Quasars in a Cosmological Context

Philip Hopkins

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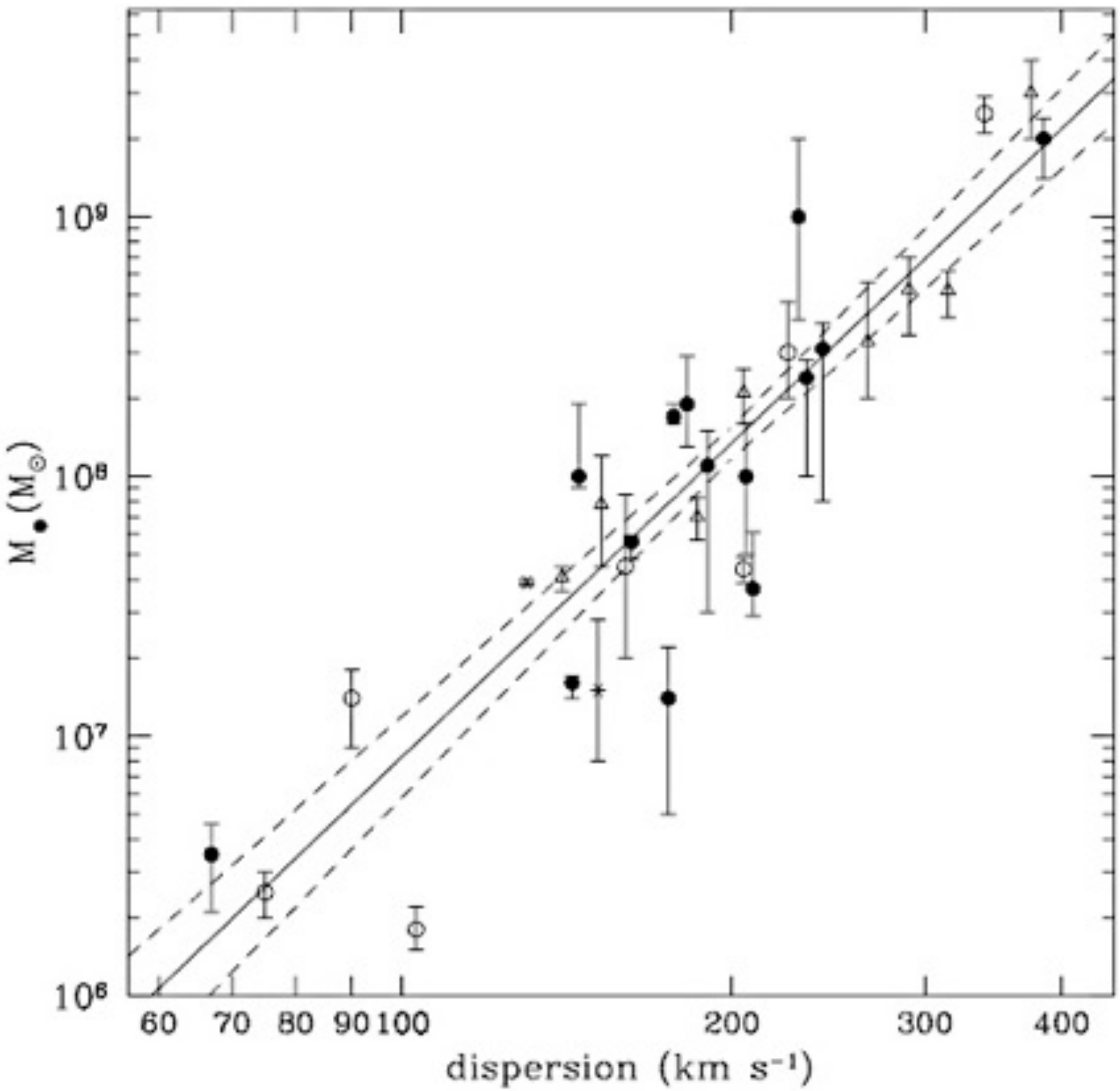
Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

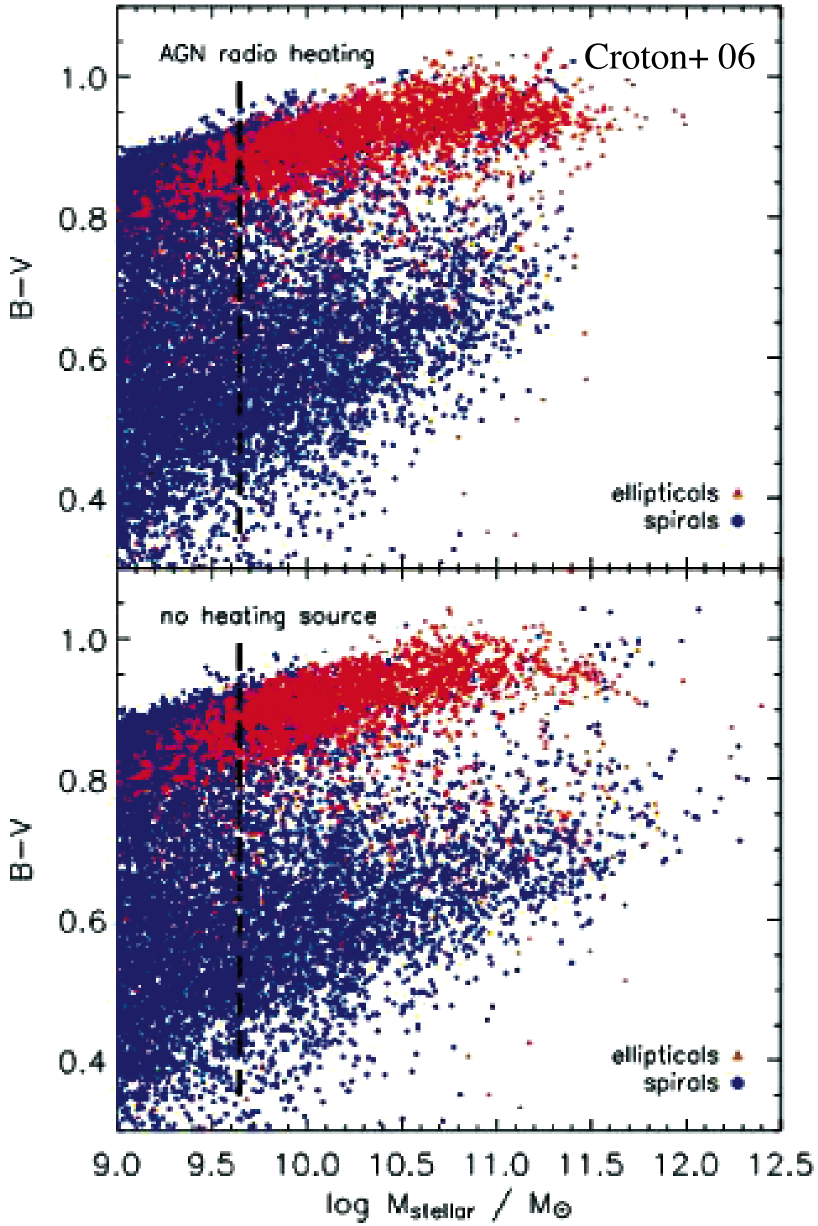
- Black holes somehow tied to galaxy formation:

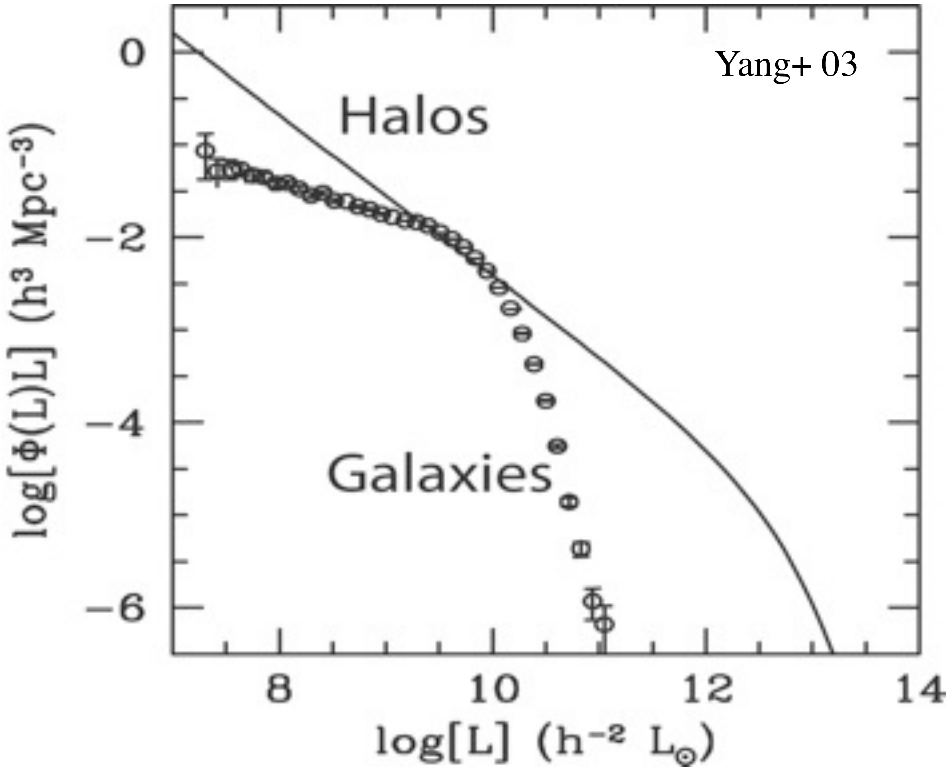


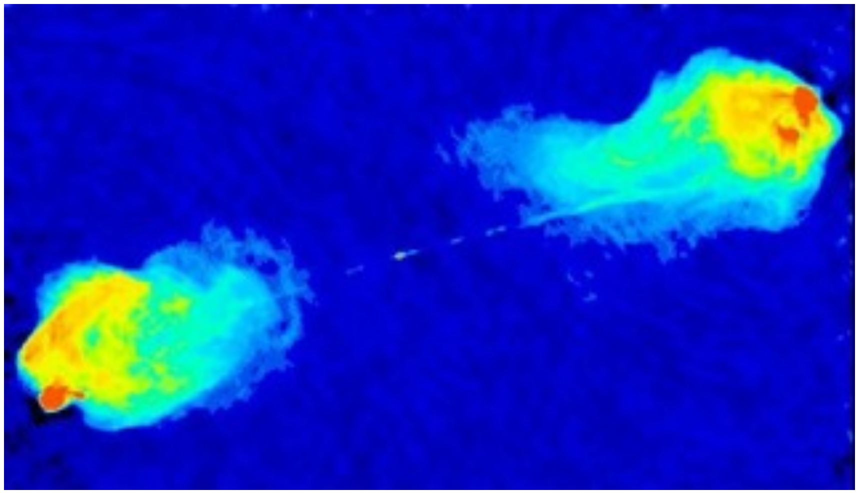
Ferrarese & Merritt ’00
Gebhardt+ ’00
Tremaineet al. ‘02

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?



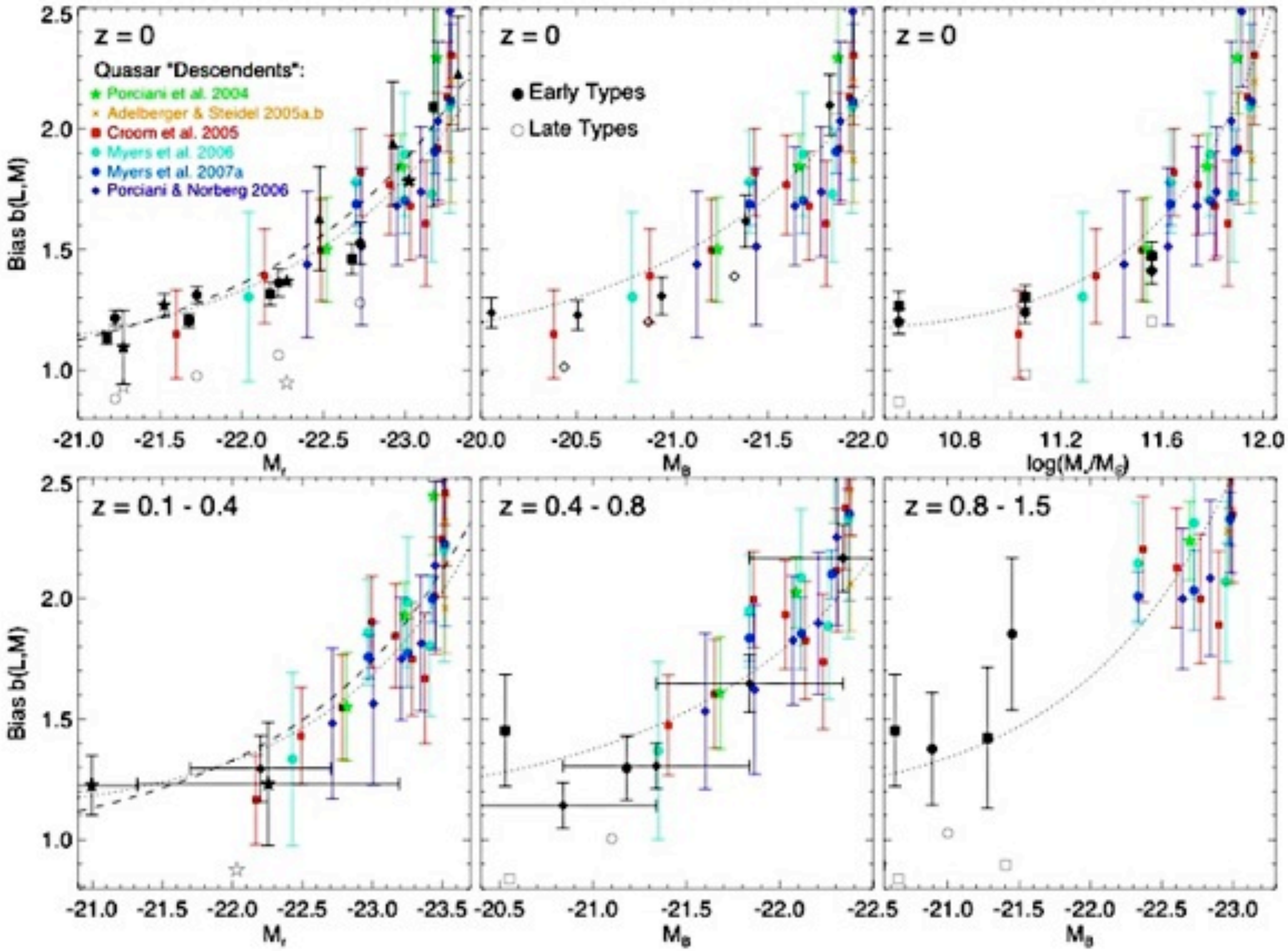




Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

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

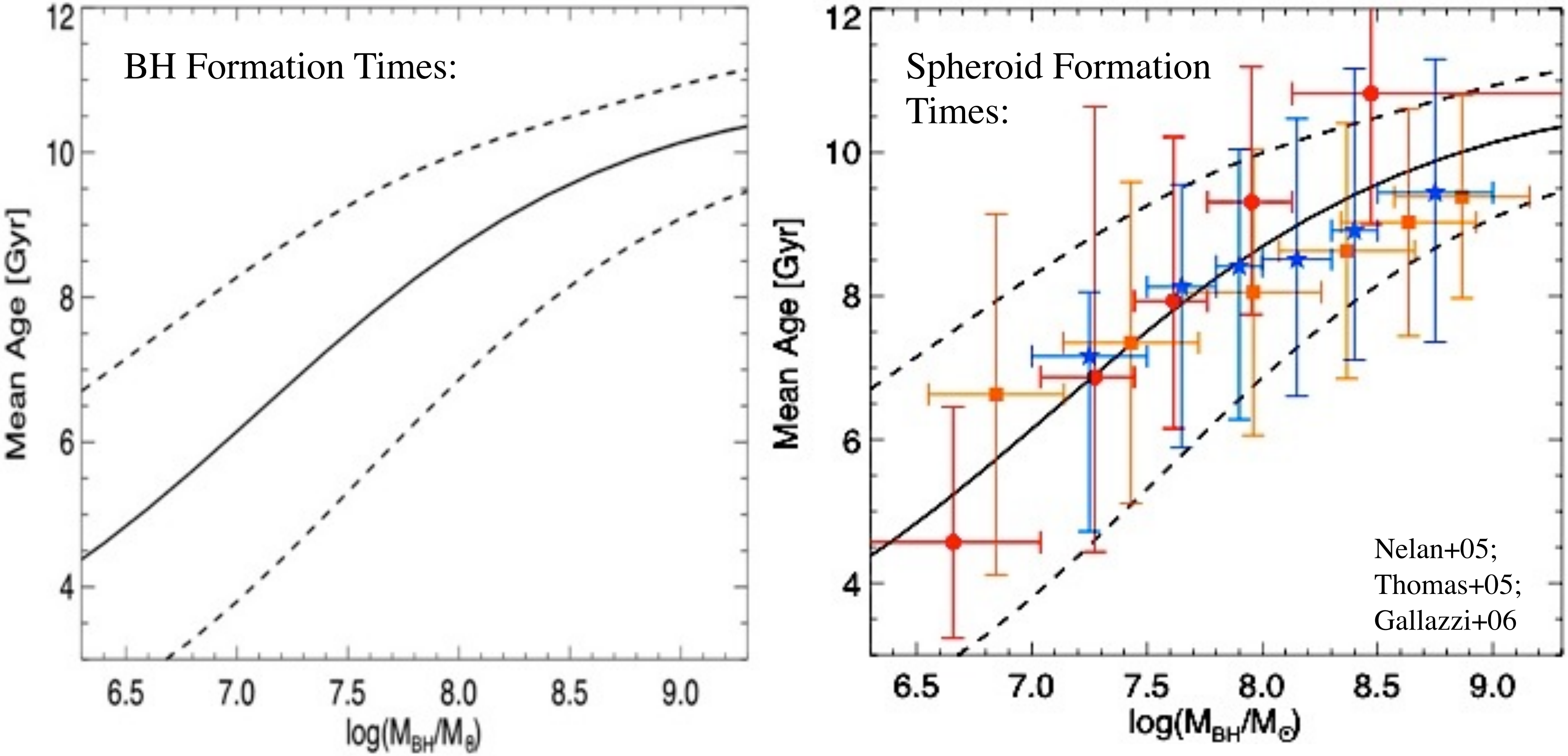


PFH, Lidz, Coil, Myers+

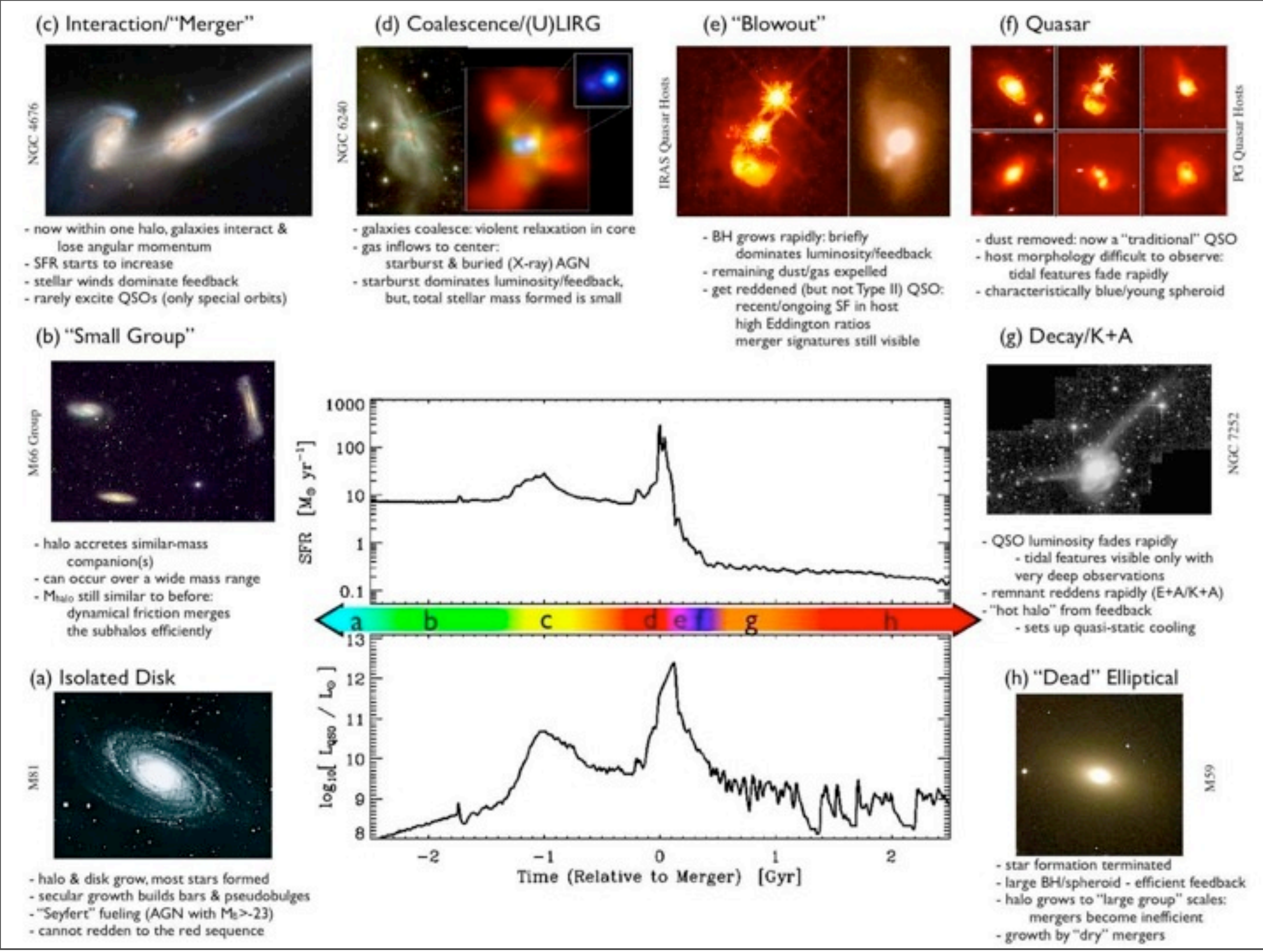
Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

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



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


(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

Lightcurves

Feedback

Three Outstanding (Inseparable?) Questions:

Triggering

How?
When?
Angular Momentum?
Self-suppression?

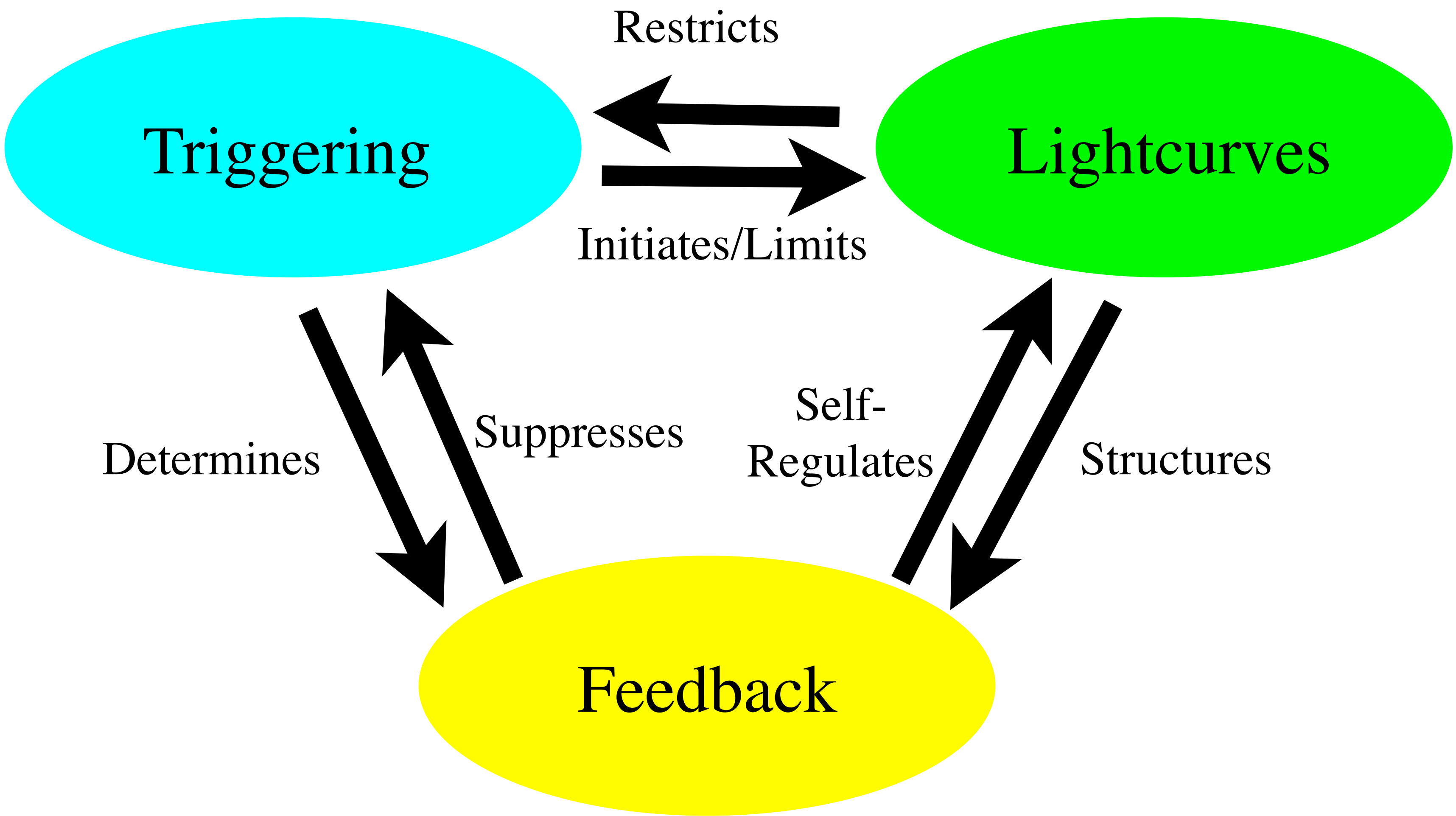
Lightcurves

Lifetimes?
Self-Regulation?
Variability?
Feedback?

Feedback

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

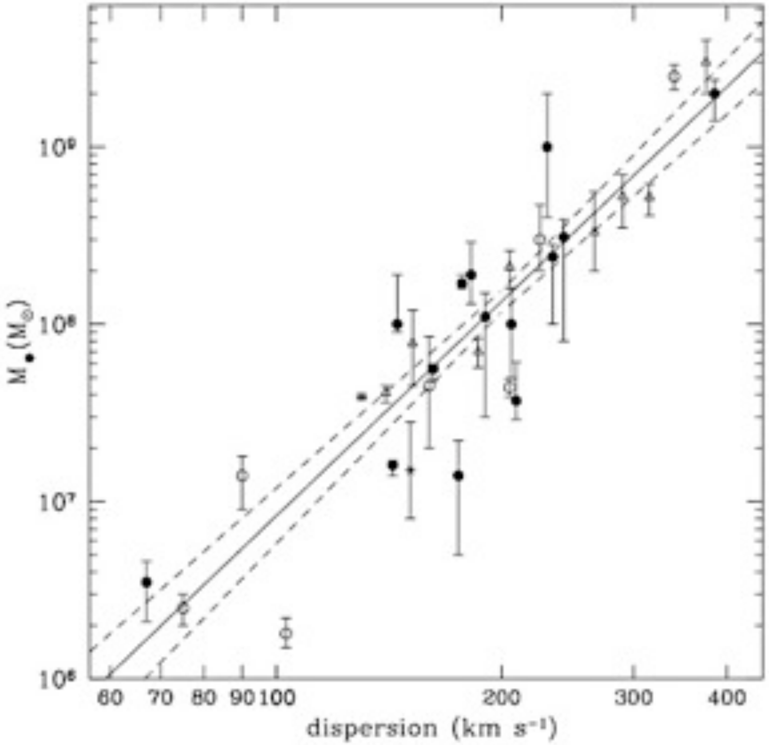
Three Outstanding (Inseparable?) Questions:



“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

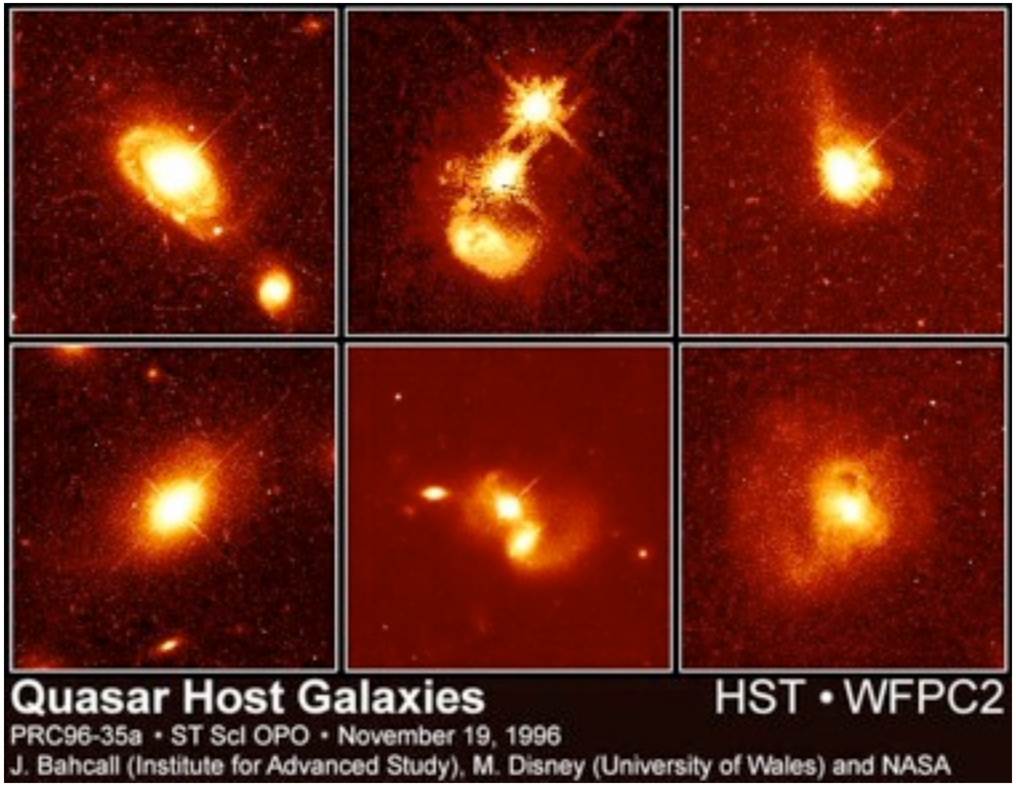
→ gas dynamics; rapid (~ few 10^7 years)

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

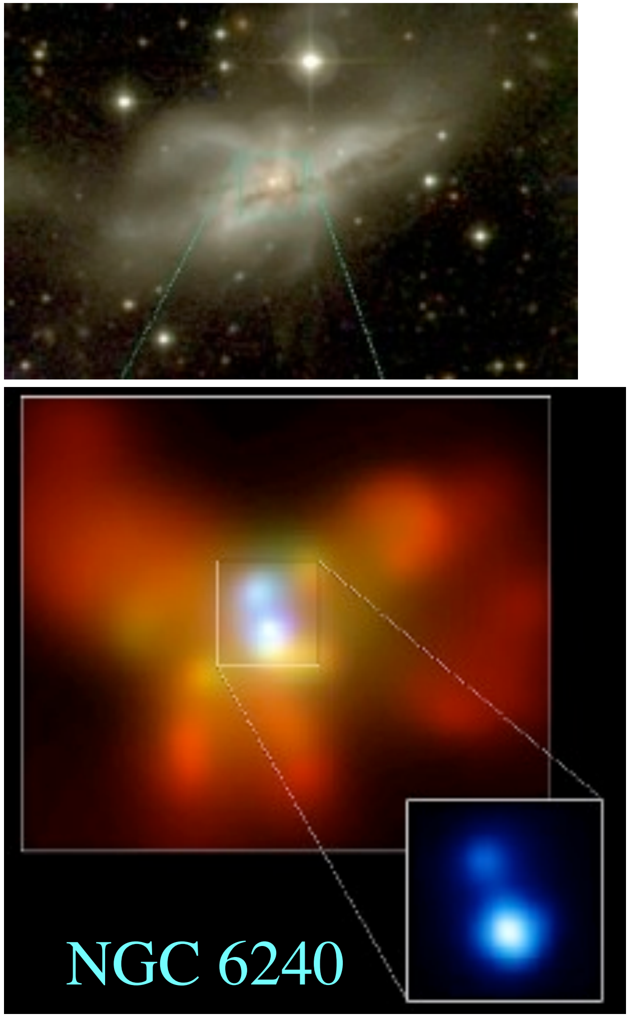
→ stellar dynamics; freefall timescale

Candidate Process: Gas-Rich, Major Merger

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

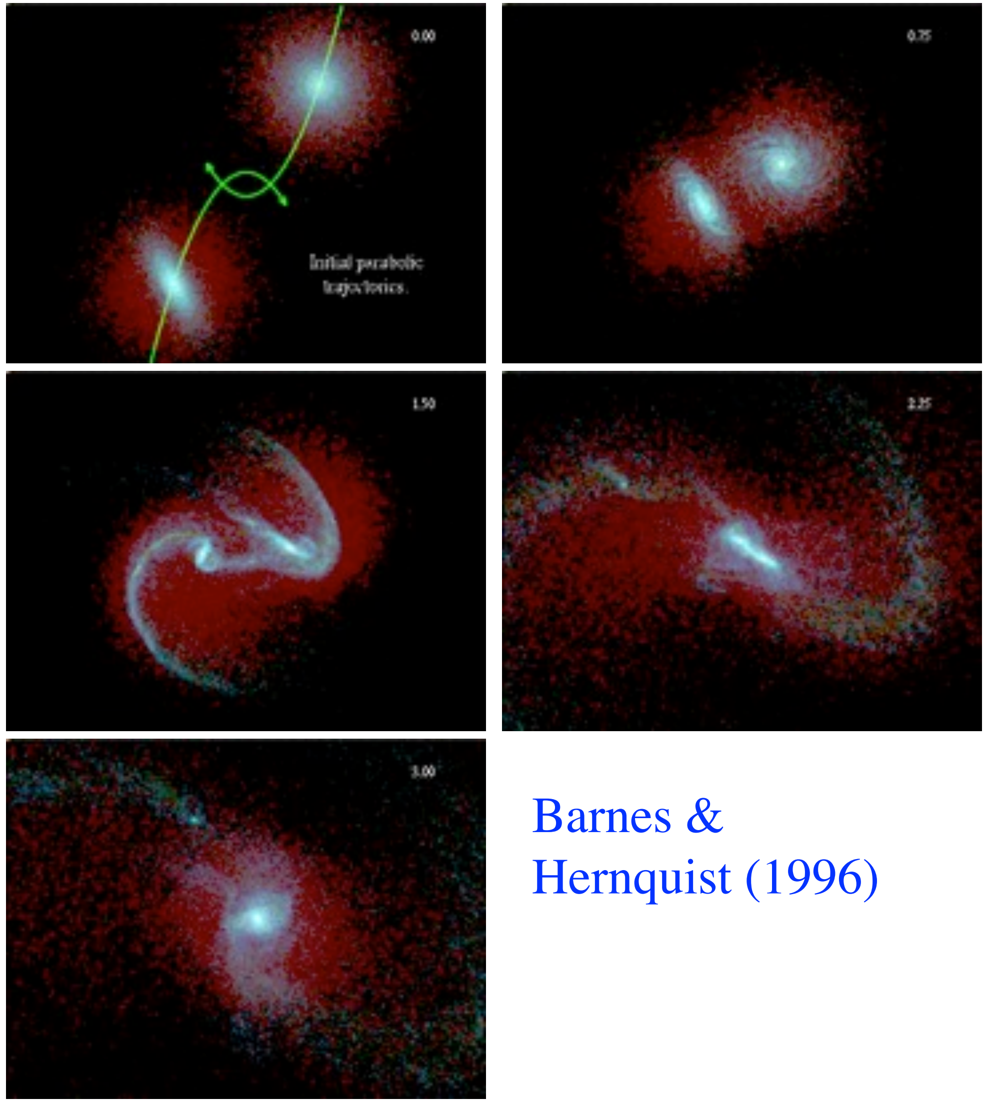


Komossa et al. (2003)

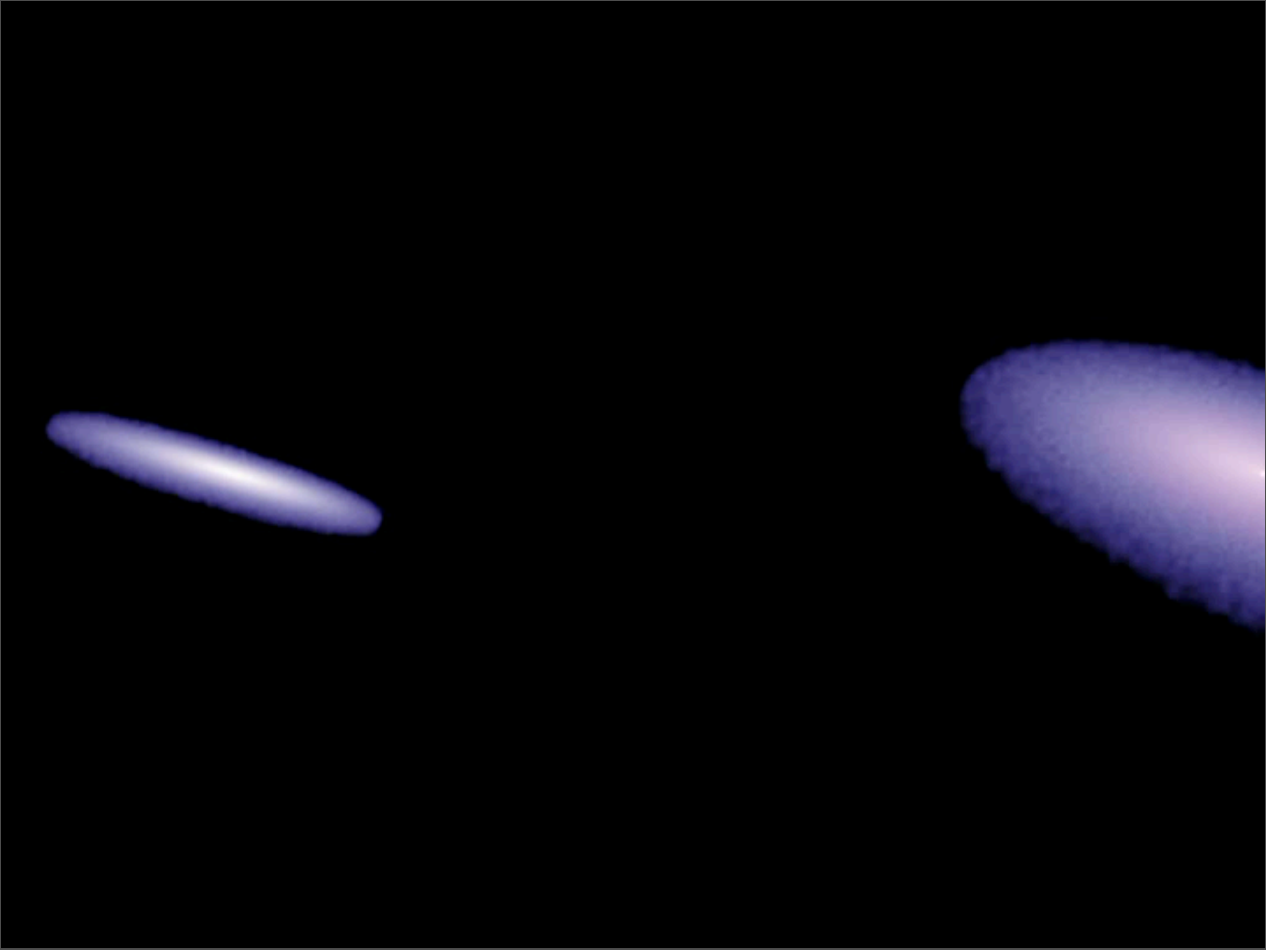


Plausible Physical Mechanism

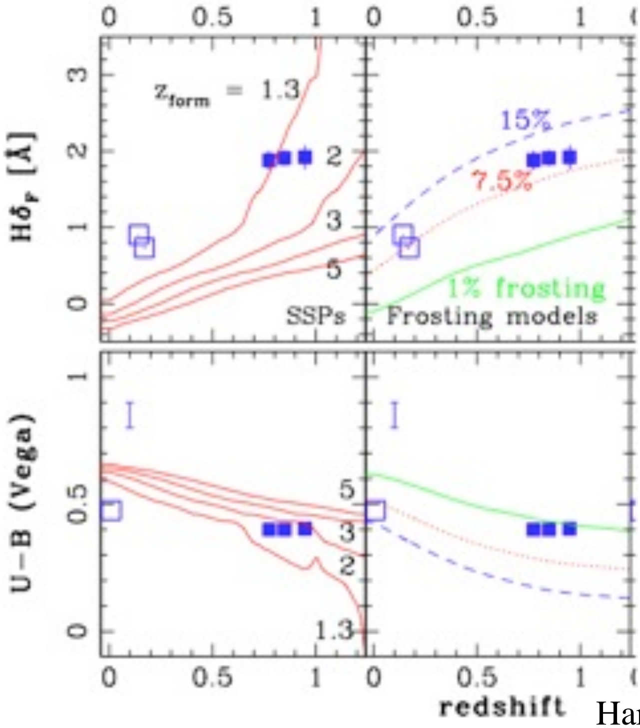
- Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & LH 1991)
- Triggers starburst (e.g. Mihos & LH 1996)
- Feeds BH growth (e.g. Di Matteo et al. 2005)
- Merging stellar disks grow spheroid
- Requirements:
  - major merger
  - supply of cold gas ("cold" = rotationally supported)



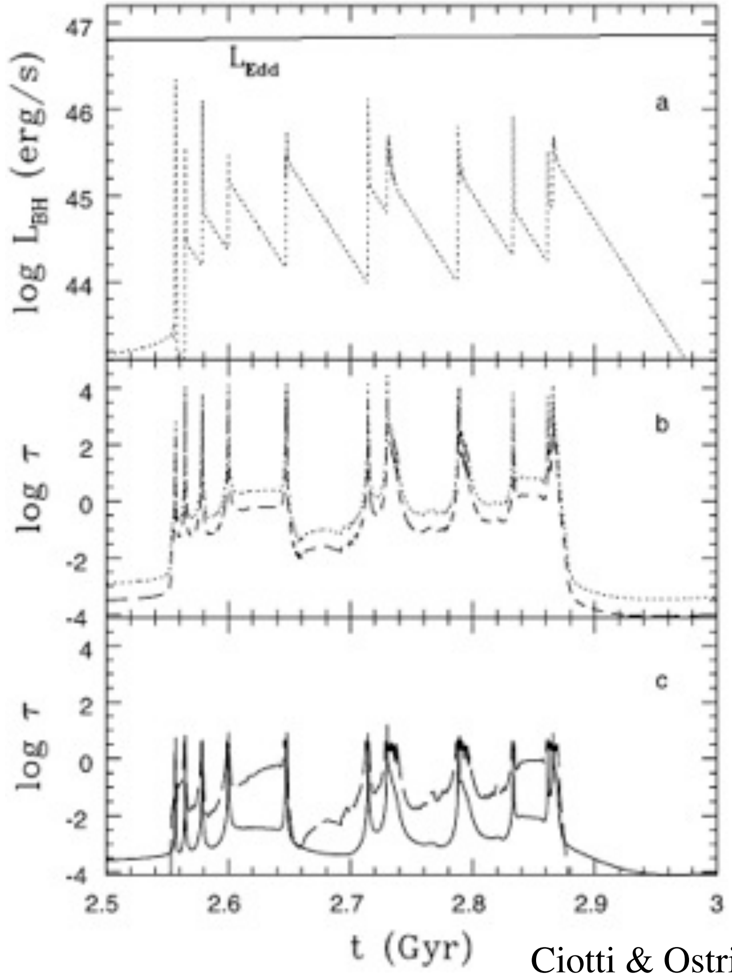
Barnes & Hernquist (1996)



Other Fueling Mechanisms?



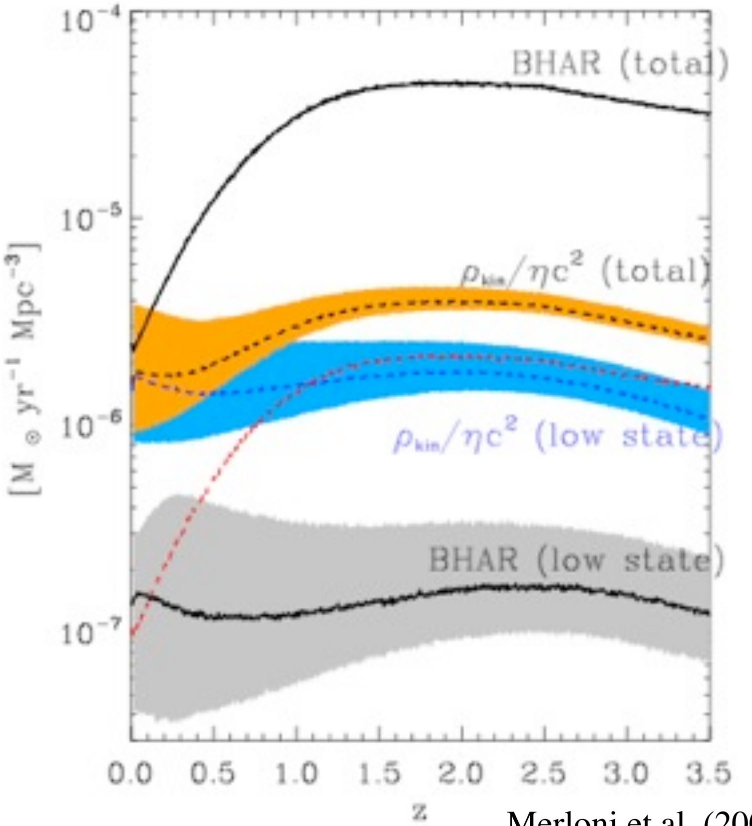
Harker et al. (2006)



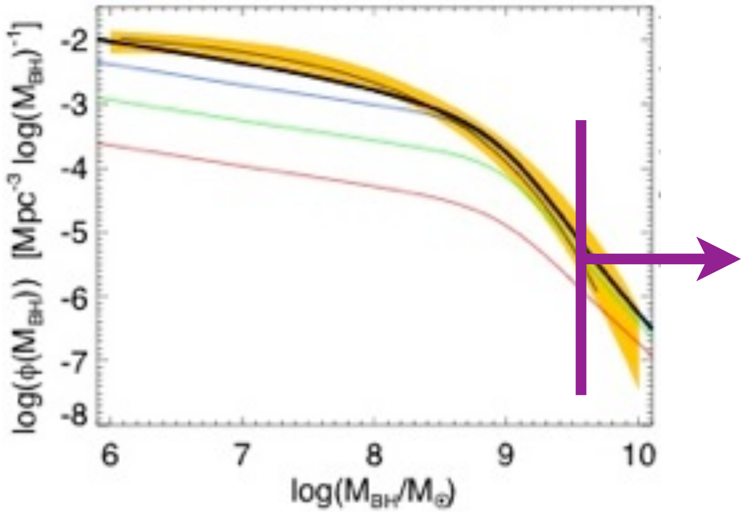
Ciotti & Ostriker

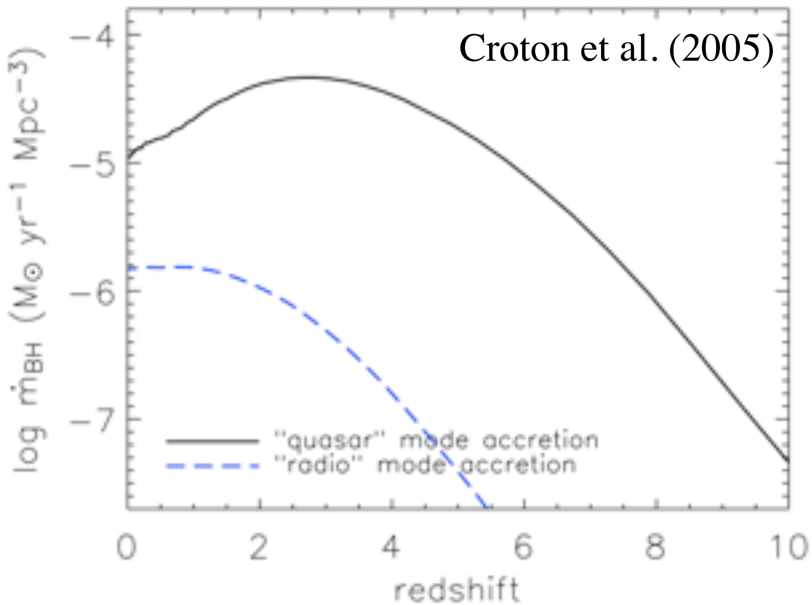
- Stellar Mass Loss
  - Low Accretion Rate
  - No Bulge Formation/Violent Relaxation
  - Can't "allow" this gas to cool in already-formed ellipticals (too much star formation!)
    -- Recurring mini-bursts? PG-like quasars?

Other Fueling Mechanisms?



Merloni et al. (2007)





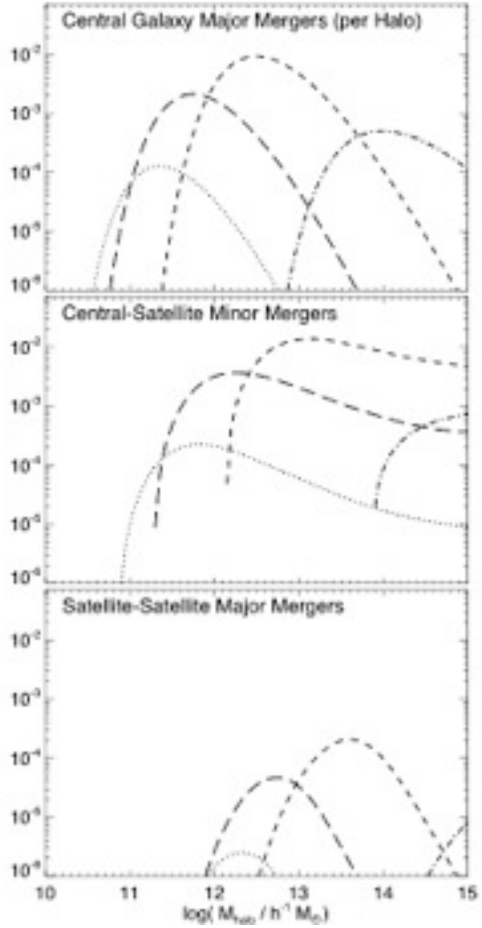
Croton et al. (2005)

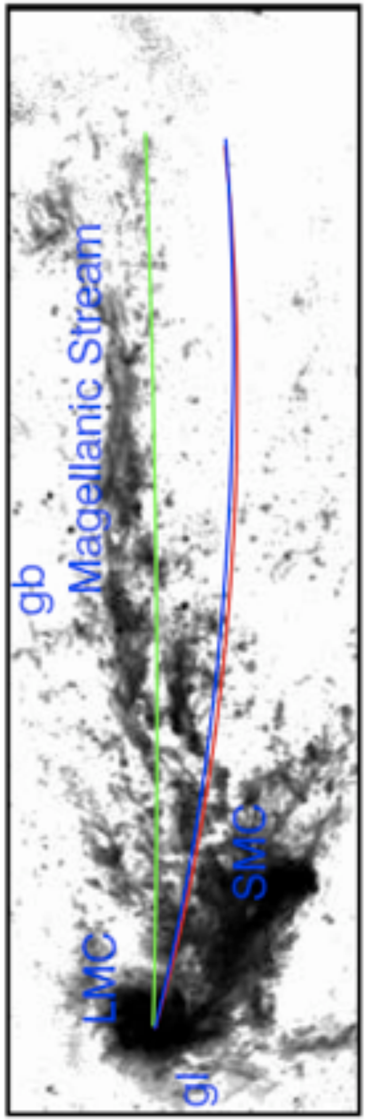
- Cooling Flows
  - Relatively Late Phenomenon
  - No Bulge Formation
  - BHs already massive in cooling-flow clusters
  - *But* -- important for “radio mode” accretion?

Other Fueling Mechanisms?

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

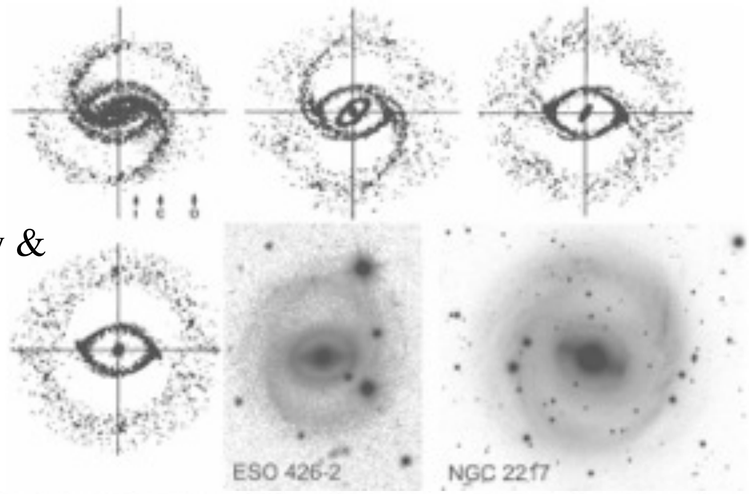




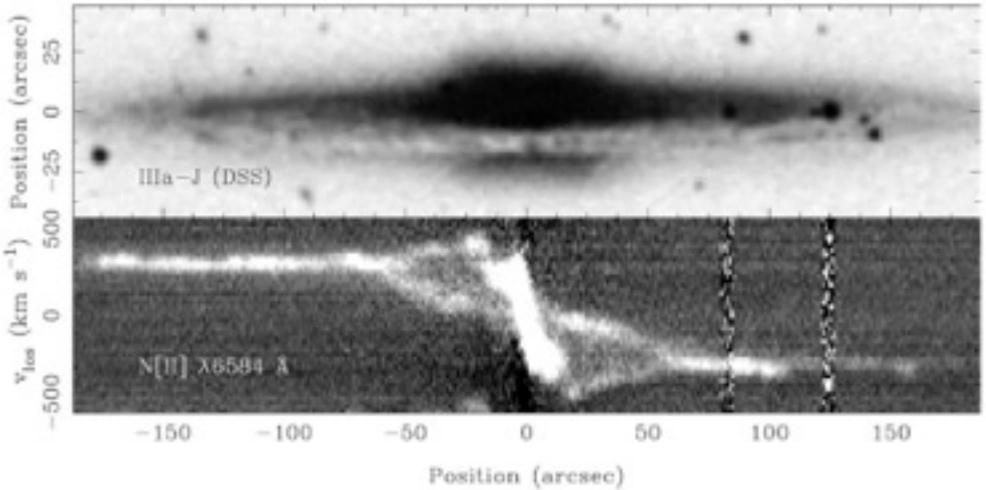
Besla et al. (2007)

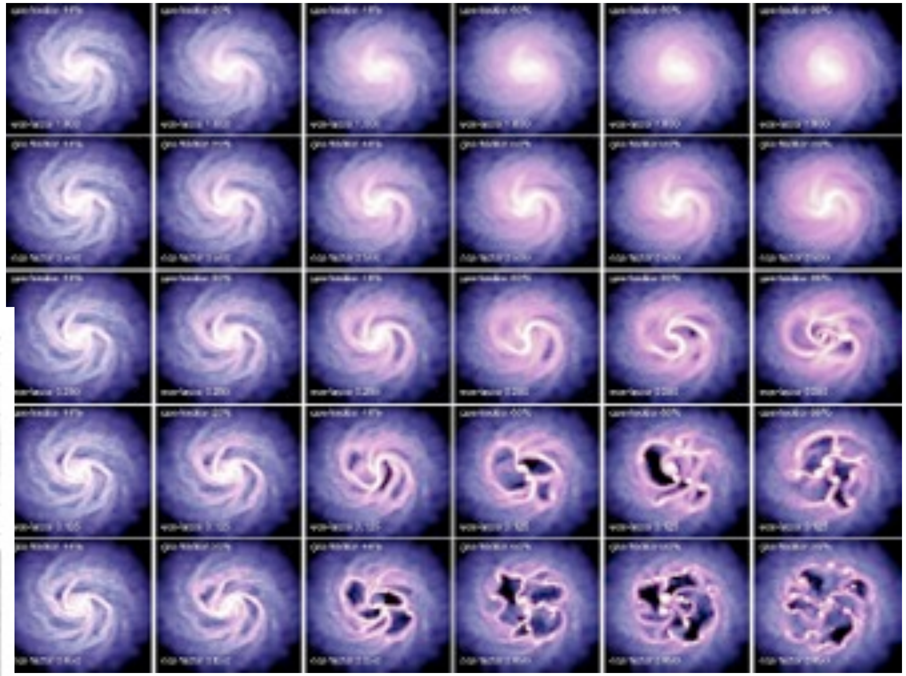
- Minor Mergers
  - Not so violent -probably don't dominate spheroid formation (LMC/SMC)
  - Can they torque much gas?
  - Major mergers dominate mass growth in mergers (~L*)

Other Fueling Mechanisms?



Kormendy & Kennicutt





Springel et al. (2005)

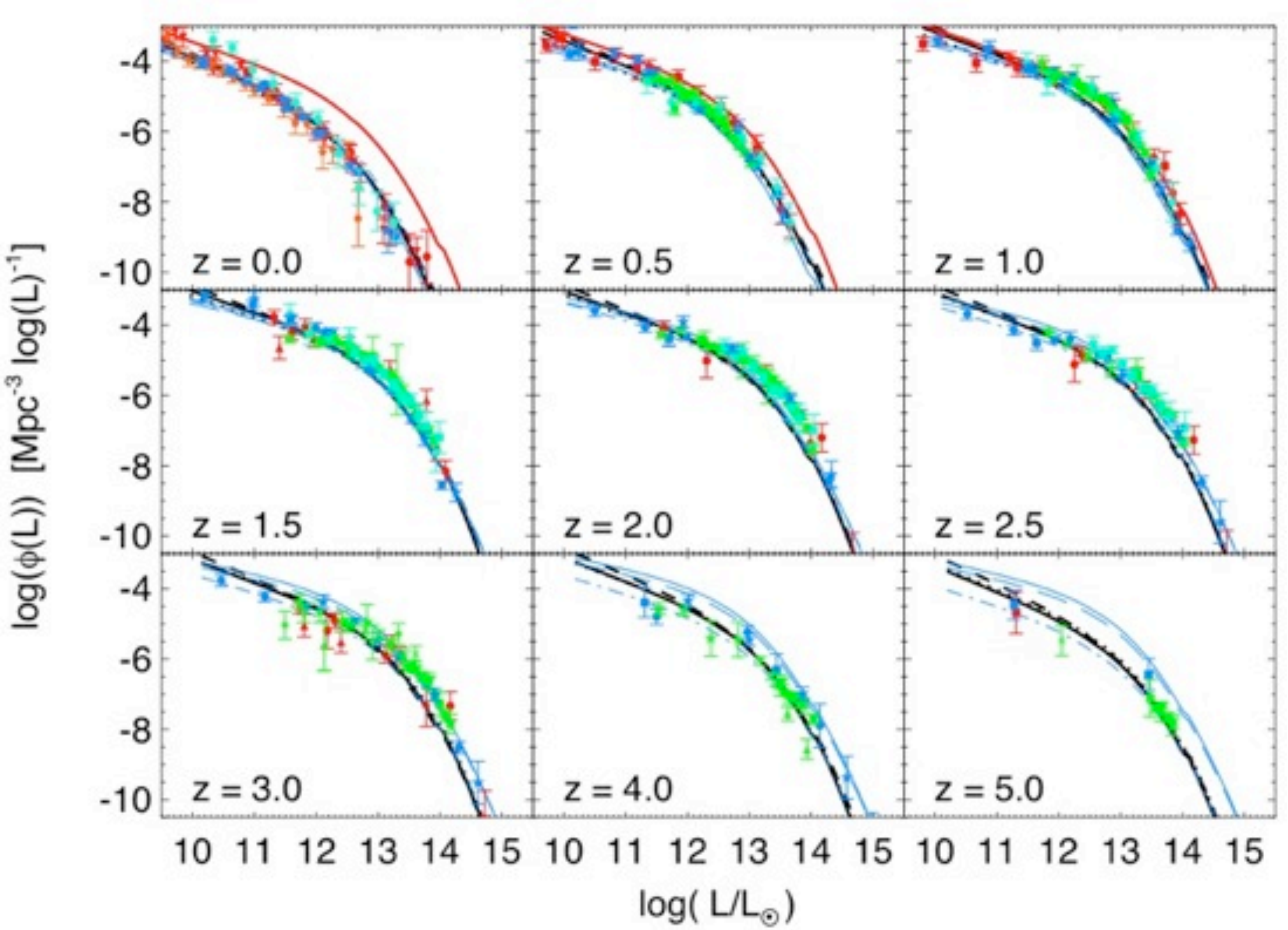
- Secular Evolution/Disk Instabilities
  - Most mass in “classical” bulges, not “pseudobulges”:
    - But, *are* important below <~ Sa-types
  - Does it really solve the angular momentum problem? (Jogee et al.)

Some Basic Checks:

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

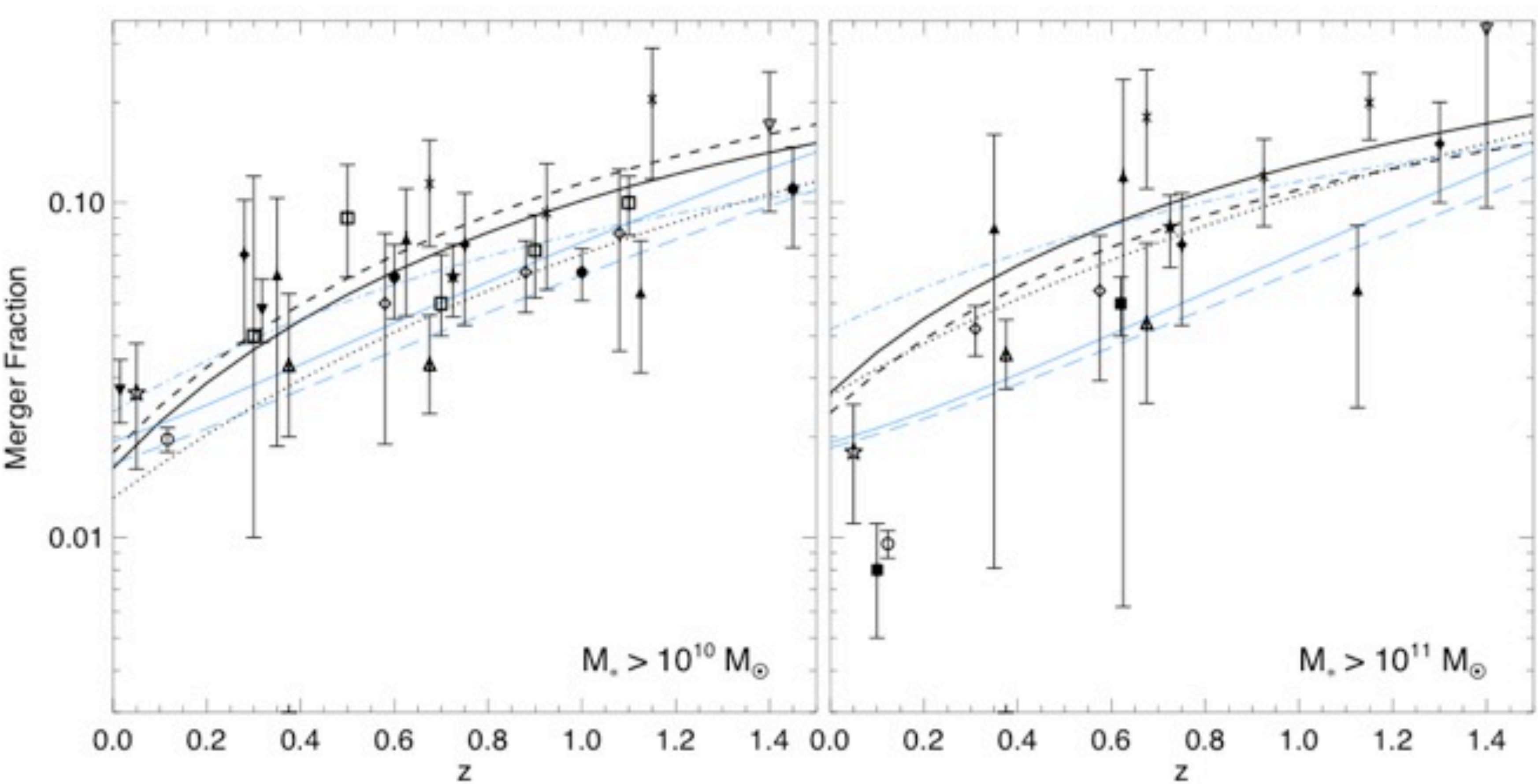
- Predicts the QLF vs. redshift, luminosity, wavelength



PH07

Predictions

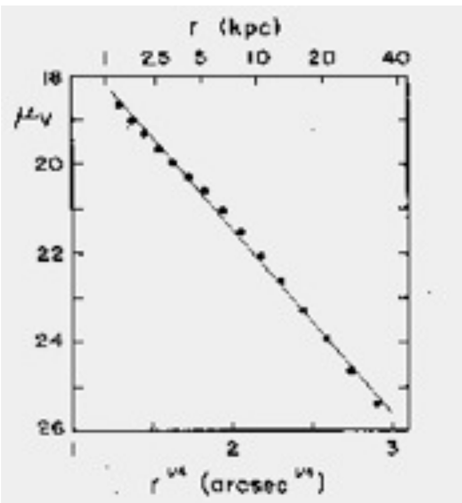
- Predicts the QLF vs. redshift, luminosity, wavelength
- There are “enough” mergers!

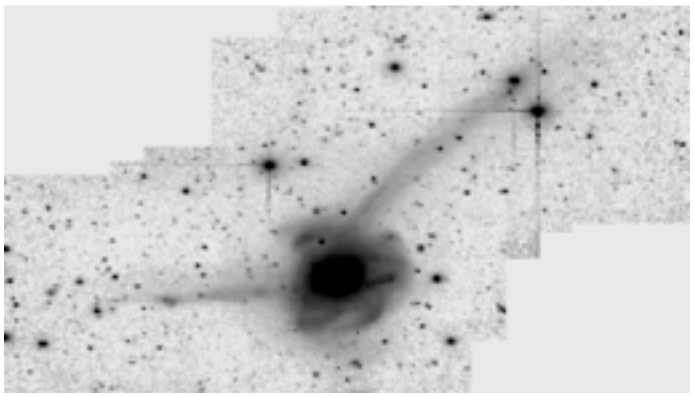


PH07

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)



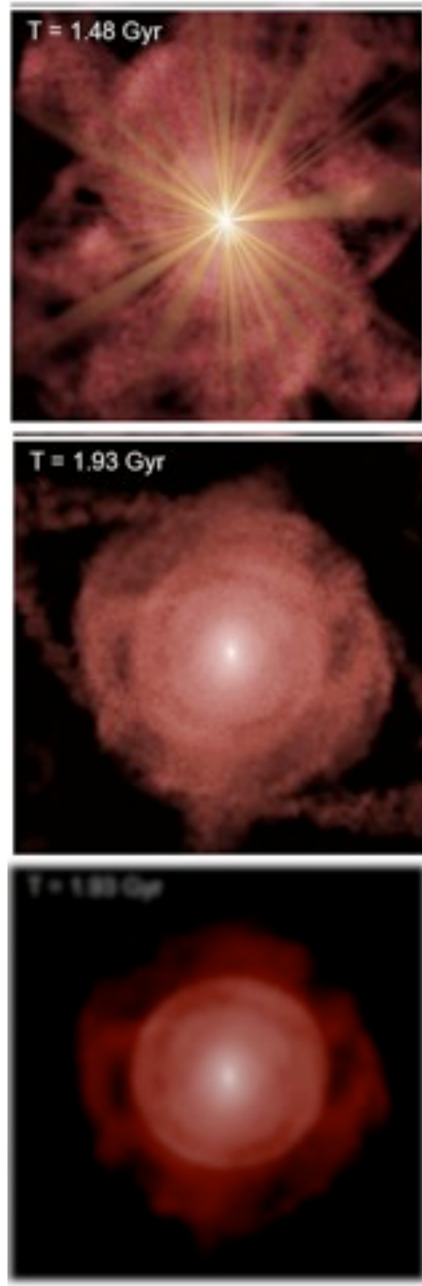


Schweizer (1982)

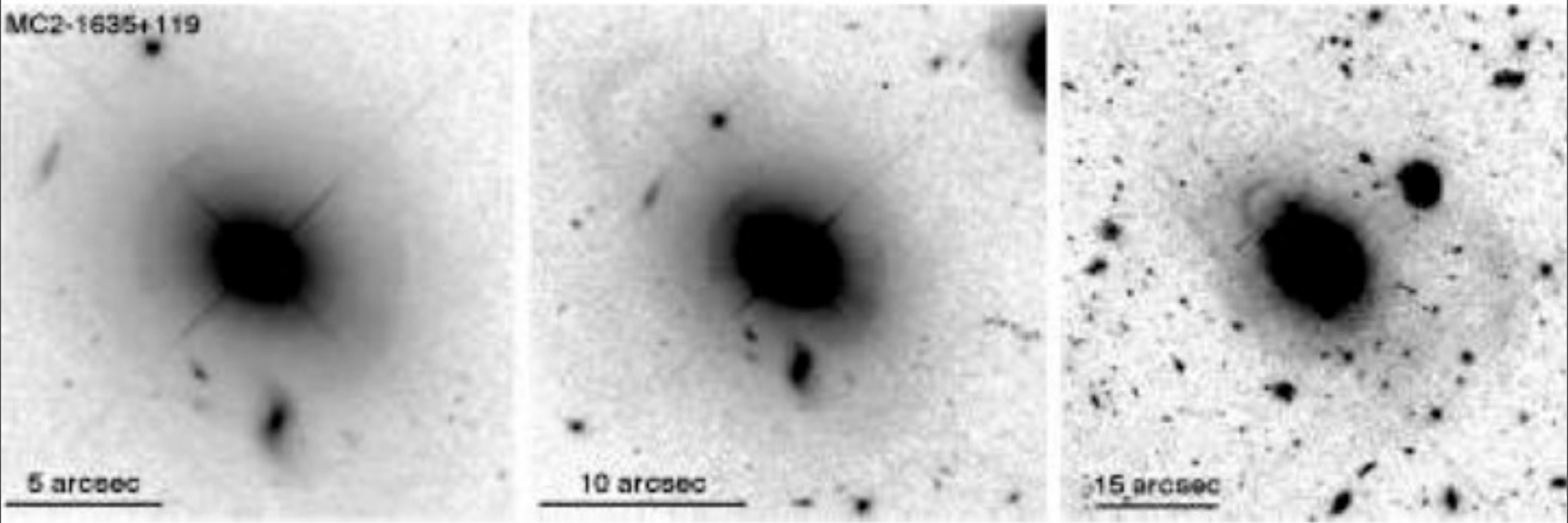
QSO = 1000xHost

QSO = Host

QSO = 0.1xHost



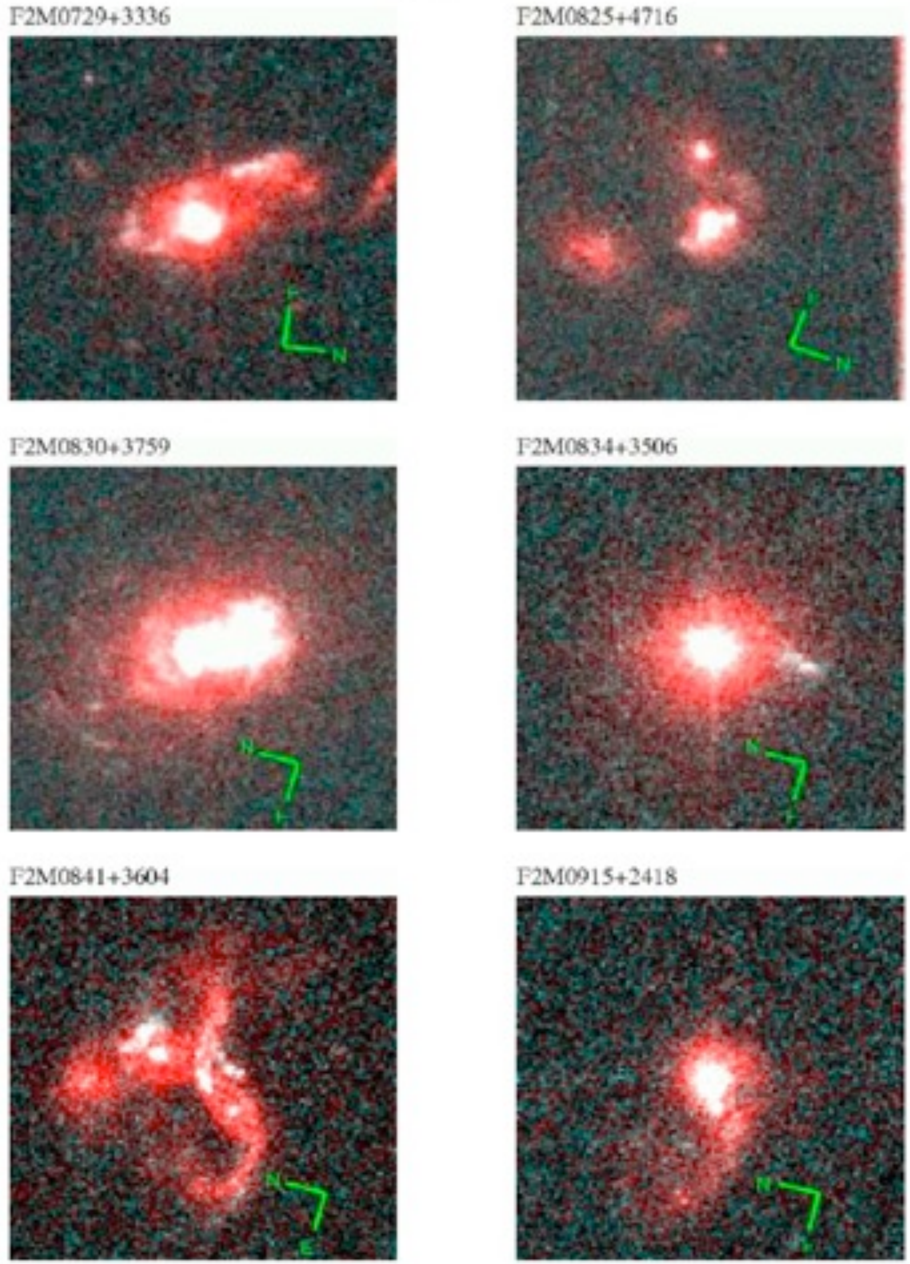
The Difficulty



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

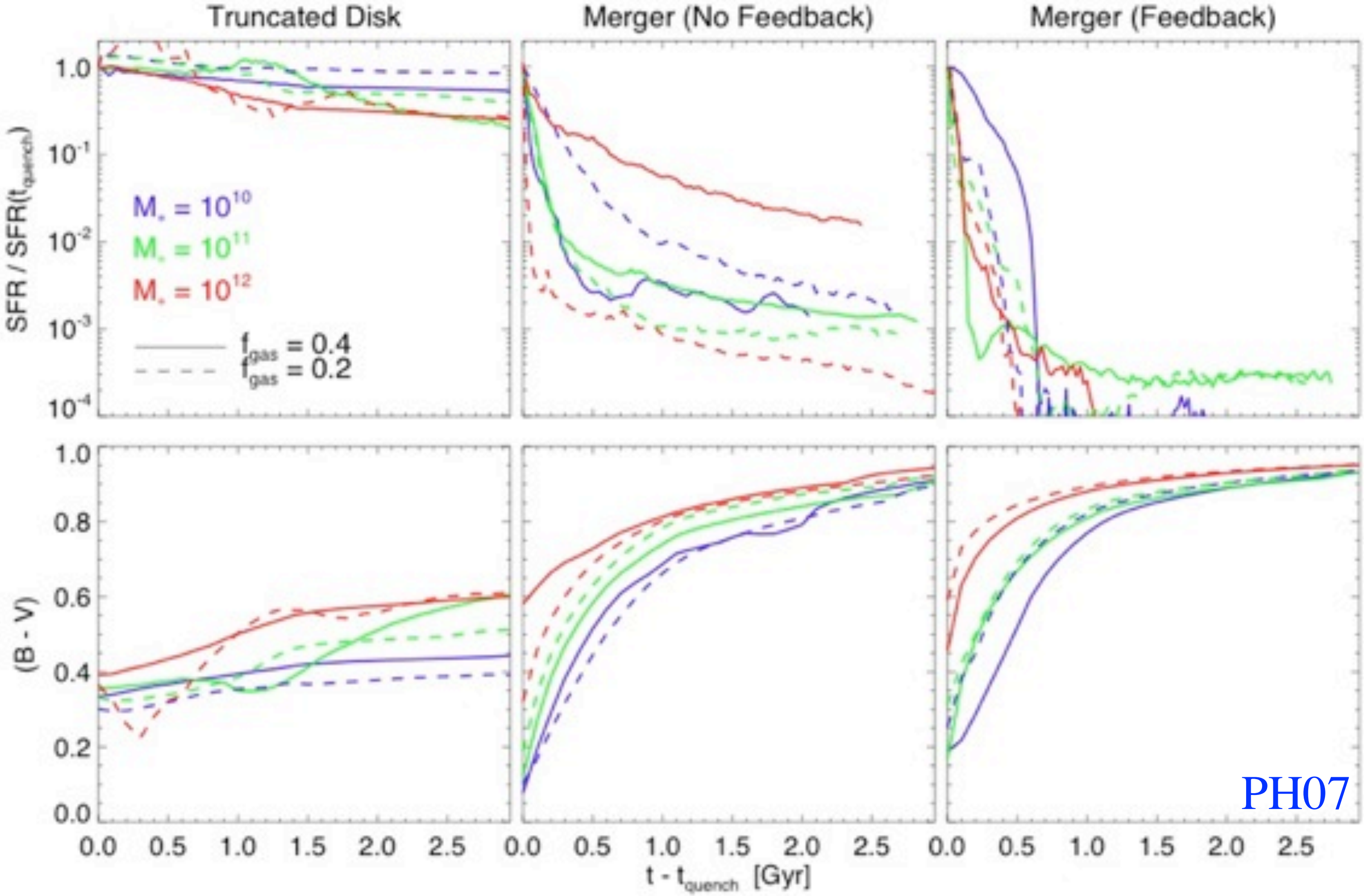
The Difficulty

- 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”



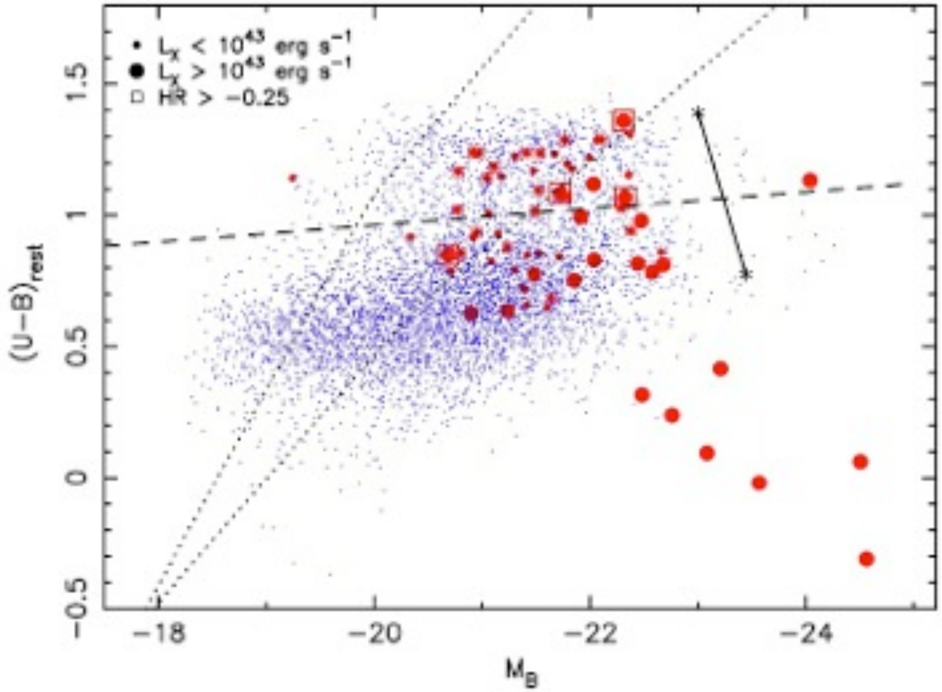
Color Evolution of Quasar Hosts

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

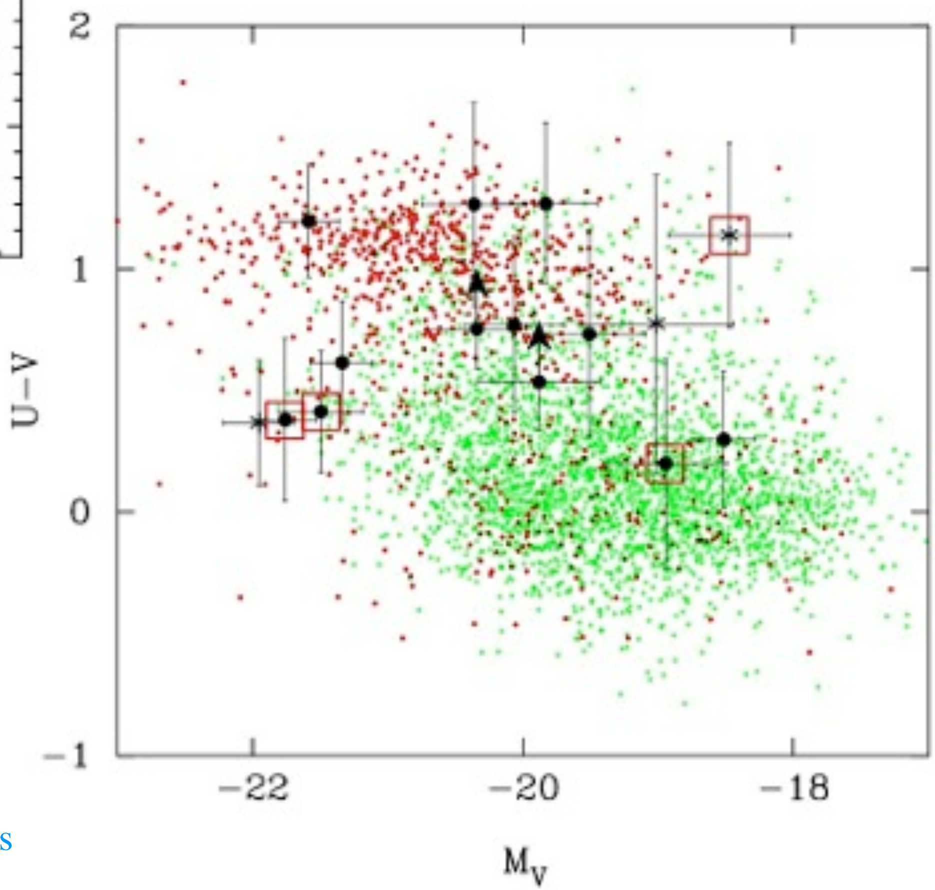


- Not true of secular evolution/pseudobulges (Kormendy, Balcells et al.)

Color Evolution of Quasar Hosts



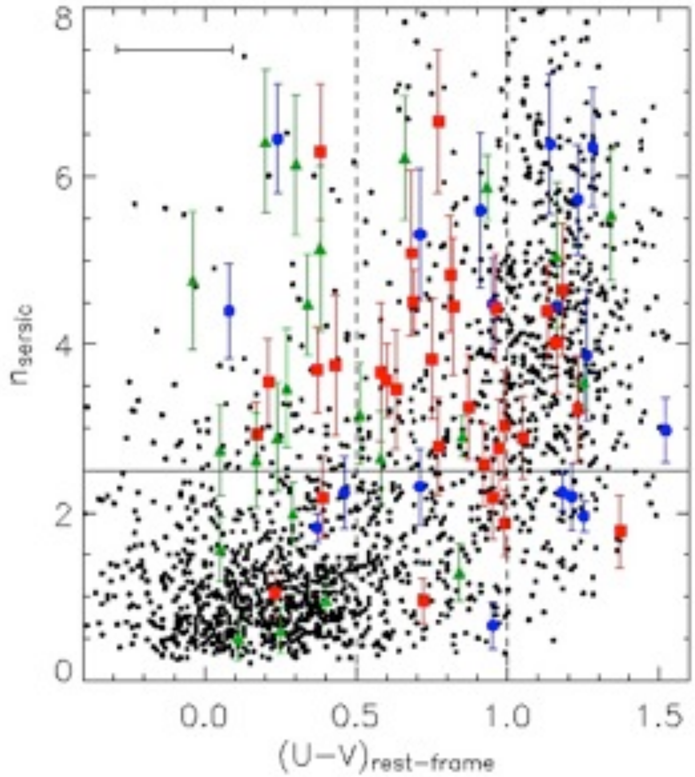
Nandra+ '06
DEEP2
0.7 < z < 1.4
X-ray QSOs



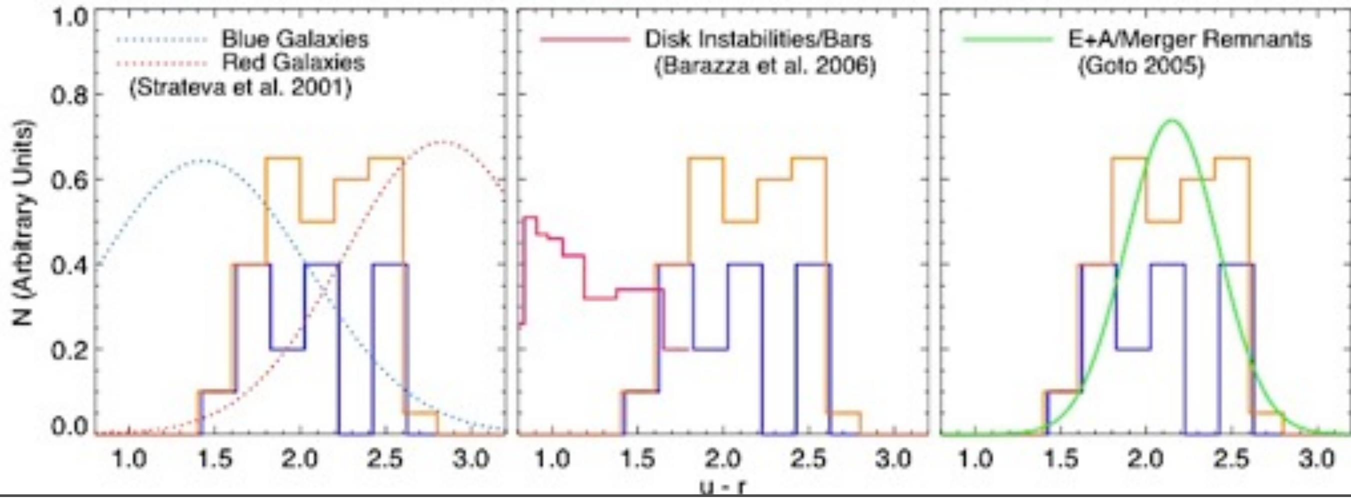
Sanchez+ '05
GEMS
0.5 < z < 1.1
Optical QSOs

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.

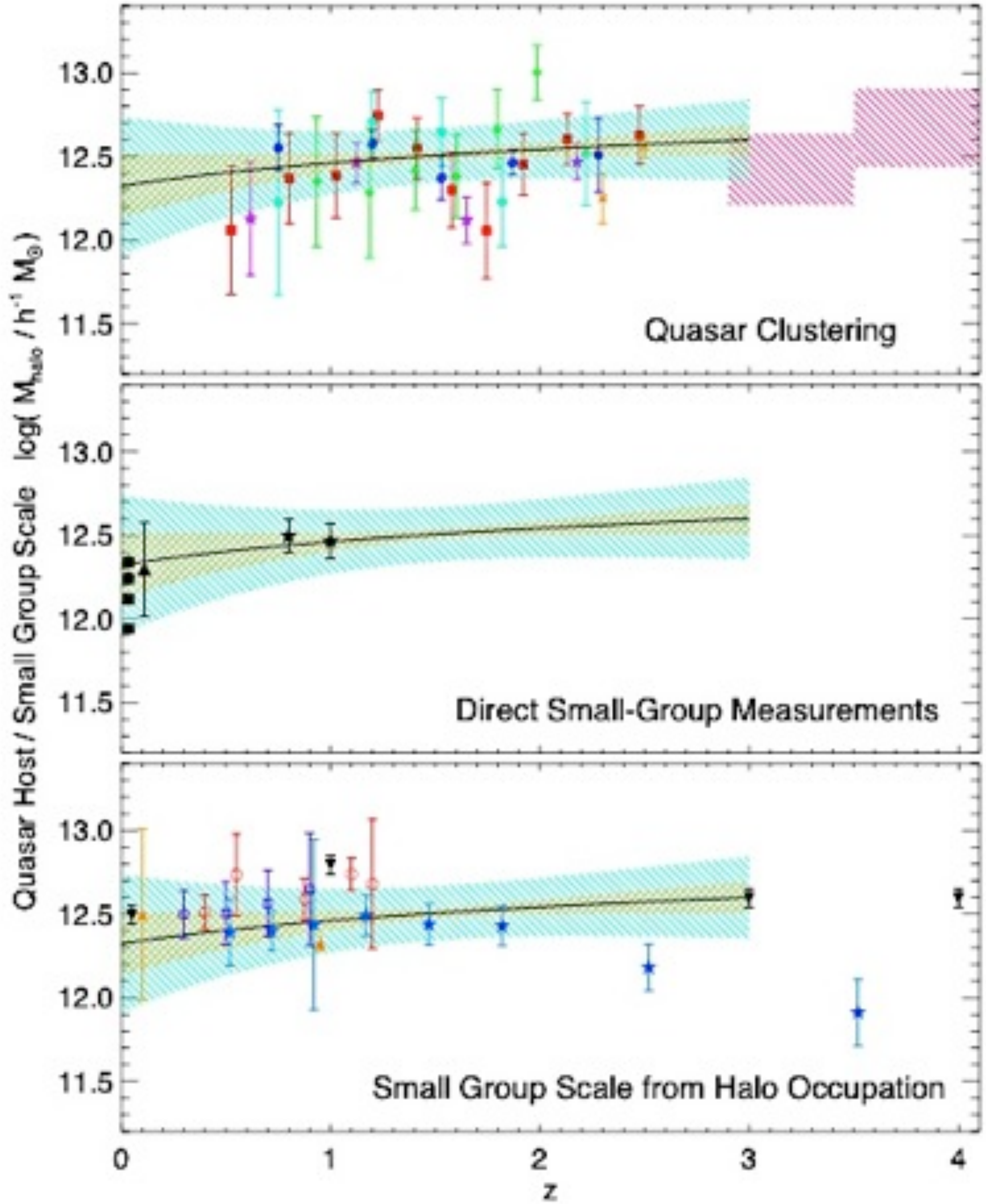


PH07

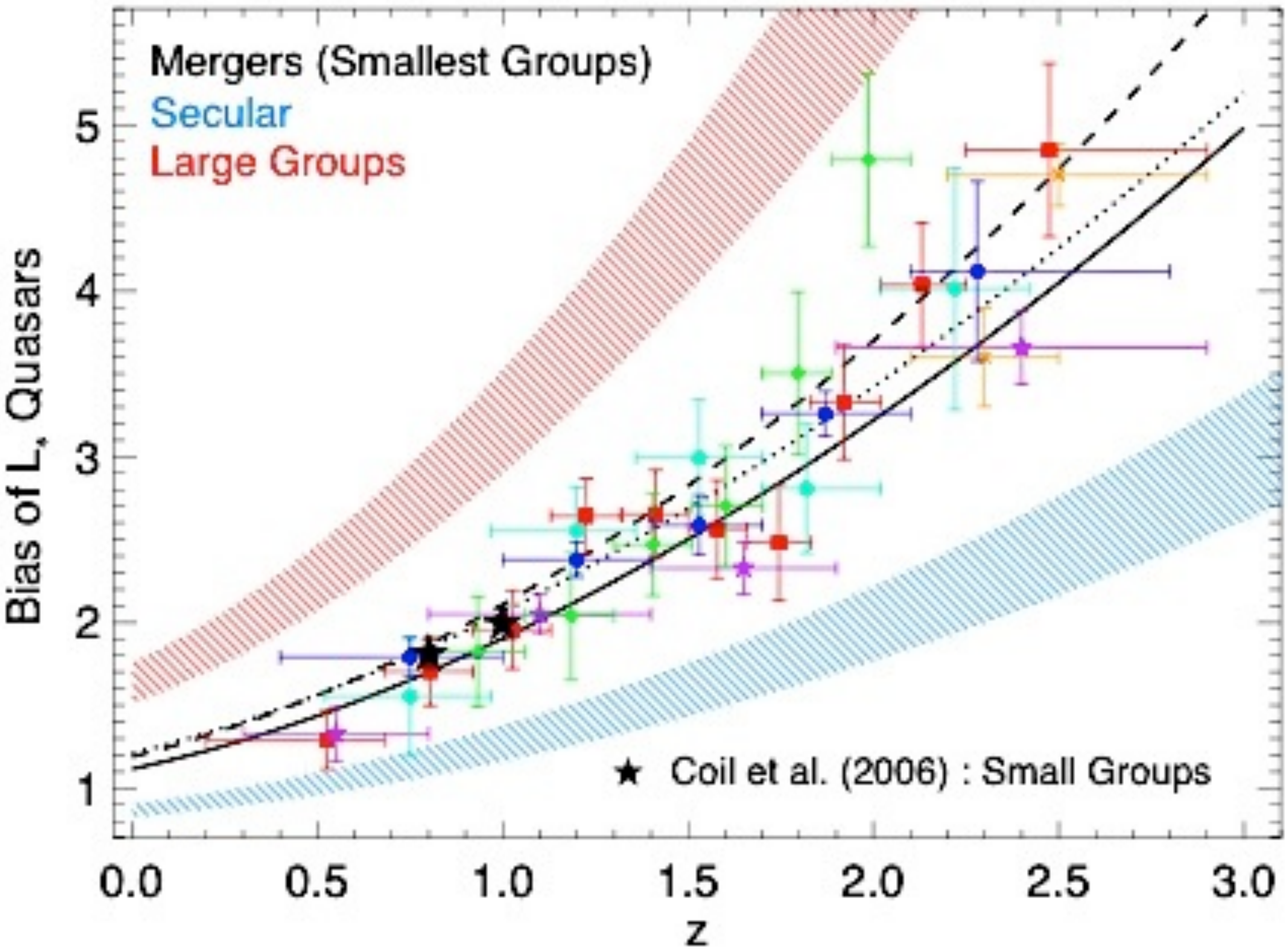
Where Quasars Are Born

PH07

- Croom et al. (2005) (+others): from 2dF QSO survey
  - M_{halo}(QSO host) ~ 3.0 ± 1.6 h^{-1} M_{solar} at z ~ 1 - 6
  - Faucher - Giguere et al. (2006): independent, similar conclusion from proximity effect analysis
- HOD theory: characteristic halo mass for 2 large galaxies
- Simulations: "Small Group" scale of efficient ~L* galaxy mergers



Where Quasars Are Born

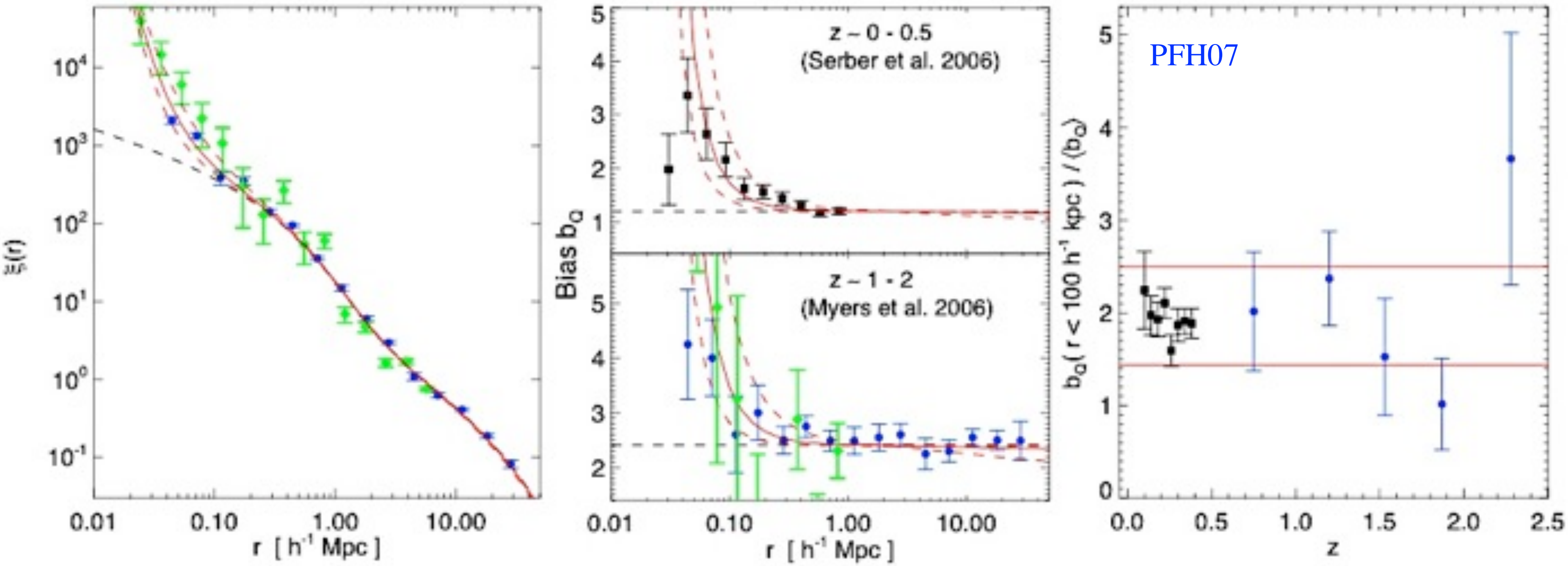


PH07

- Is clustering of ~L* quasars is different from ~L* disks (secular expectation) ?

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

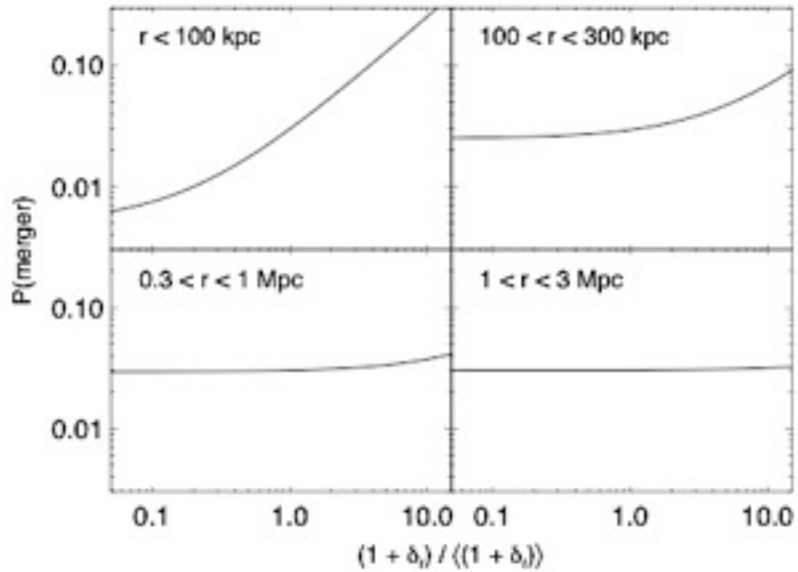


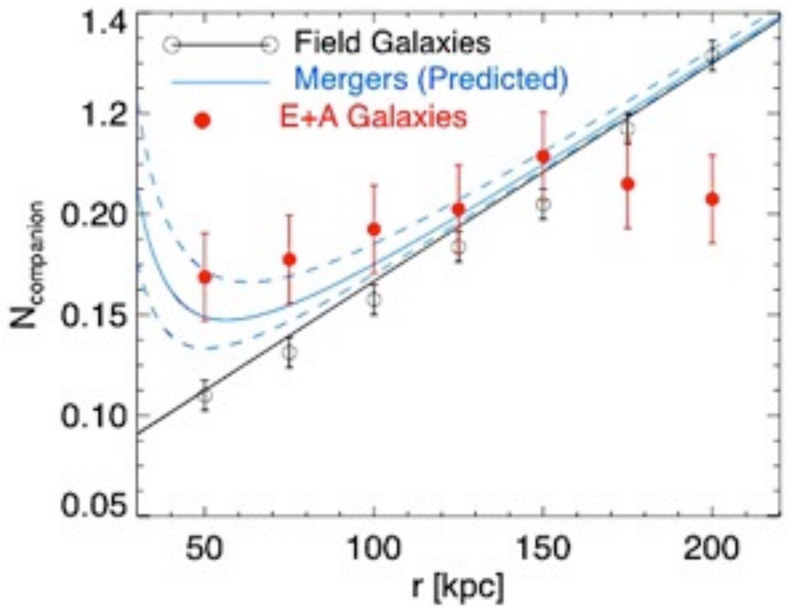
- Predicted by merger models (Thacker & Scannapieco et al., PFH)

Where Quasars Are Born

PFH07

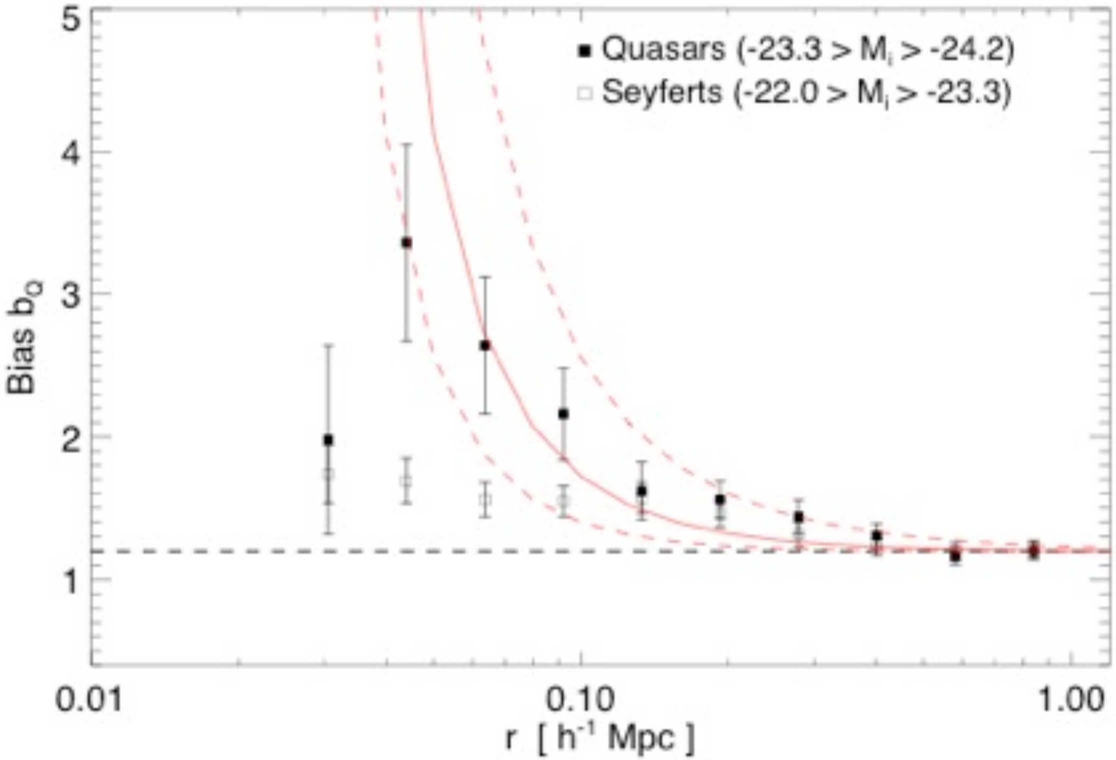
- Small-Scale Excess:
  - Predicted in merger models
    - Mergers biased to regions with *small-scale* overdensities
    - Seen in cosmological simulations (Thacker et al.)
    - Seen in merger remnants! (Goto et al.; Hogg et al.)
  - *Not* expected in secular/instability, cooling flow, stellar mass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





Where Quasars Are Born

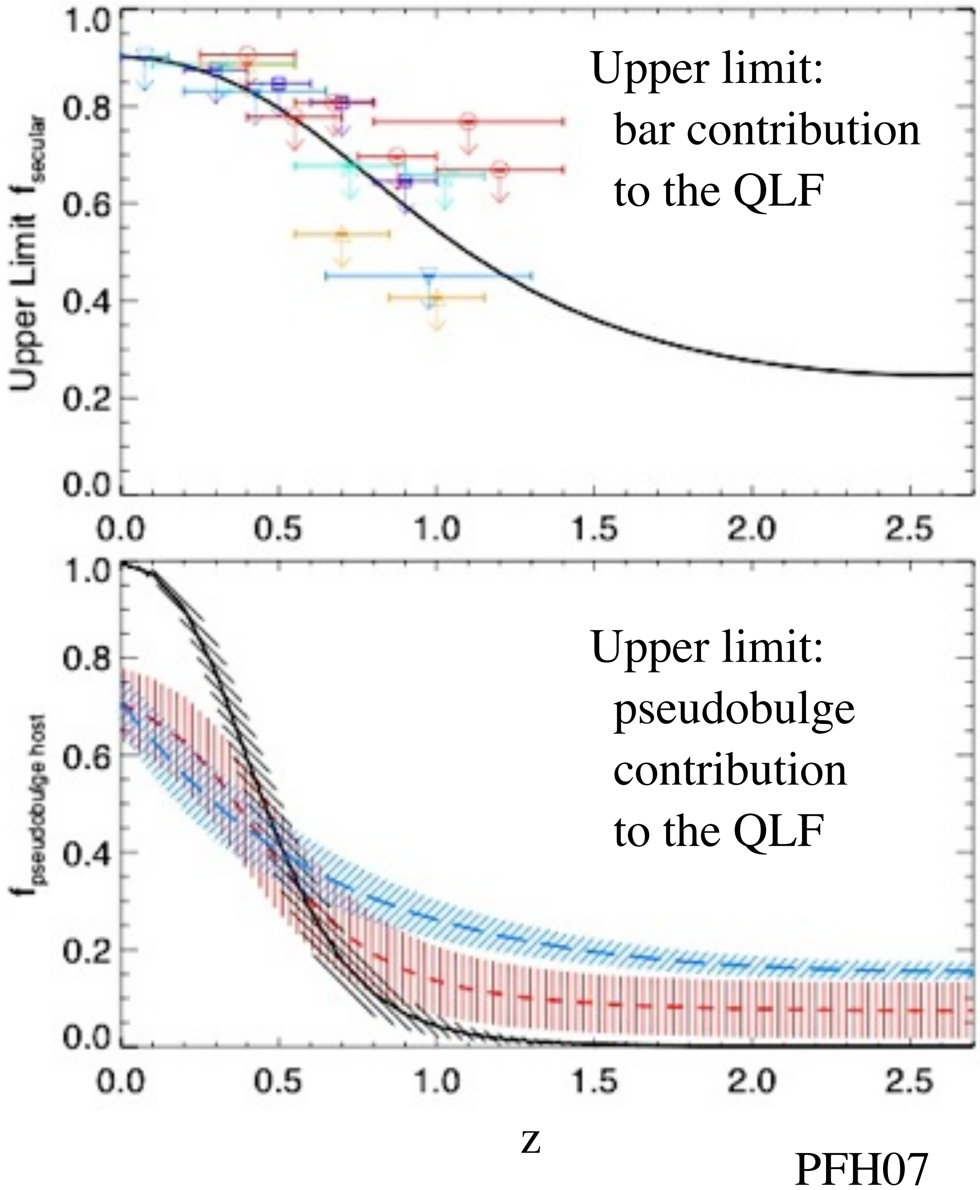
- Small-Scale Excess:
  - Not seen in Seyferts:
    - Suggests different processes dominate fueling below M_B ~ -23 (M_bh ~ 10^7)?



Serber et al. 2006

Morphology of Quasar Hosts

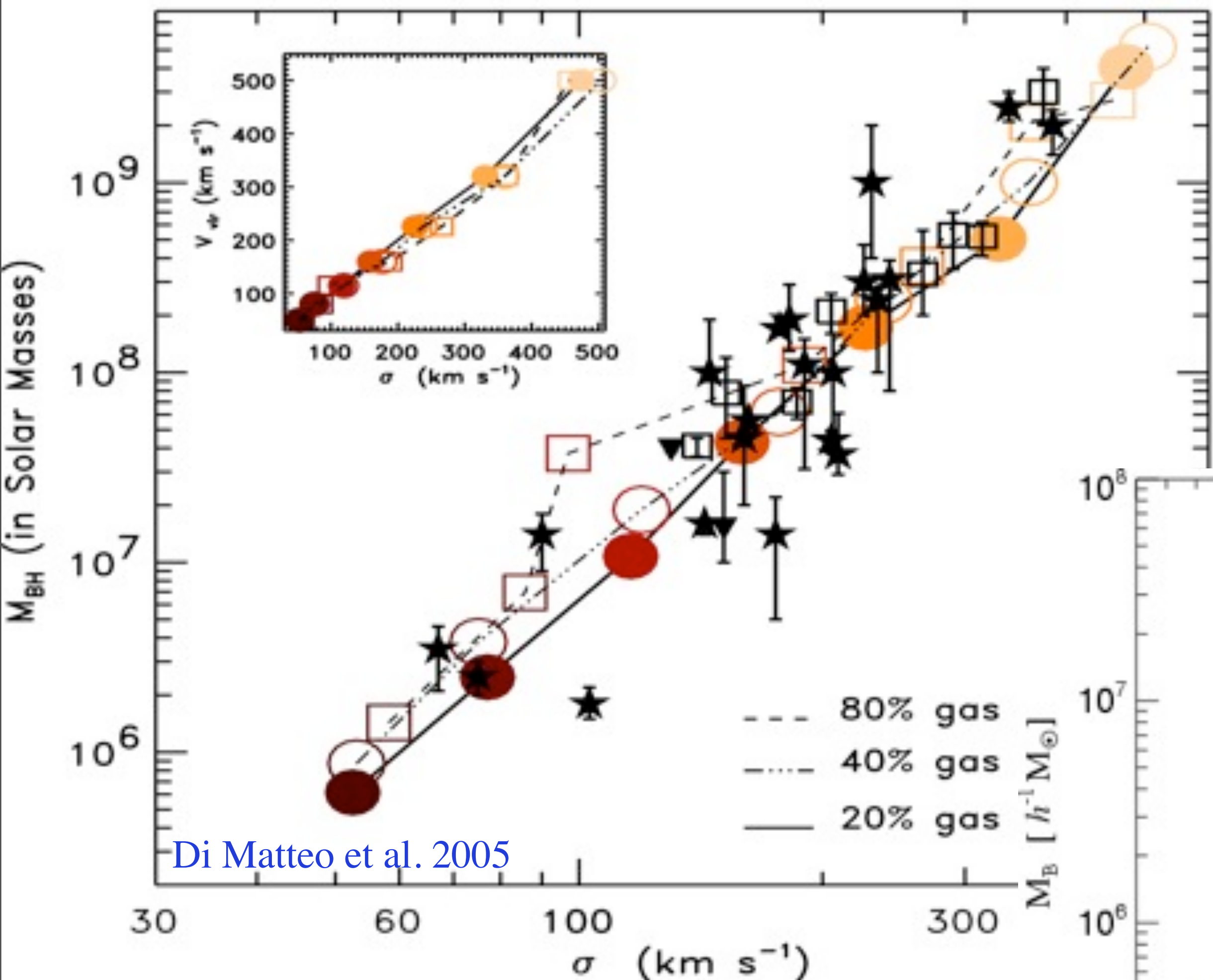
- Mergers form "classical" bulges; secular evolution forms "pseudobulges"
- Pseudobulges important only in relatively late-type galaxies; small M_bh
- Bar fraction & pseudobulge fraction ~constant to z~1-2

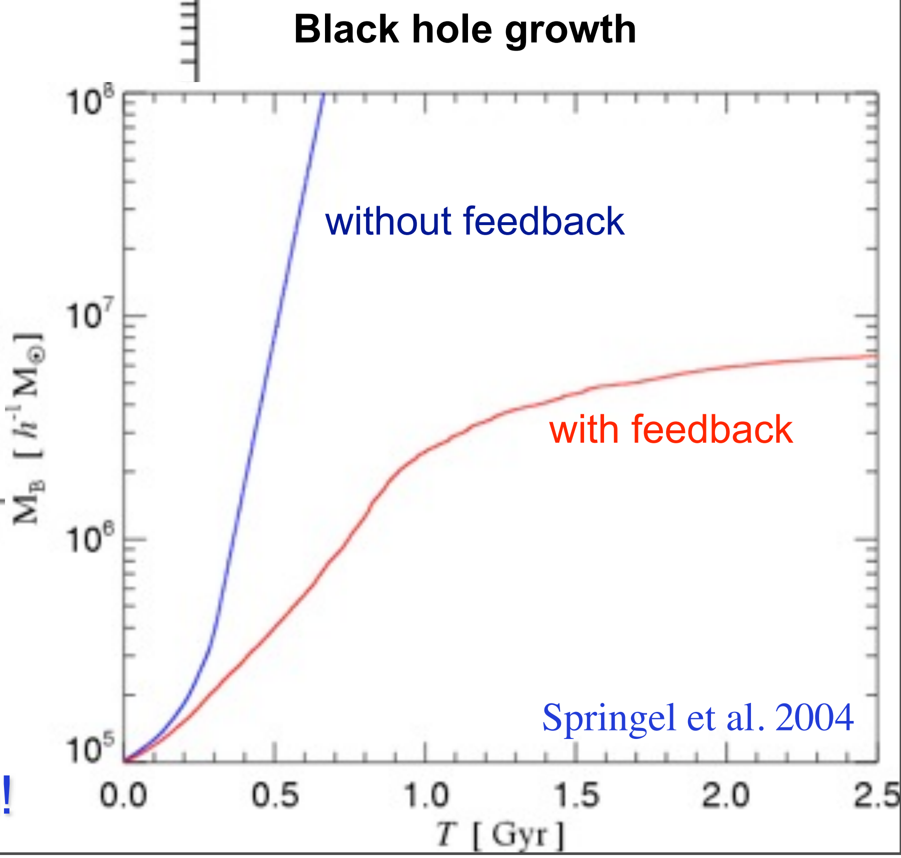


Self-Regulation
and
Quasar Lightcurves

M-sigma Relation Suggests Self-Regulated BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH





If only ~1% of gas mass lost angular momentum, would get runaway accretion!

Simplest Idea:

FEEDBACK ENERGY BALANCE

- Constant fraction (h) of BH radiated energy couples to the ISM: couple

  $E = h * (e_r * M\_bh * c^2)$

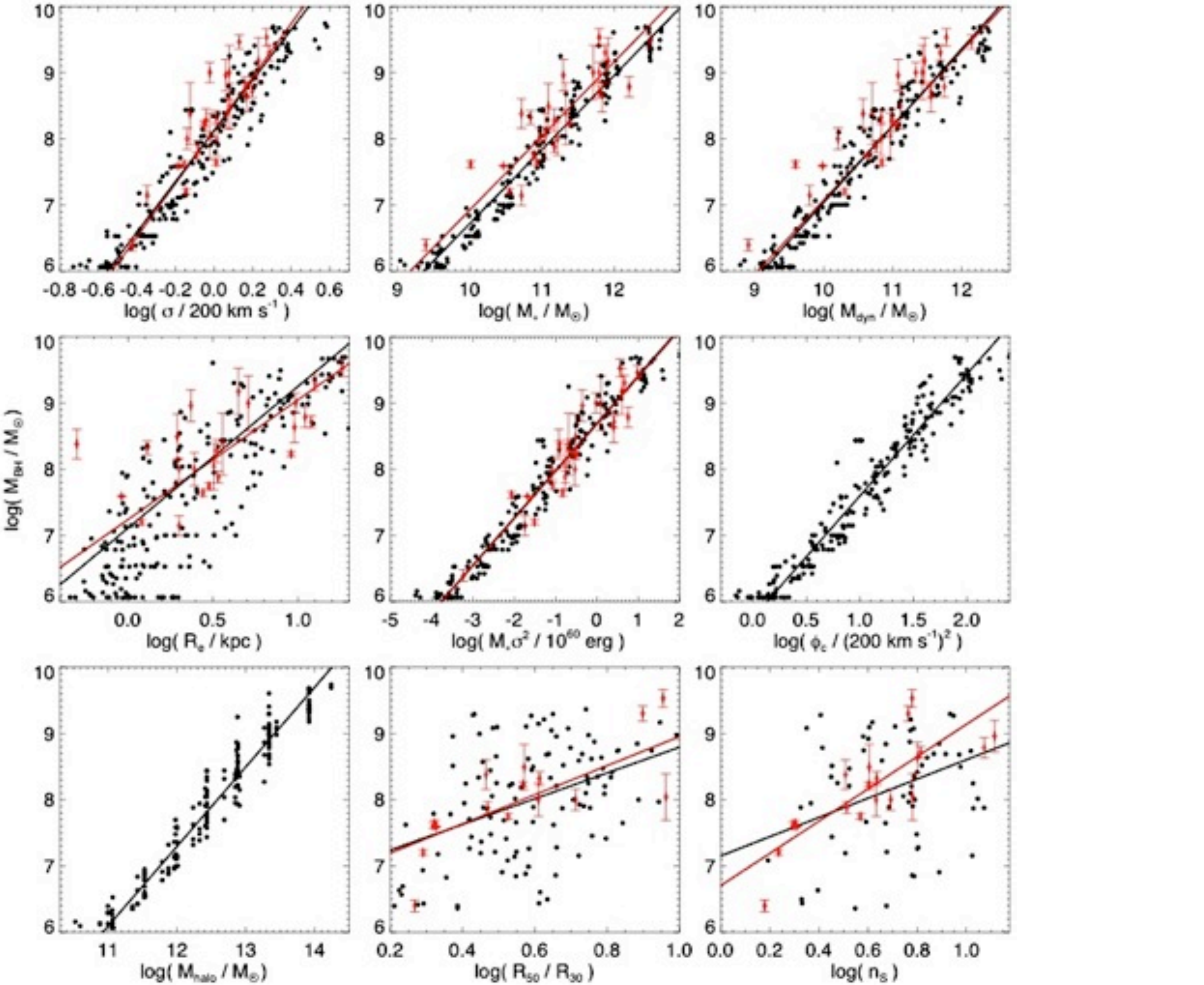
  when this is comparable to the binding energy of the gas in the galaxy, it will be blown out

  $E_g = y * (M_{halo} * v_c^2) \sim v_c^5 \sim s^5$

  So, self-regulate when $M\_bh \sim s^5$

  (Silk & Rees 1998)

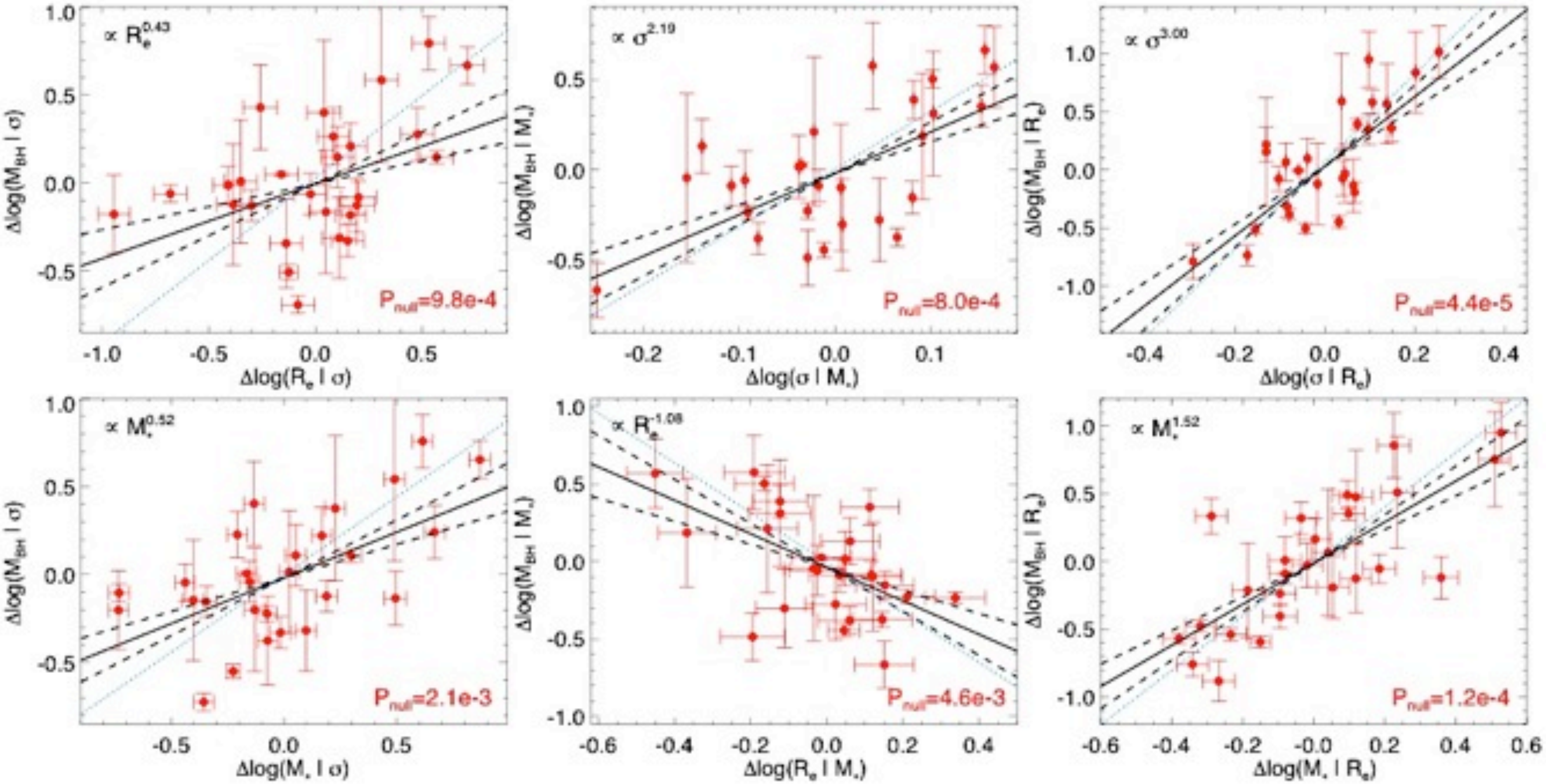
- But....


log(σ / 200 km s⁻¹)
log(M* / M⊙)
log(M_dyn / M⊙)
log(M_BH / M⊙)
log(R_e / kpc)
log(M*σ² / 10⁶⁰ erg)
log(φ_c / (200 km s⁻¹)²)
log(M_halo / M⊙)
log(R_50 / R_90)
log(n_S)

Which Correlation Is “Most Fundamental”?

COMPARE RESIDUALS

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

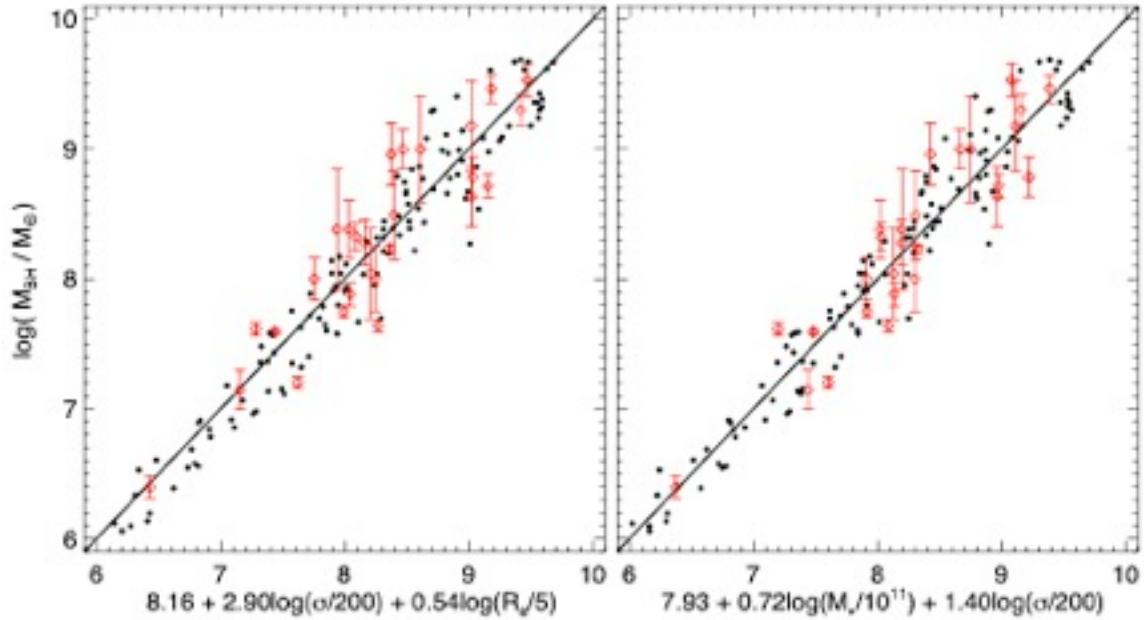


~3s significant residual trend with respect to ANY single variable correlation!

Which Correlation Is “Most Fundamental”?

WHAT ELIMINATES THE SECONDARY VARIABLES?

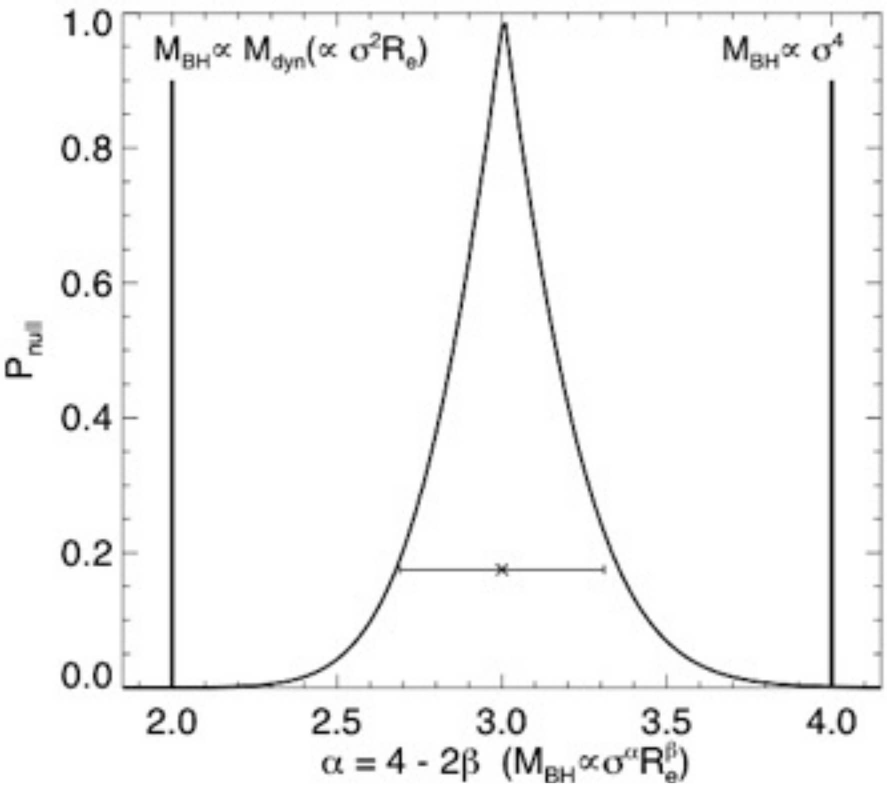
- Find a FP-like correlation:
  - $M_{bh} \sim M_{bul}^{a}\ s^{b}$
  - $M_{bh} \sim R_{e}^{a}\ s^{b}$
  - $M_{bh} \sim M_{bul}^{a}\ R_{e}^{b}$

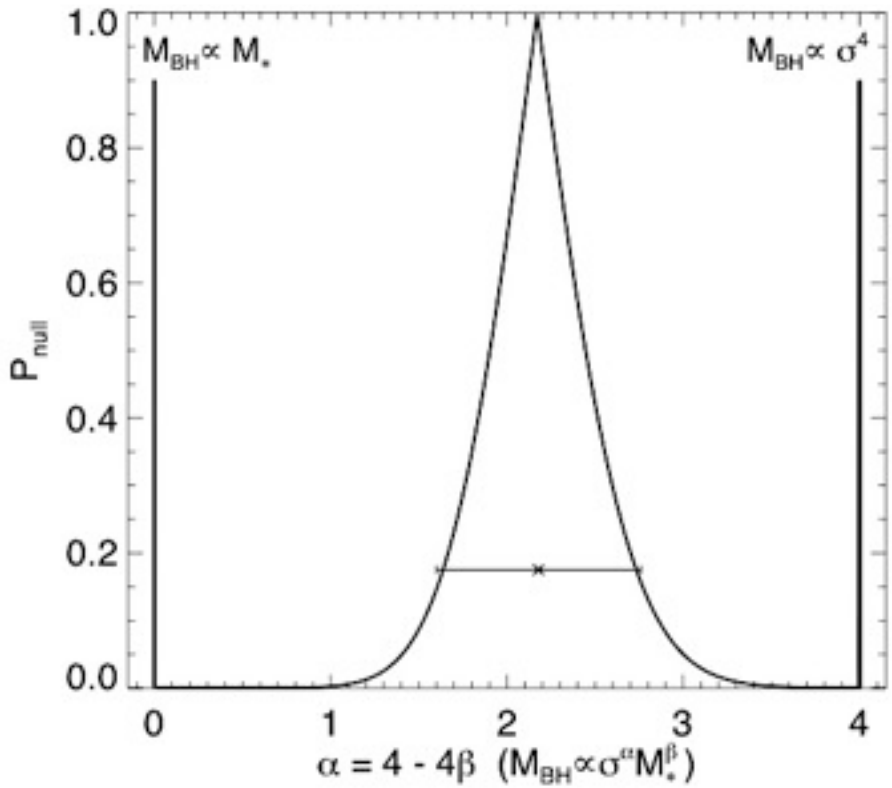


- Given the spheroid FP, these are the *same*

Which Correlation Is “Most Fundamental”?

WHAT ELIMINATES THE SECONDARY VARIABLES?

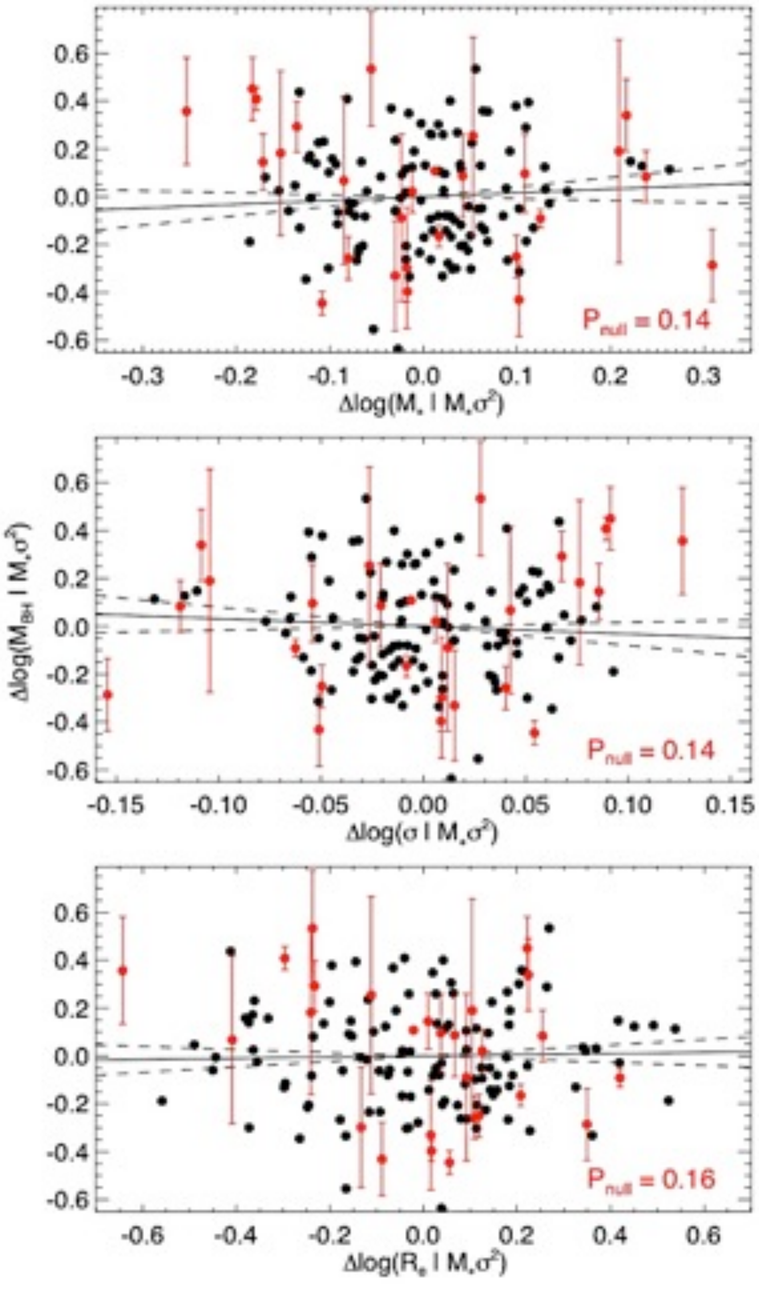


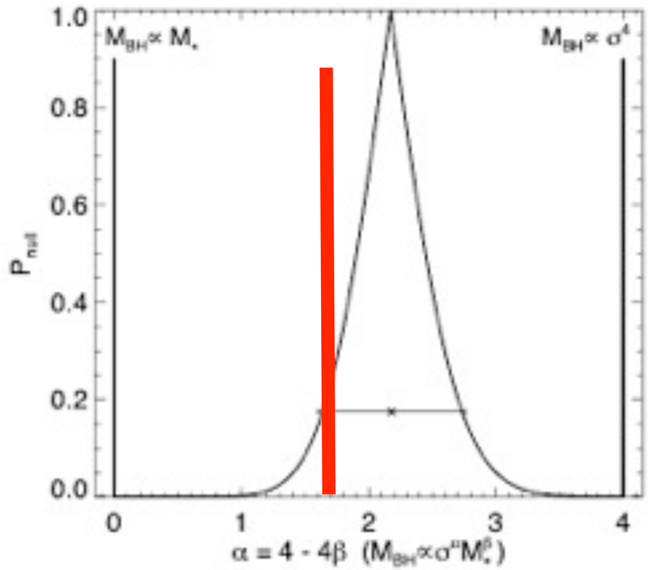


What Does this FP-Like Relation Imply?

IS THERE ANY PHYSICAL MEANING?

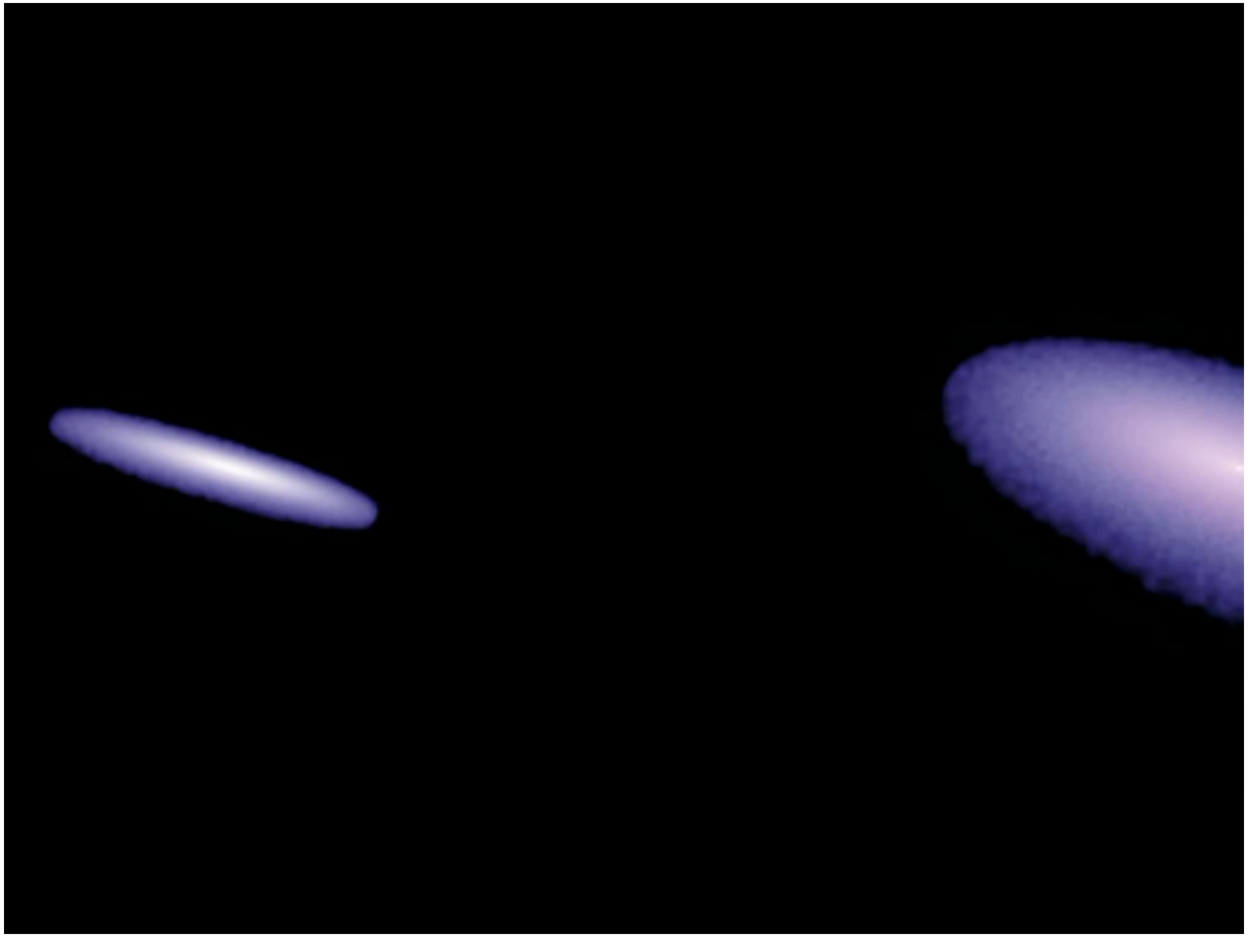
- Reasonably close to binding energy, but with “tilt”:
    - $M_{bh} \sim E_{binding}^{2/3} \sim (M_{bul}\, s^2)^{2/3}$

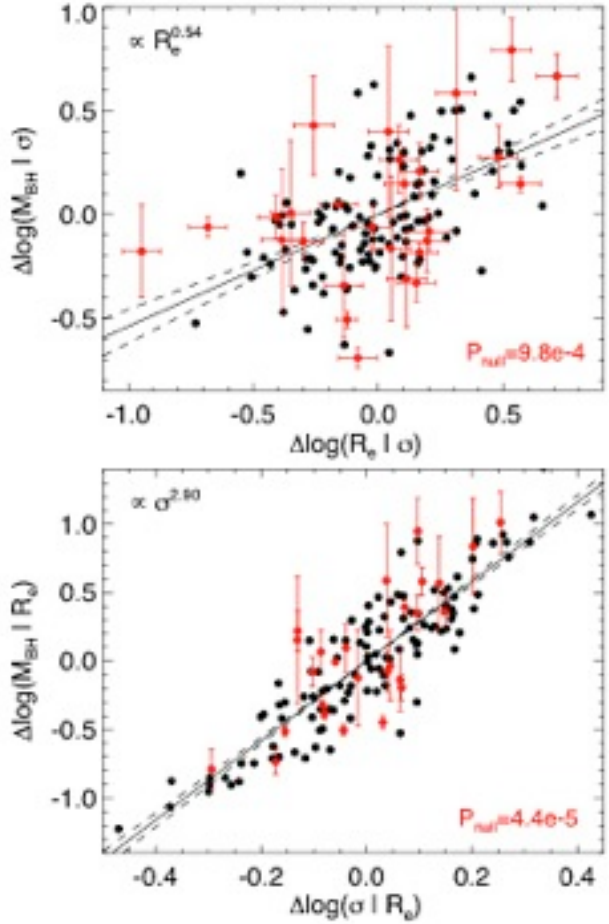




Do Feedback-Regulated Simulations Predict This?

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

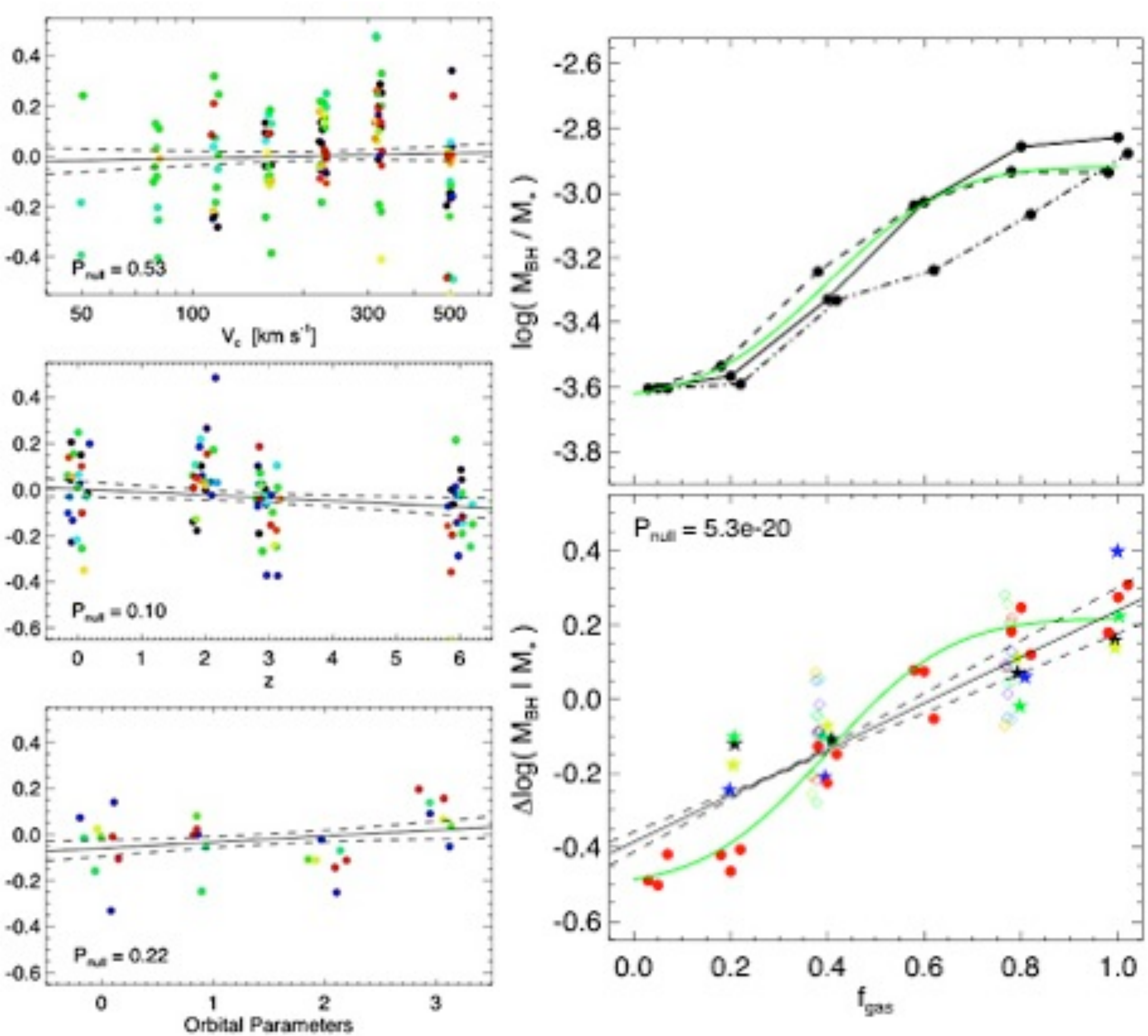




- Supports basic Silk & Rees ’98 argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential of material to be unbound

Can We Get Away From This?

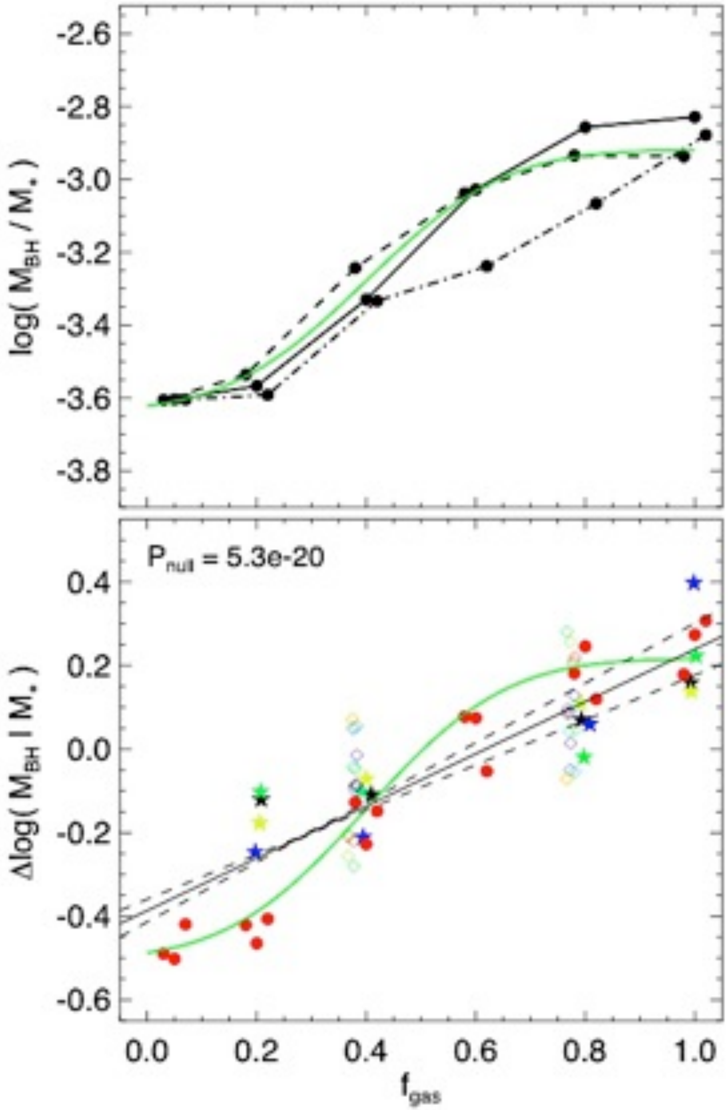
HOW DOES THE RELATION DEPEND ON INITIAL CONDITIONS?



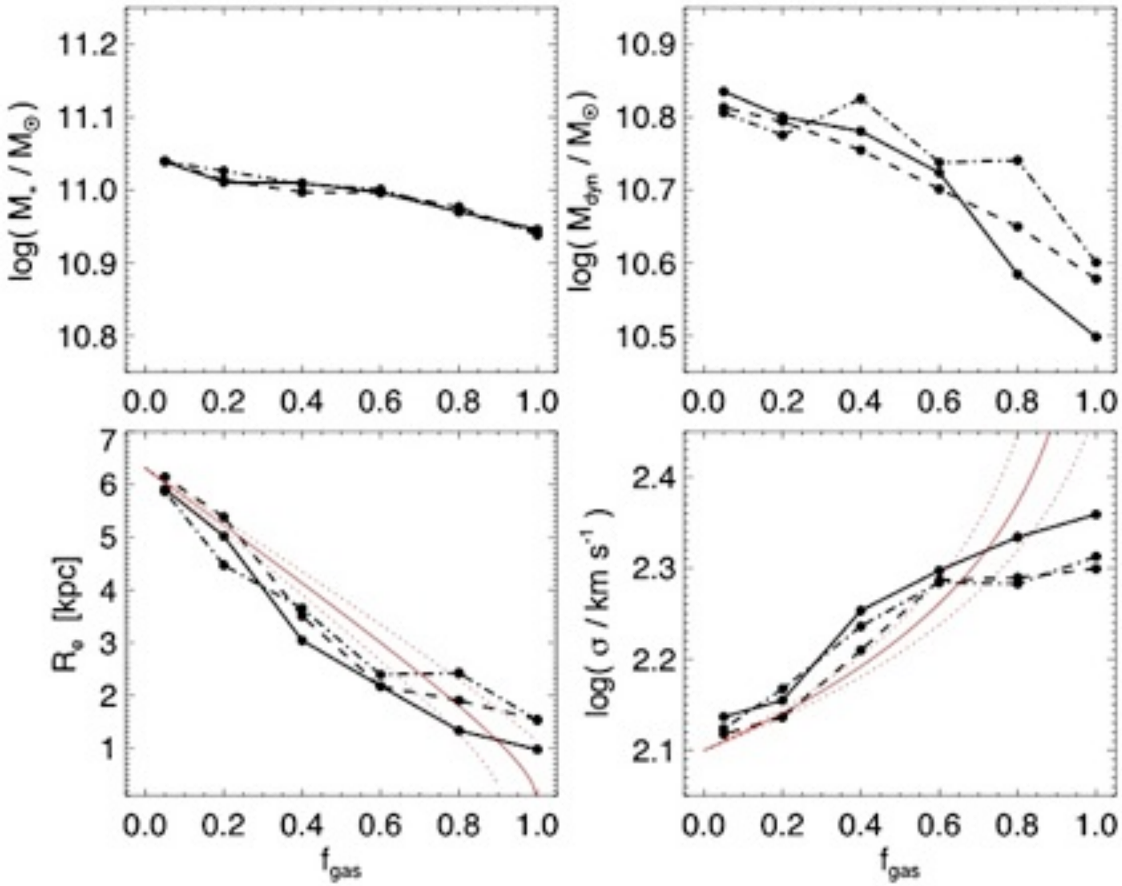
- Primarily a *local* correlation with *final* state:
  - Can't get "off" this correlation if feedback still self-regulates
- Can move *along* the correlation
  - Changes projections:
    - M_{bh} - M_{bul}
    - M_{bh} - s

Moving Along the BH FP-Like Correlation

GIVEN THIS CORRELATION, HOW DO YOU MOVE IN ITS PROJECTIONS



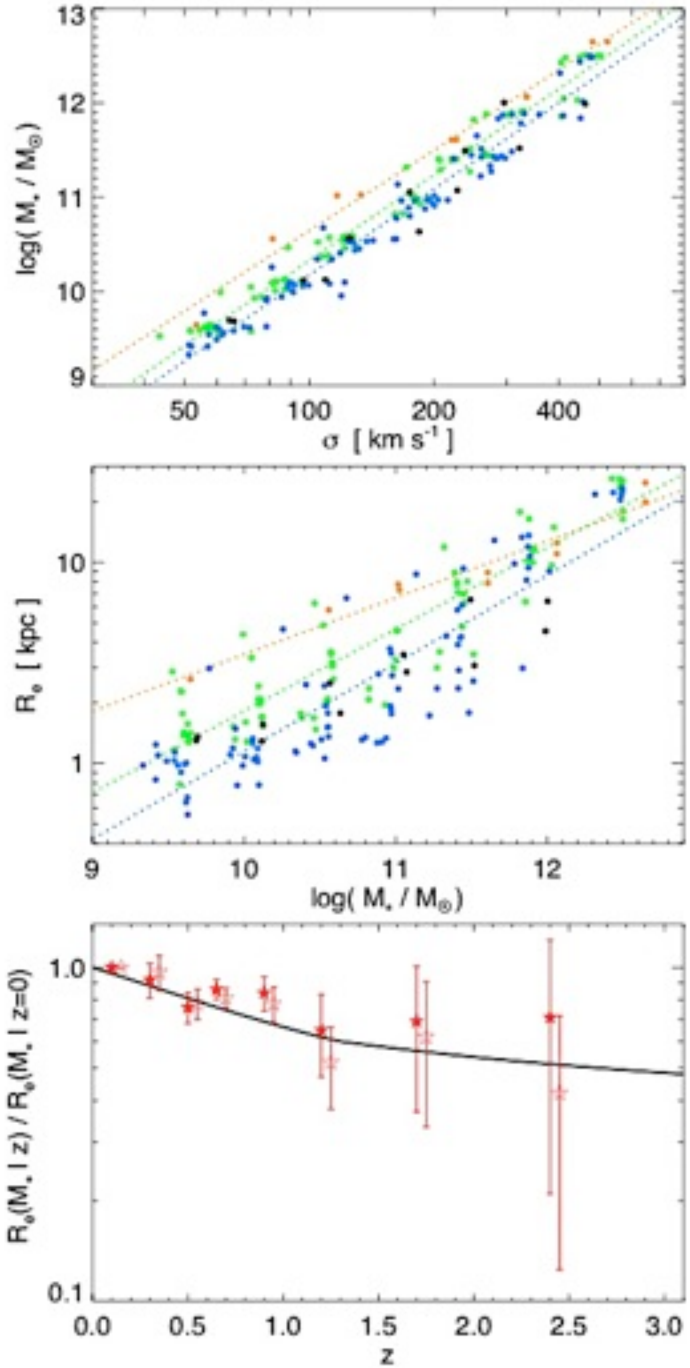
- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
- Deepens the central potential



Moving Along the BH FP-Like Correlation

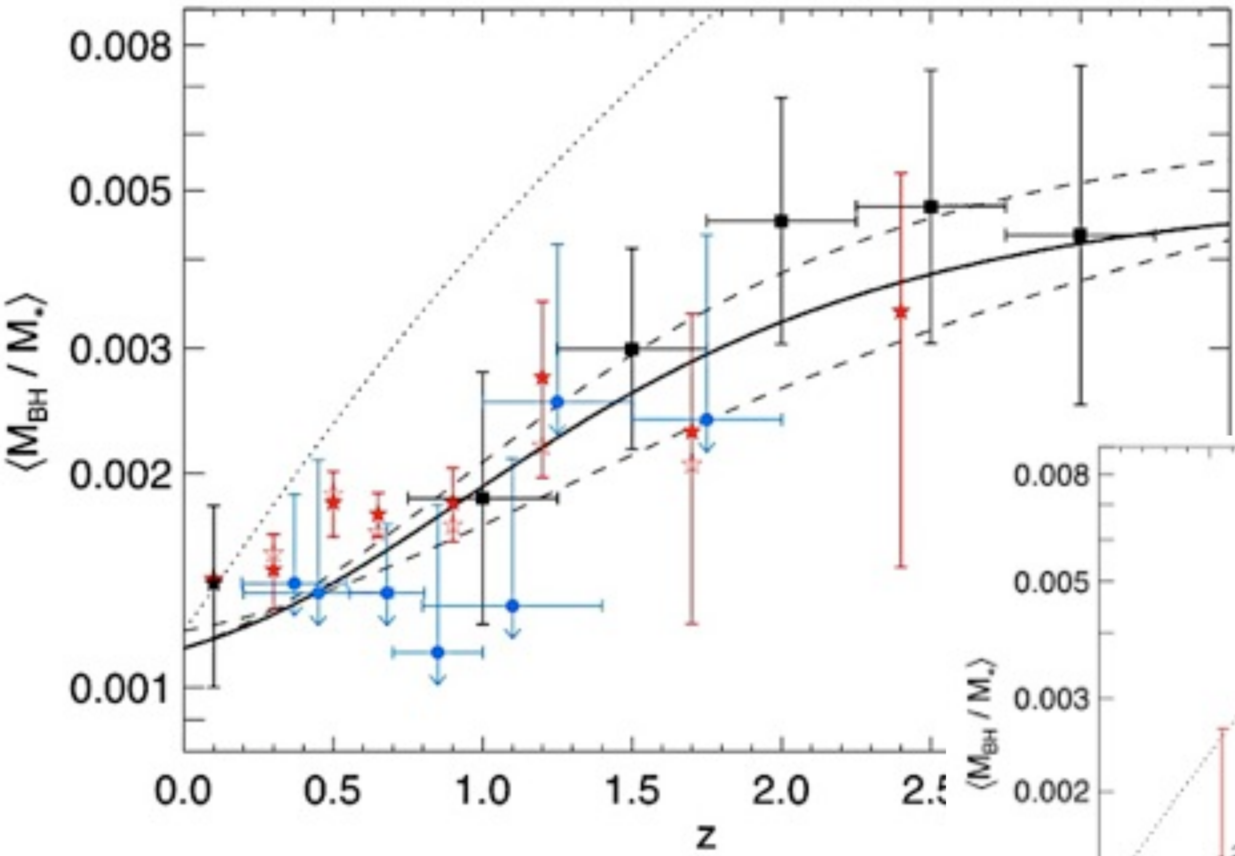
IMPLICATIONS FOR REDSHIFT EVOLUTION

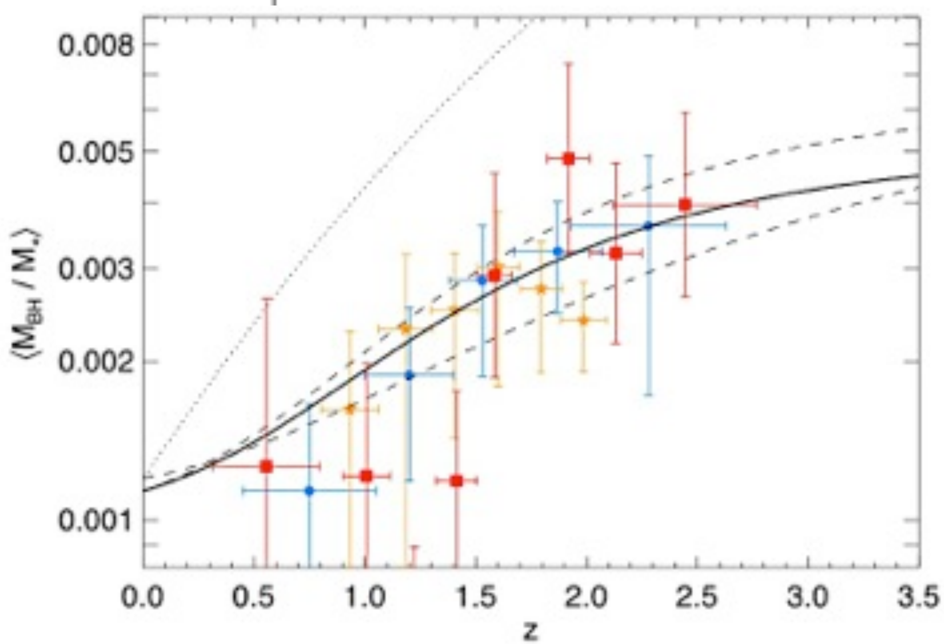
- High-z galaxies are more gas-rich:
  - Expect more compact remnants
    - Khochfar & Silk
  - See them: smaller R_e, larger s at fixed M_{bul}
    - Trujillo et al.; Zirm et al.



Moving Along the BH FP-Like Correlation

IMPLICATIONS FOR REDSHIFT EVOLUTION

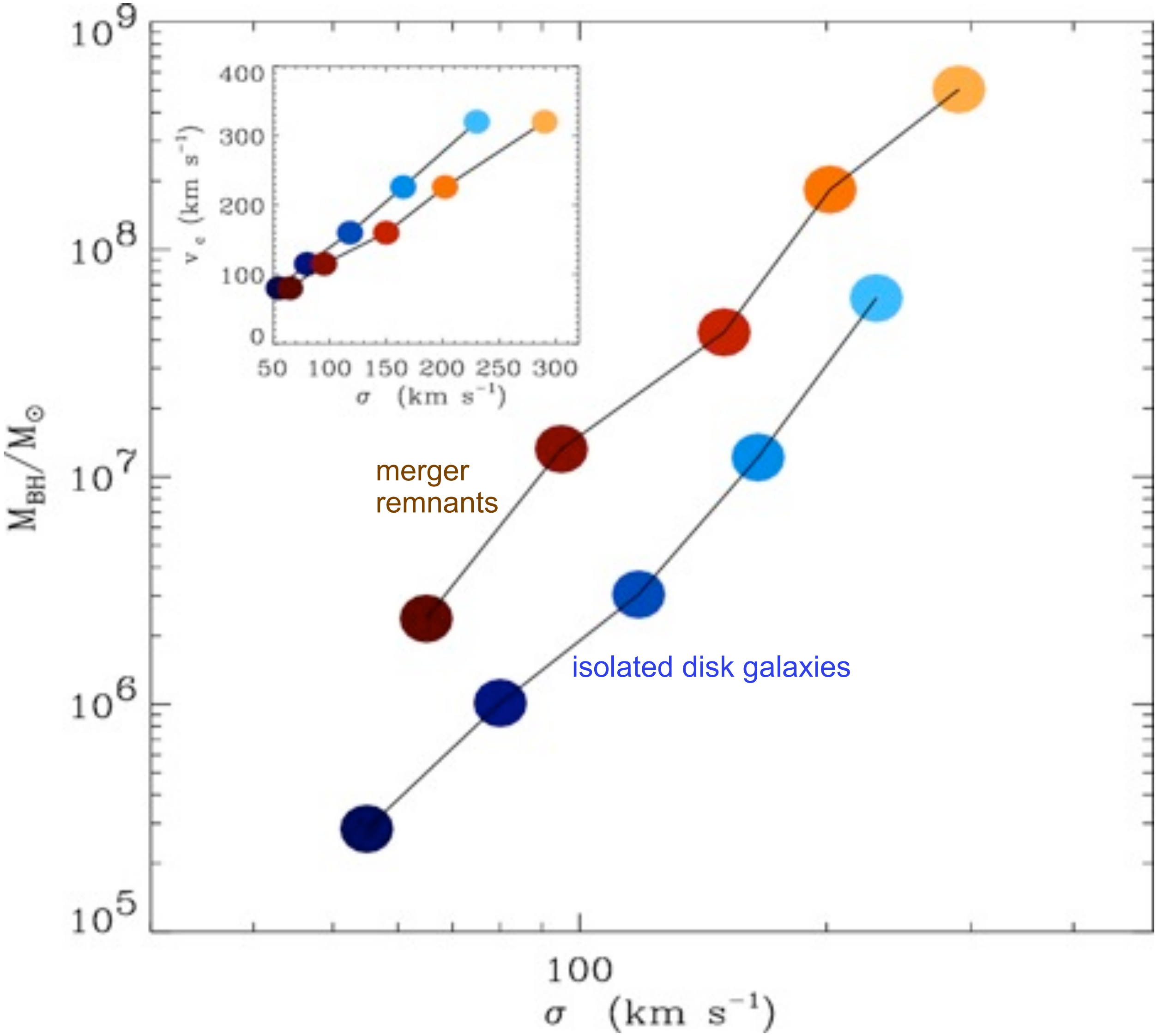




- $M_{bh} \sim (M_{bul}\ s^2)^{2/3}$
  - Larger M_{bh} at fixed M_{bul}
    - Peng et al.; Fine et al.; Shields et al.; Merloni et al.; Walter et al.
  - Different evolution in M_{bh}-M_{bul} & M_{bh}-s

What about other fueling mechanisms?

BLACK HOLE MASSES IN ISOLATED GALAXIES AND MERGER REMNANTS



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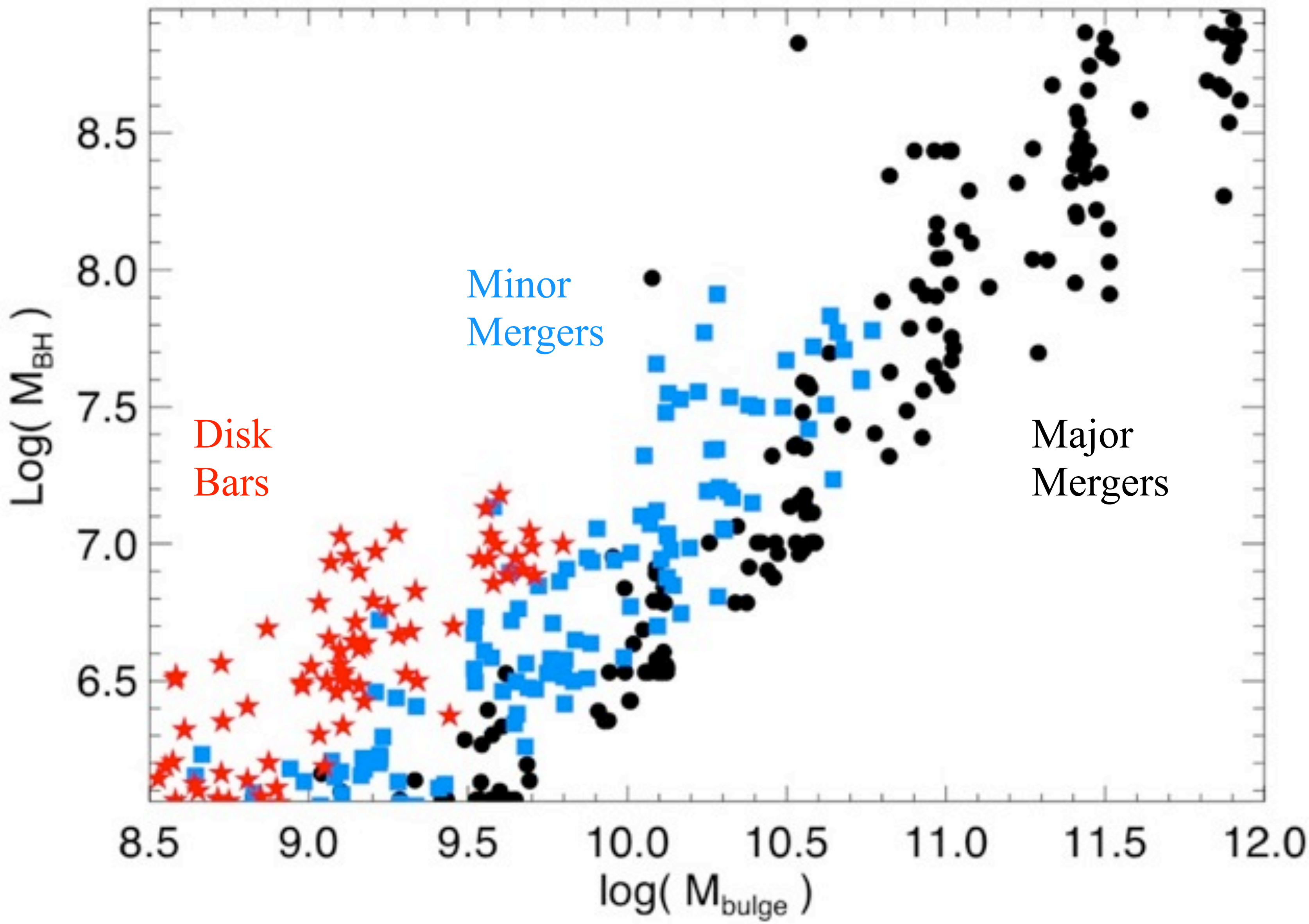

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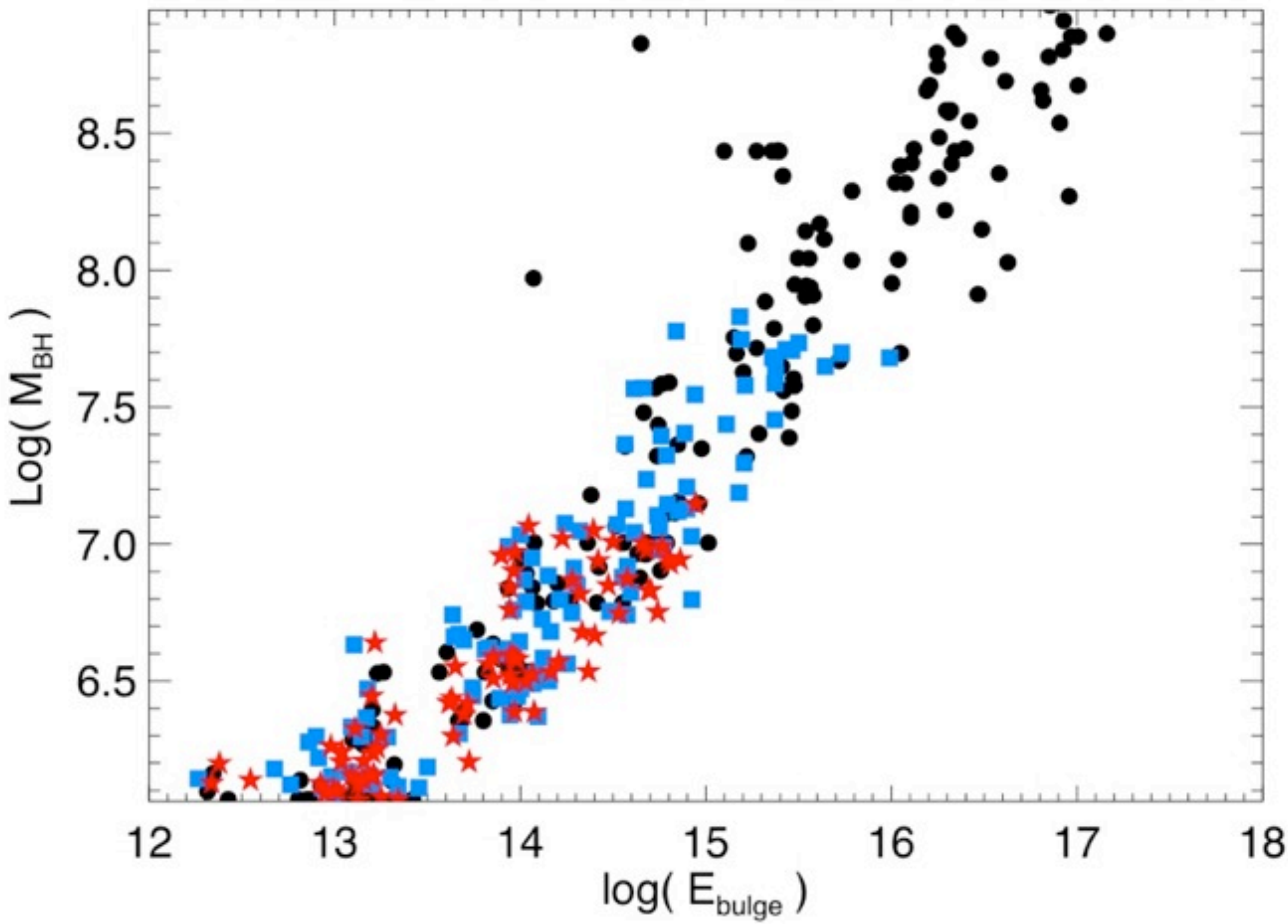
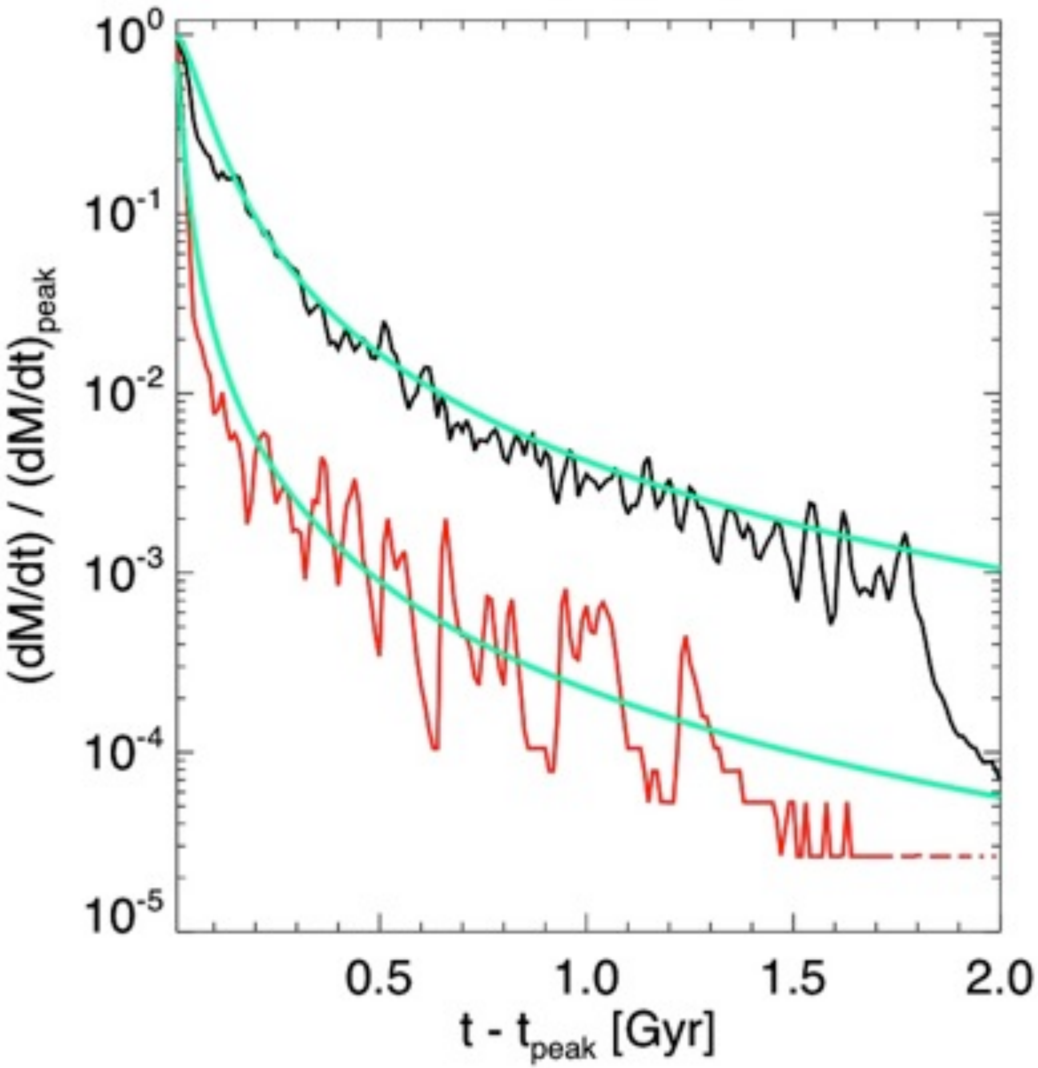


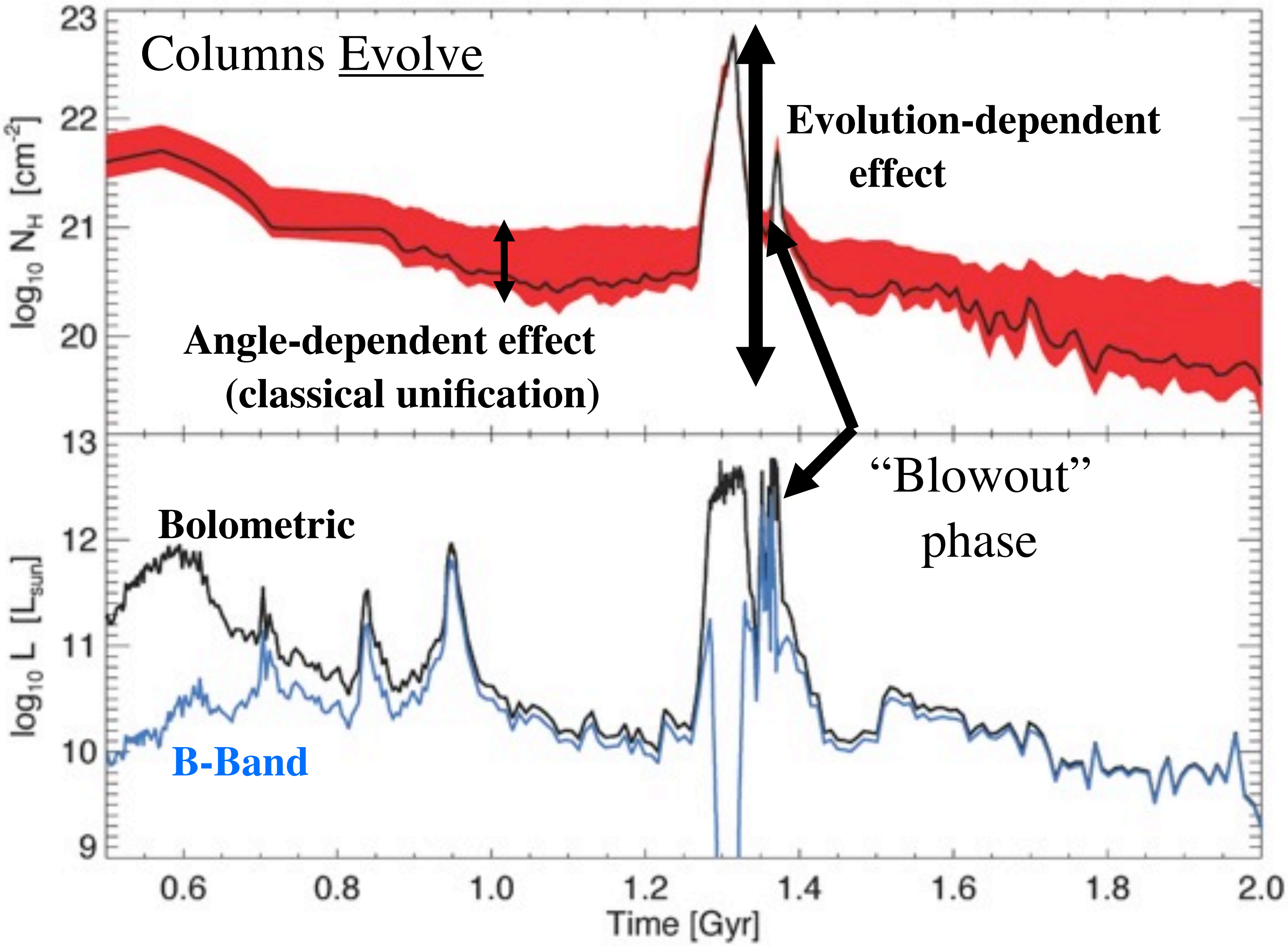
Generalizing the Model

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 (defines when the feedback is important)
- Suggests analytical solutions for decay of accretion rates in feedback-driven winds or blastwaves
    - Agrees well with simulations!
- Generalize to “Seyferts”
    - Disk-dominated galaxy, central molecular clouds
    - Calculate accretion rate(time) when a cloud “collides” with the BH



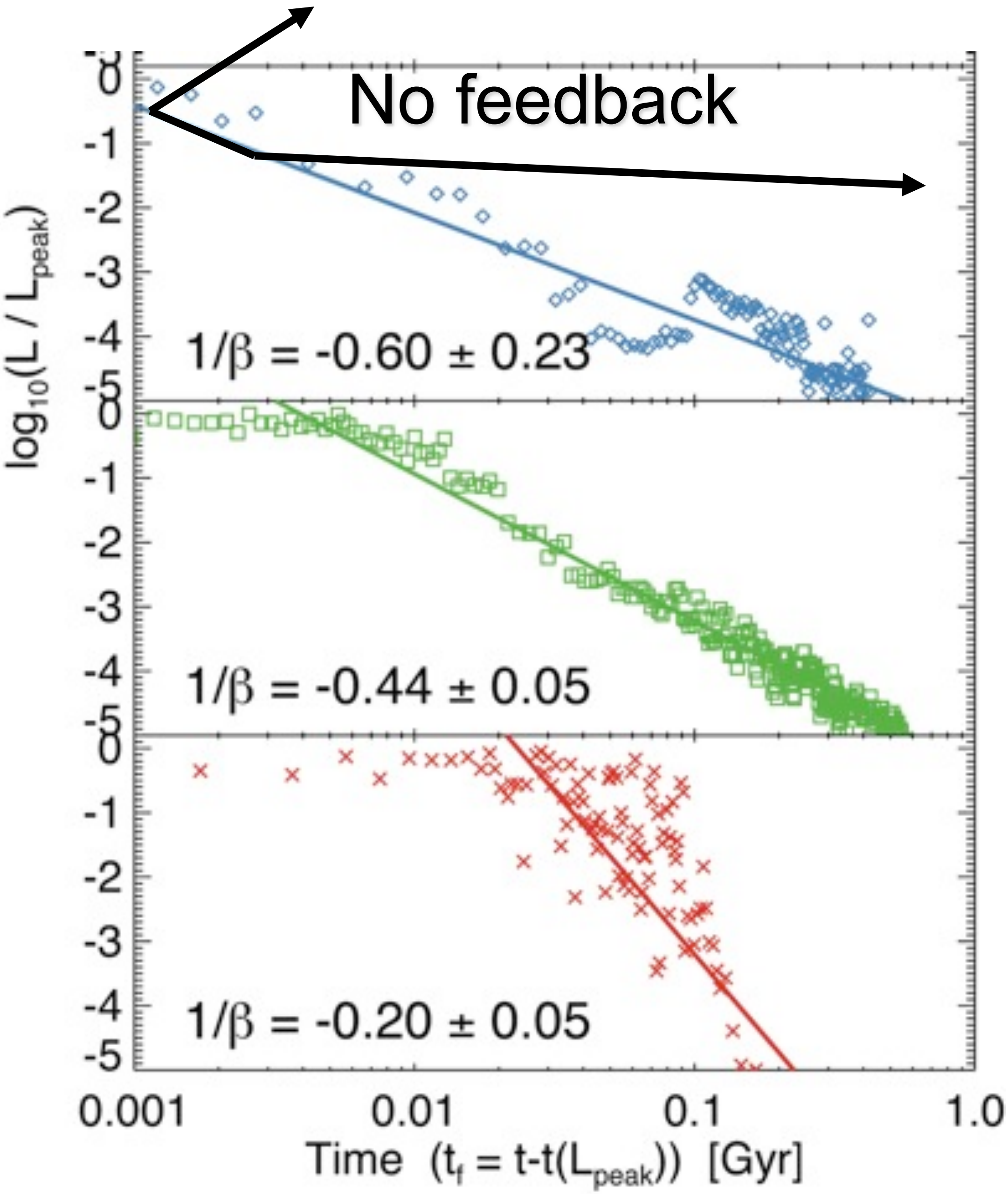
Quasar Lightcurves:



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

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME



- Simulation: 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)

Hopkins et al. 2006a

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
  - General solution depends just on energy injection

PFH 2006

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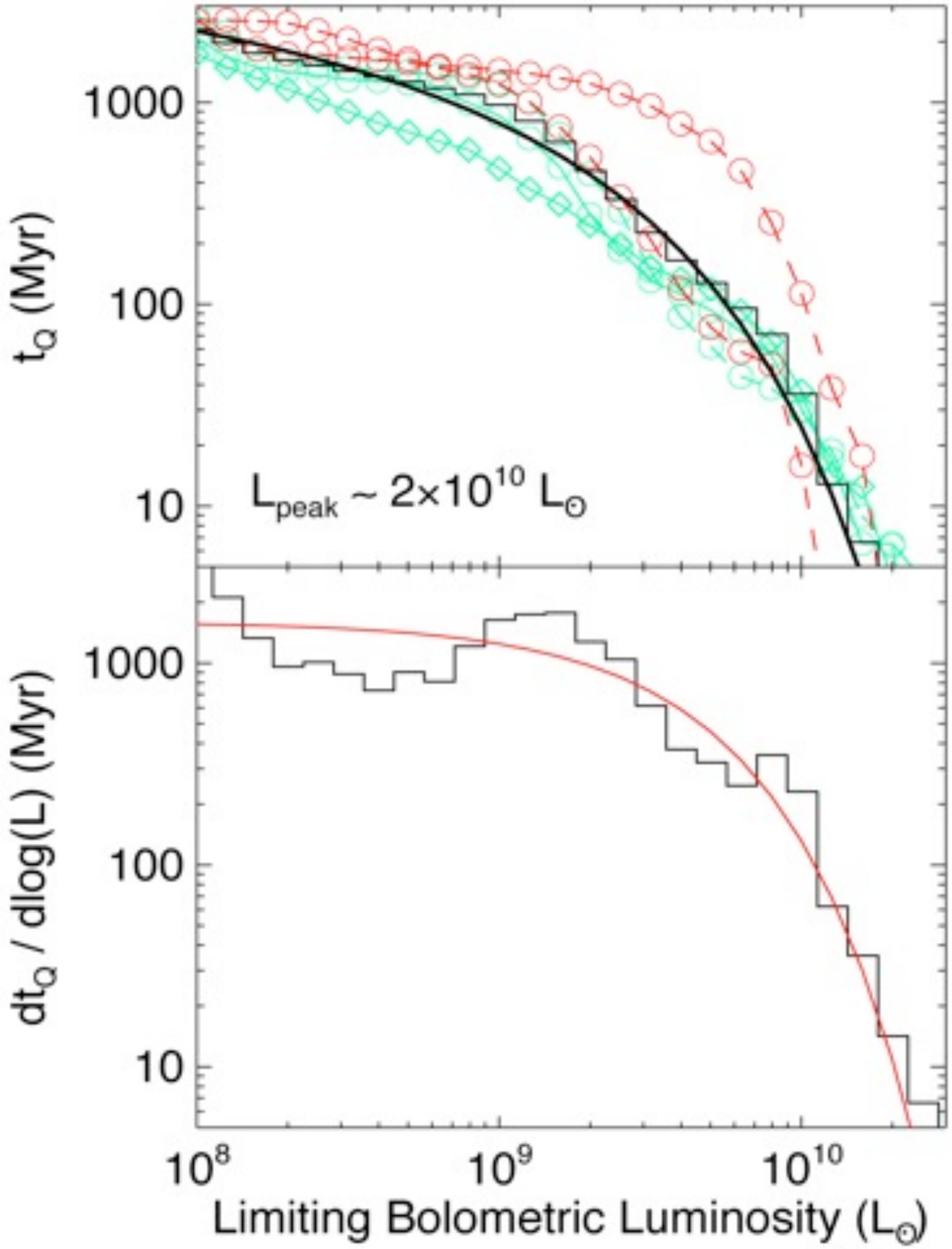

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PFH 2006

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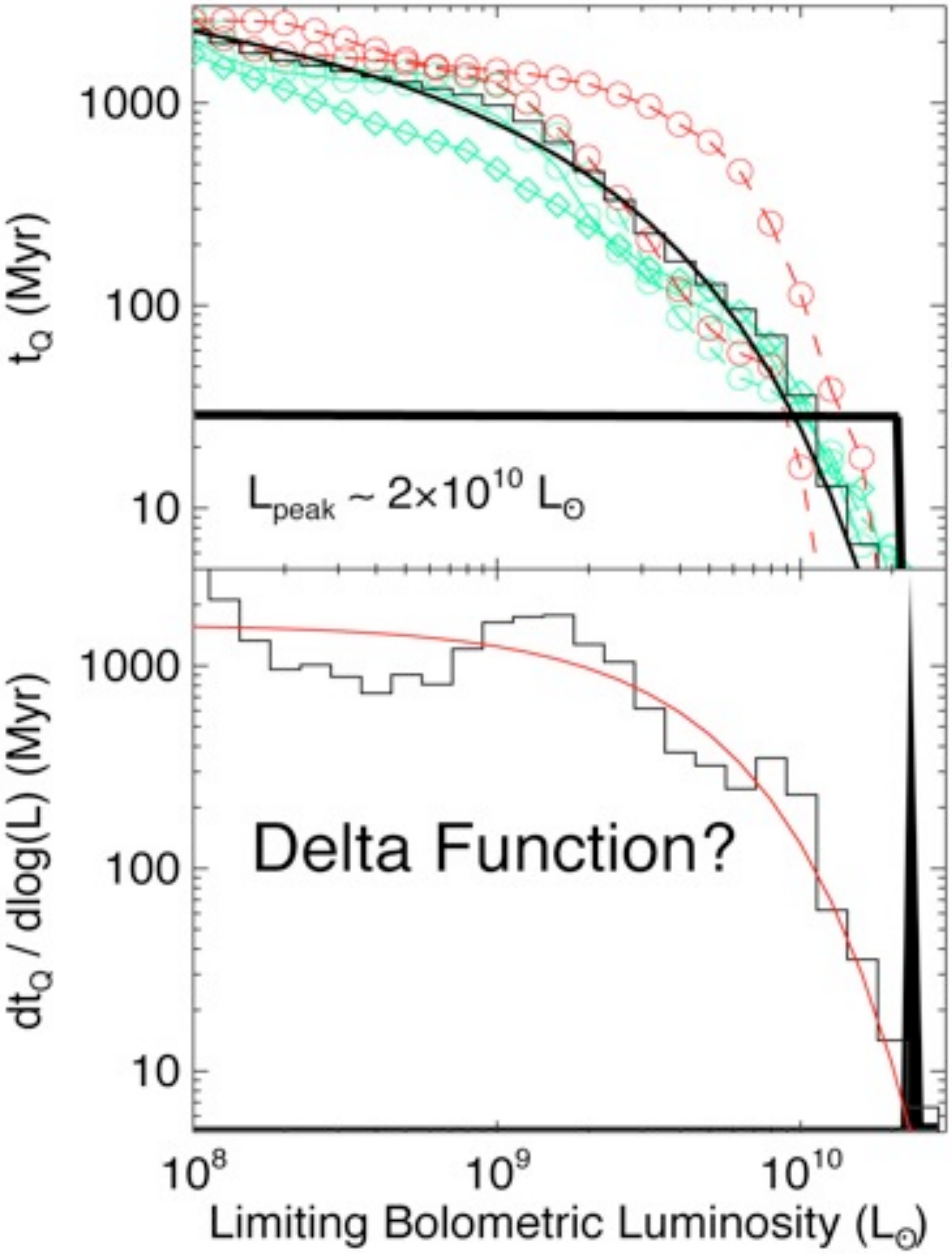

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PFH 2006

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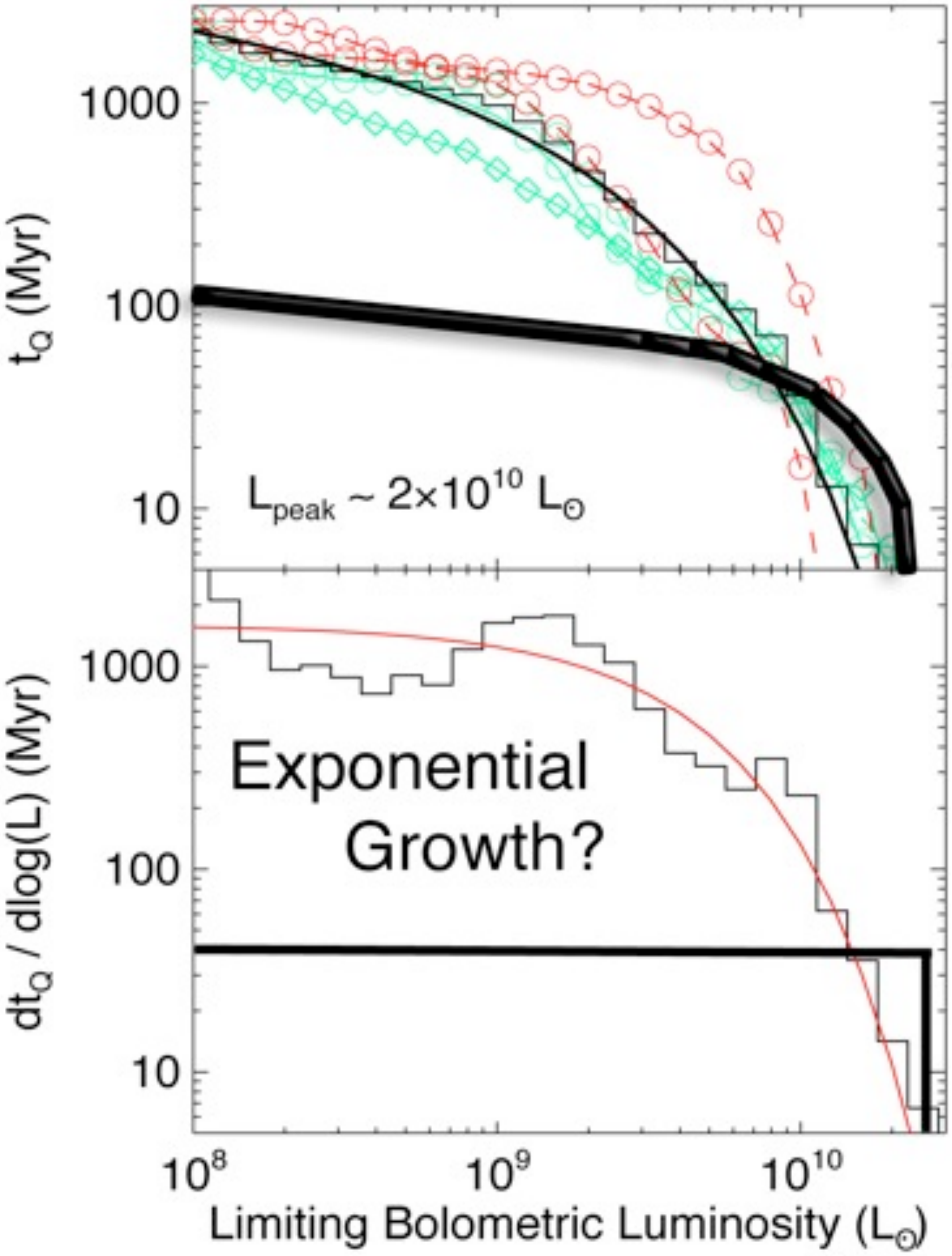

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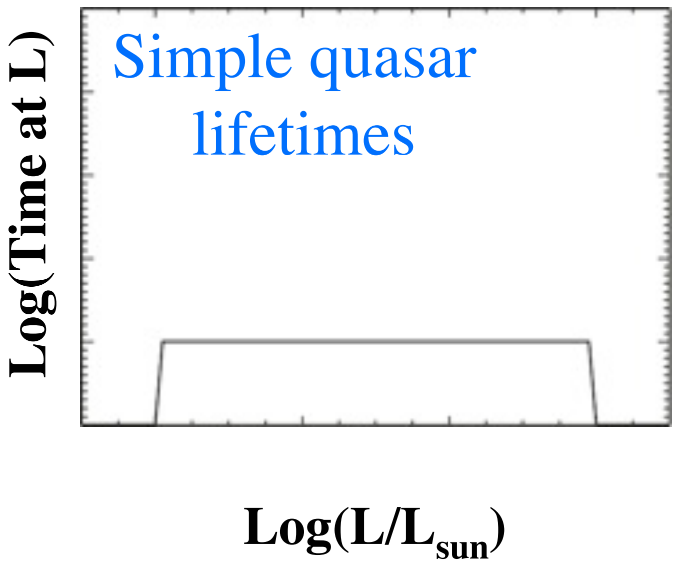
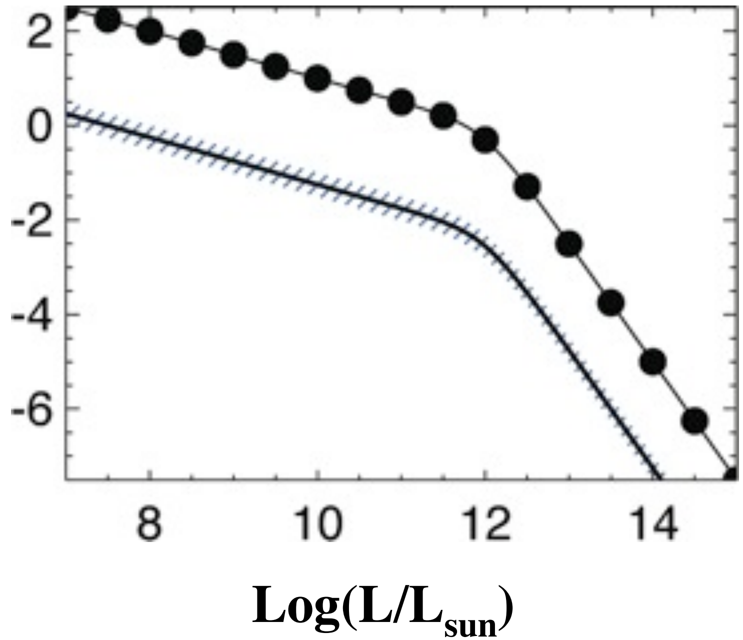
PFH 2006

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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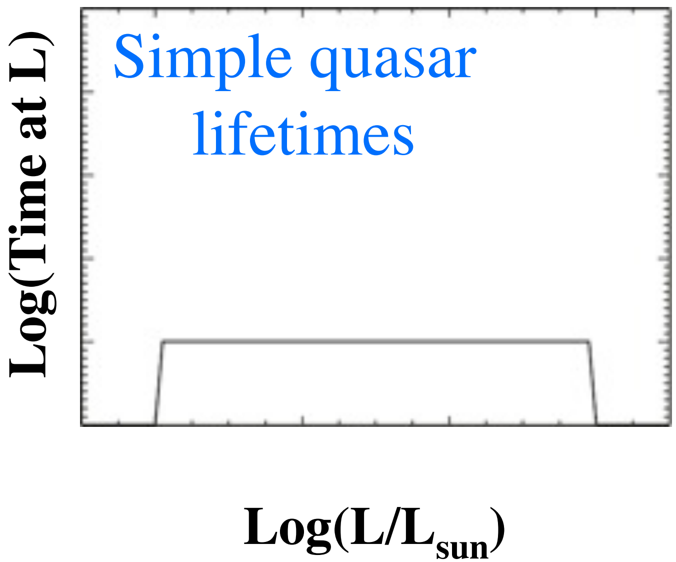

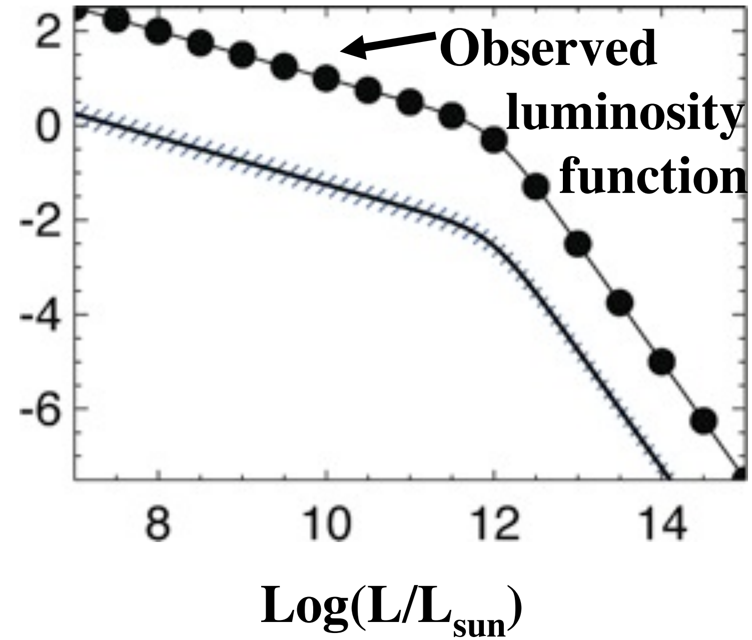

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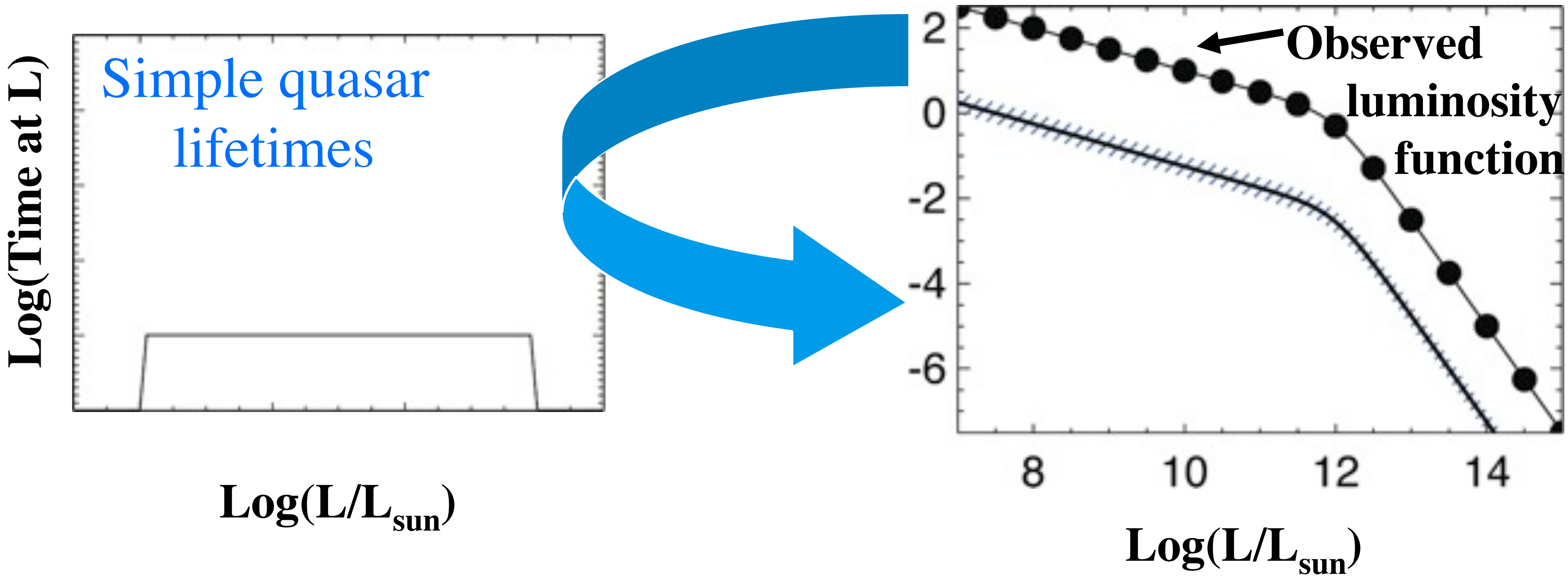

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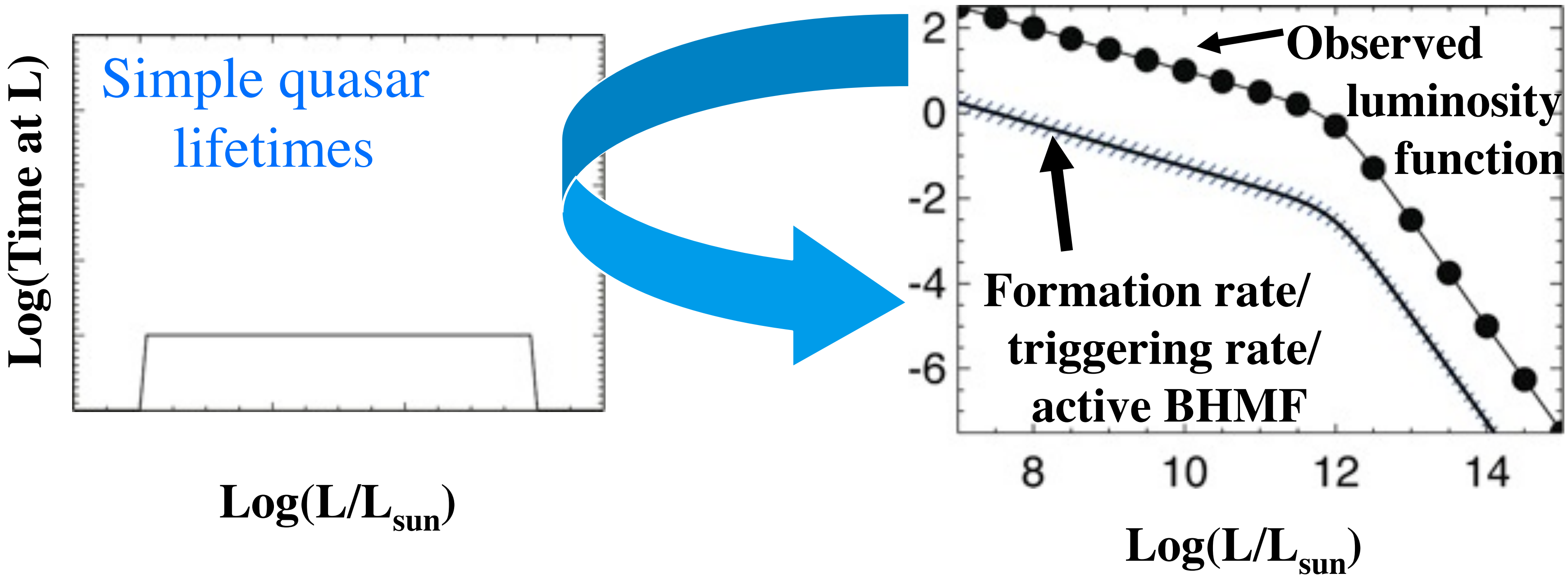

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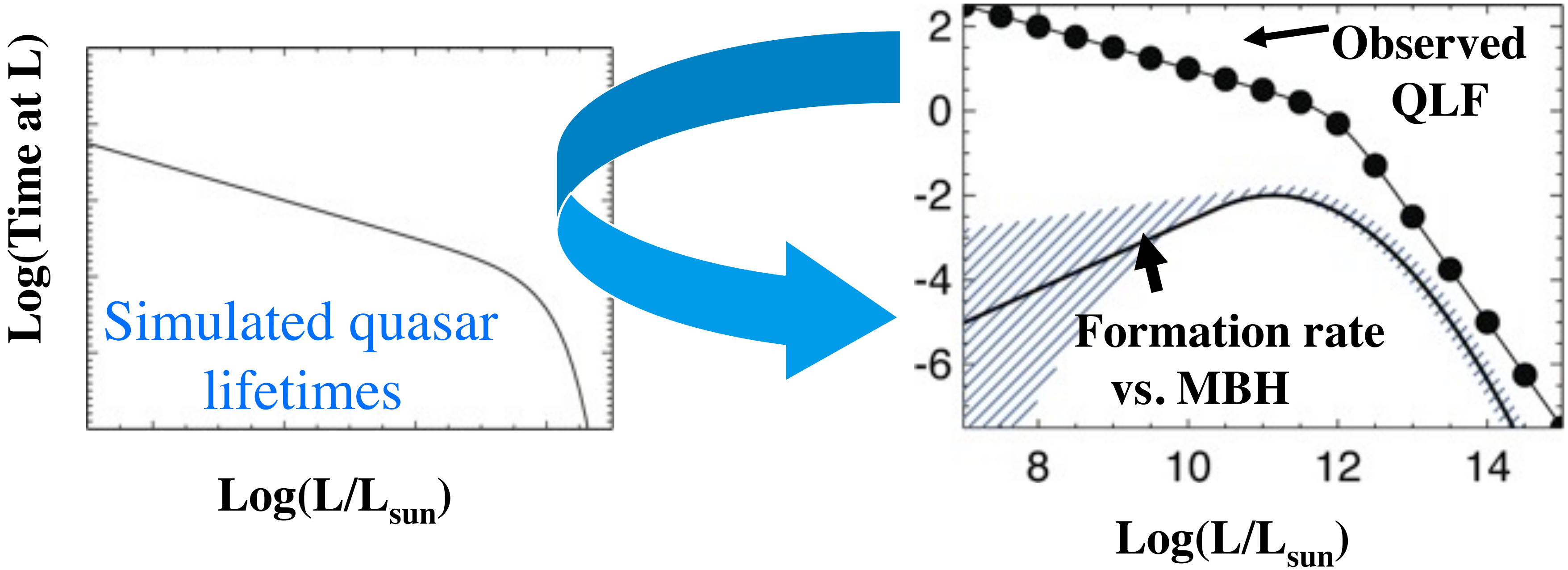
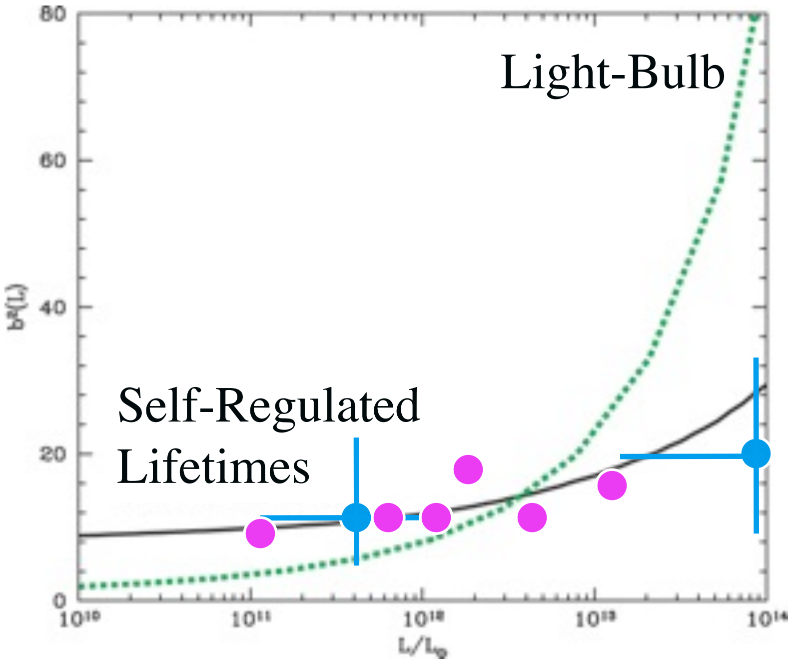


- Feedback-regulated lifetime drives a given QSO to lower L after blowout, and spends more time at low-L
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts

Quasar Clustering is a Strong Test of this Model

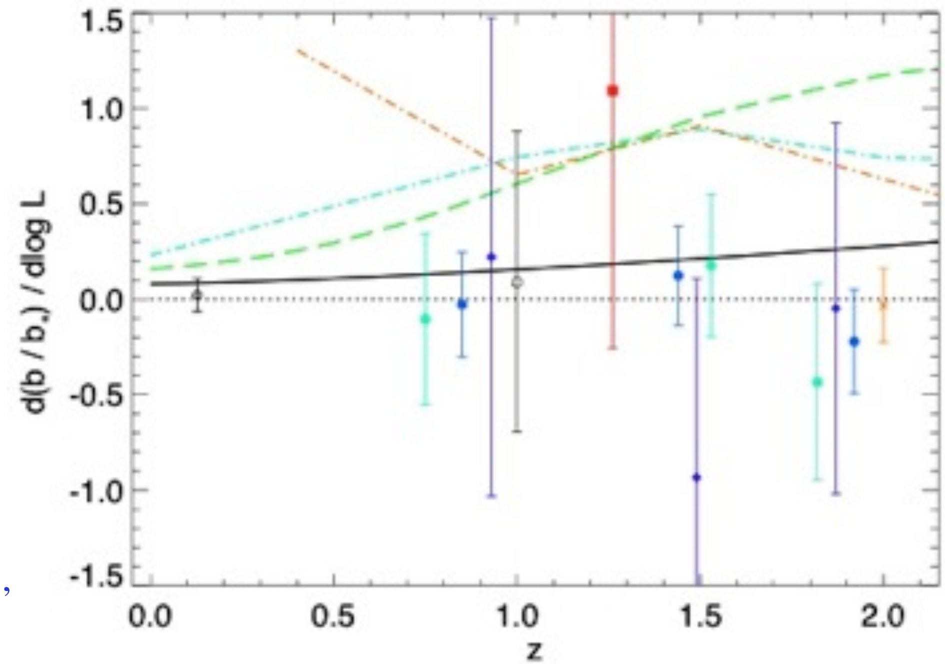
IF FAINT QSOS ARE DECAYING BRIGHT QSOS - SHOULD BE IN SIMILAR HOSTS



- Adelberger & Steidel 05
- Myers et al. 05

Lidz et al. 2005

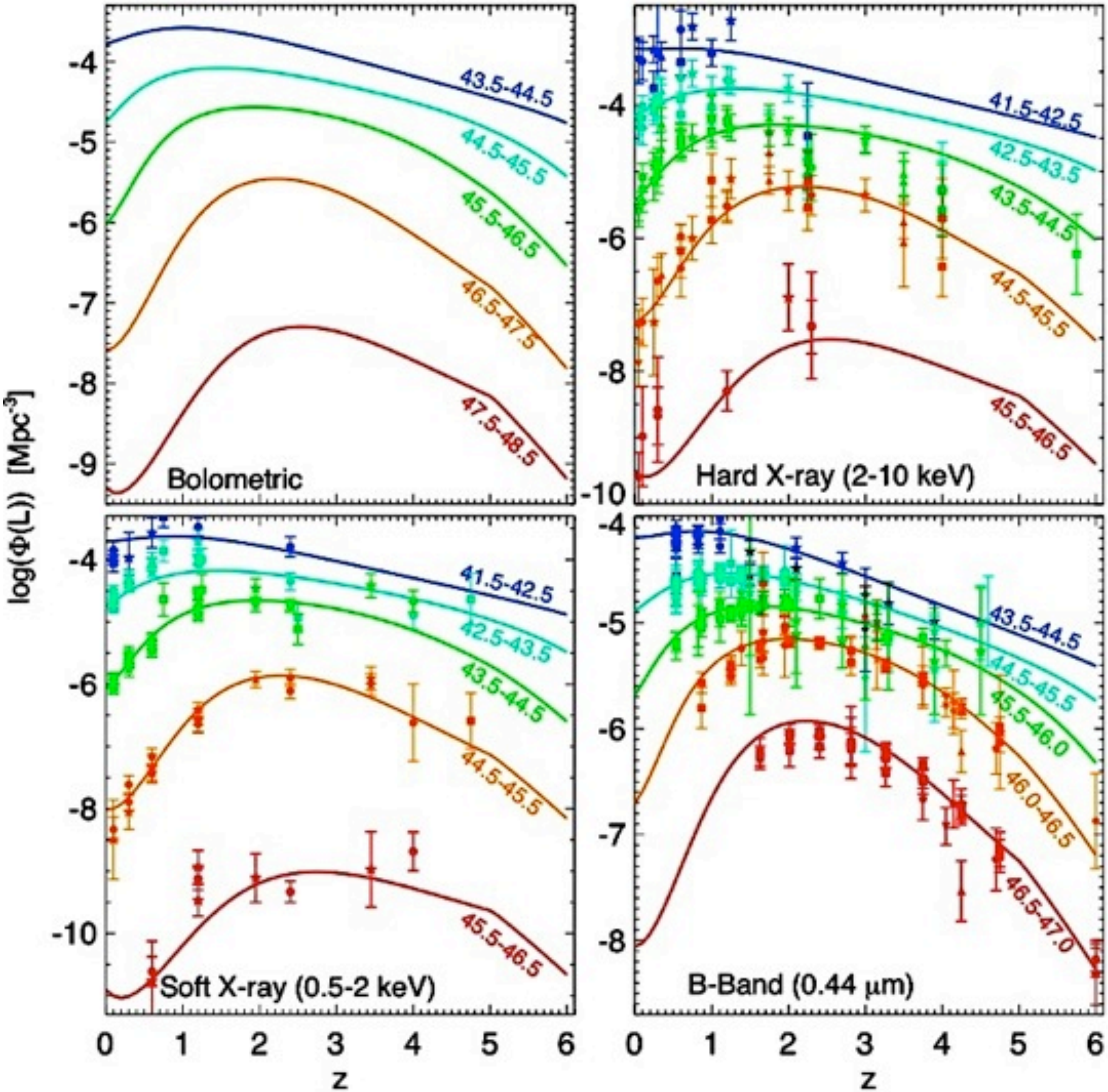
- Weak dependence of clustering on observed luminosity
  - (Croom et al., Adelberger & Steidel, Myers et al., Coil et al., Porciani et al.)



Hopkins, Lidz, Coil, Myers et al. 2007

Luminosity-Dependent Density Evolution

"SECOND ORDER"

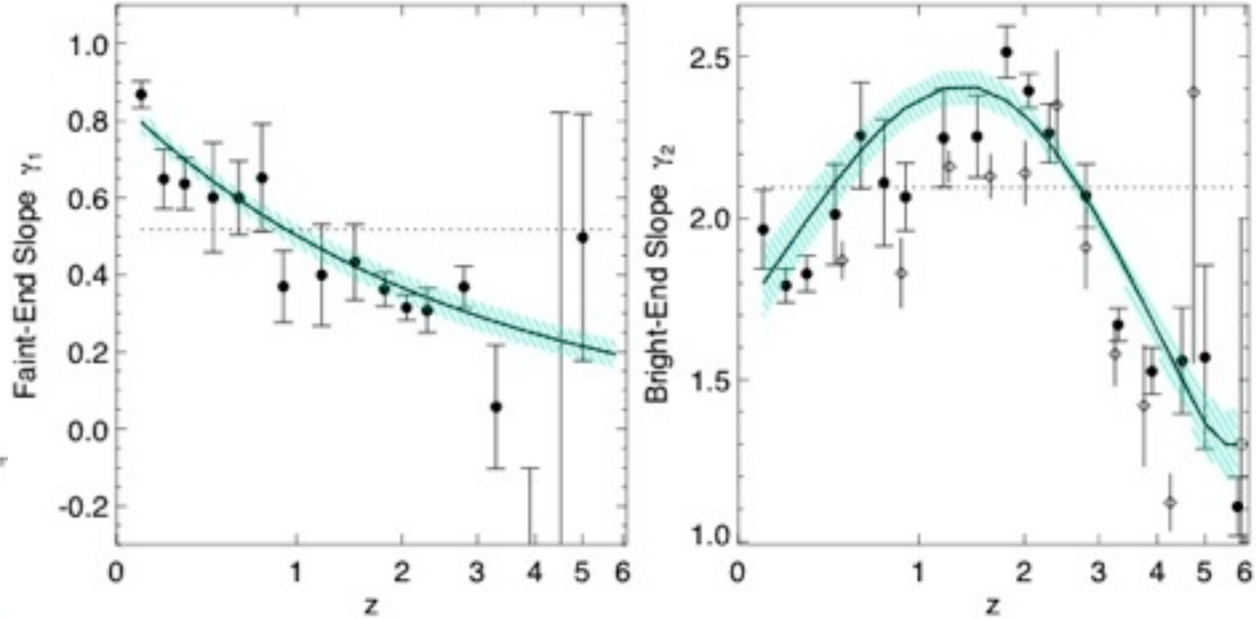


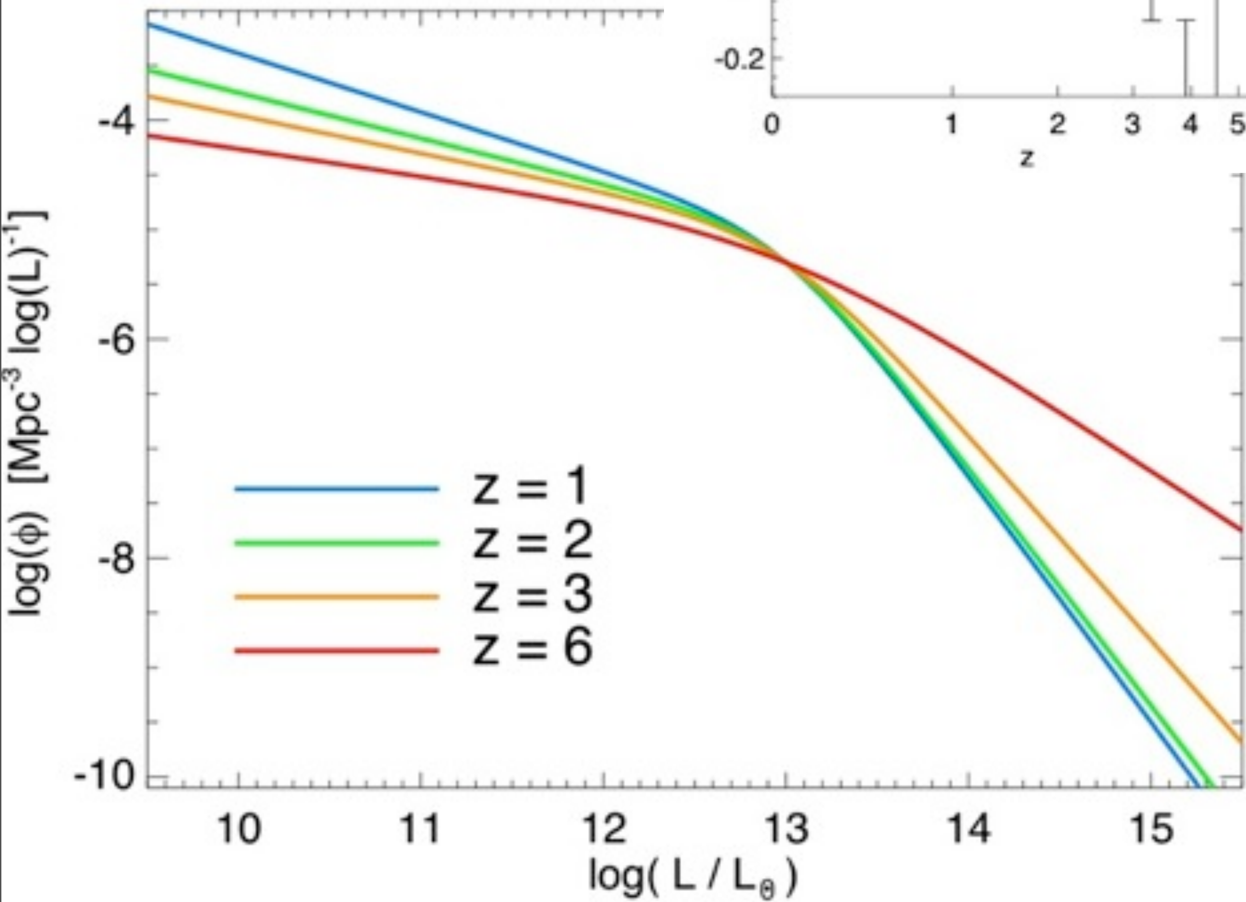
PFH, Richards, Hernquist

(also: Hasinger et al. 2007)

What Do We Learn?

"SECOND ORDER"

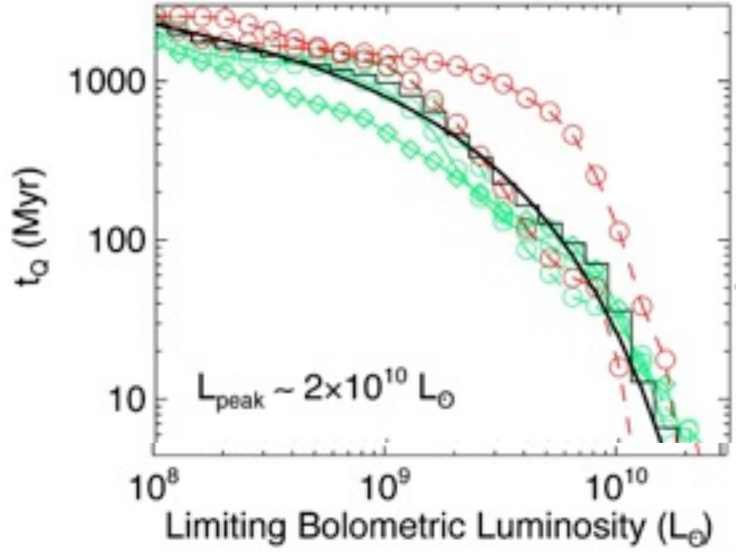




- Equivalently, slopes flatten with z

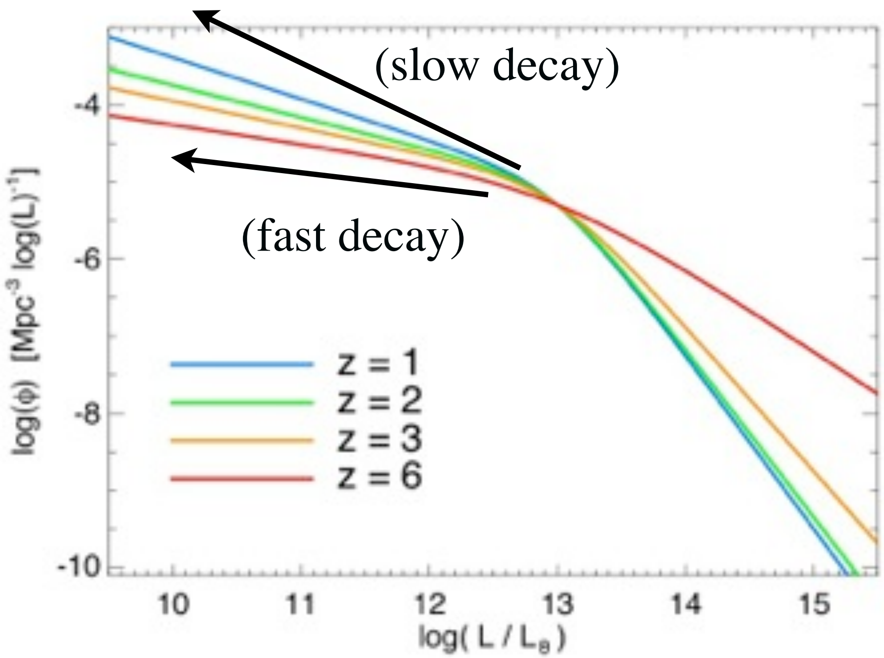
What Do We Learn?

"SECOND ORDER"



- Faint End (X-ray "LDDE")
  - Change in effective duty cycle/lifetime for more massive BHs at low mdot

Luminosity-Dependent Quasar Lifetimes



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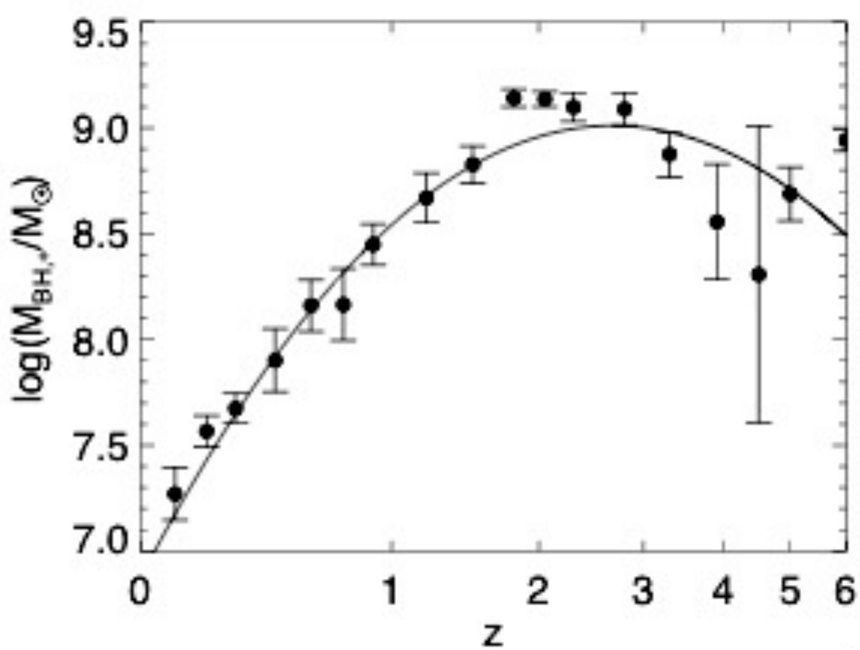

What Do We Learn?

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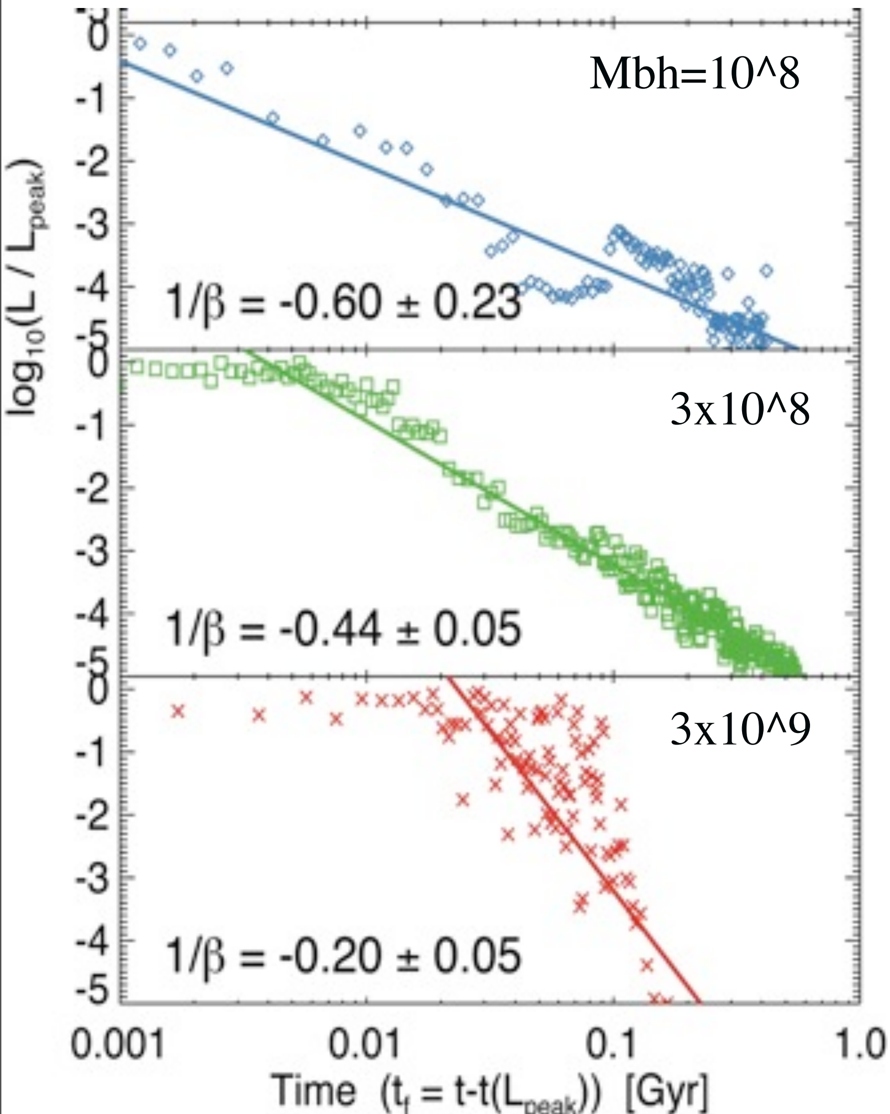
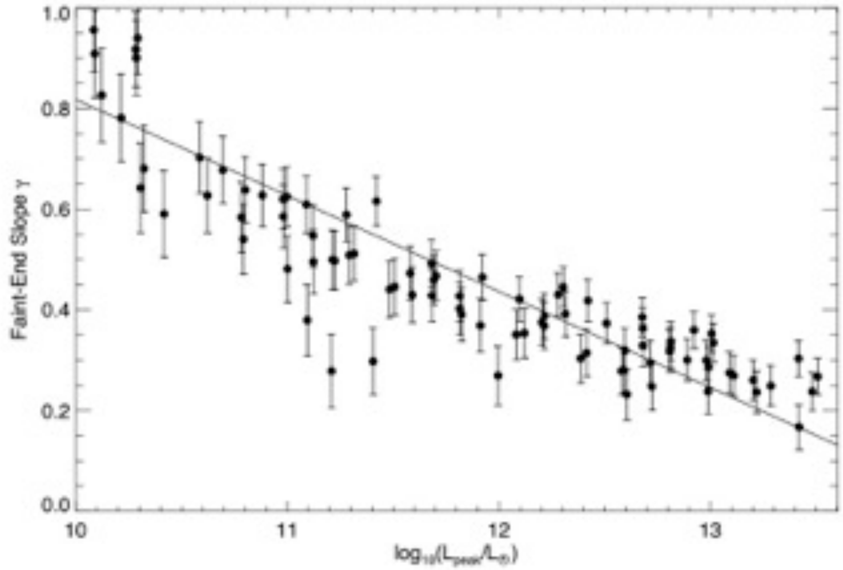
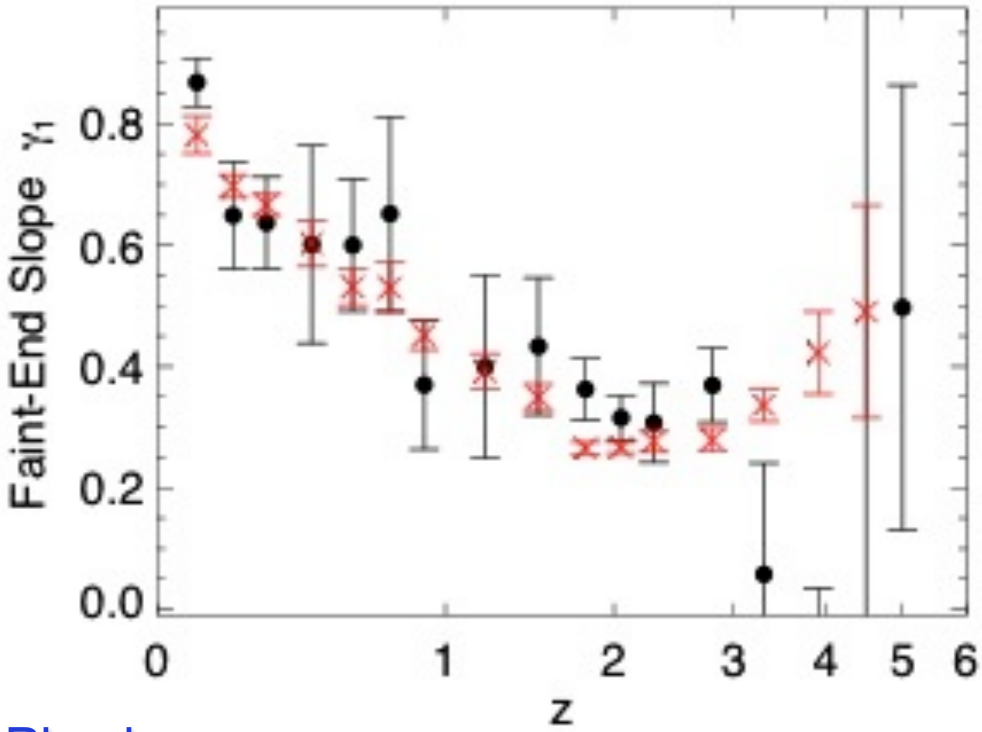


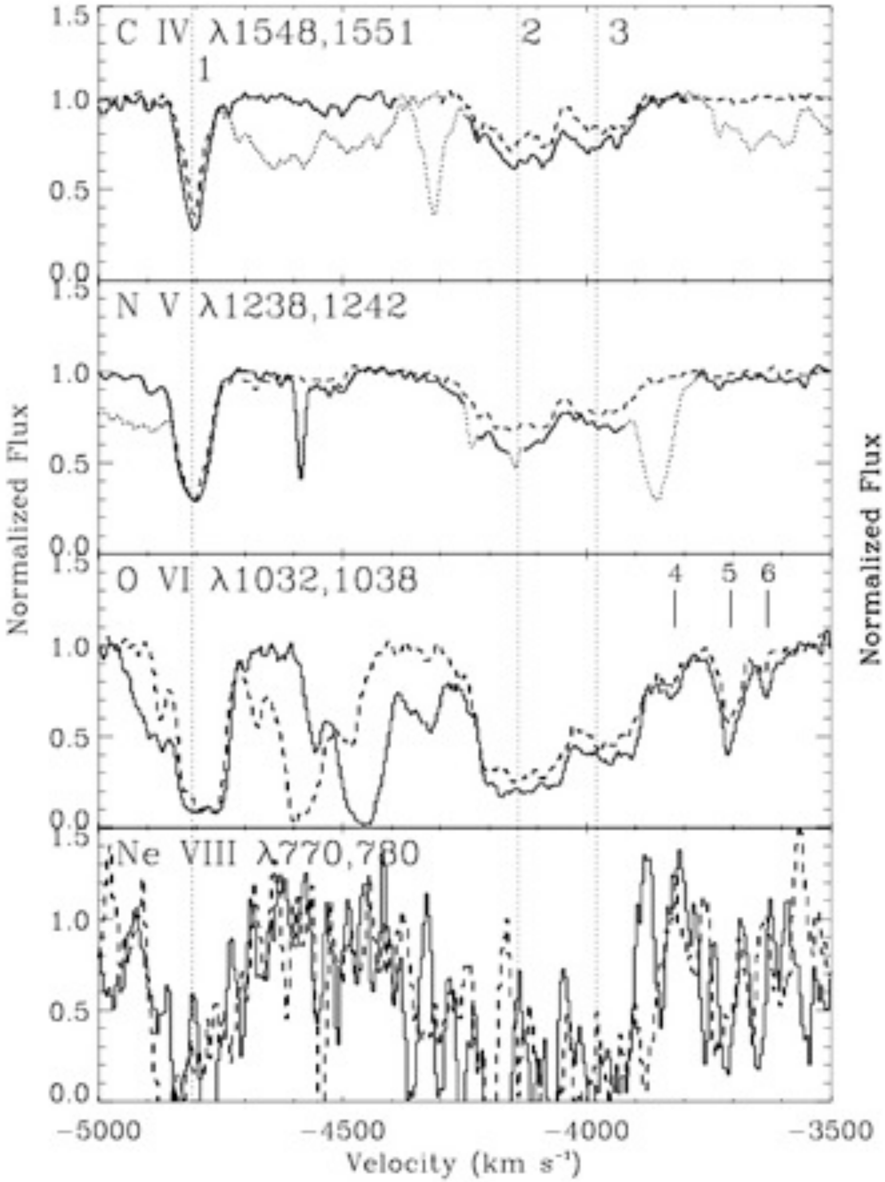




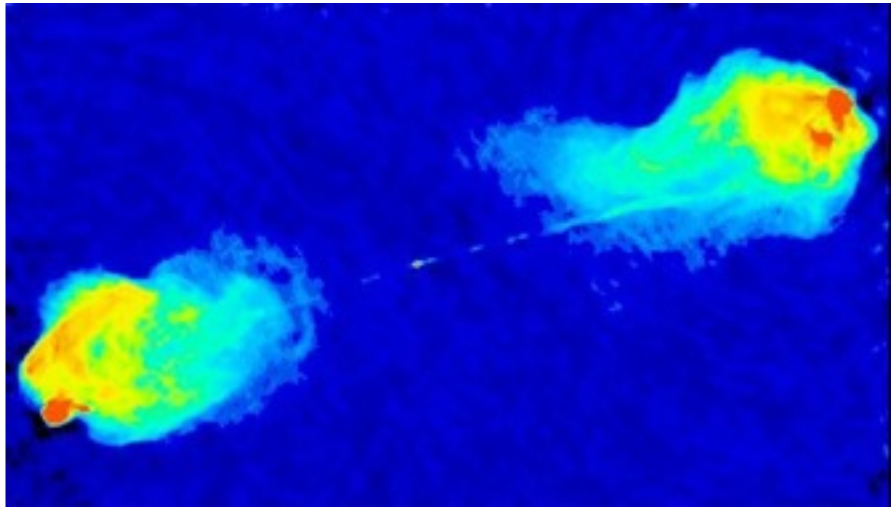
- Constrain Lifetimes + Feedback Physics

The Feedback: Where Does It Go?

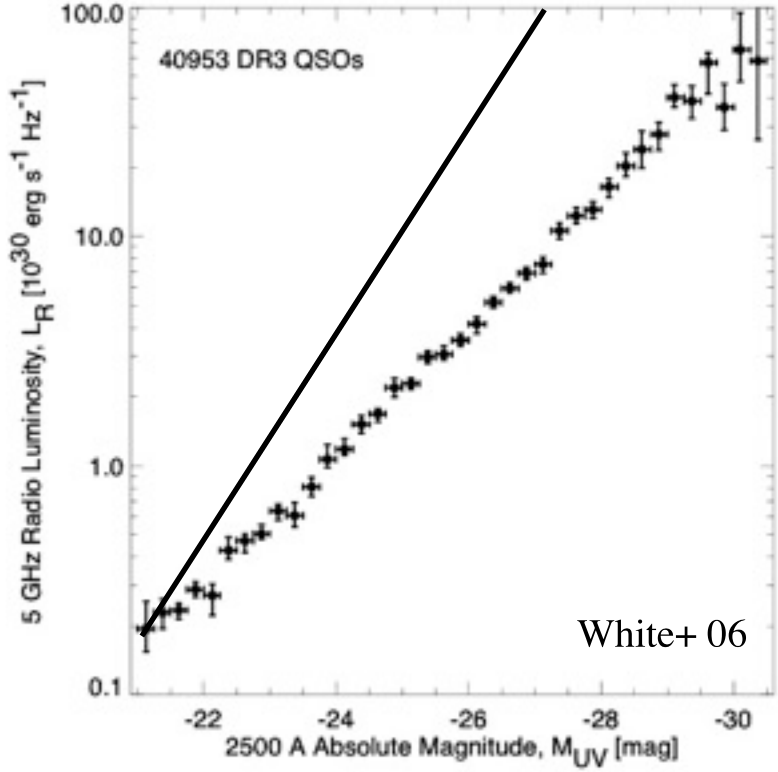
QUASAR FEEDBACK *DOES* EXIST



Gabel & Arav et al.



but...

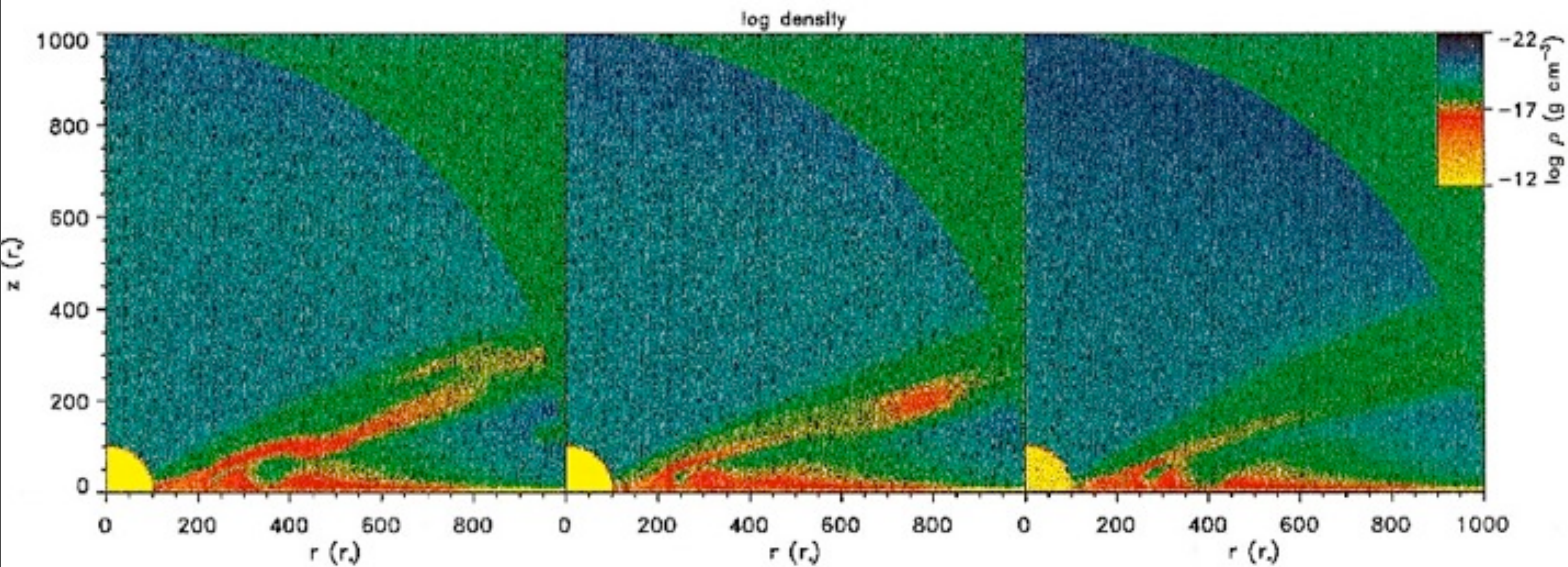


White+ 06

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.)

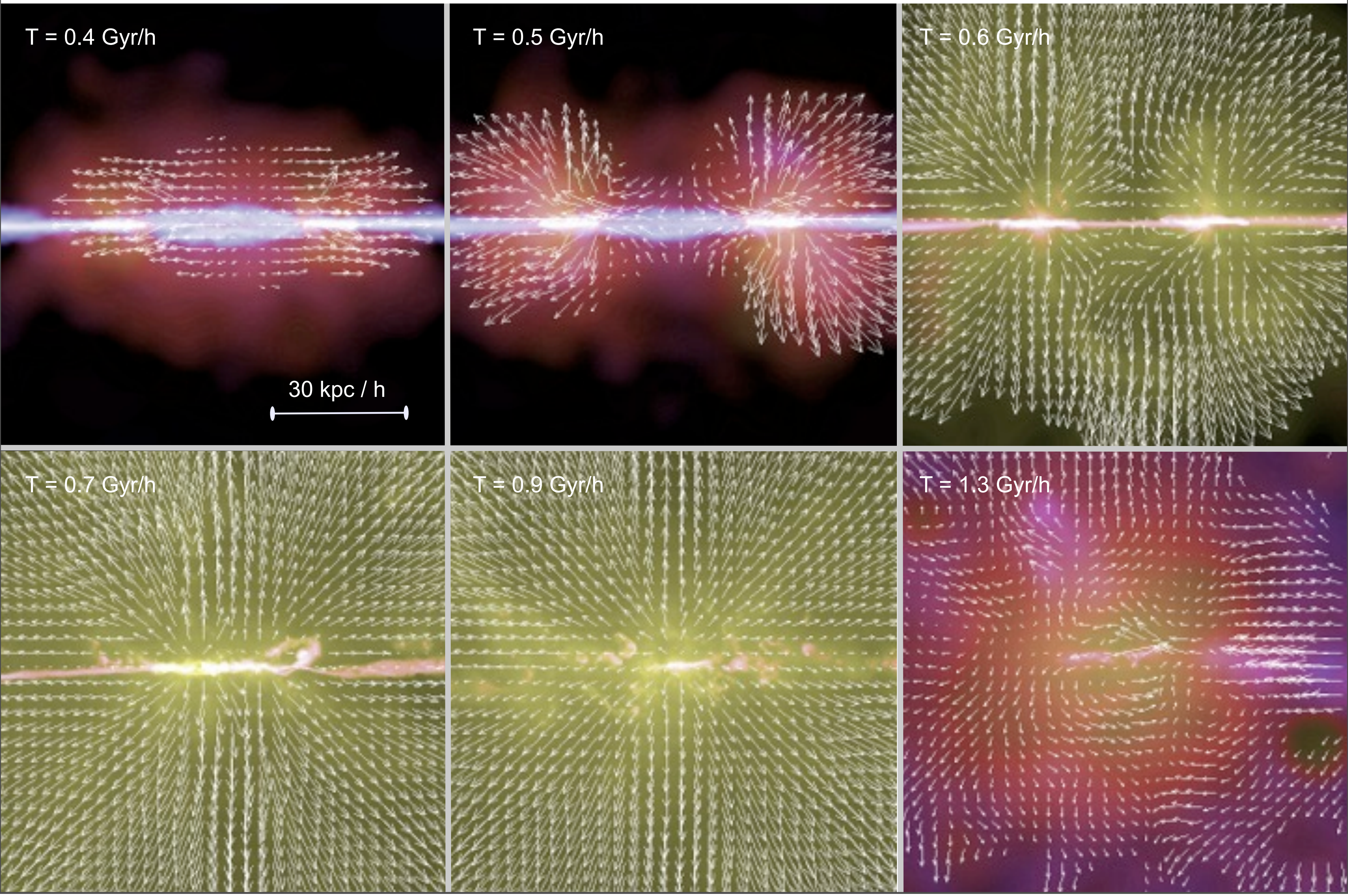


- Probably *not* radio jets

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

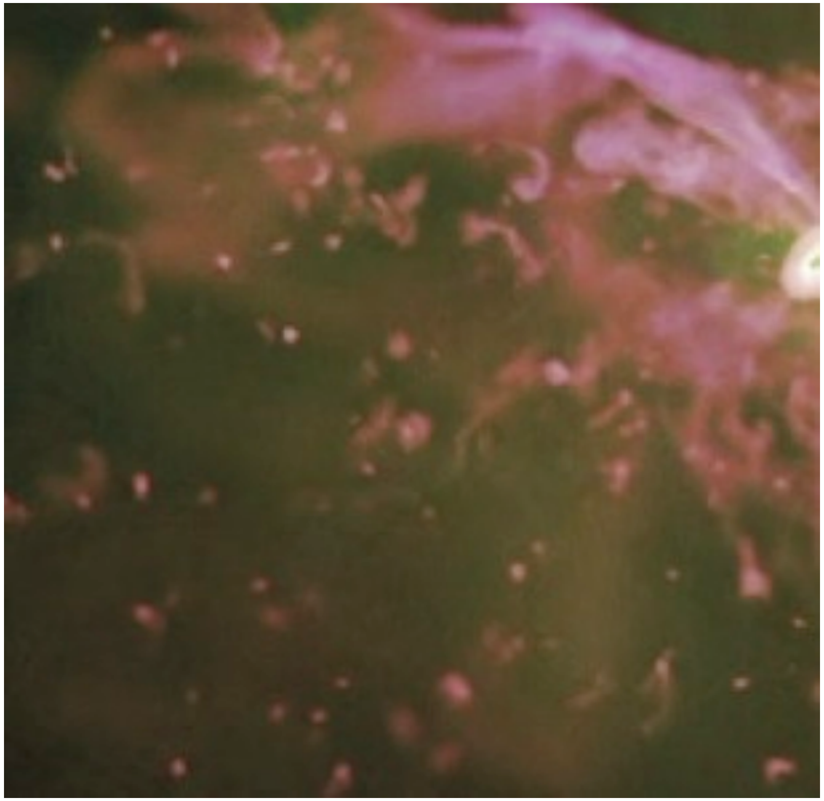
GAS OUTFLOW BY AGN FEEDBACK

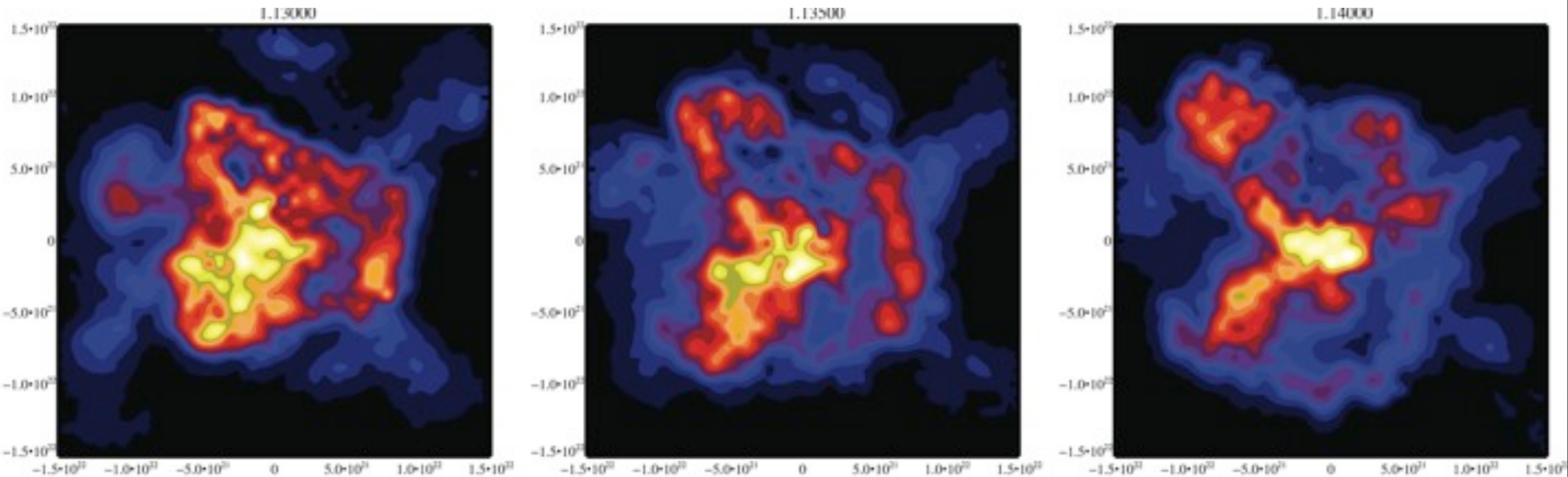
(outflow reaches speeds of up to ~1800 km/sec)



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)

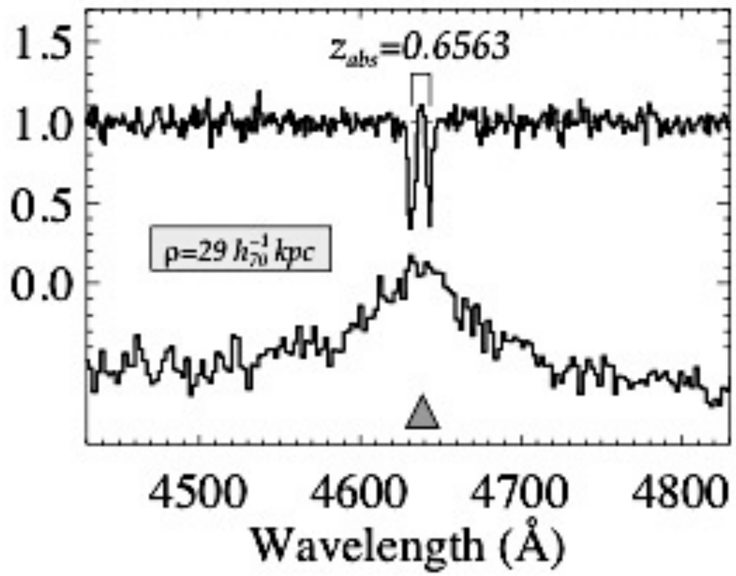


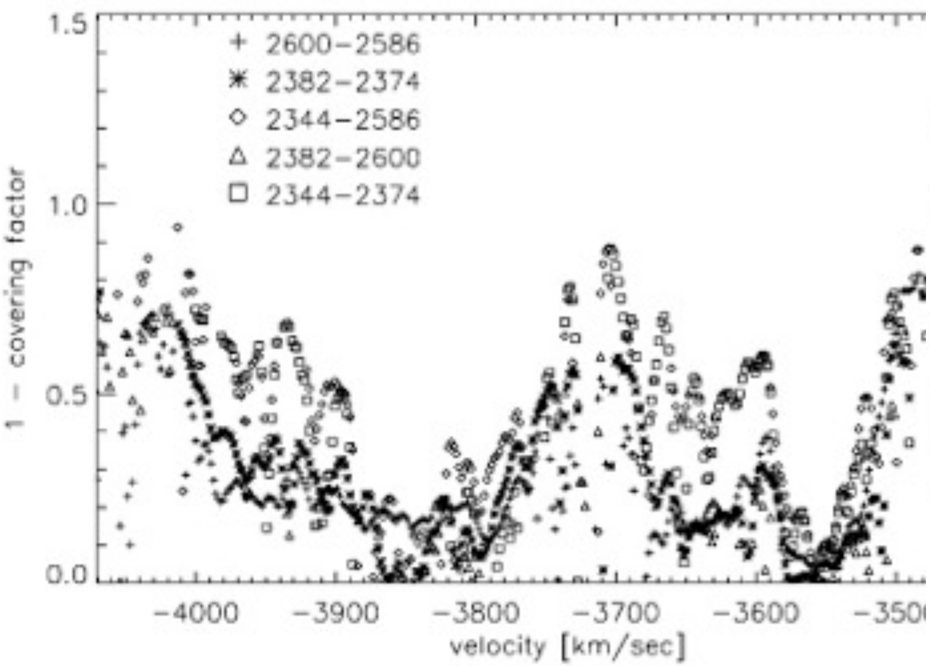


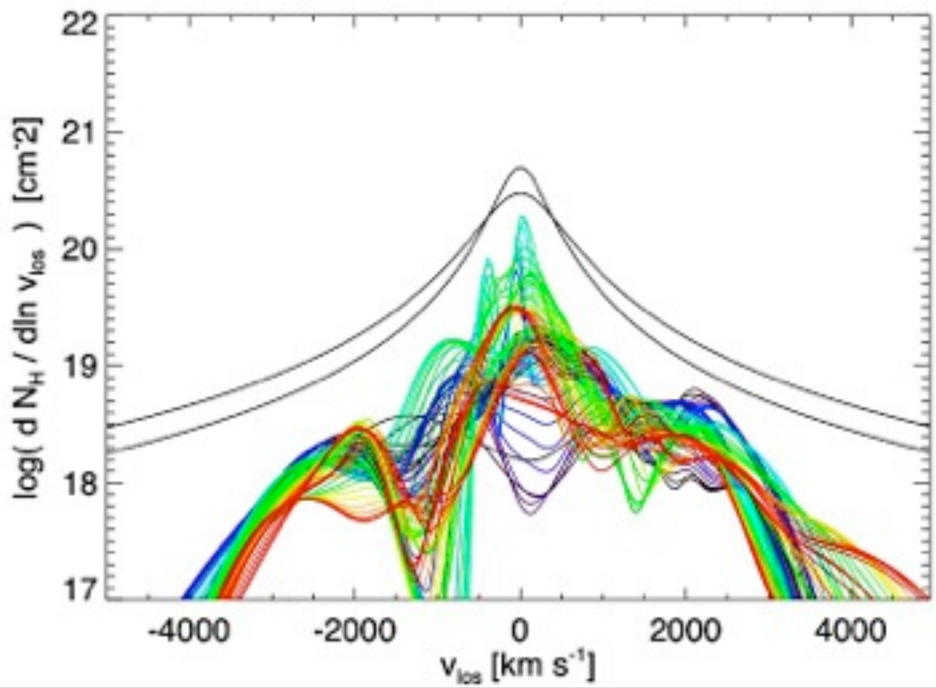
Observational Prospects

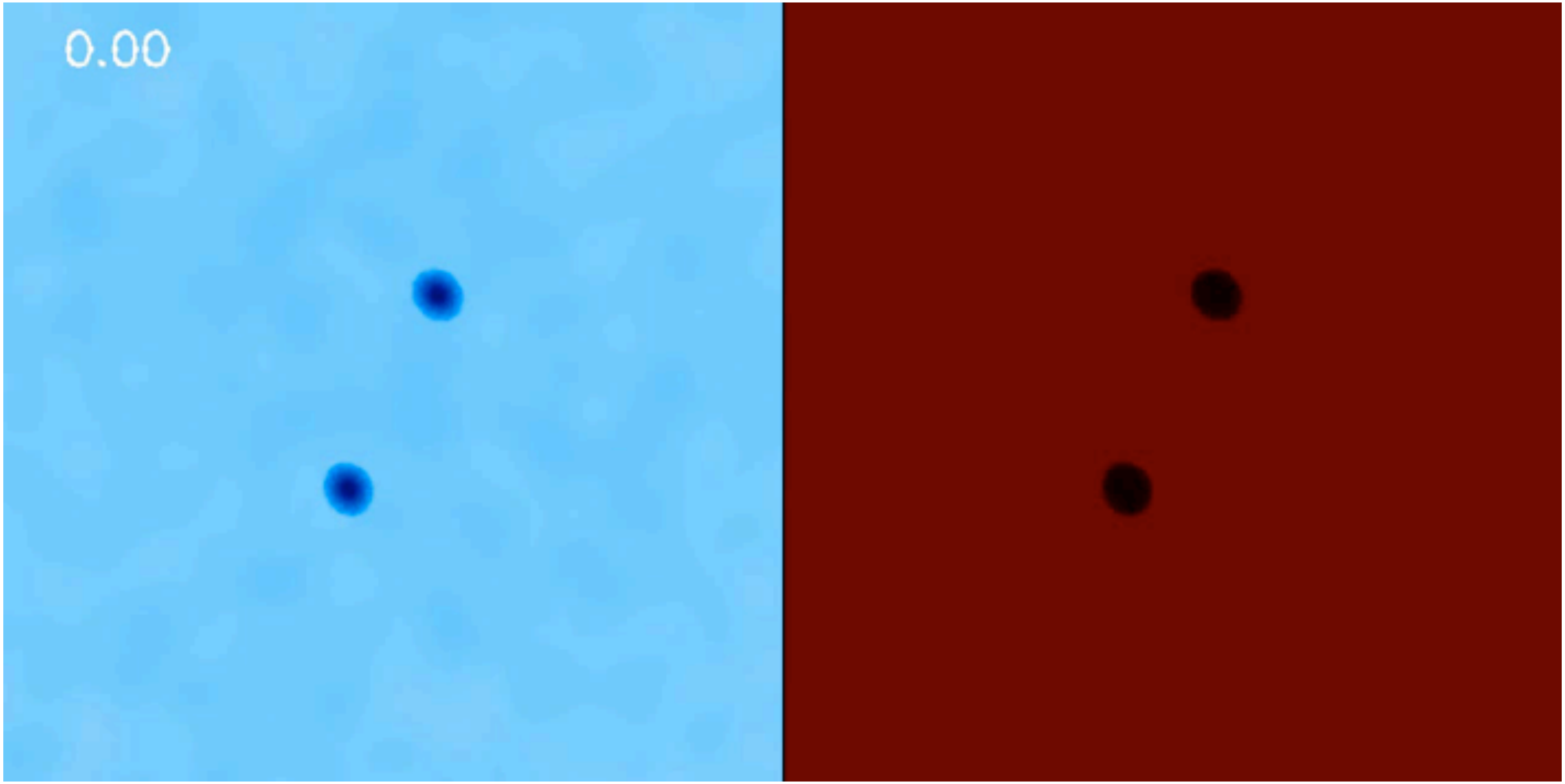
“QUASAR” WINDS

- High-velocity outflows
  - >~ 1000 km/s at 1-1000 kpc
  - Local metal absorbers (Bowen+ 06)
  - BALs at “large distances” (deKool+ 01)
  - High-v outflow in non-BALs (Pounds 06)
- Clumpy substructure
- Preferentially w. high-Eddington ratio?





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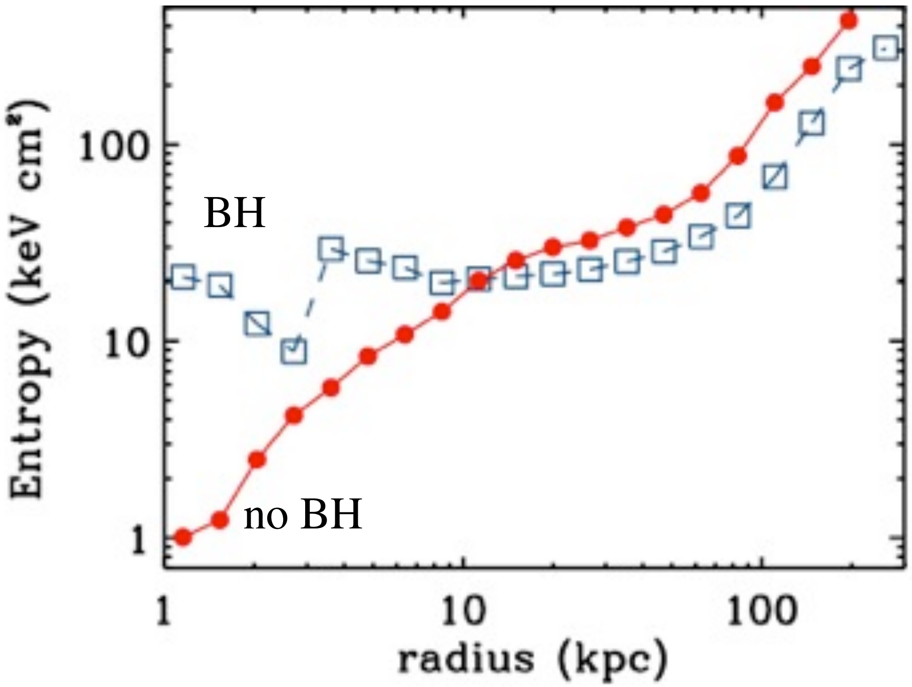
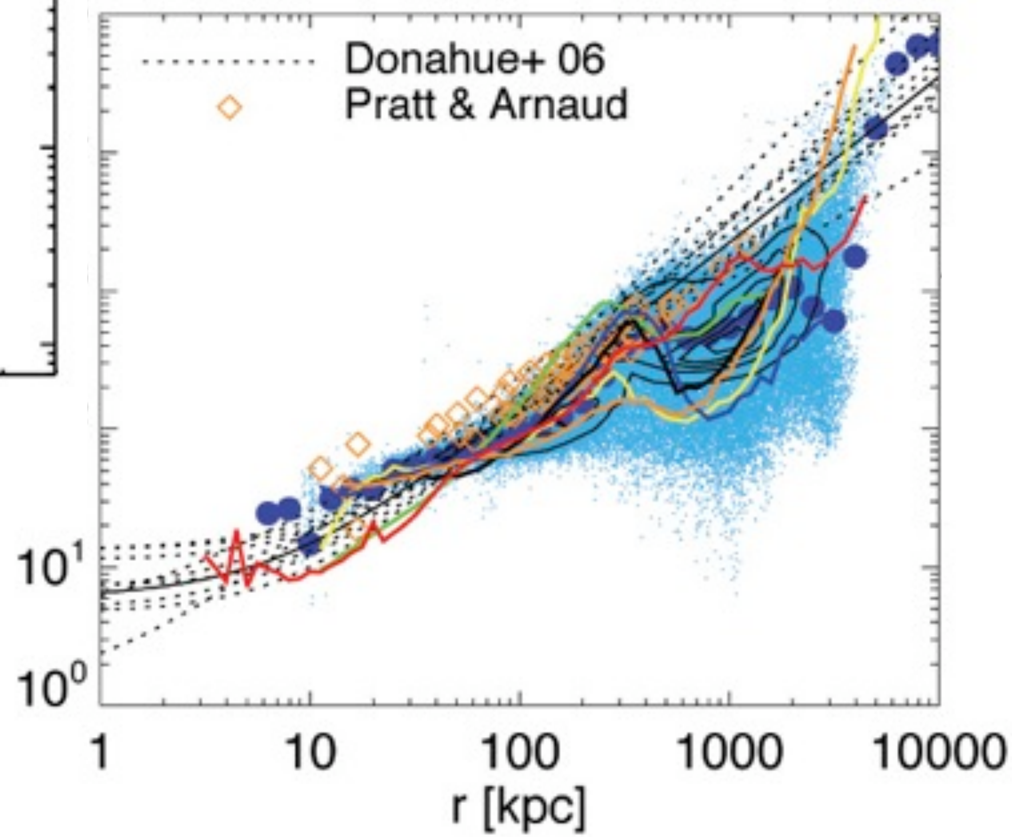
Feedback-Driven Winds
HEATING & ENTROPY

- Single, high-impact event can "set up" observed T/S profiles & correlations in ellipticals
  - Groups, even Clusters as well?

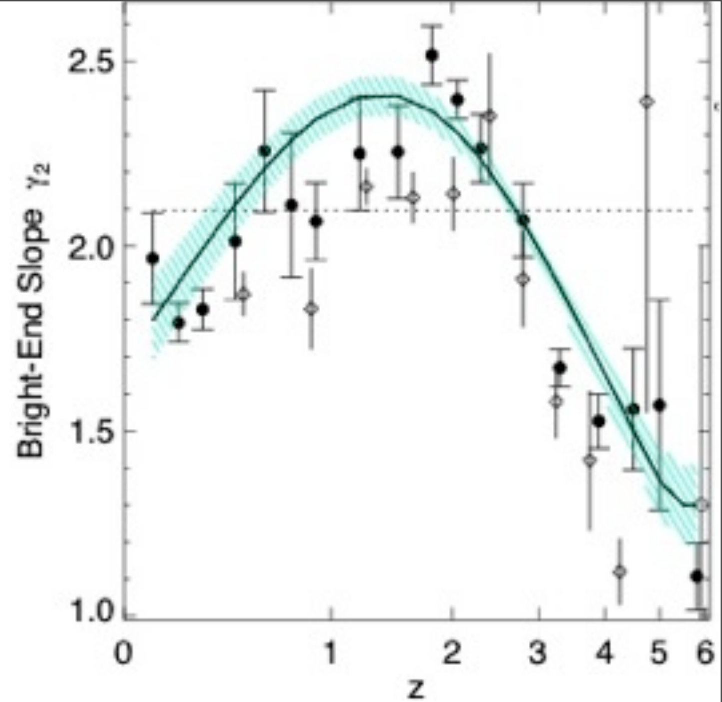


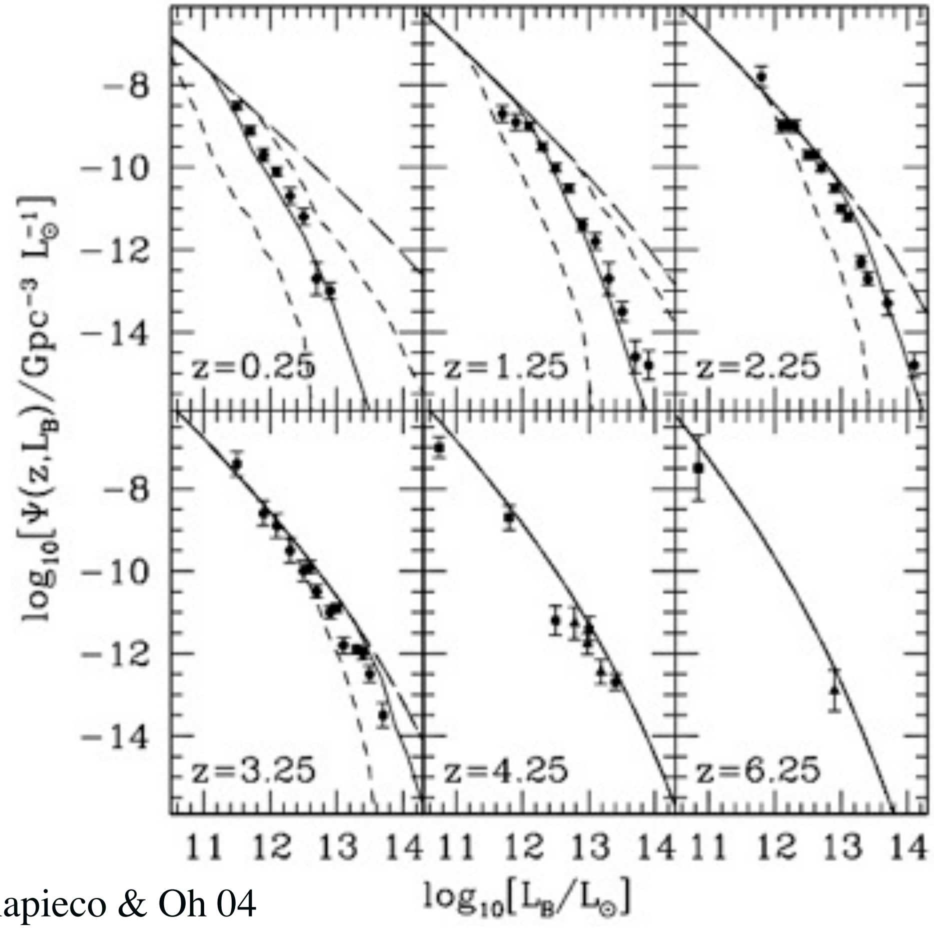


Reflected in the Bright-End Slope of the QLF?

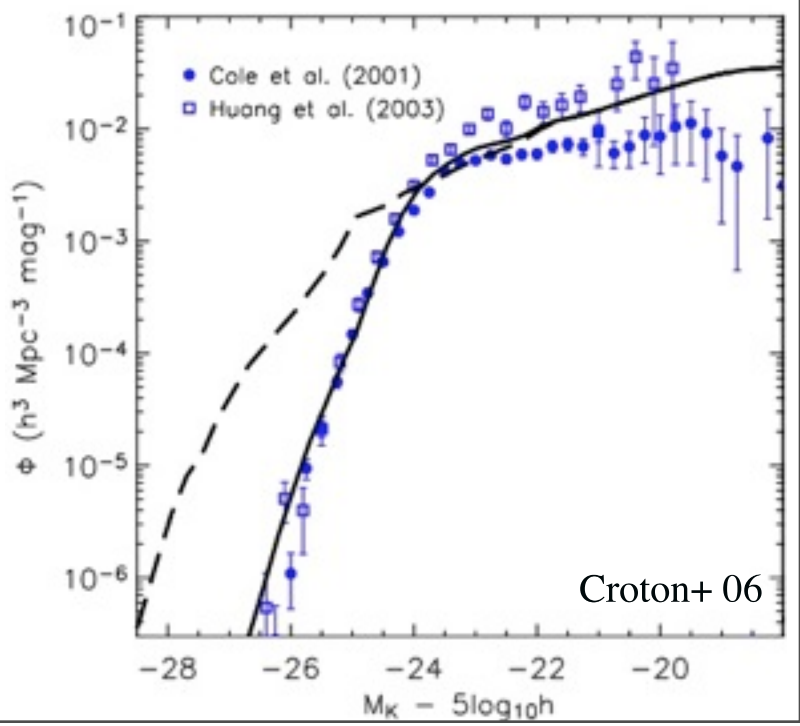
"SECOND ORDER"

- Bright End
  - (Systematics?)
  - Reflects shape of halo MF/buildup?
  - Feedback again?





Scannapieco & Oh 04



Croton+ 06

Summary

- Our picture for quasar evolution can incorporate more detail:
  - complex, evolving lightcurves, lifetimes
  - evolving pattern of obscuration: increases with luminosity, drops during blowout

- "Higher-Order" measurements can break model degeneracies:
  - clustering vs: spatial scale, luminosity, redshift
  - QLF shape evolution

- How do we more tightly link observations of hosts & descendants (galaxies) with the quasars themselves?