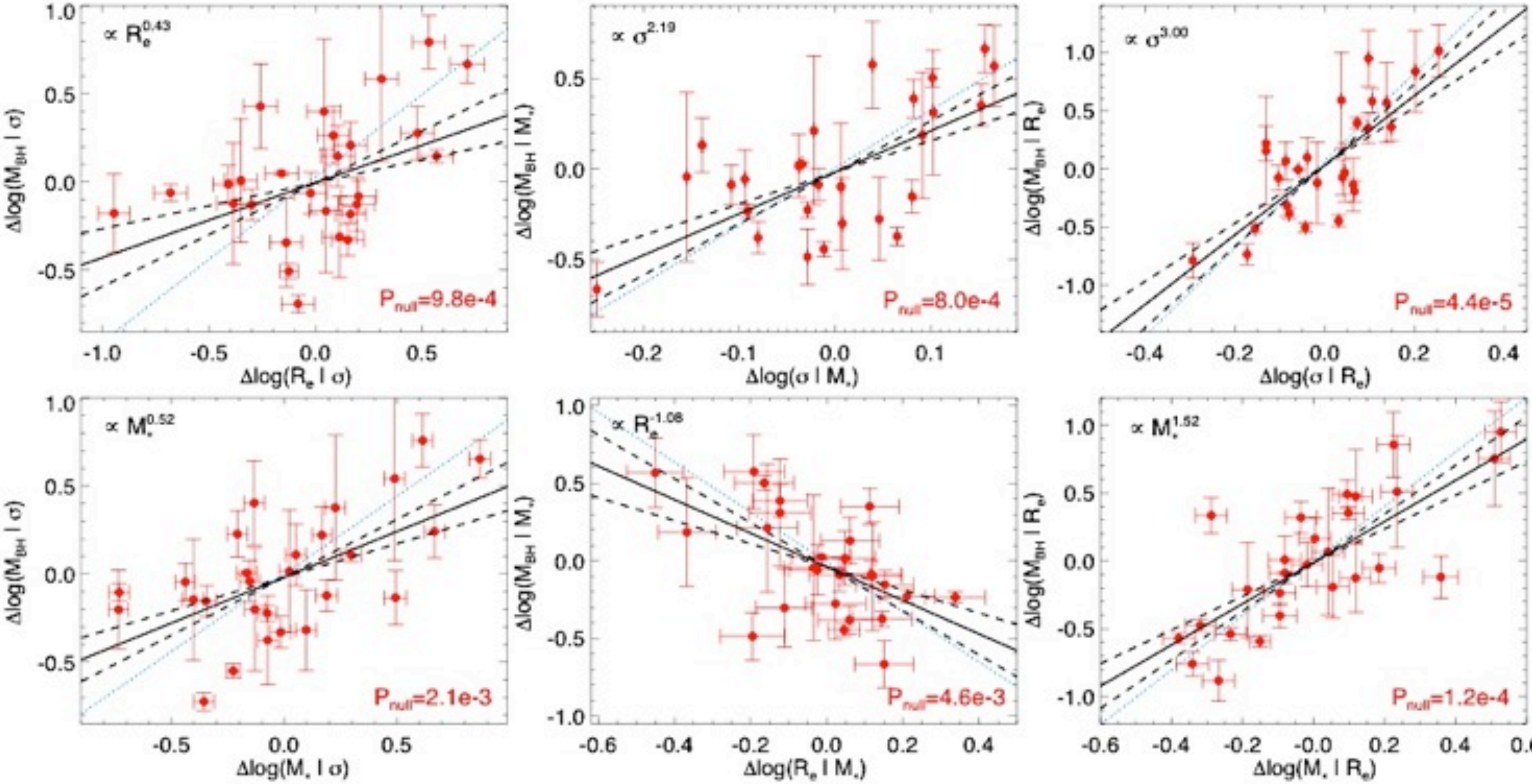
PFH et al. 2007

Which Correlation Is “Most Fundamental”?

PFH et al. 2007

COMPARE RESIDUALS

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



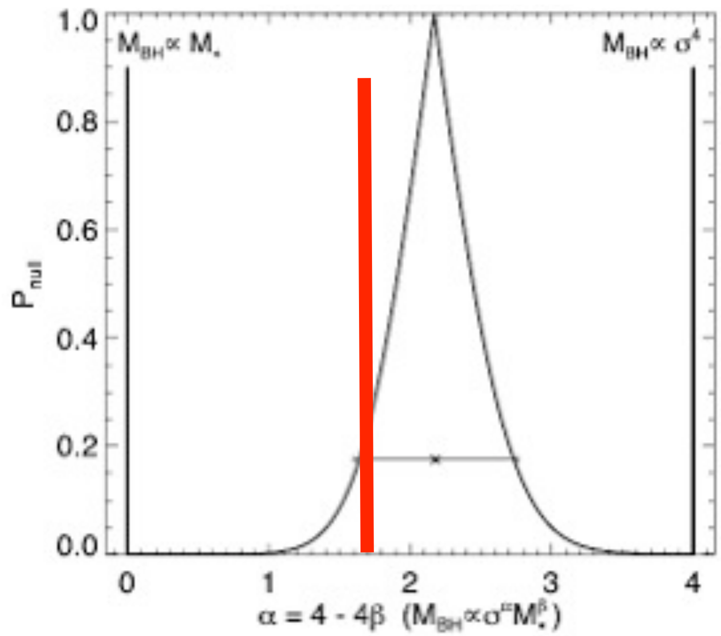
~3s significant residual trend with respect to ANY single variable correlation!

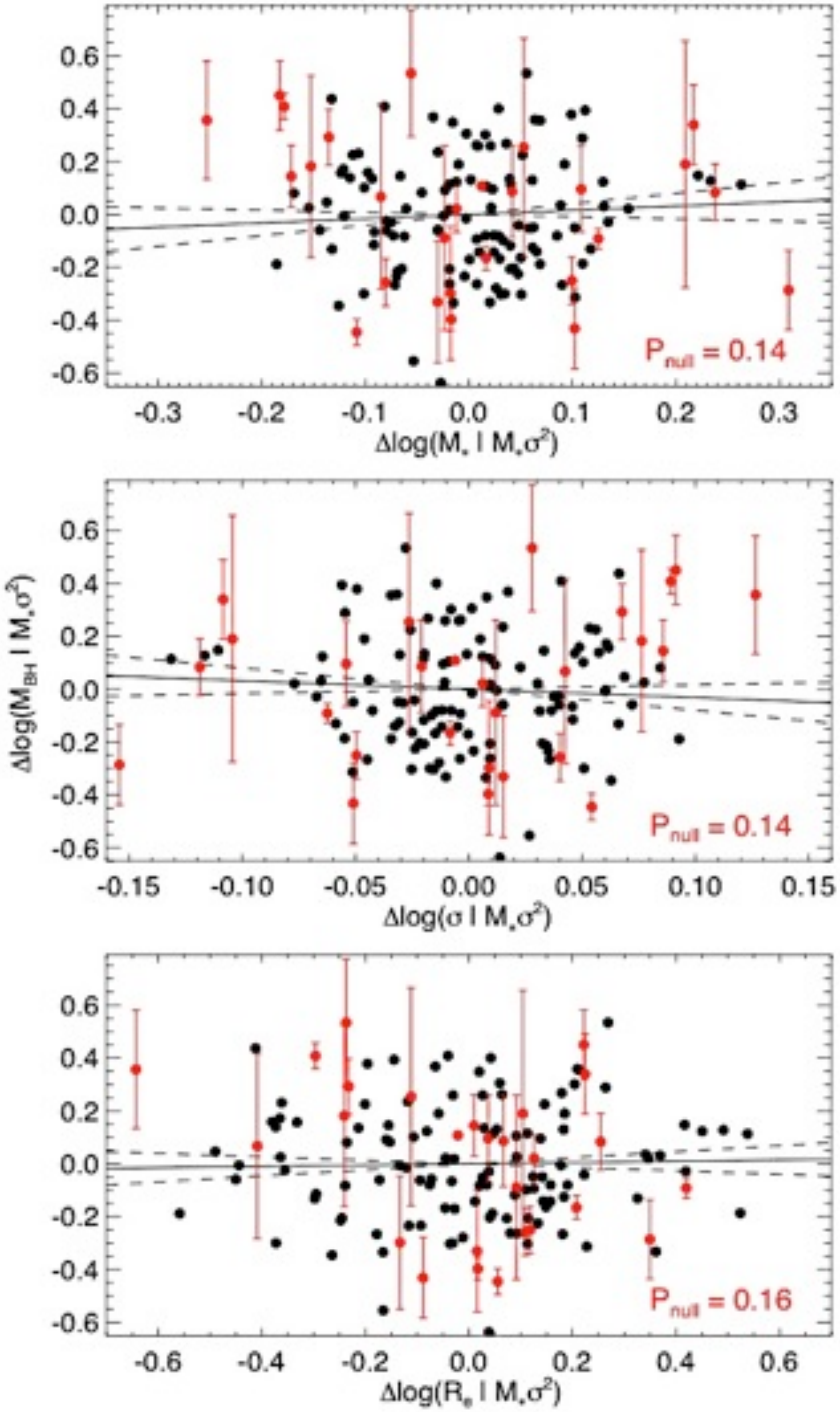
Which Correlation Is “Most Fundamental”?

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

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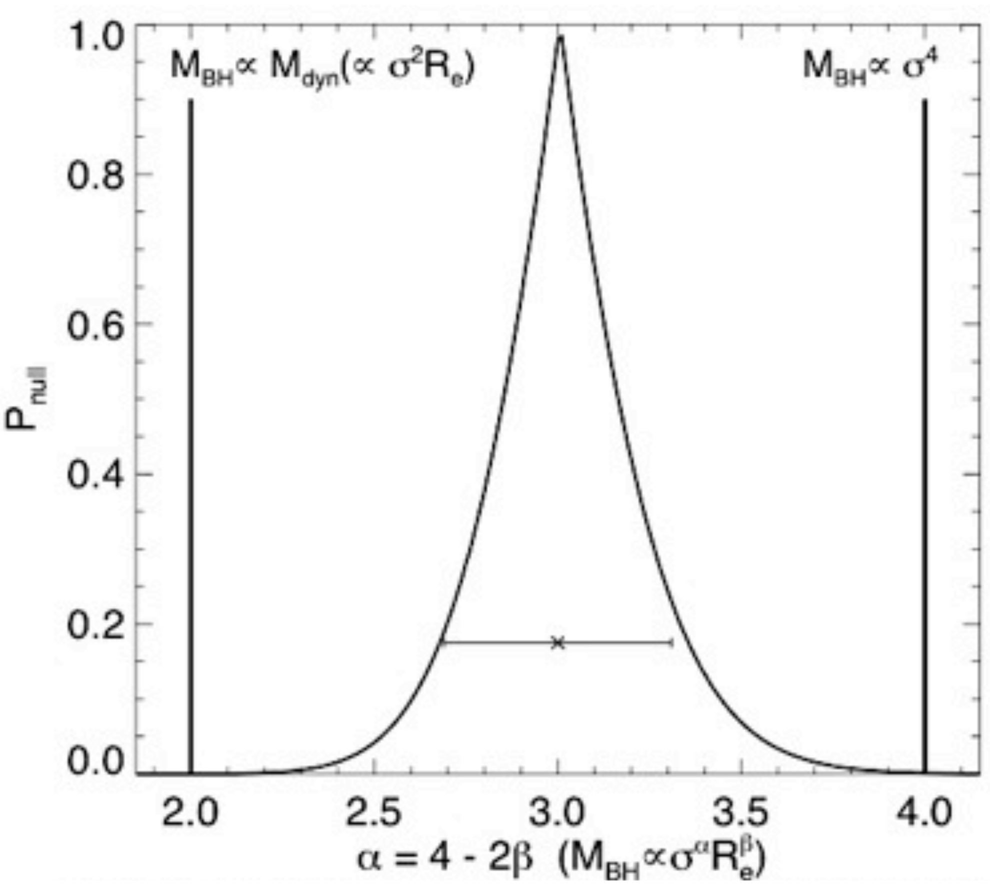
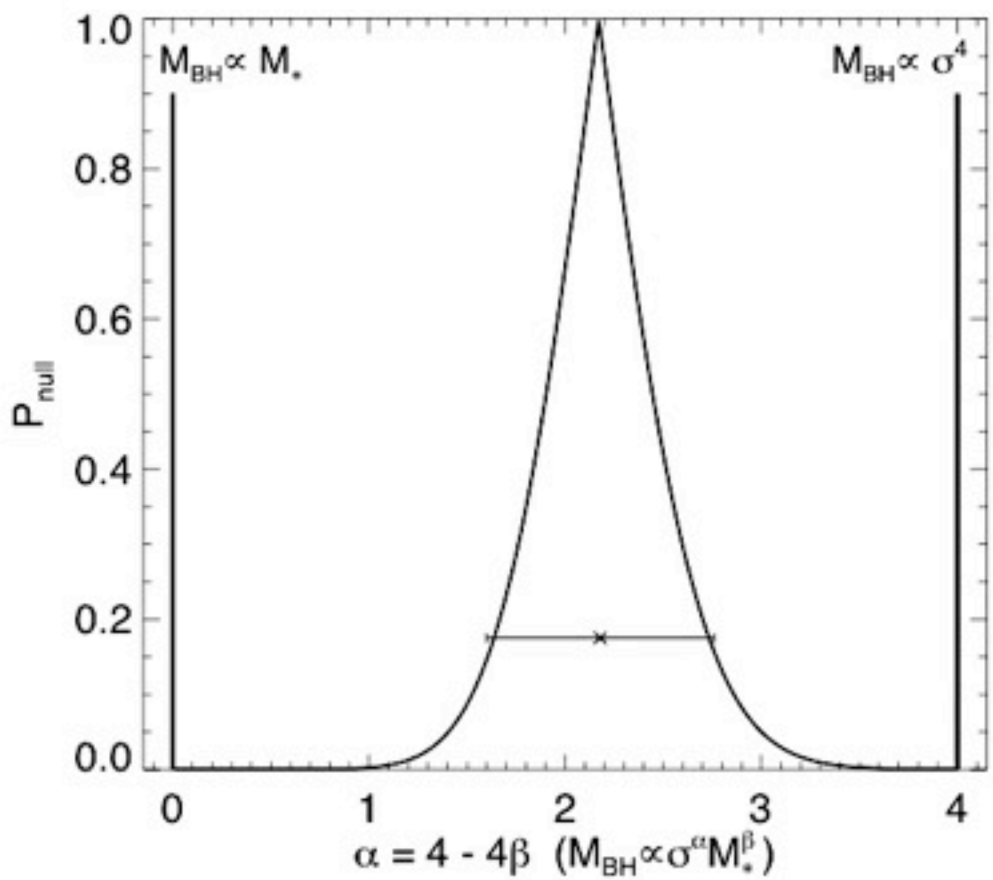
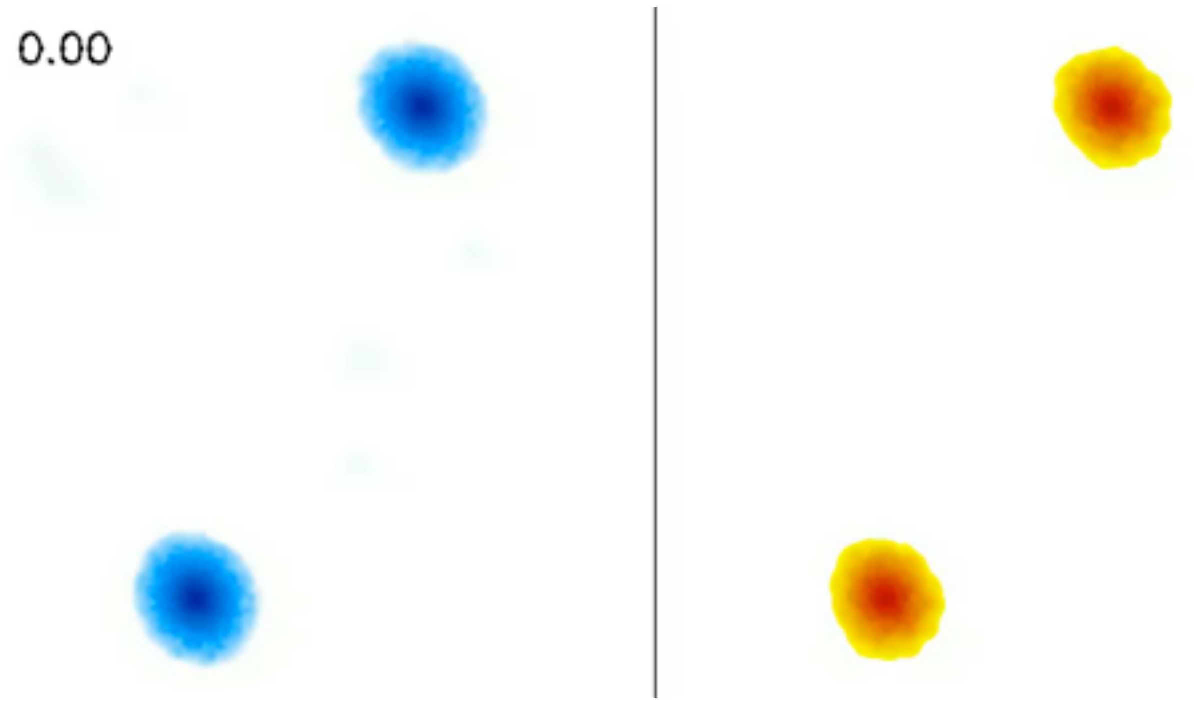




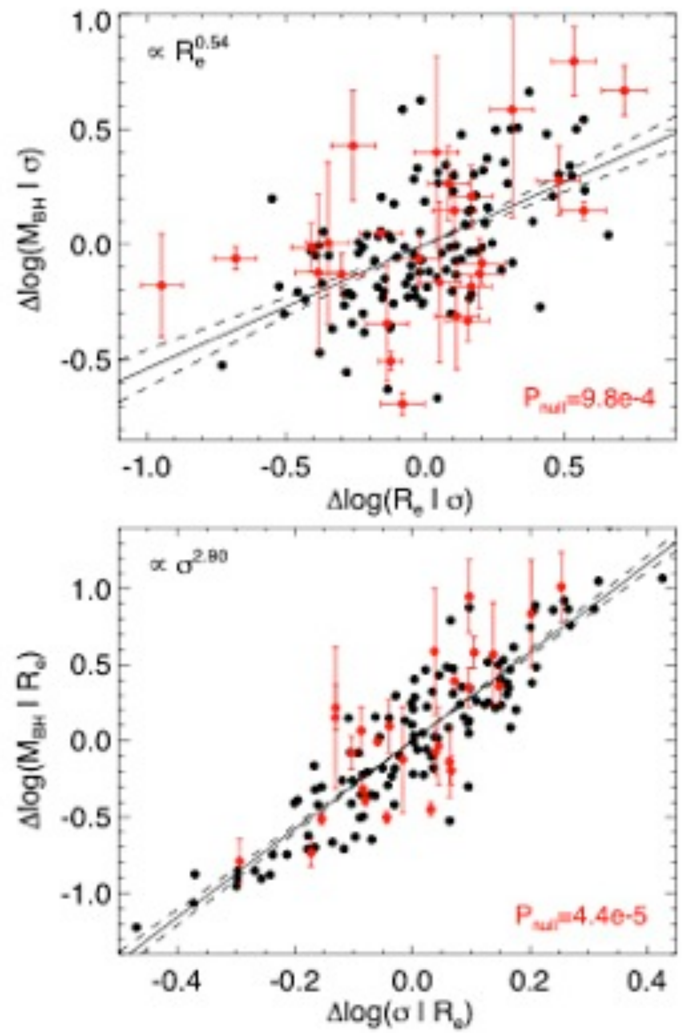
PFH et al. 2007

Observations & Simulations Suggest this Simple Picture Works

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



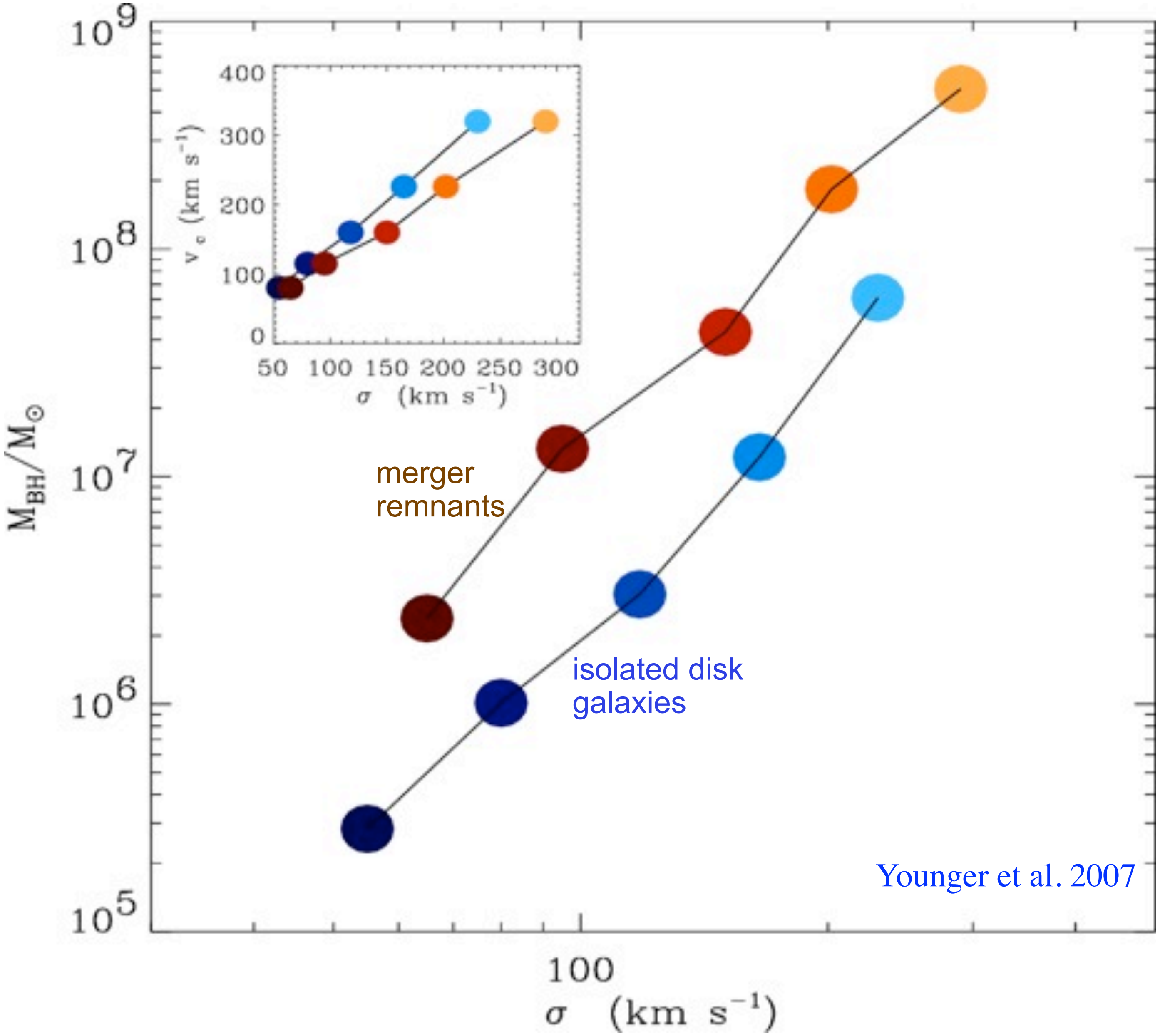
PFH et al. 2007



- 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?

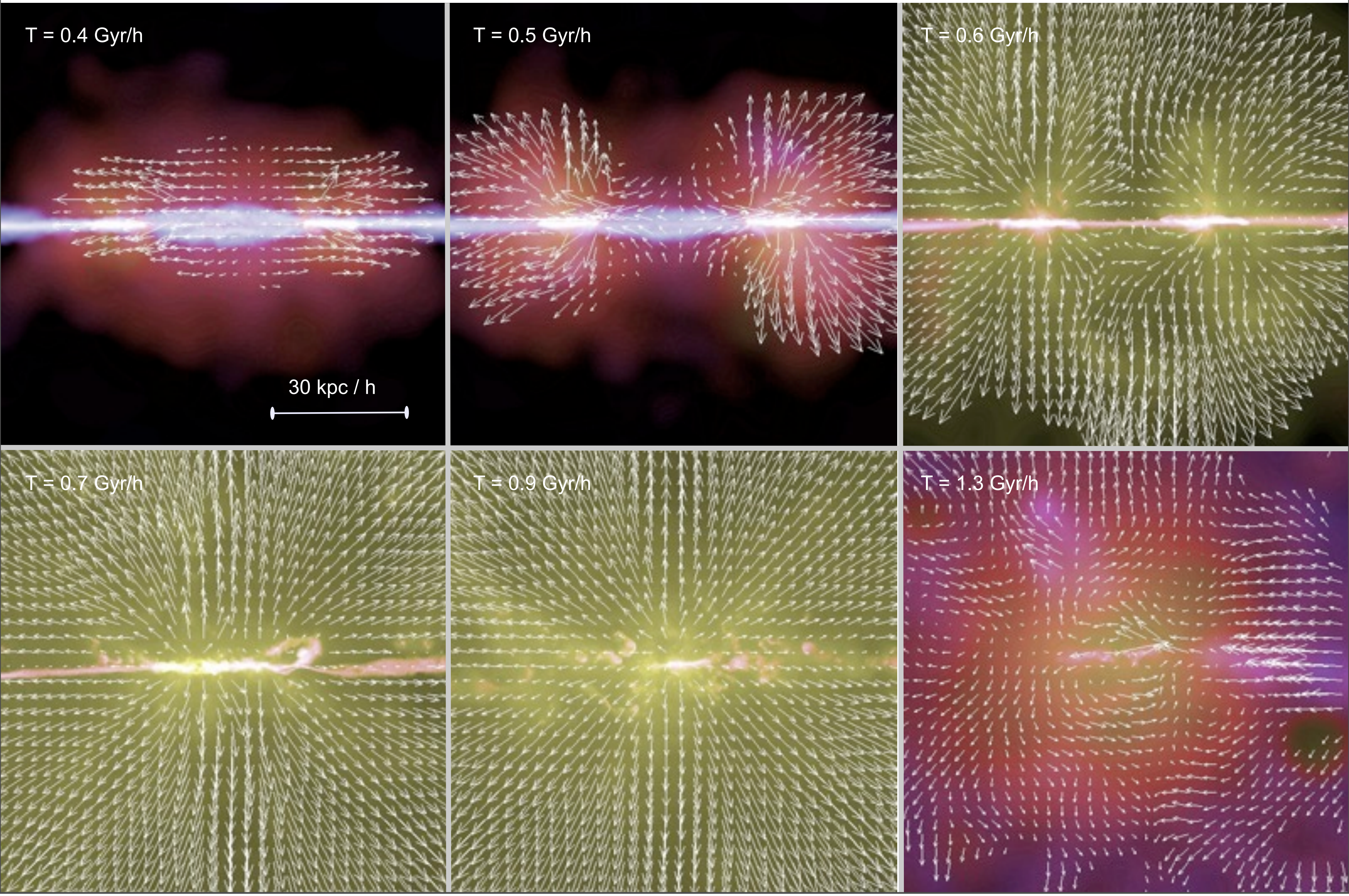
BLACK HOLE MASSES IN ISOLATED GALAXIES AND MERGER REMNANTS



Where Does the Energy/Momentum Go?

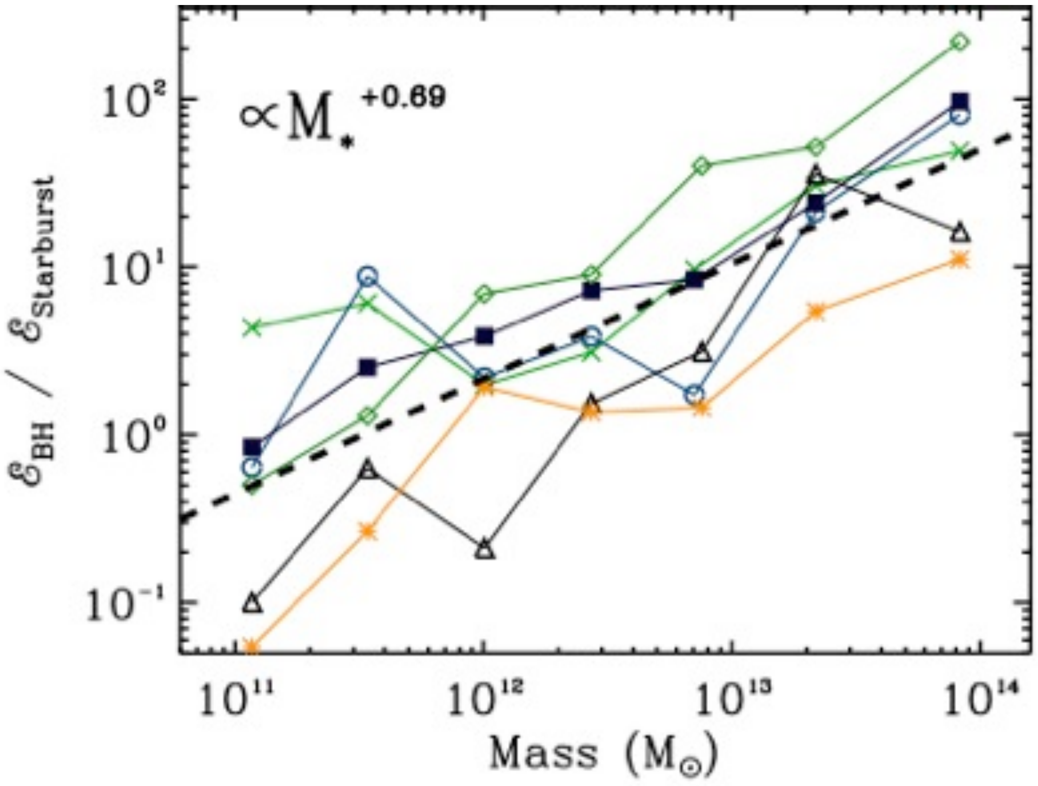
QUASAR-DRIVEN OUTFLOWS?

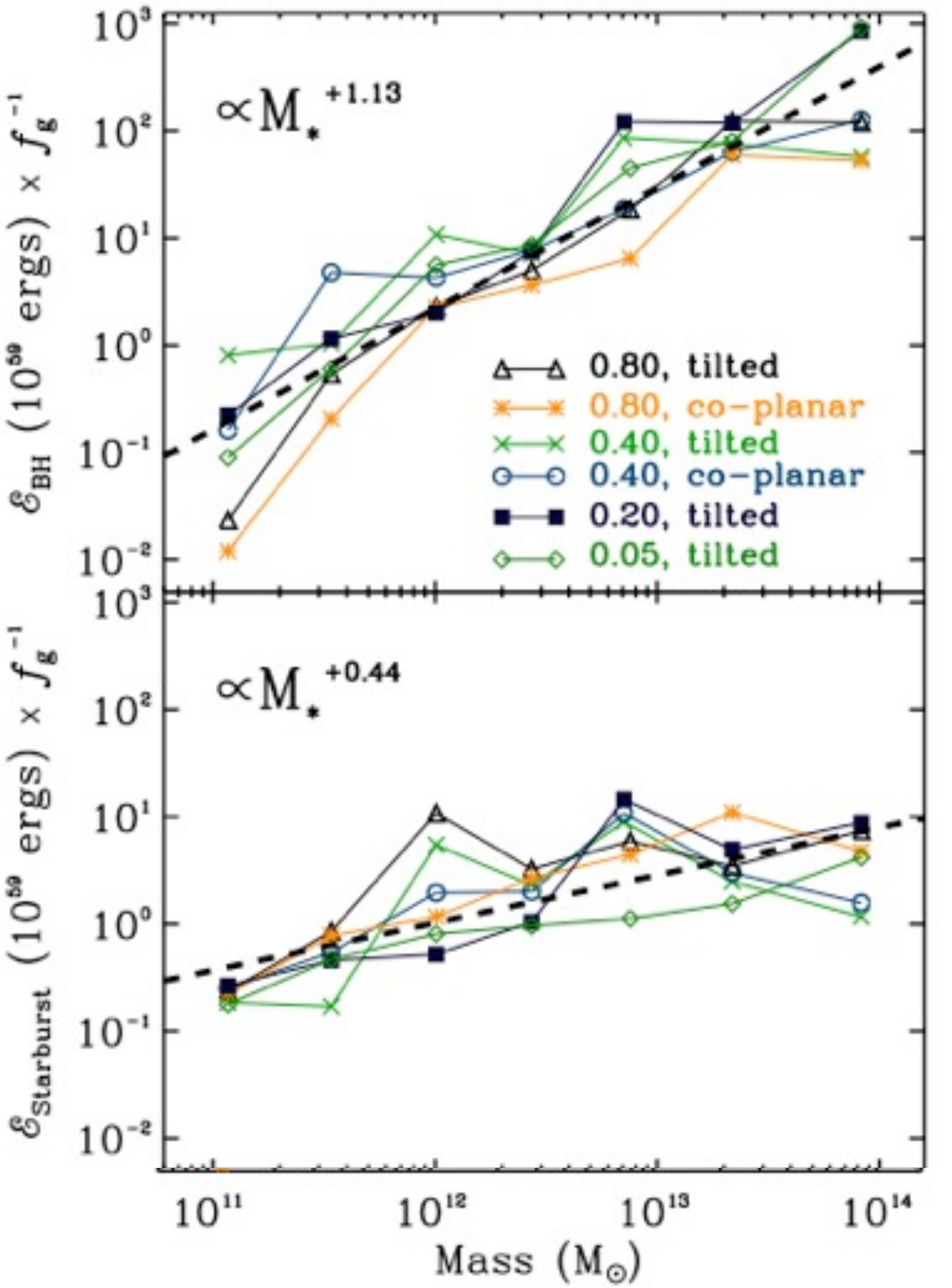
(outflow reaches speeds of up to ~1800 km/sec)



Feedback-Driven Winds

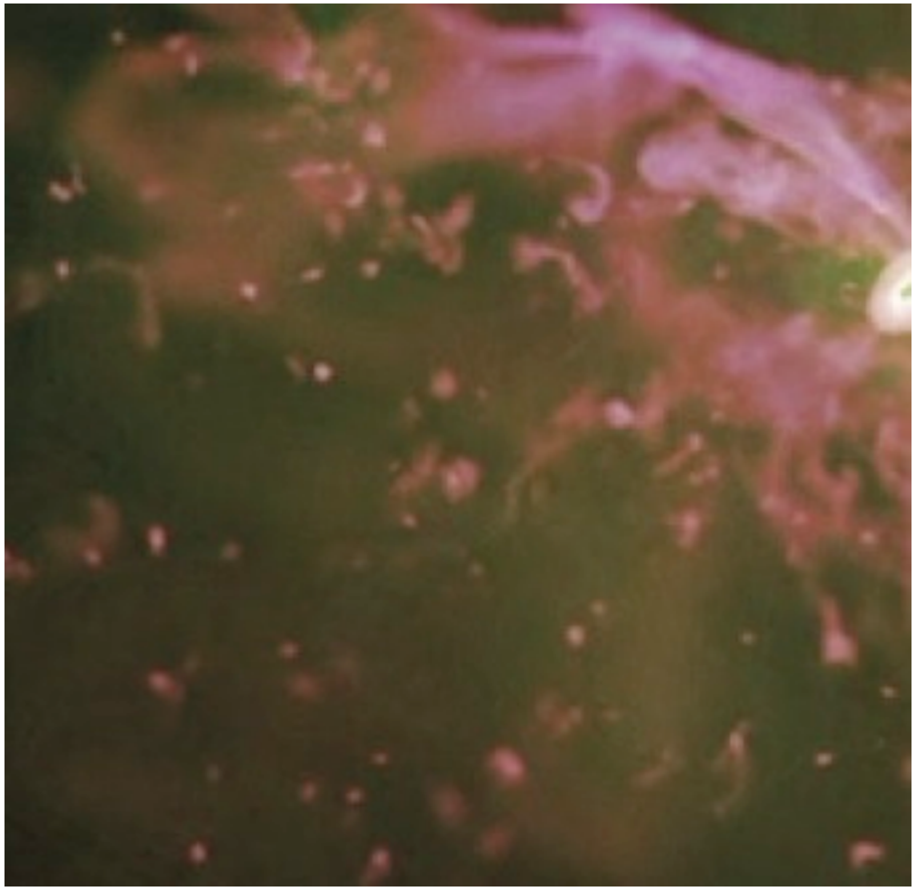
COMPARISON TO STARBURST-DRIVEN WINDS

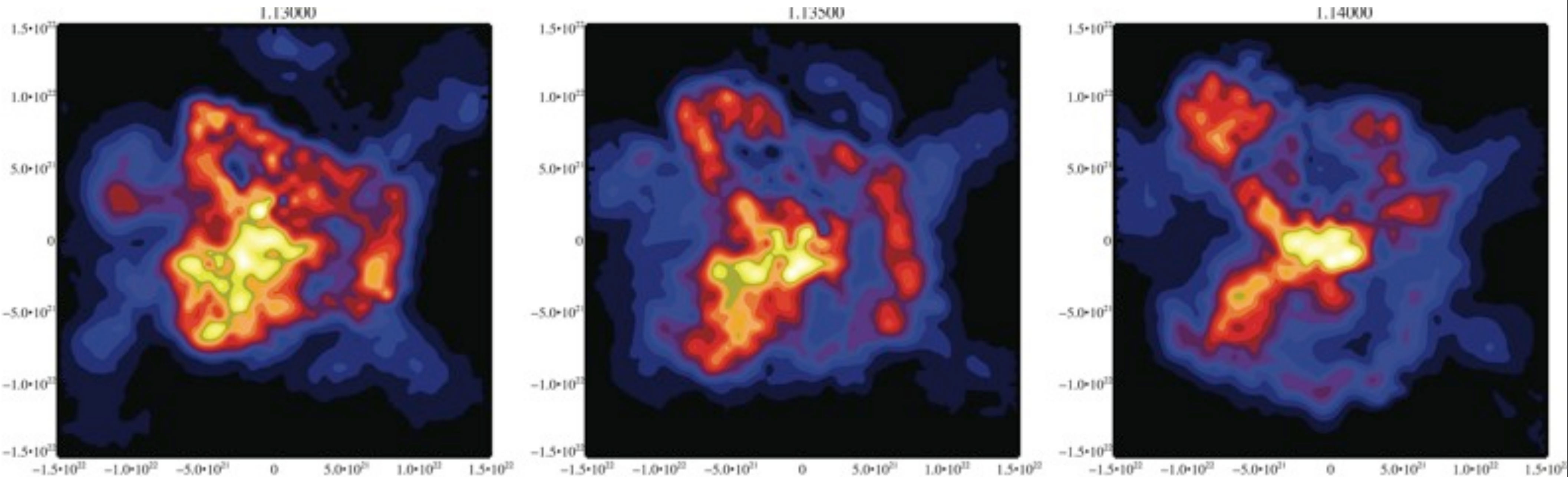




Outflows are Explosive and Clumpy

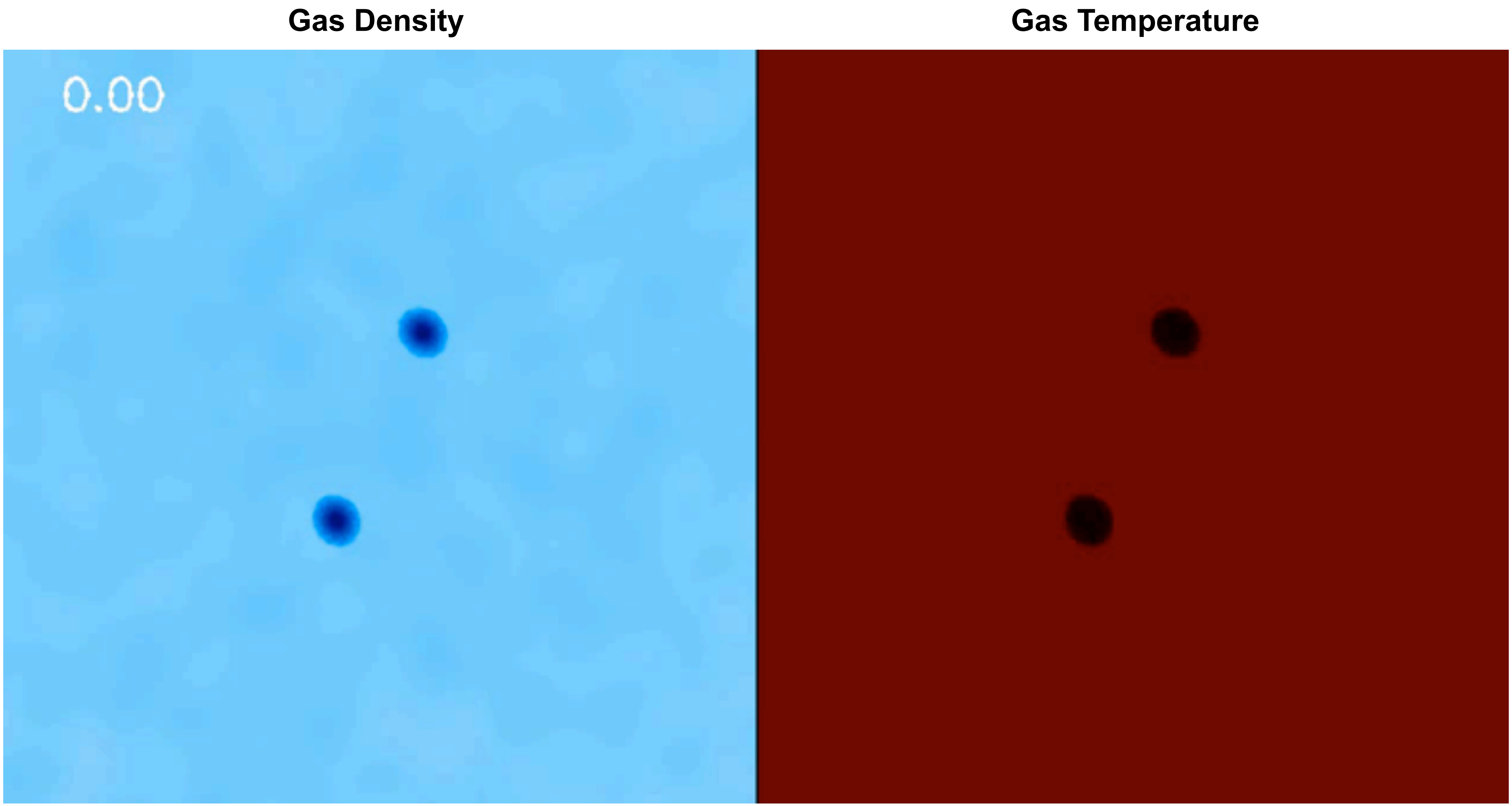
- Rapid BH growth => point-like injection
  - "Explosion-like", independent of coupling
- Clumpy
  - ULIRG cold/warm transition (S. Chakrabarti)
  - CO outflows (D. Narayanan)
- Cold shell (through galaxy)





Quasar Outflows May Be Significant for the ICM & IGM

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



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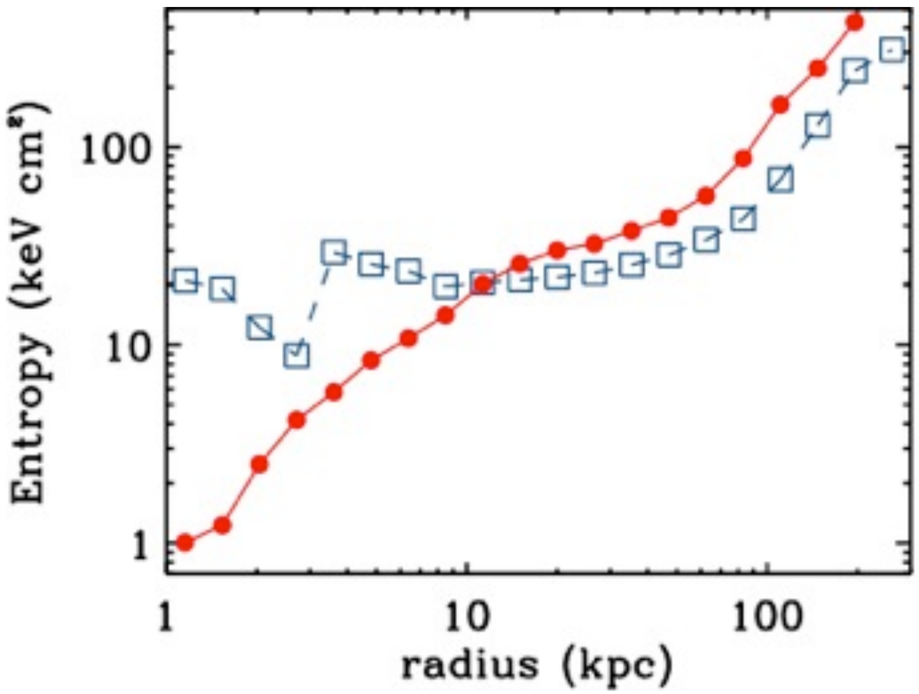
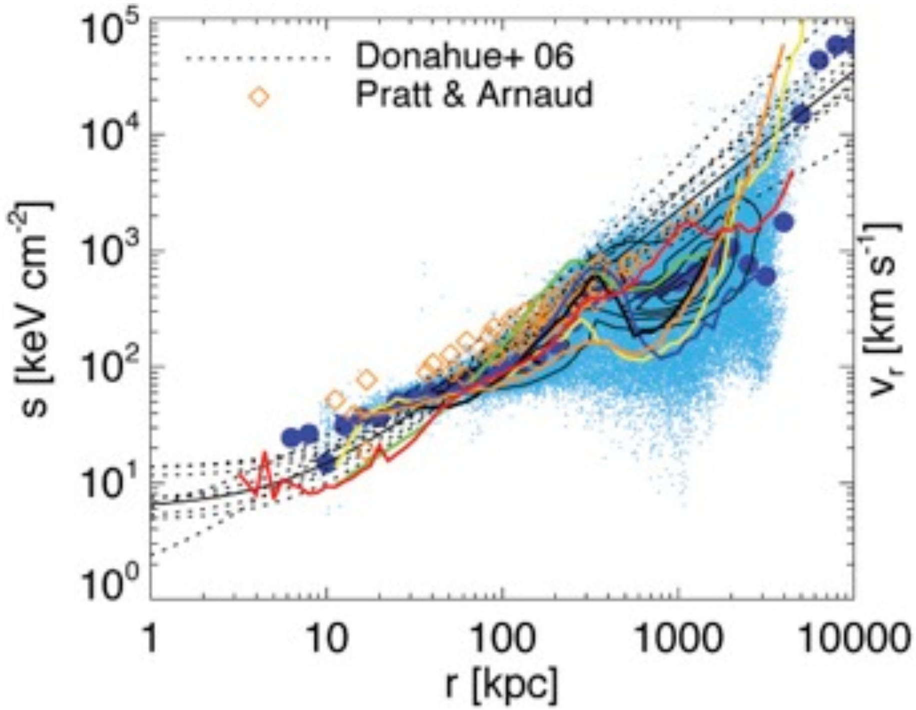
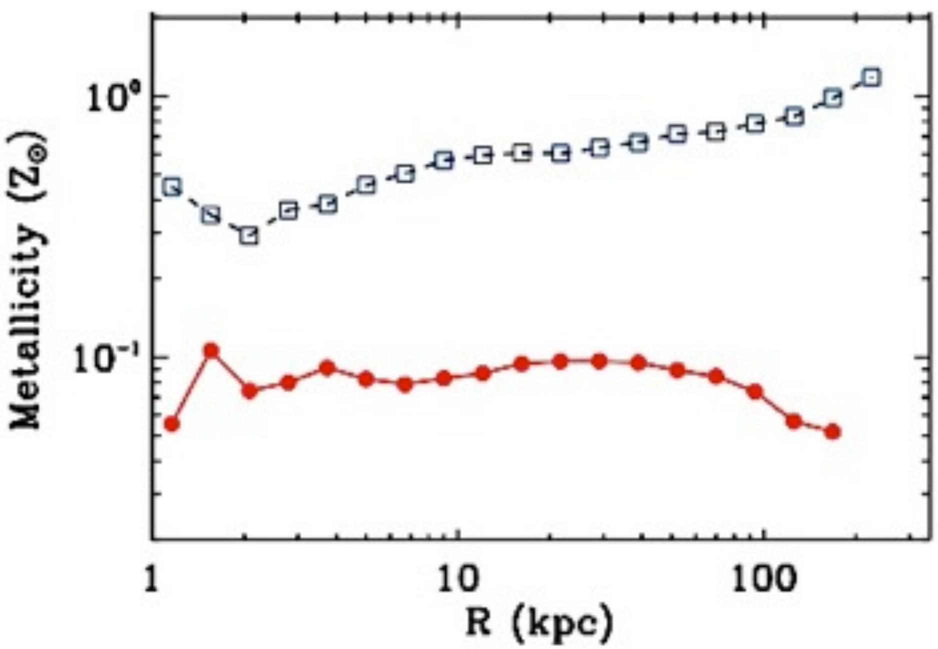
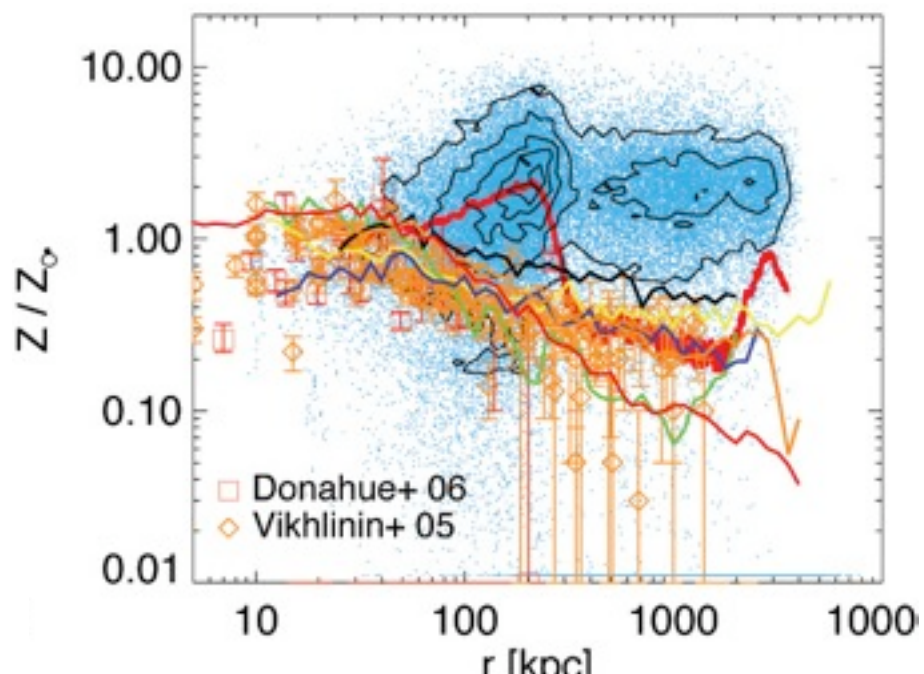


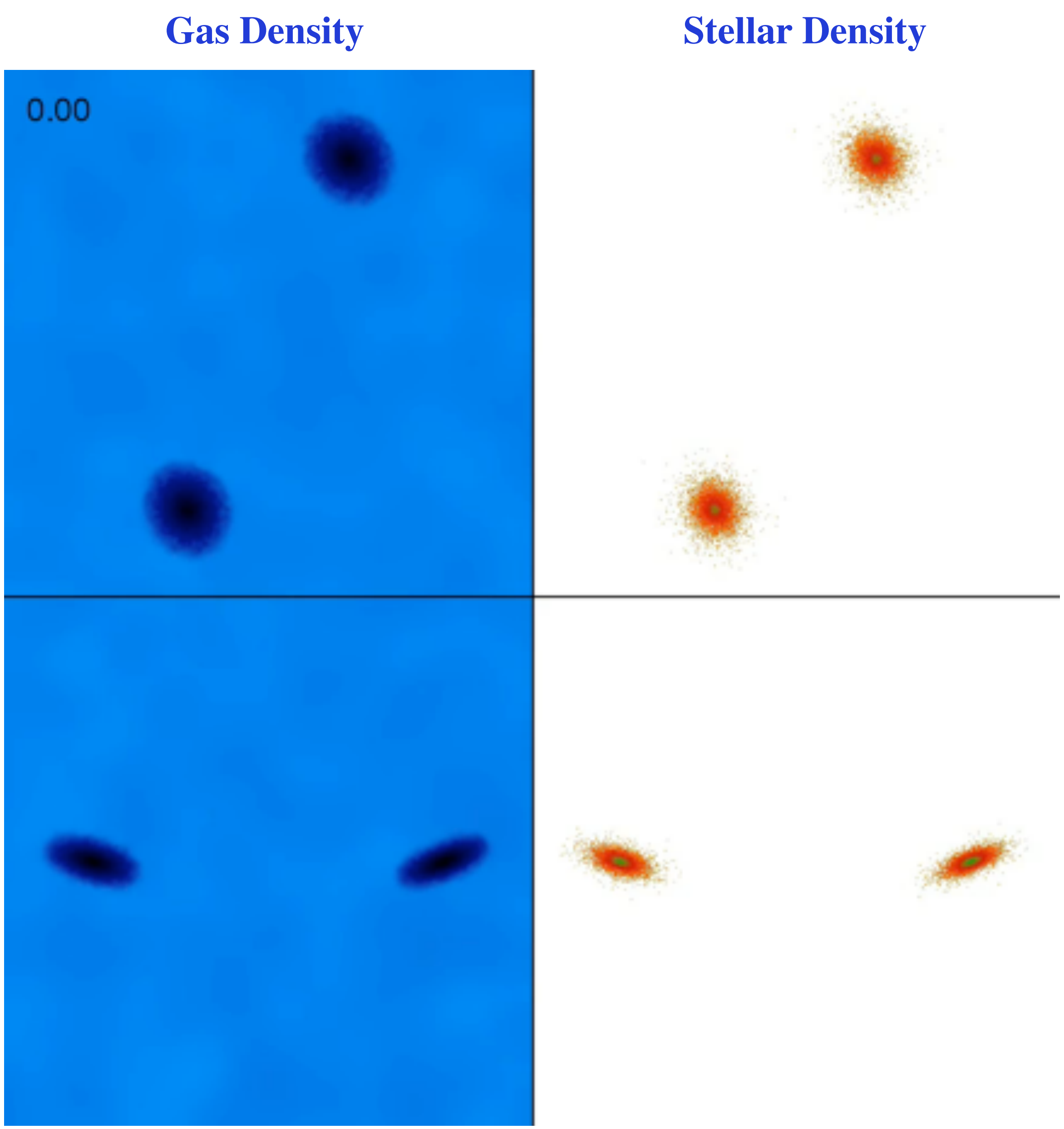


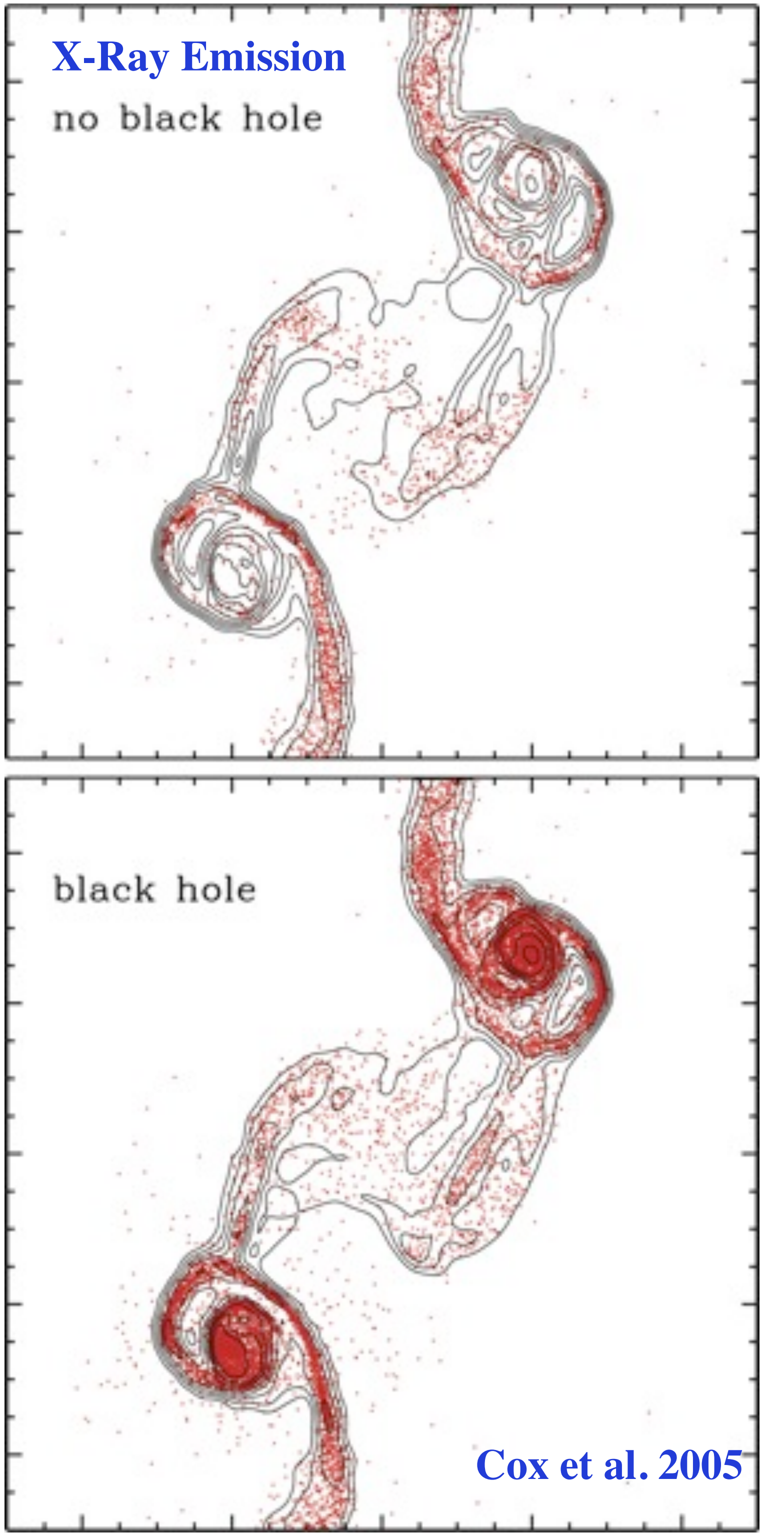




Feedback-Driven Winds

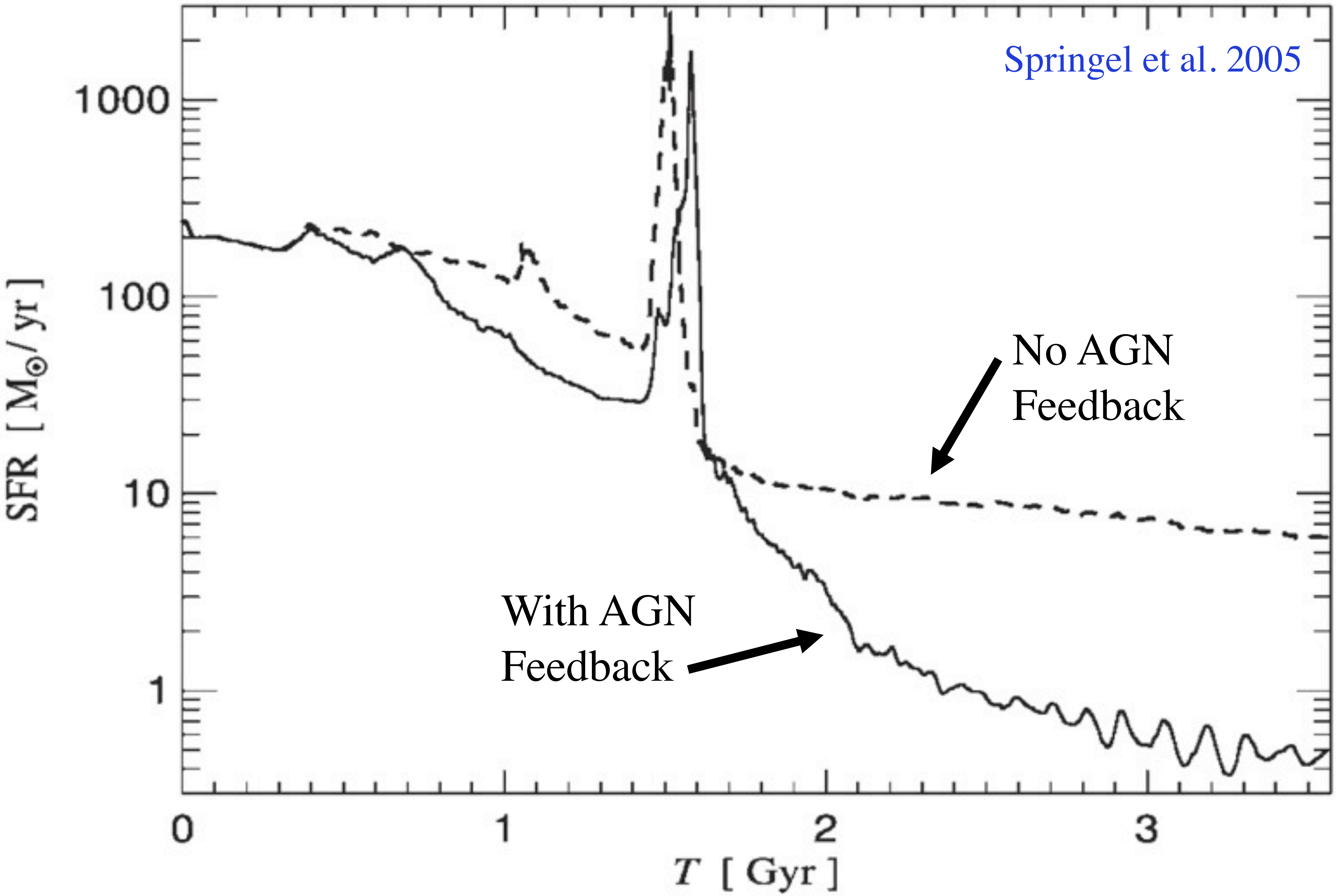
METAL ENRICHMENT & BUILDING THE X-RAY HALO





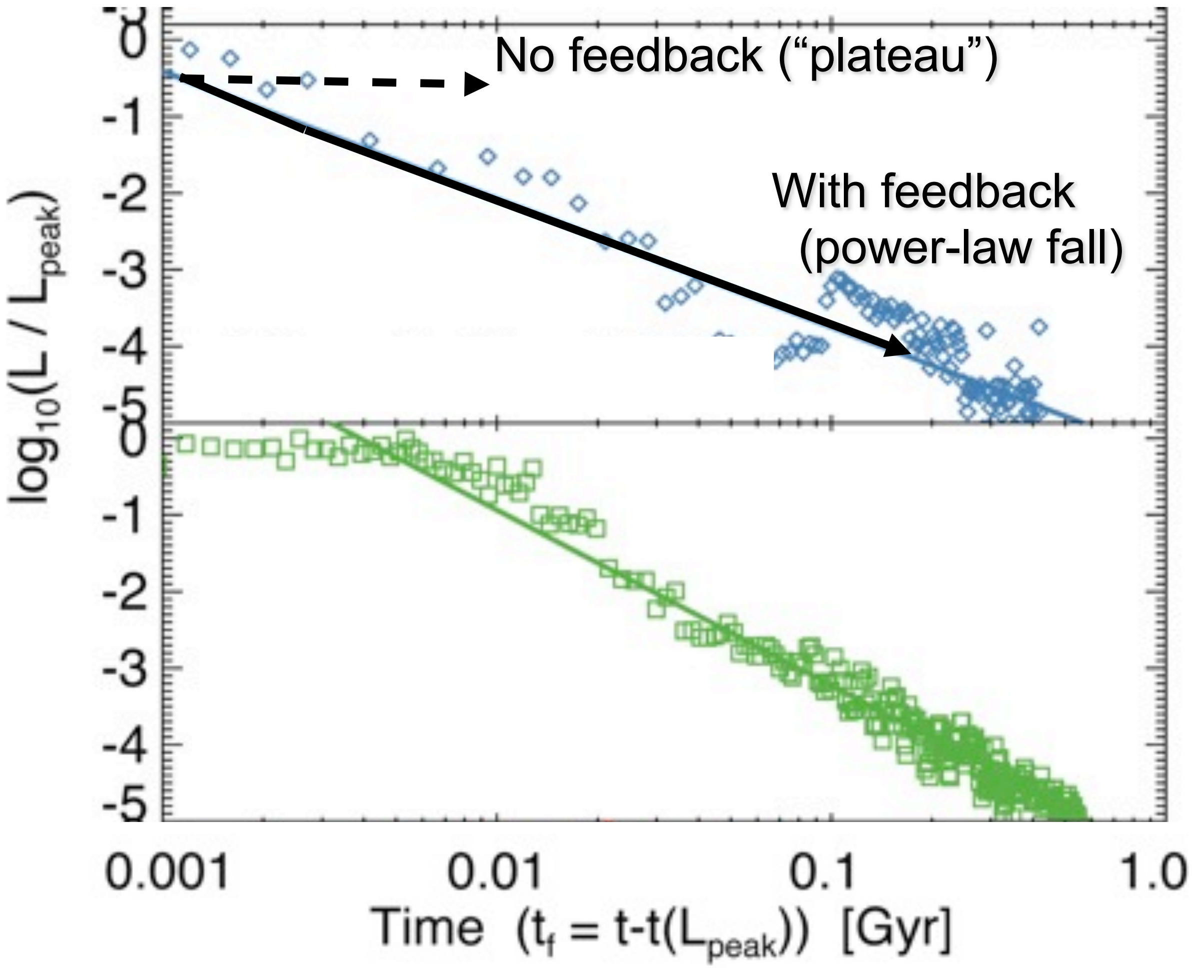
Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?



Quasar Light Curves & Lifetimes

- Feedback determines the decay of the quasar light curve:

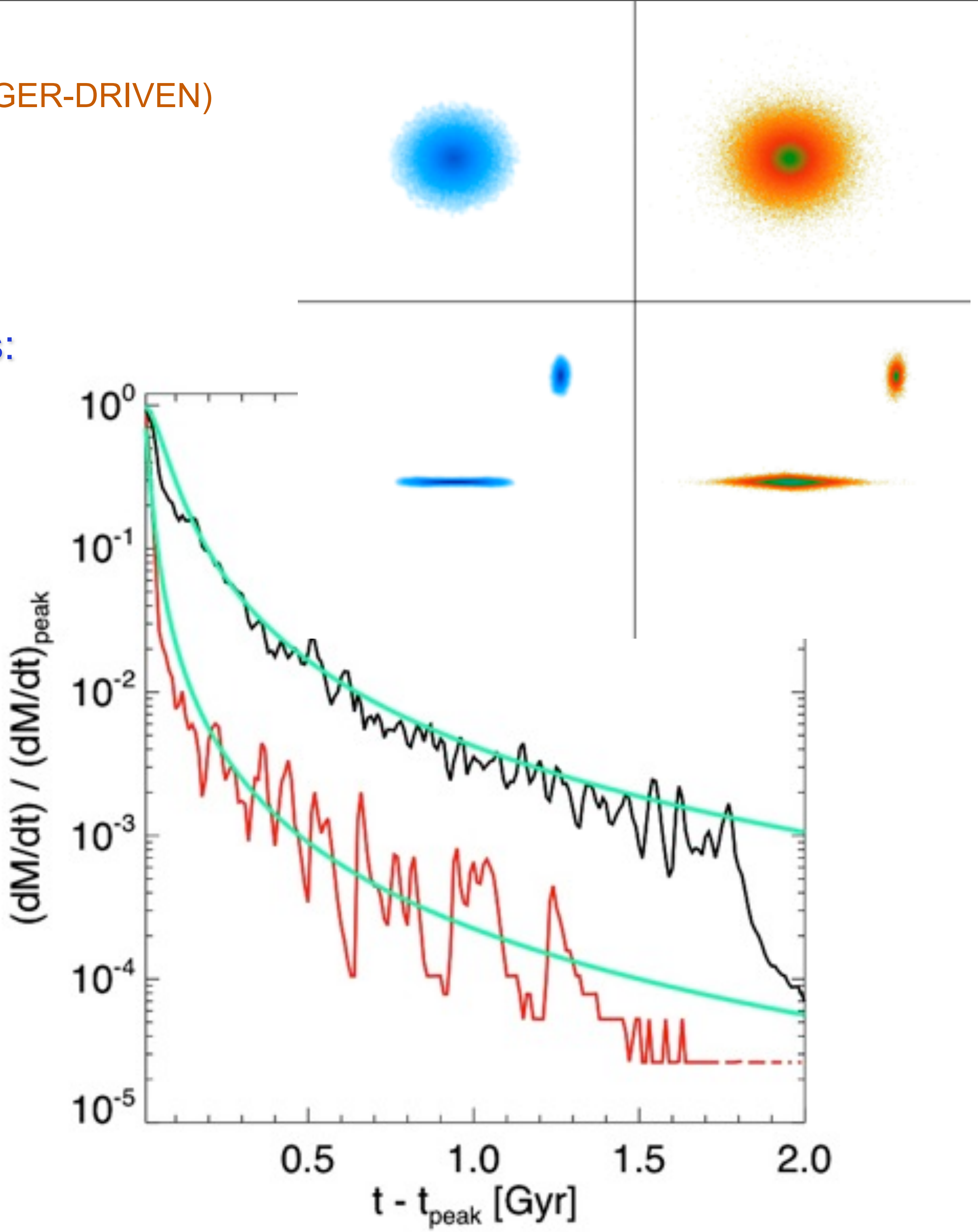


- Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)

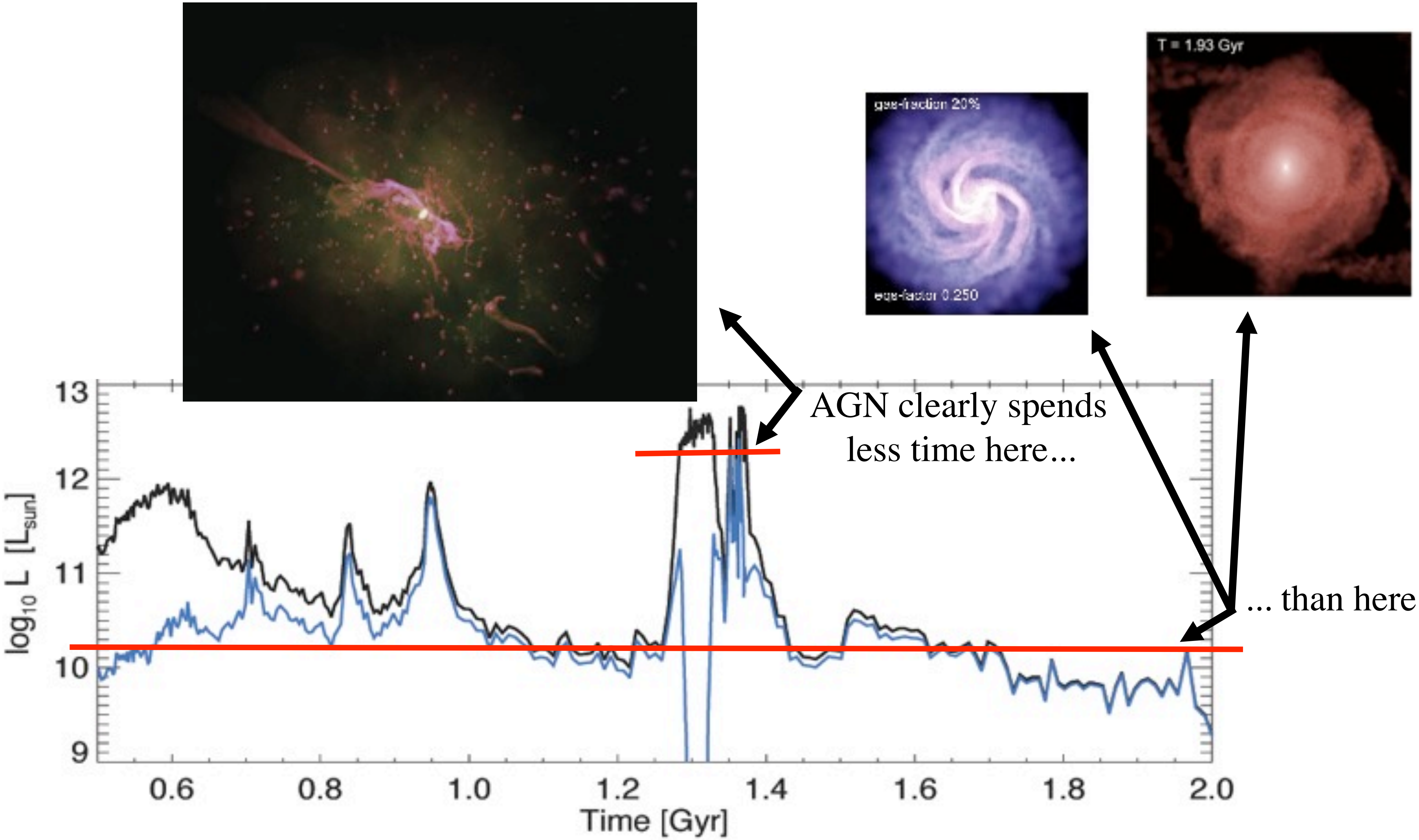
PFH et al. 2006a

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



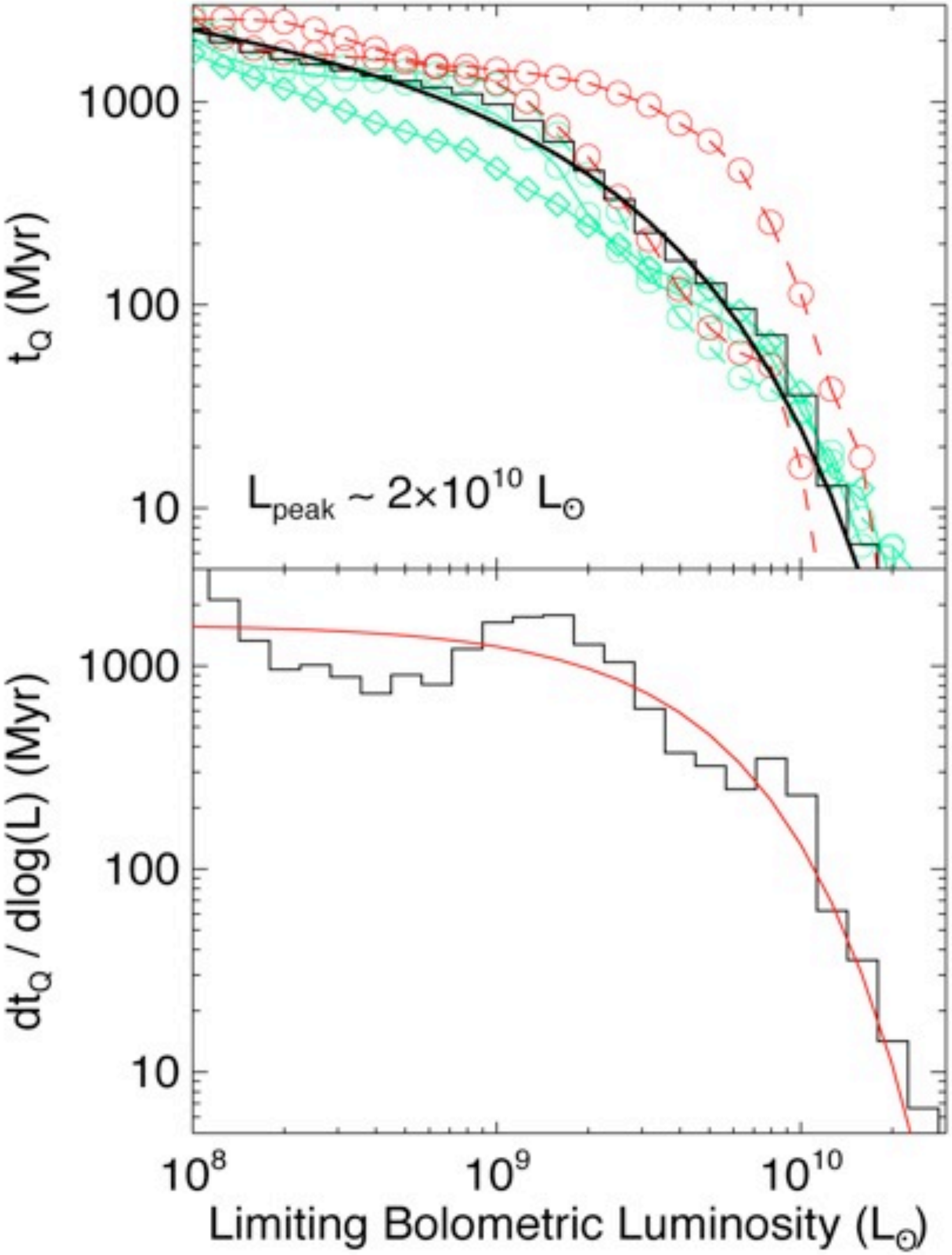
So What Is the “Quasar Lifetime”?



- “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

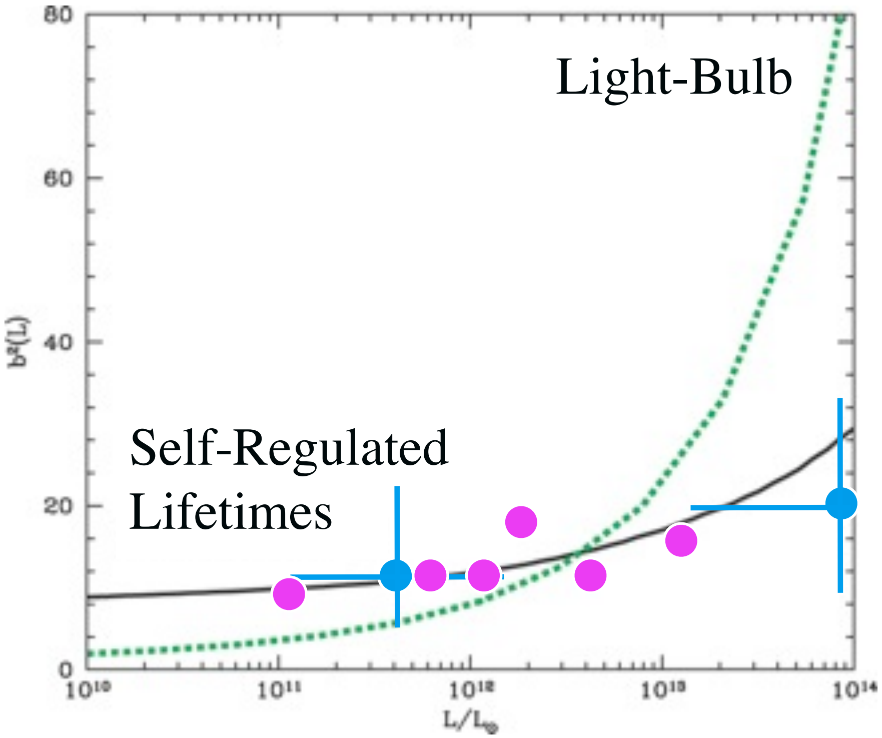


- "Quasar Lifetime": a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity

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

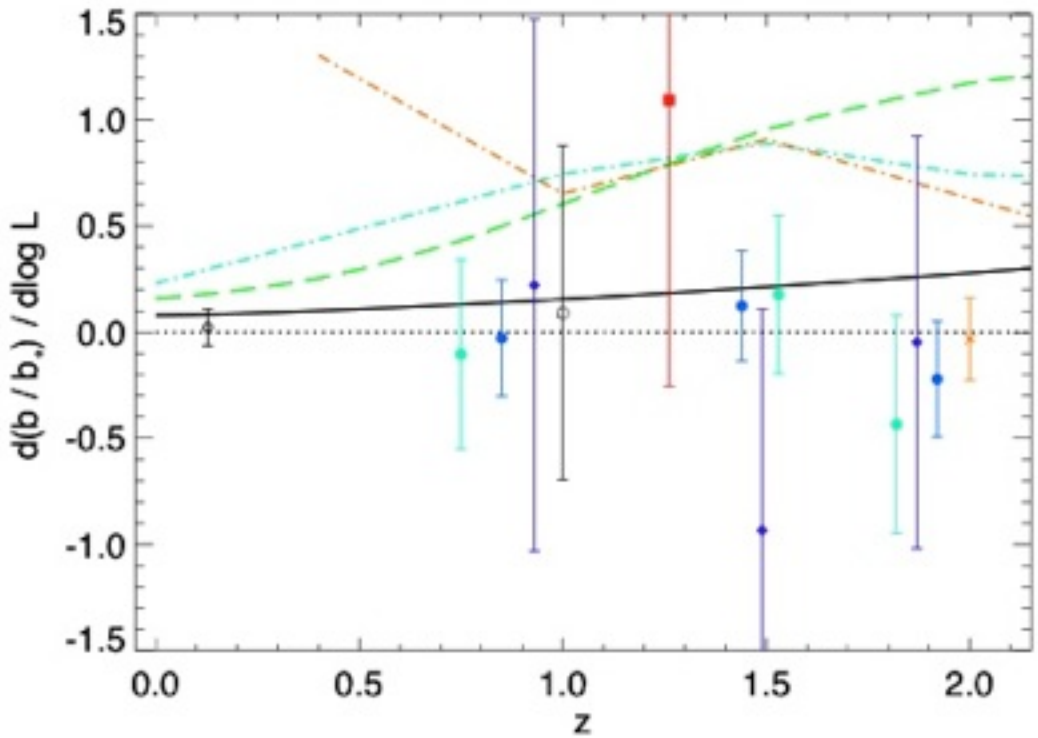


● Adelberger & Steidel 05

● Myers et al. 05

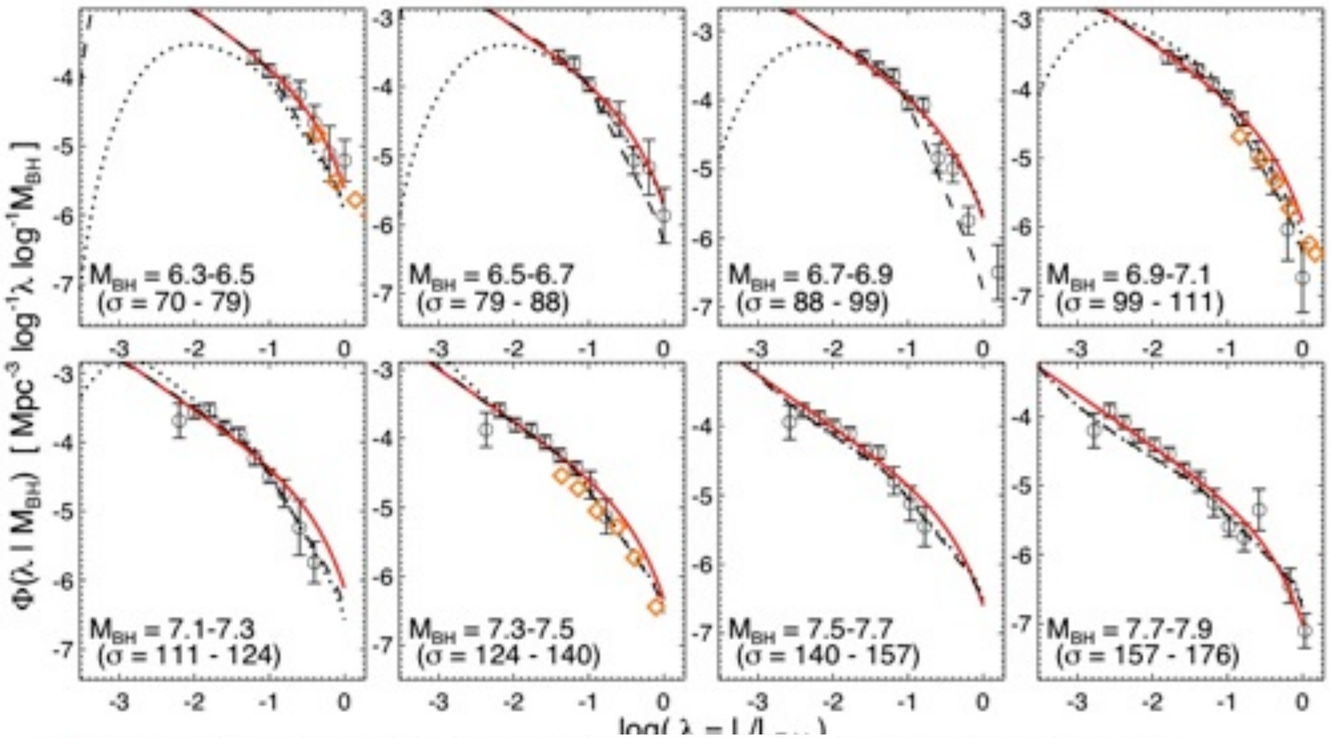
Lidz et al. 2005

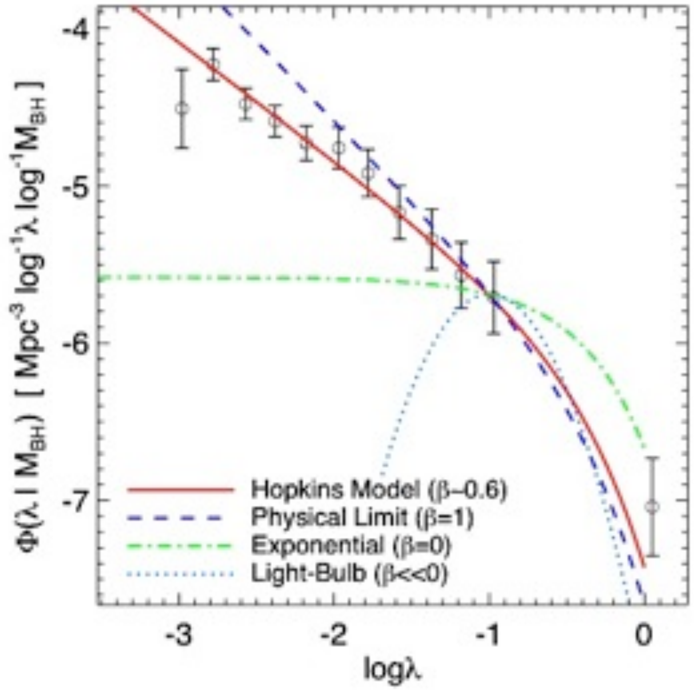
- Weak dependence of clustering on observed luminosity
  - (Croom et al., Adelberger & Steidel, Myers et al., Coil et al., Porciani et al.)

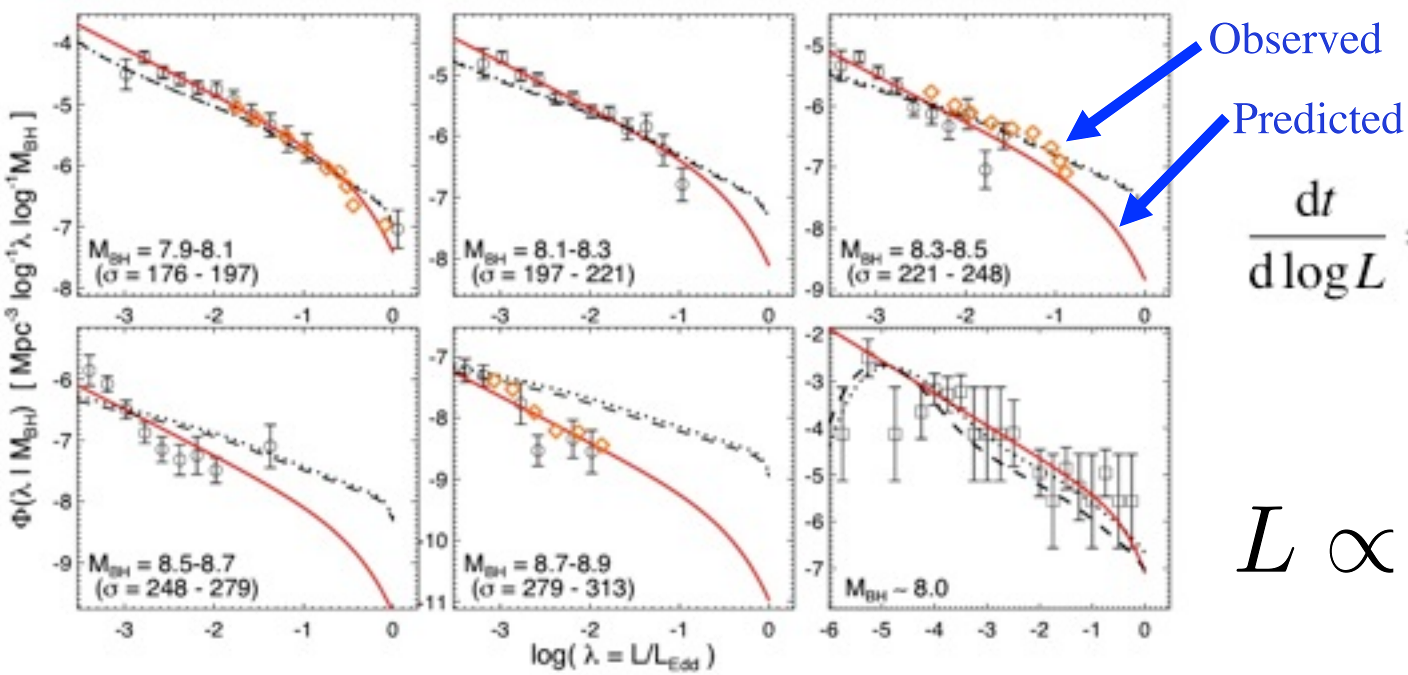


Hopkins, Lidz, Coil, Myers et al. 2007

Directly Apparent in the Observed Eddington Ratio Distribution



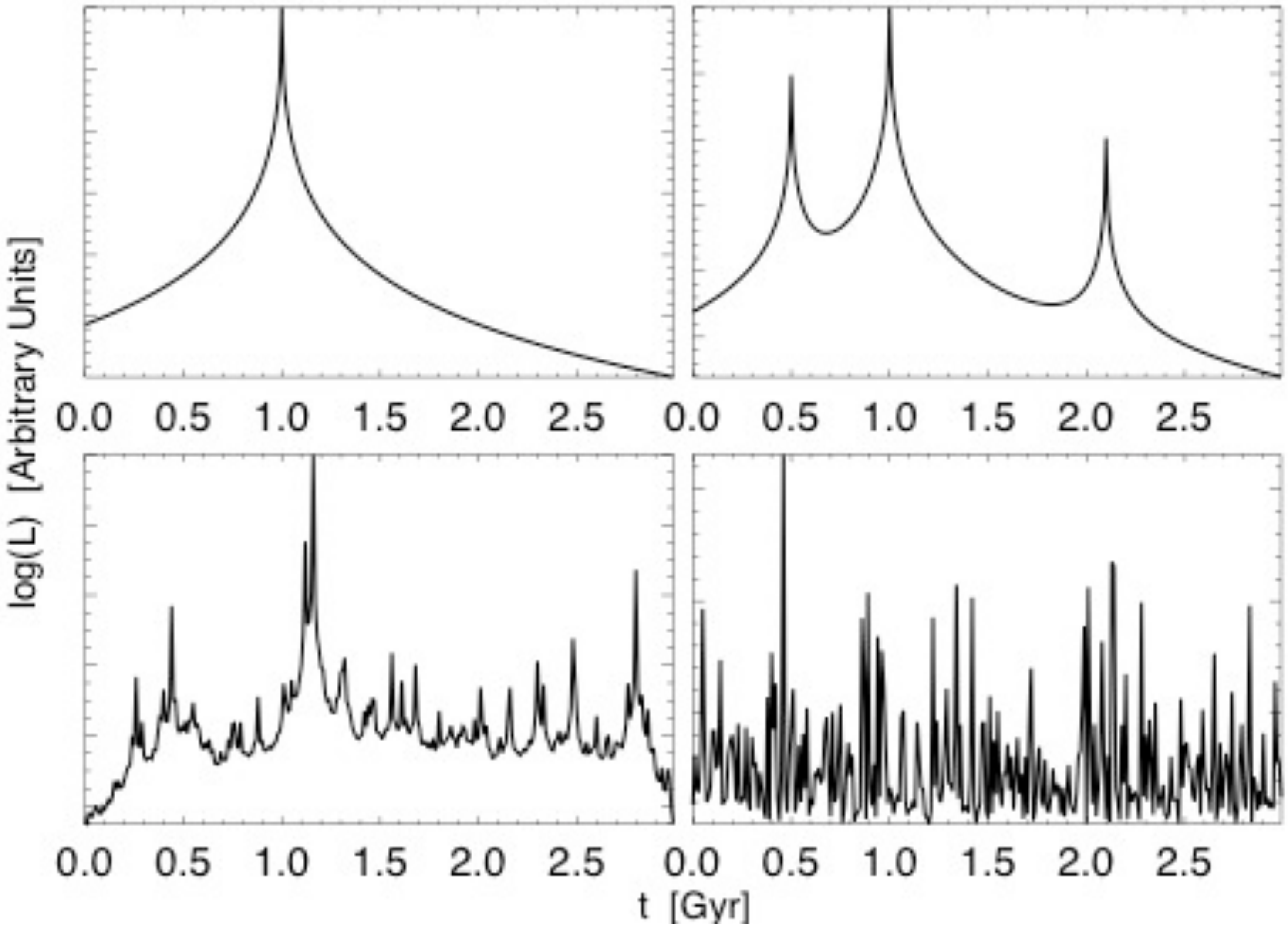




$$\frac{dt}{d\log L} = t_0 \left(\frac{L}{L_{peak}}\right)^{-\beta} \exp\left(-L/L_{peak}\right)$$

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

Directly Apparent in the Observed Eddington Ratio Distribution



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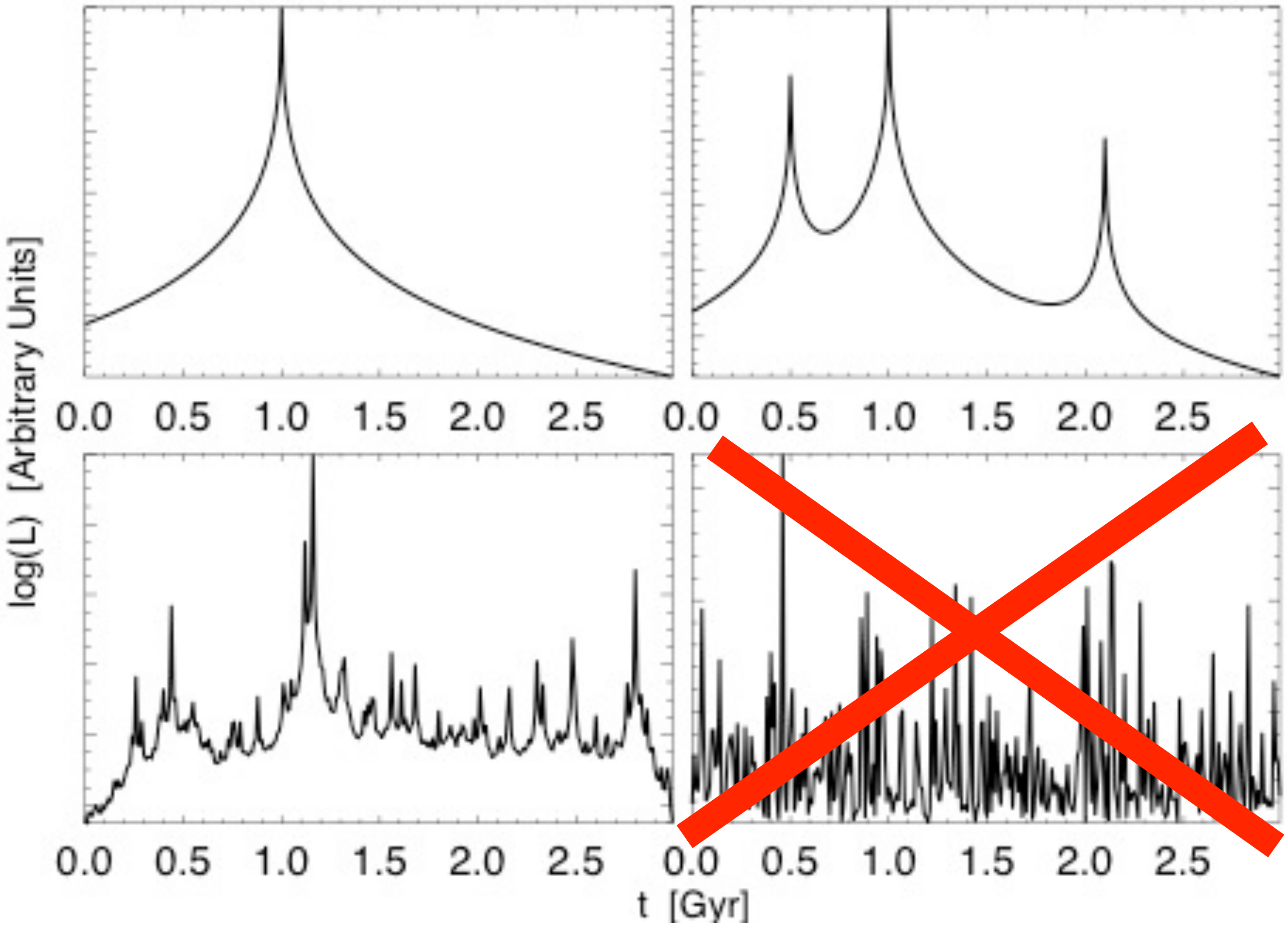


Ruled out by transverse proximity effect

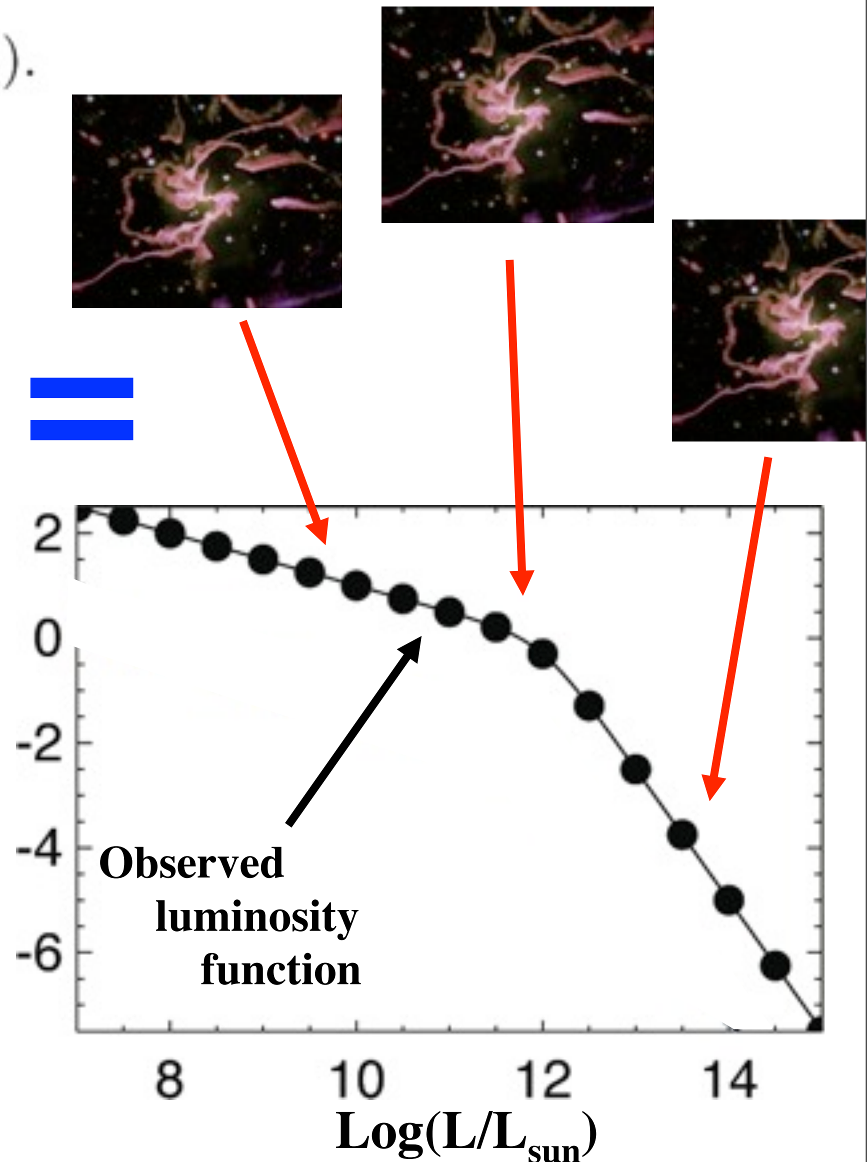
$t_{episodic} \sim t_{total}$

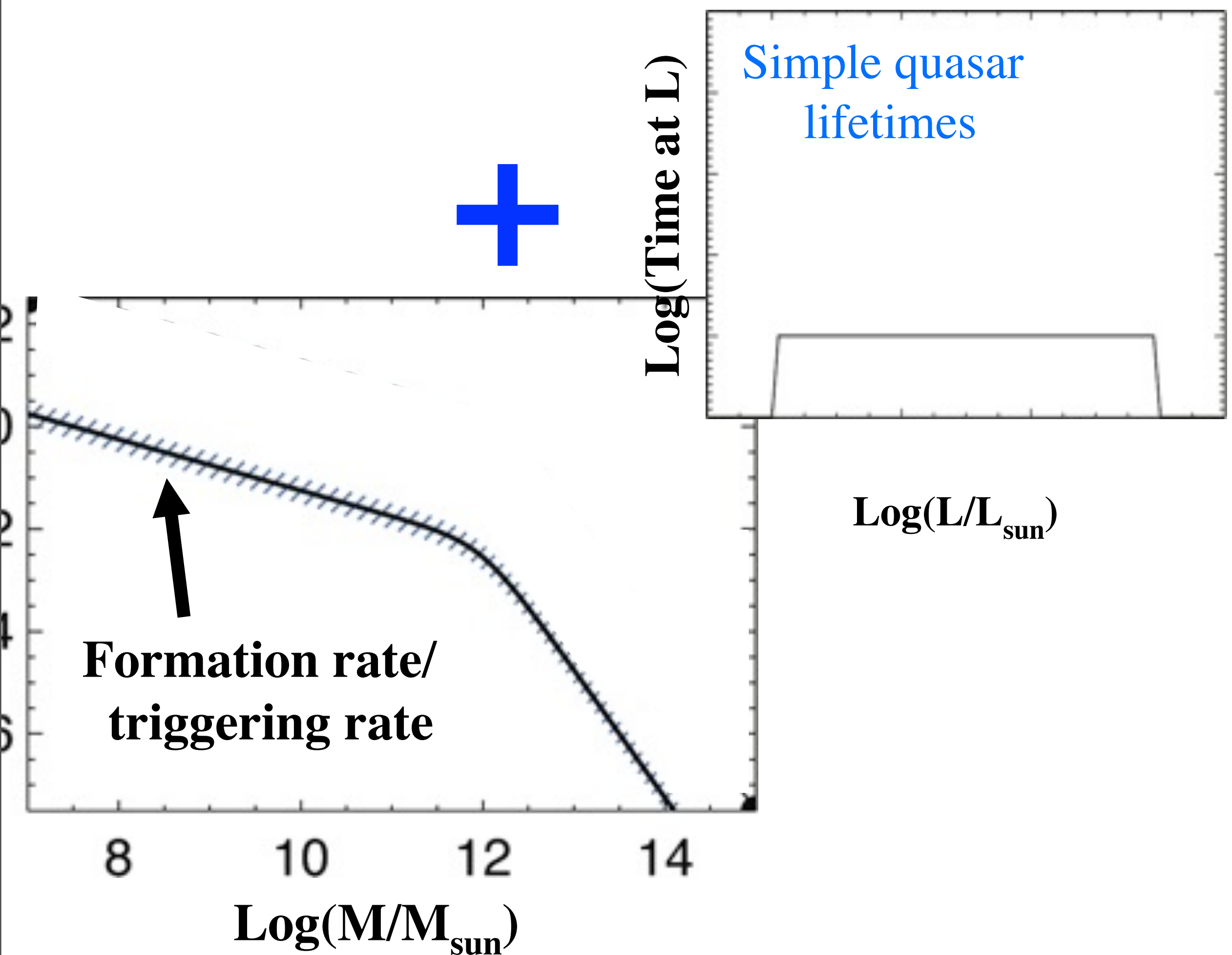
$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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

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





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

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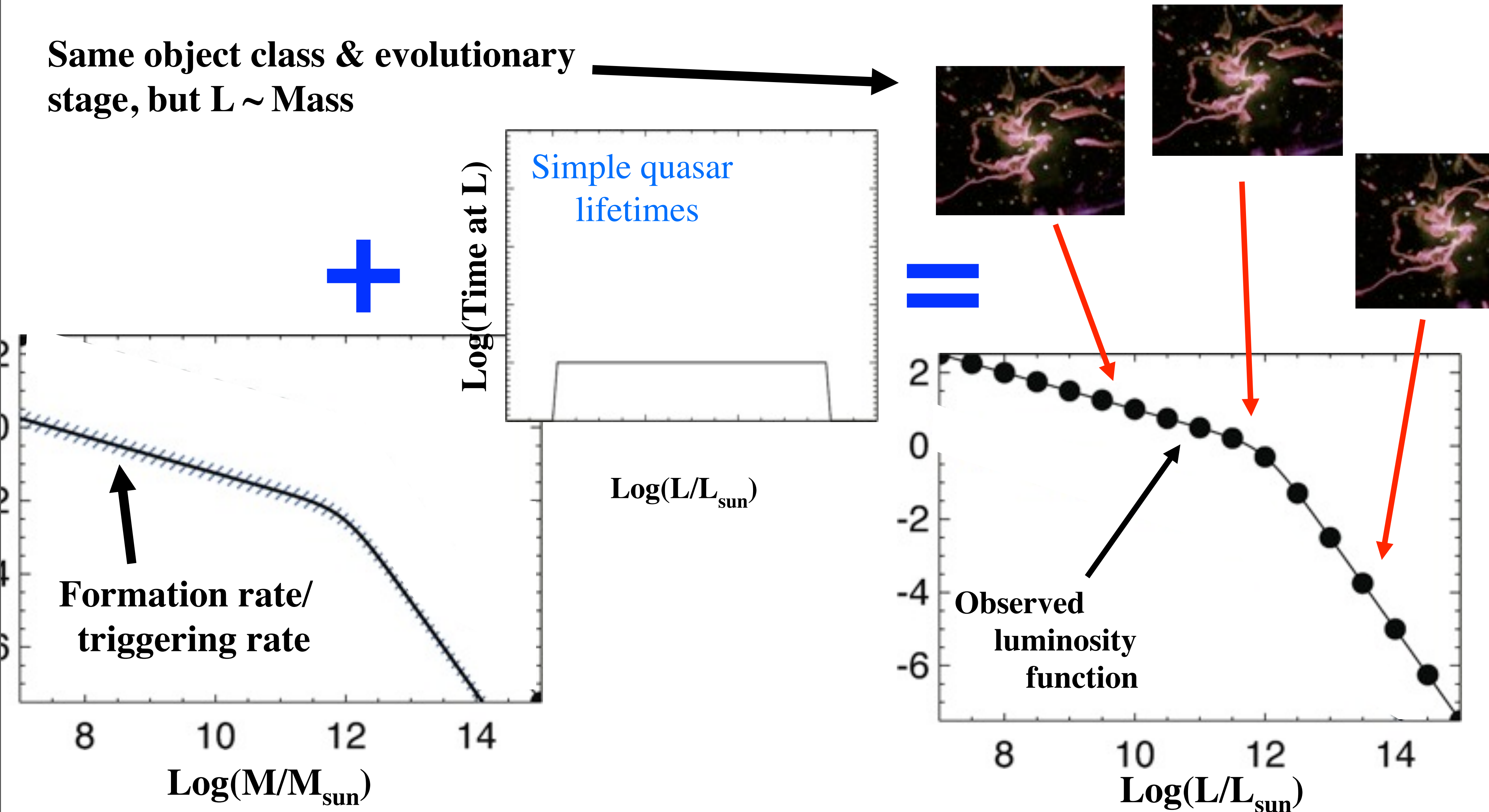
QUANTIFIED IN THIS MANNER, UNIQUELY DETERMINES THE RATE OF “TRIGGERING”



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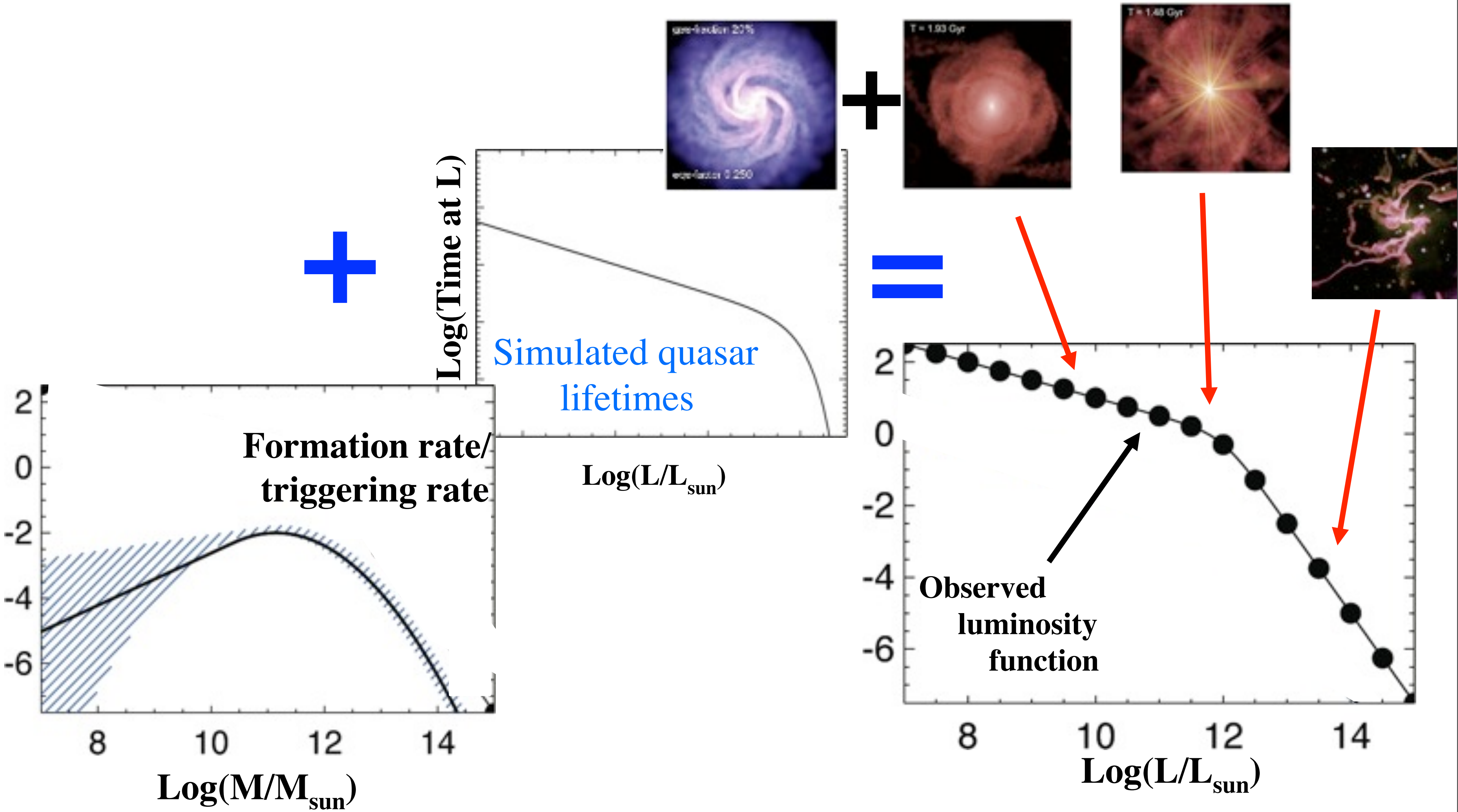
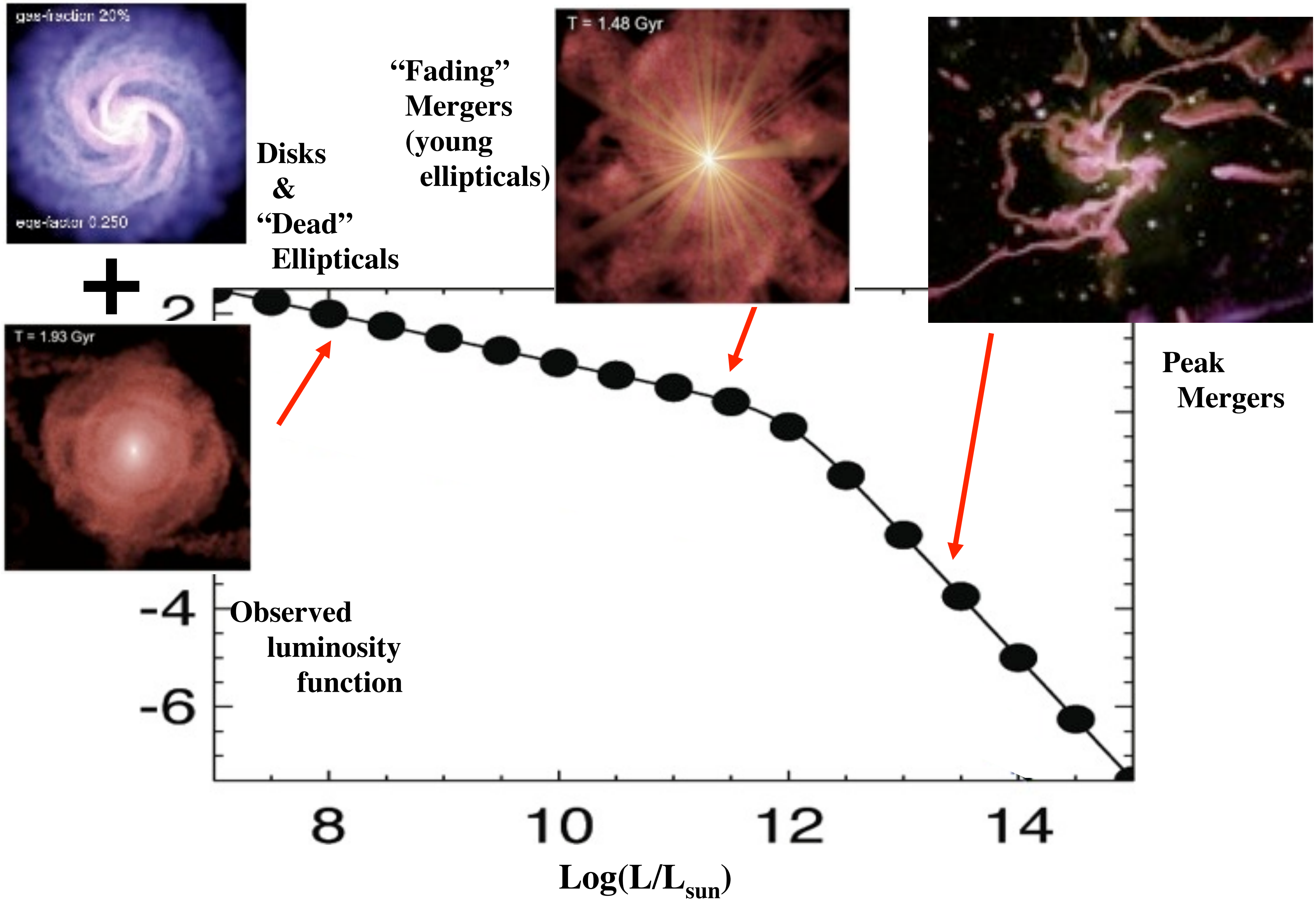


- *Different* shapes
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts



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

Summary

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

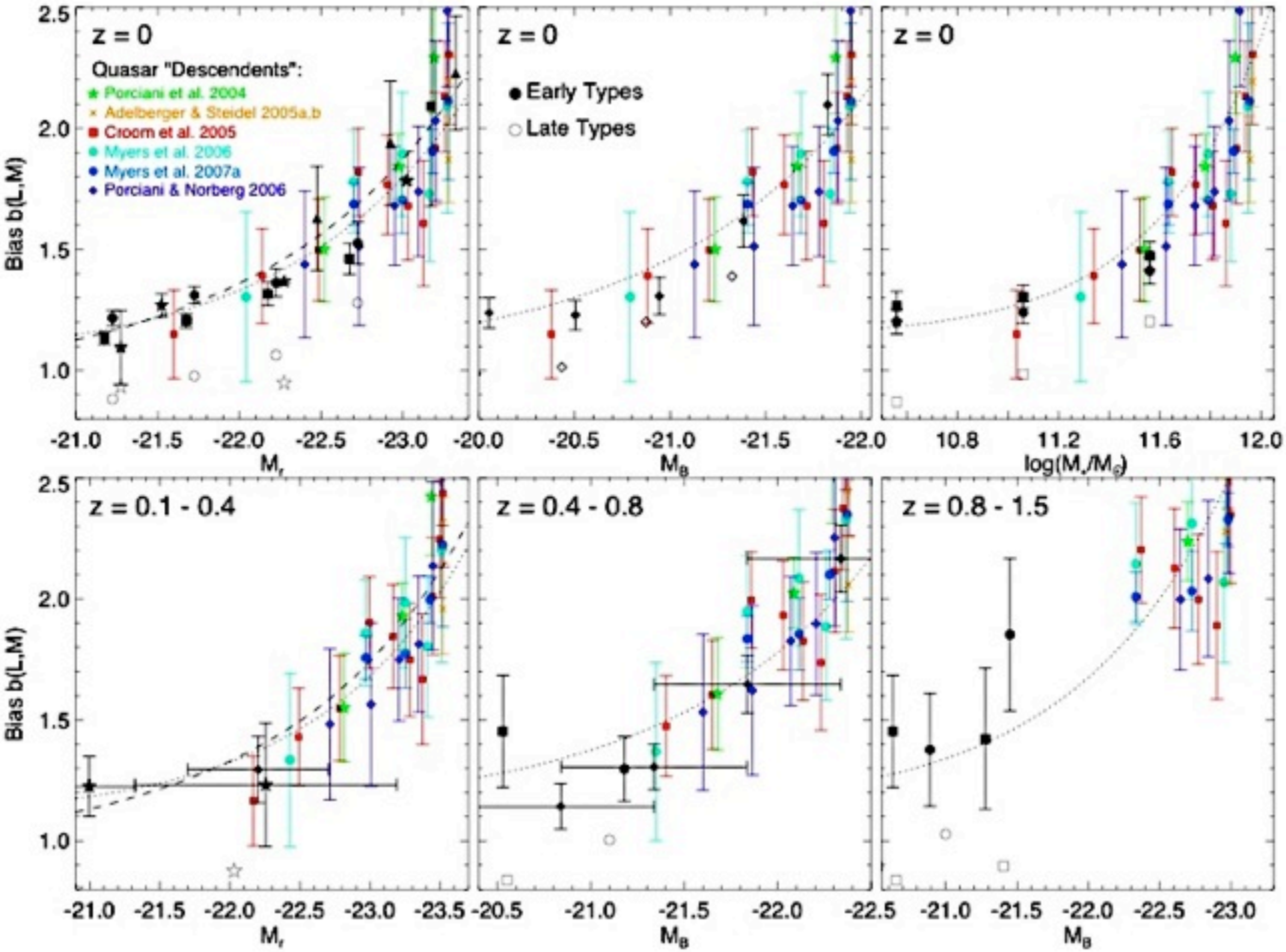
- If self-regulated, this feedback is potentially radically important:
  - Heating gas, ejecting metals, shutting down SF
  - Self-regulated decay of QSO luminosity:
    - Luminosity-dependent quasar lifetimes
    - Changes the meaning of the QLF

- "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+