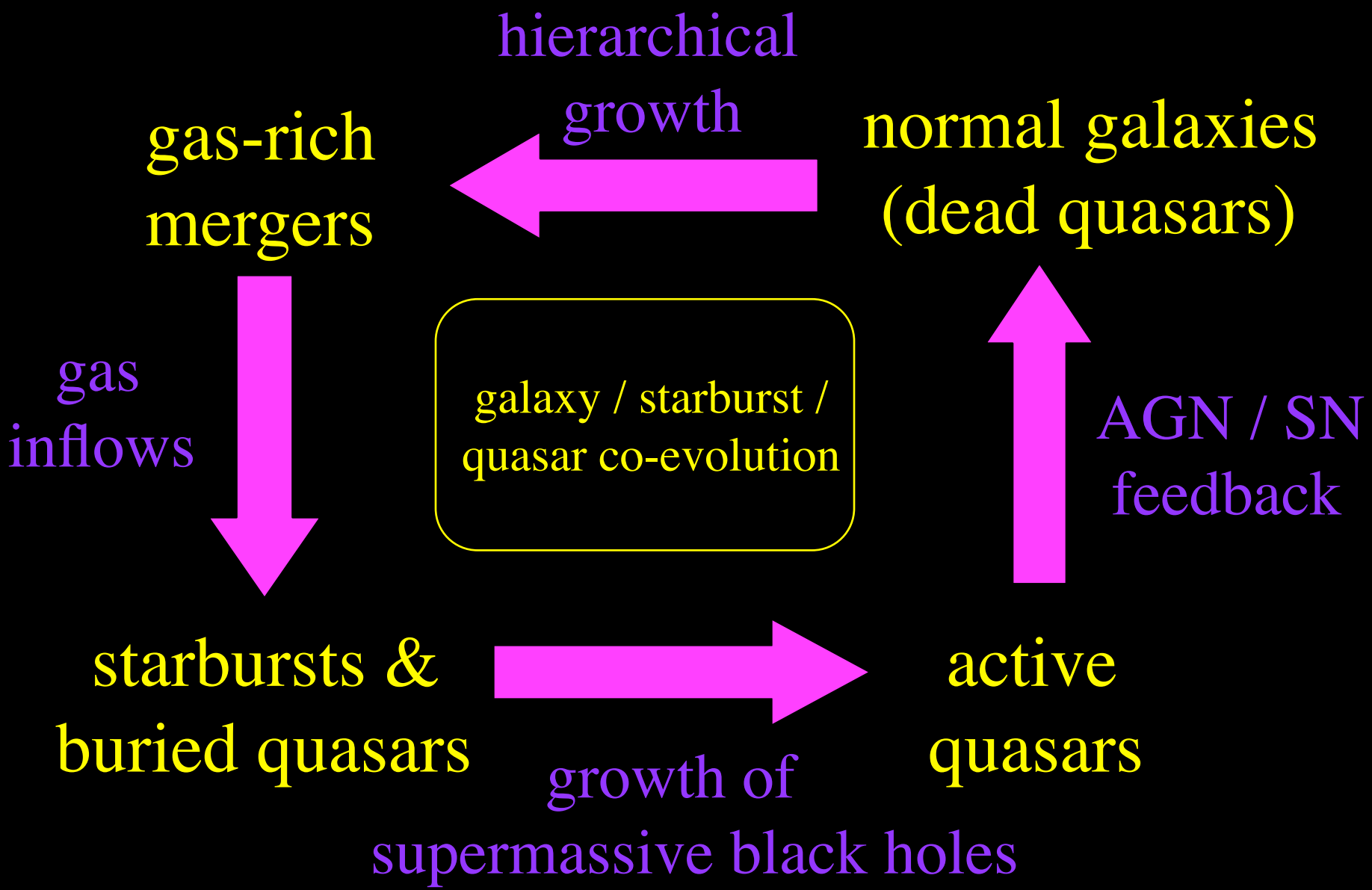
Merger-Driven Evolution of Galaxies, Quasars & Starbursts

Philip Hopkins
Harvard University

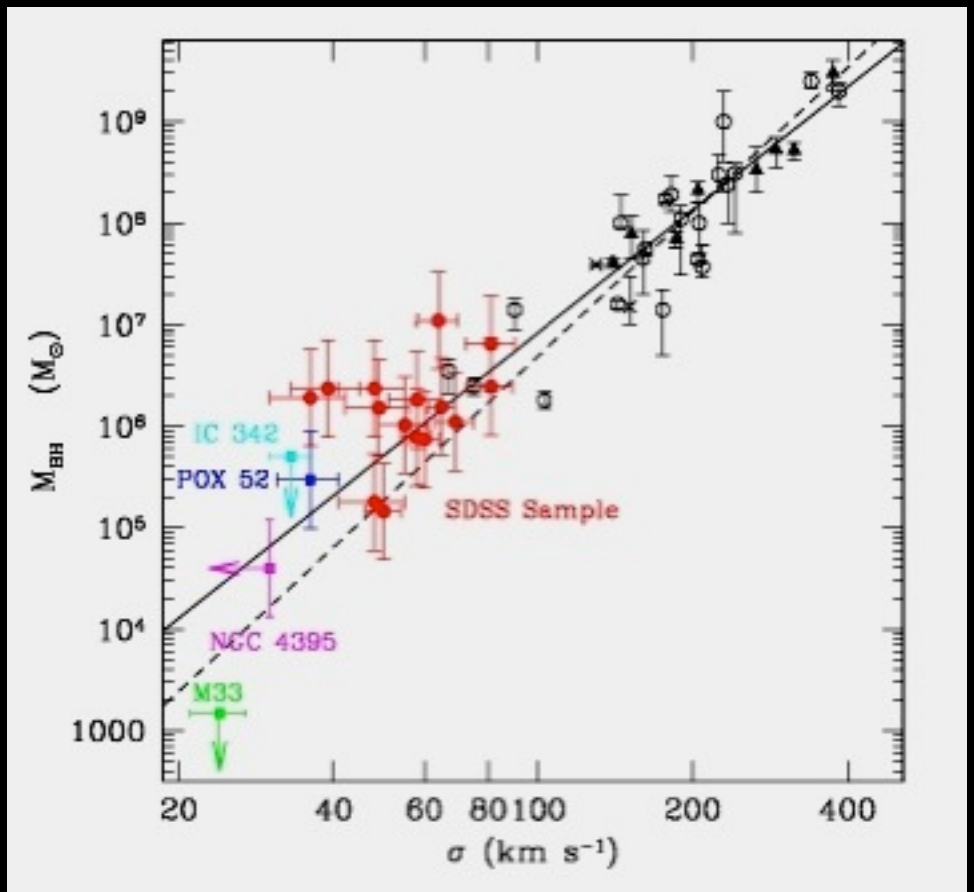
with: Lars Hernquist, TJ Cox, Volker Springel, Dusan Keres,
Rachel Somerville, Gordon Richards, Tiziana Di Matteo,
Yuexing Li, Kevin Bundy, Brant Robertson, Josh Younger

An evolutionary sequence?



How are Supermassive Black Holes, Galaxies Connected?

- Black holes, spheroids correlated ⇒ formation related
- Simplest picture: originate primarily in one event
- Is this sensible?



Barth, Greene & Ho (2004)

Requirements on Single "Event"

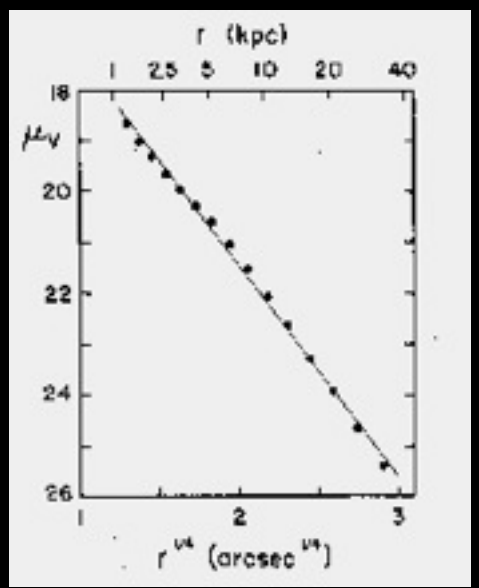
- Fast, violent
- Blend of gas & stellar dynamics
- Why?
  * Soltan (1982): bulk of SMBH mass density grown through radiatively efficient accretion in quasars

    → gas dynamics; rapid (~ few 10^7 years)
  * Lynden-Bell (1967): orbits of stars redistributed in phase space by large, rapid potential fluctuations

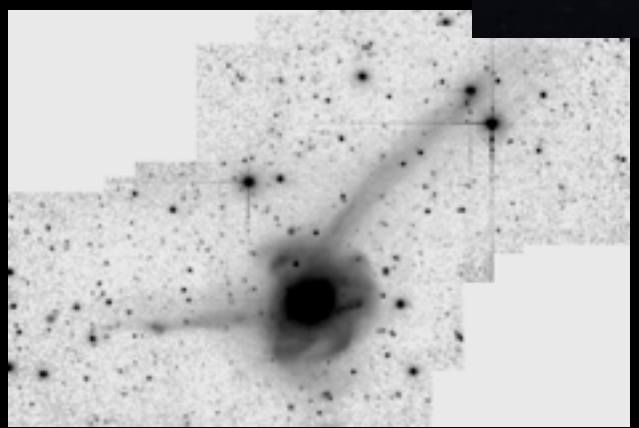
    → stellar dynamics; freefall timescale

Candidate Process: Gas-Rich, Major Merger

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



NGC 7252

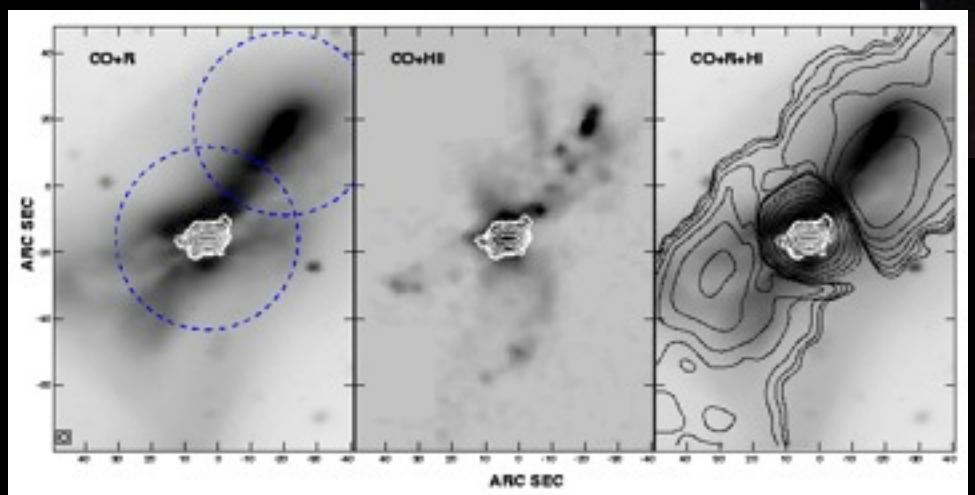


Schweizer (1982)

HST image of Mice

Candidate Process: Gas-Rich, Major Merger

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

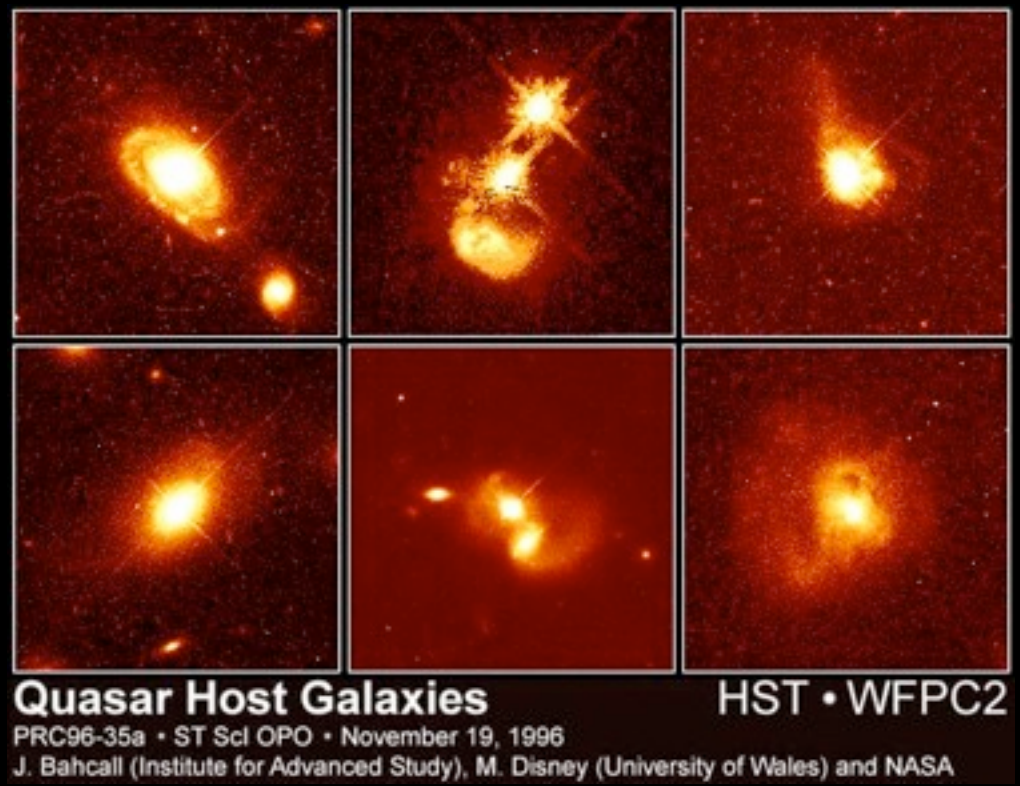


NGC 520 (Arp 157)

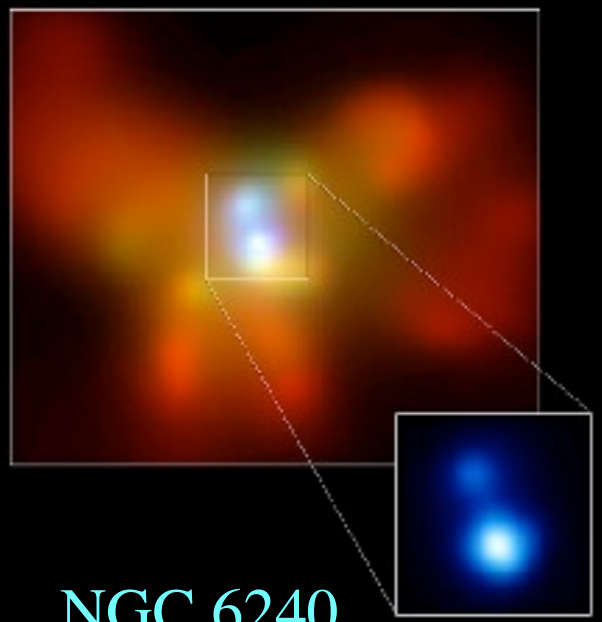
Yun & Hibbard (2001)

Candidate Process: Gas-Rich, Major Merger

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



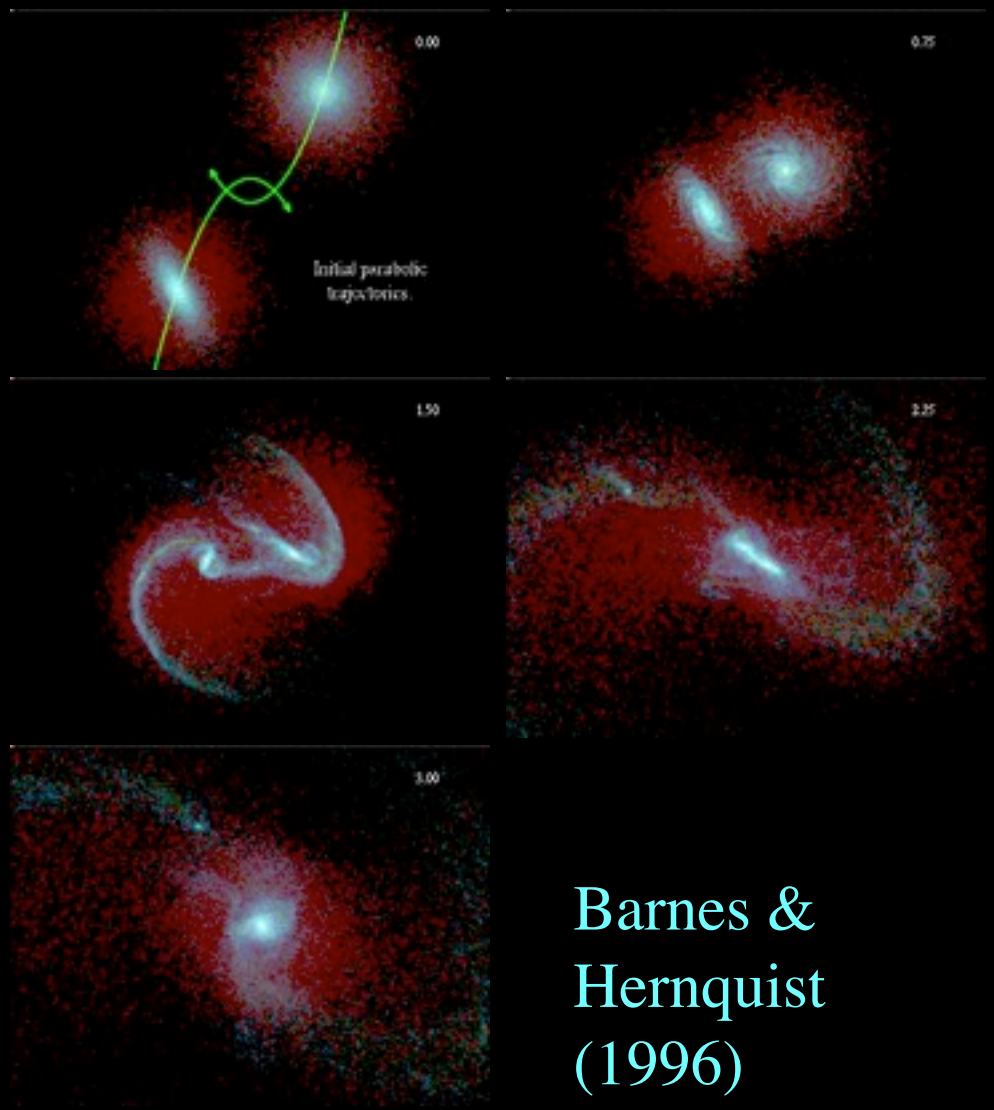
Komossa et al. (2003)



NGC 6240

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)

Generalized Merger Hypothesis

- Mergers of gas-rich disks dominant process for forming spheroid, SMBH populations

  (following Toomre 1977)
- Further implication → main mechanism for:
  * most intense starbursts (ULIRGs)
  * bright quasar activity

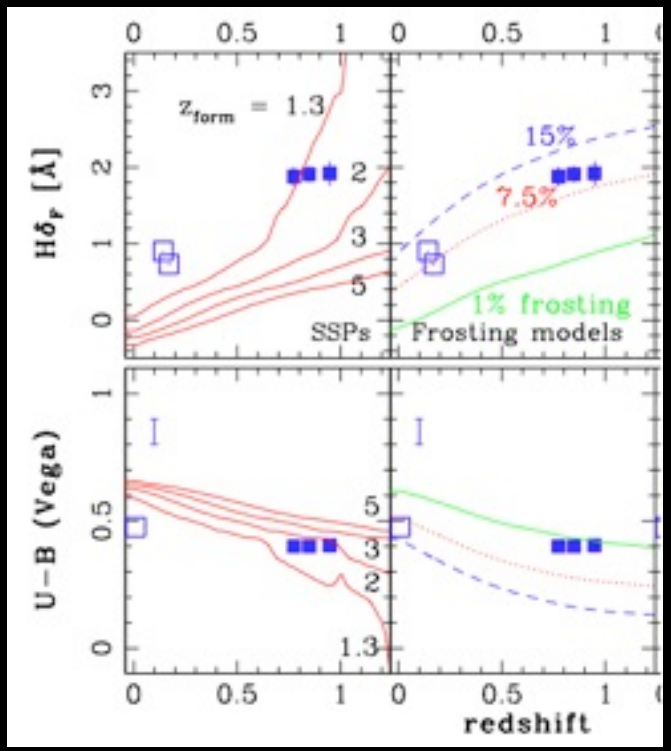
Disclaimer: What This Means

- Not all AGN result from mergers (other fueling modes at faint levels; e.g. PH & Hernquist, astro-ph/0603180)

- SMBH growth by other modes (e.g. radiatively inefficient, "radio" modes) possible, but sub-dominant for entire SMBH population (e.g. PH, Narayan & LH, astro-ph/0510369)

- But, both theoretically & observationally, most bright quasars should be merger-driven

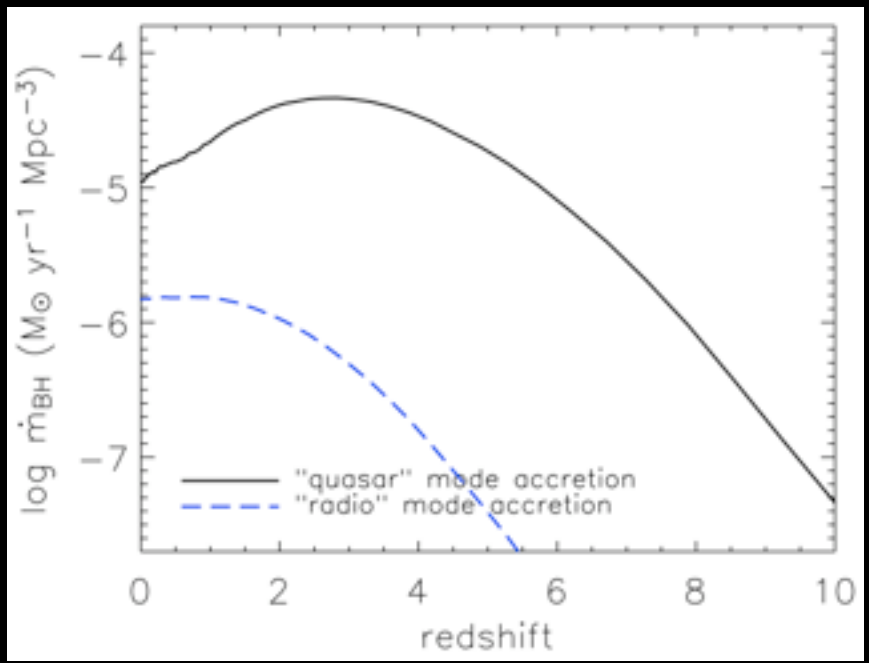
Other Fueling Mechanisms?



Harker et al. (2006)

- 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!)

Other Fueling Mechanisms?



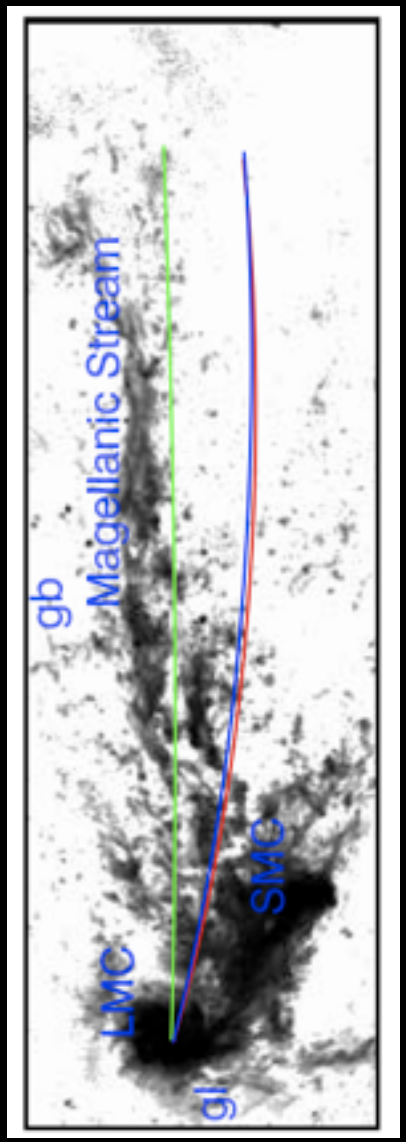
Croton et al. (2005)

- Stellar Mass Loss
- Cooling Flows
  - Relatively Late Phenomenon
  - No Bulge Formation
  - BHs already massive in cooling-flow clusters
  - “Angular Momentum Problem”

Other Fueling Mechanisms?

- Stellar Mass Loss

Besla
et al. (2007)

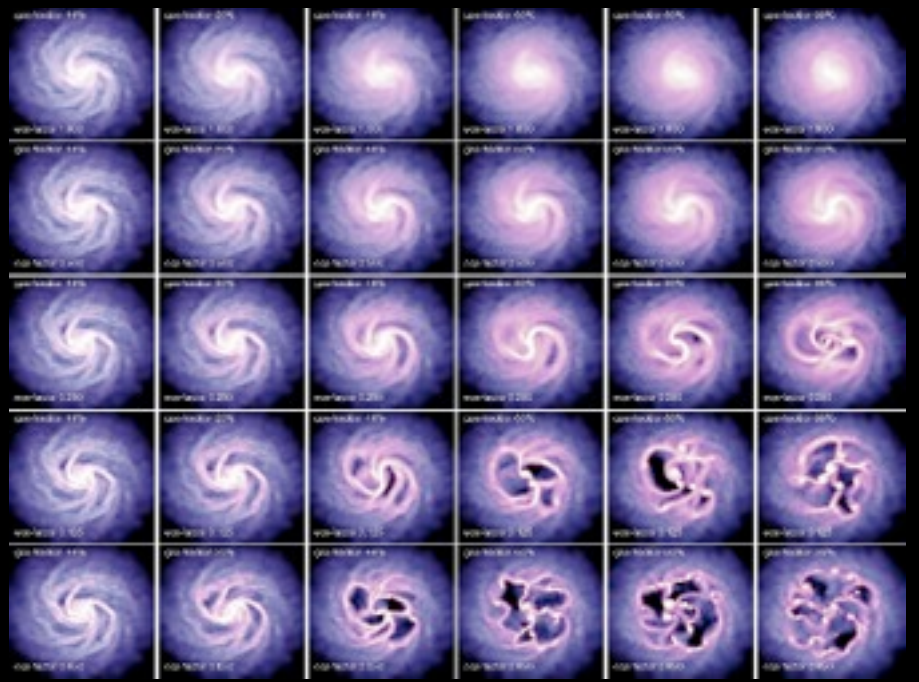


- Cooling Flows

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

Other Fueling Mechanisms?

- Stellar Mass Loss
- Cooling Flows
- Minor Mergers



Springel et al. (2005)

- Secular Evolution/Disk Instabilities
  - Most mass in “classical” bulges, not “pseudobulges”
  - Does it really solve the angular momentum problem?

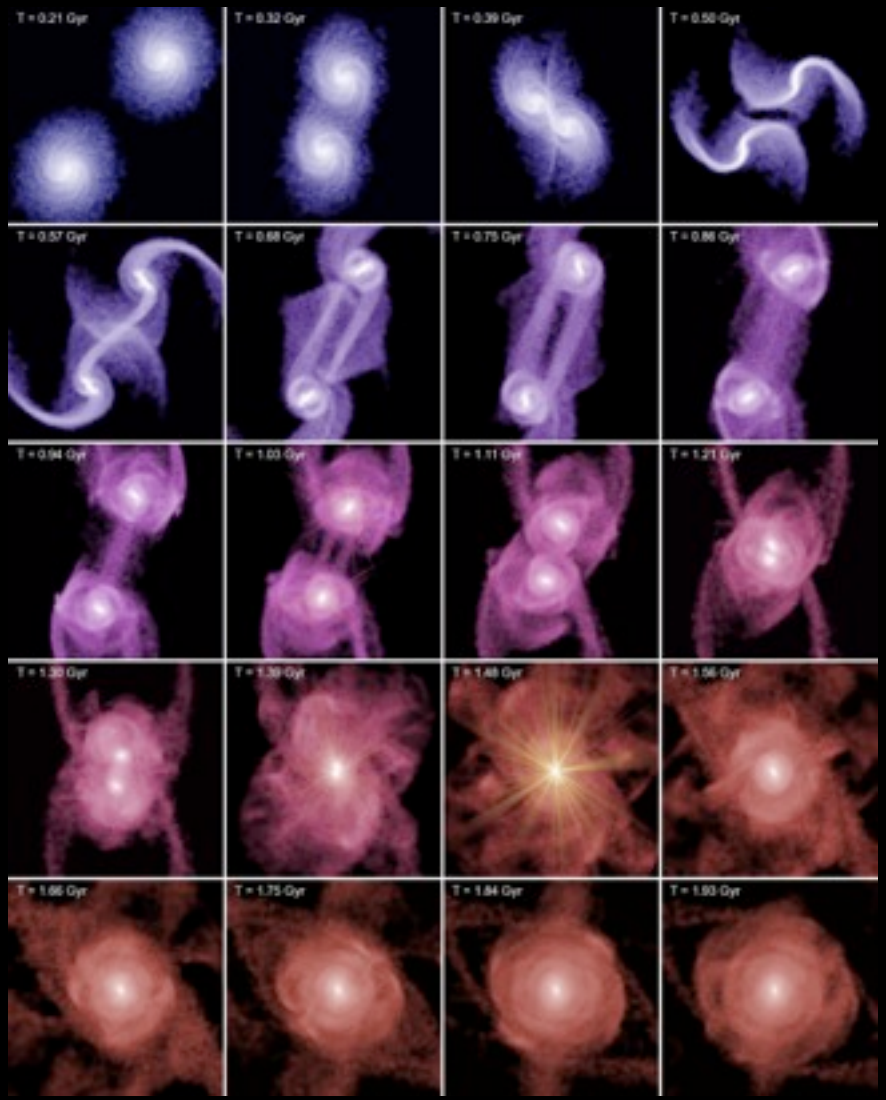
Testing the Hypothesis

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

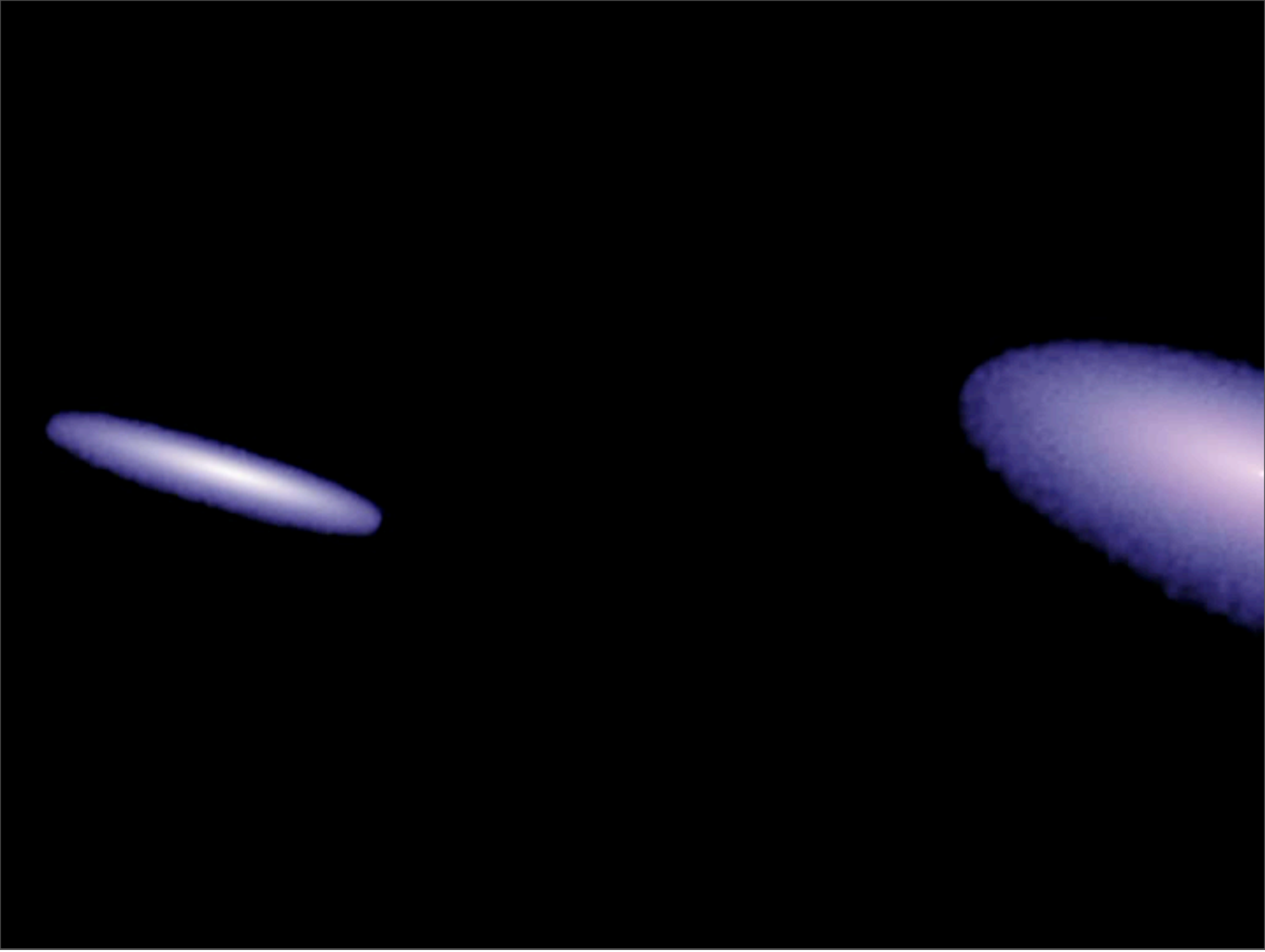
  - Populate halo+subhalo MFs (from cosmological simulations) with "initial" galaxies (according to HODs/empirical constraints)
  - Let them grow (star formation & accretion)
  - Let them merge
  - Assume major, gas-rich merger > BH/bulge
  - "Paint on" detailed simulations where necessary

Testing the Hypothesis

- Simulations: 3-D, time-dependence
- Consider:
  - single, multiple mergers
  - varying mass ratios
  - star formation, supernova feedback & winds (sub-resolution)
  - black hole growth, feedback (sub-resolution)
  - large gas fractions: made possible by SN feedback



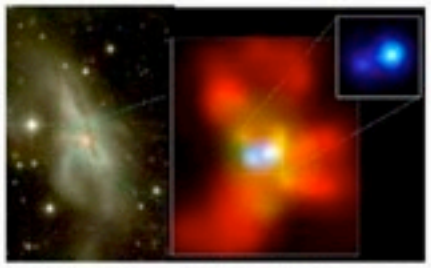
PH et al., astro-ph/0506398



(c) Interaction/"Merger"

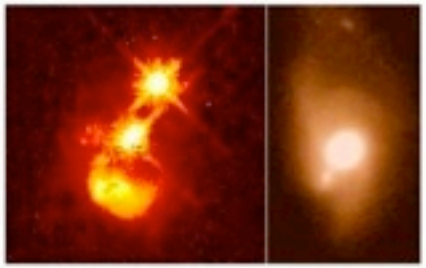
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(d) Coalescence/(U)LIRG



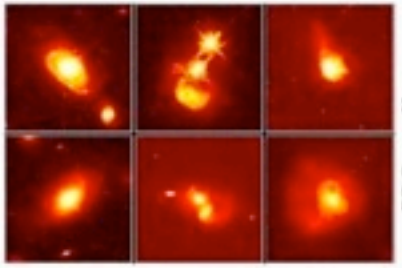
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

(e) "Blowout"



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

(f) Quasar

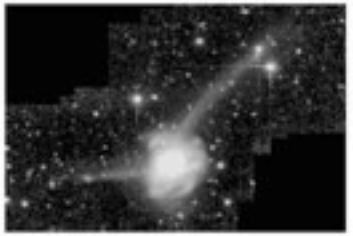


- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

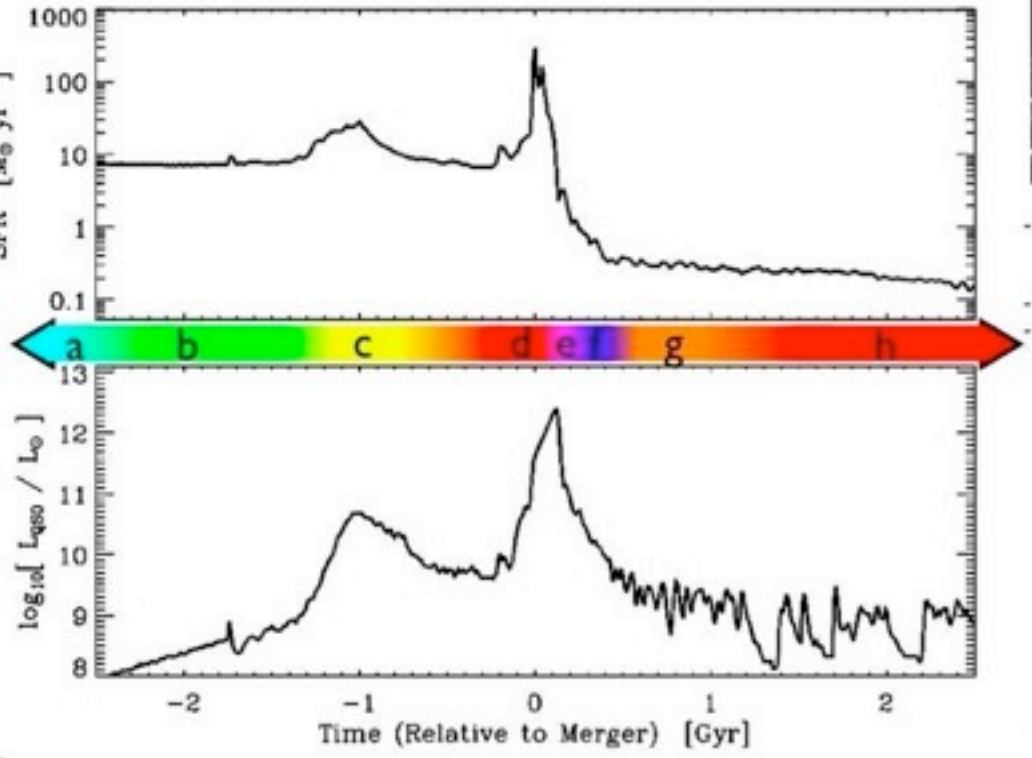
(b) "Small Group"

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

(g) Decay/K+A



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



(a) Isolated Disk

- 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

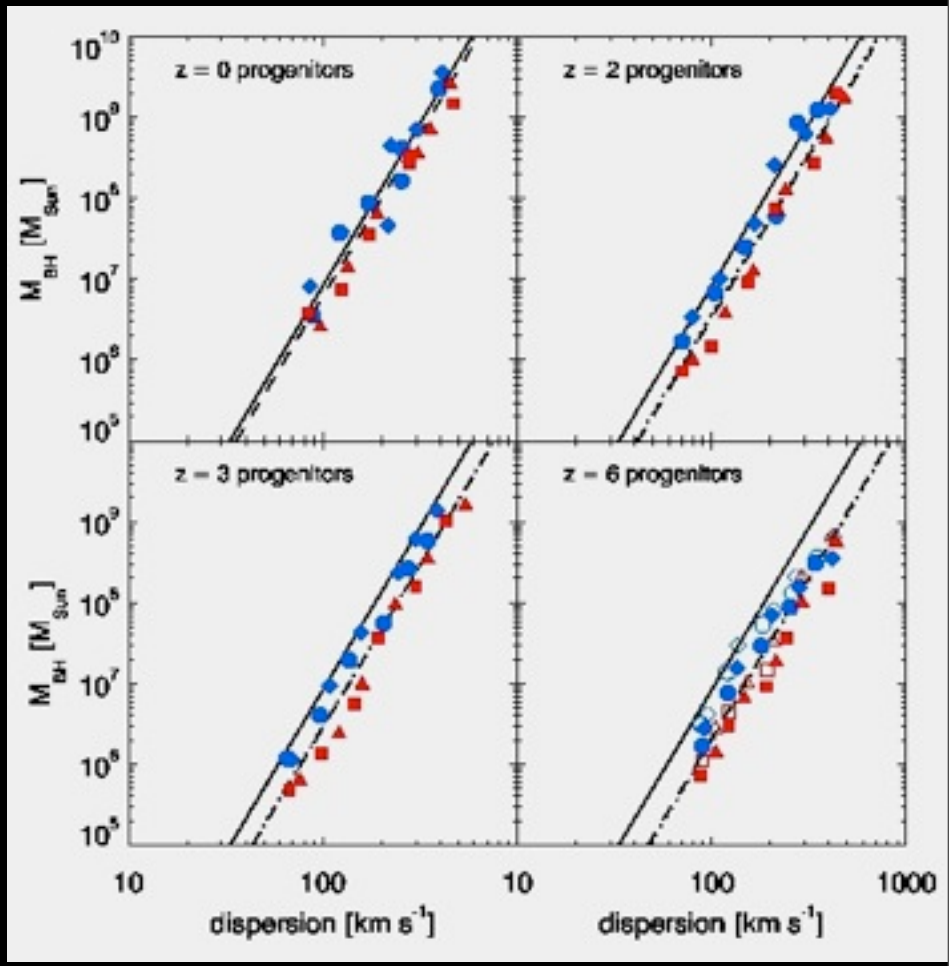
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers

Some Applications

- Starburst galaxies: ULIRGs and SMGs (energy source?)
- Nature, evolution of quasars
- $z \sim 6$ quasars & galaxies
- Quasar population: luminosity function, clustering
- Cosmic X-ray background
- Merger remnants: formation of ellipticals
- Red galaxy population
- Relation of merger / starburst / quasar / remnant / red galaxy / supermassive black hole populations

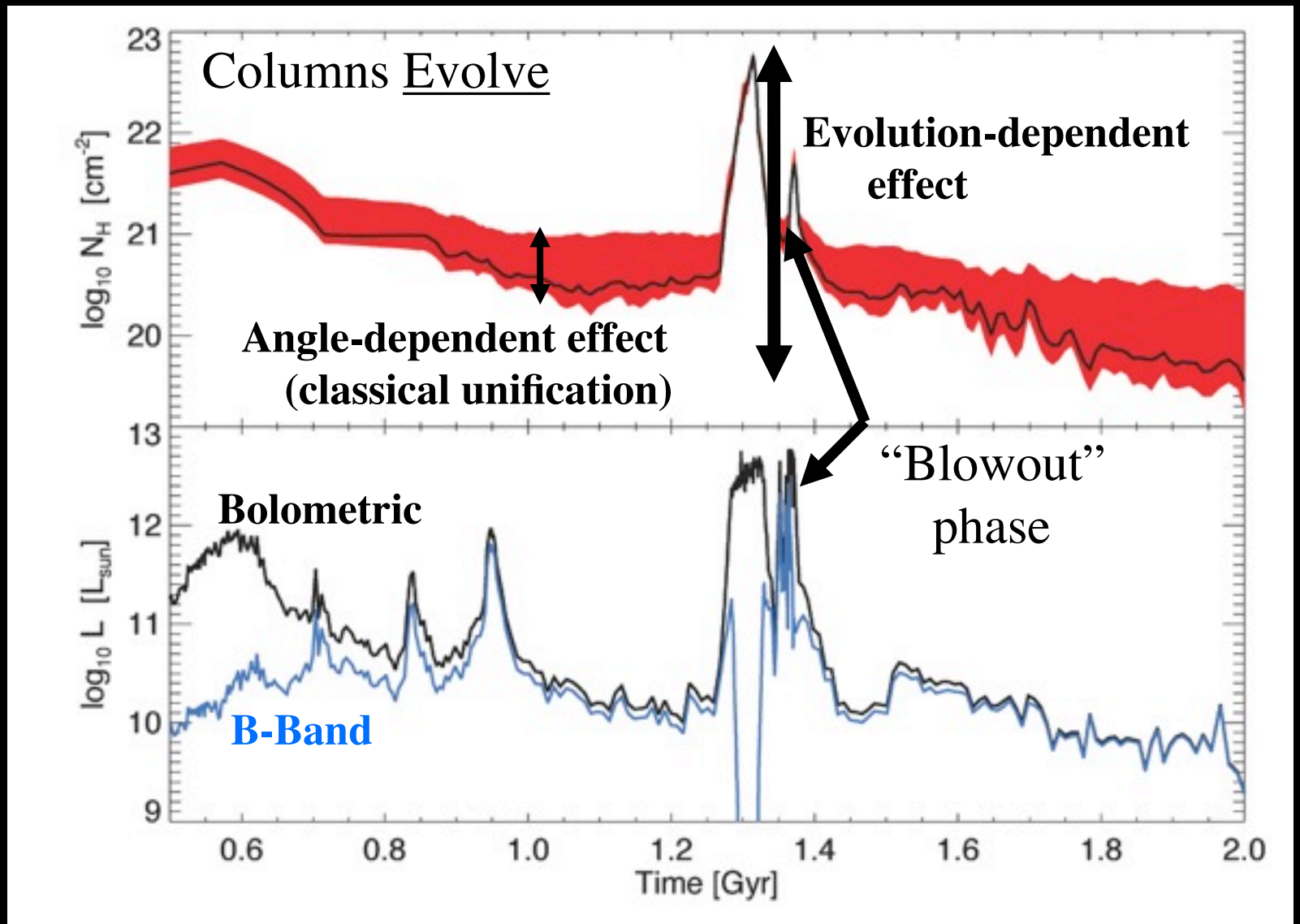
Remnants Properties: M_{BH} - σ Relation

- BH mass determined by feedback, gas cooling, potential well, gas dynamics
- BH growth self-regulated, fixing feedback efficiency $E_{feed} = \varepsilon_f M_{BH} c^2$ with $\varepsilon_f \sim 0.005$
- Reproduce observed Mbh-Mhost evolution owing to evolution in sizes & potential well depths of galaxies (PH et al. 2007)



Robertson et al., astro-ph/0506038

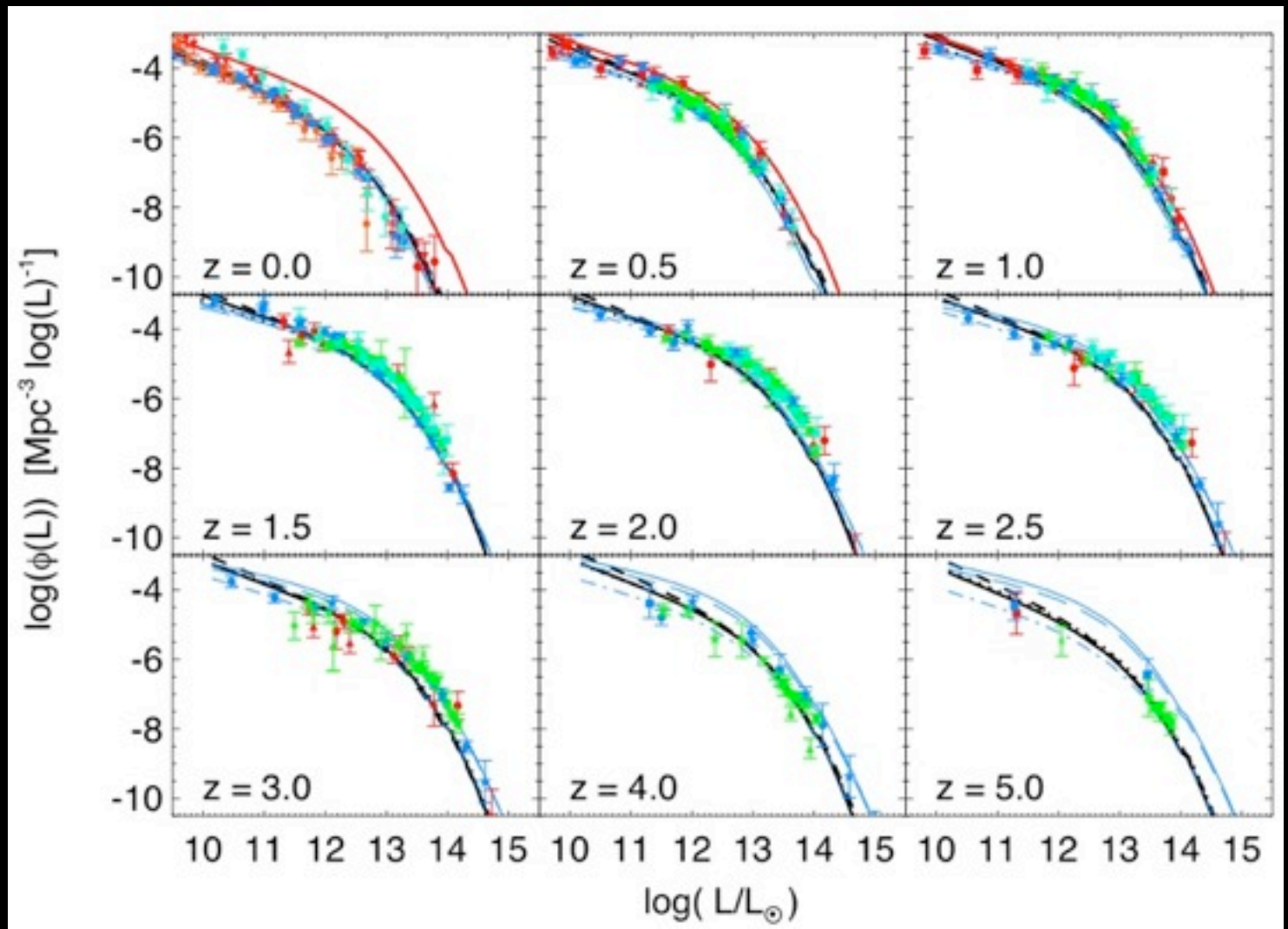
Quasar Lightcurves & Lifetimes



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

Predictions

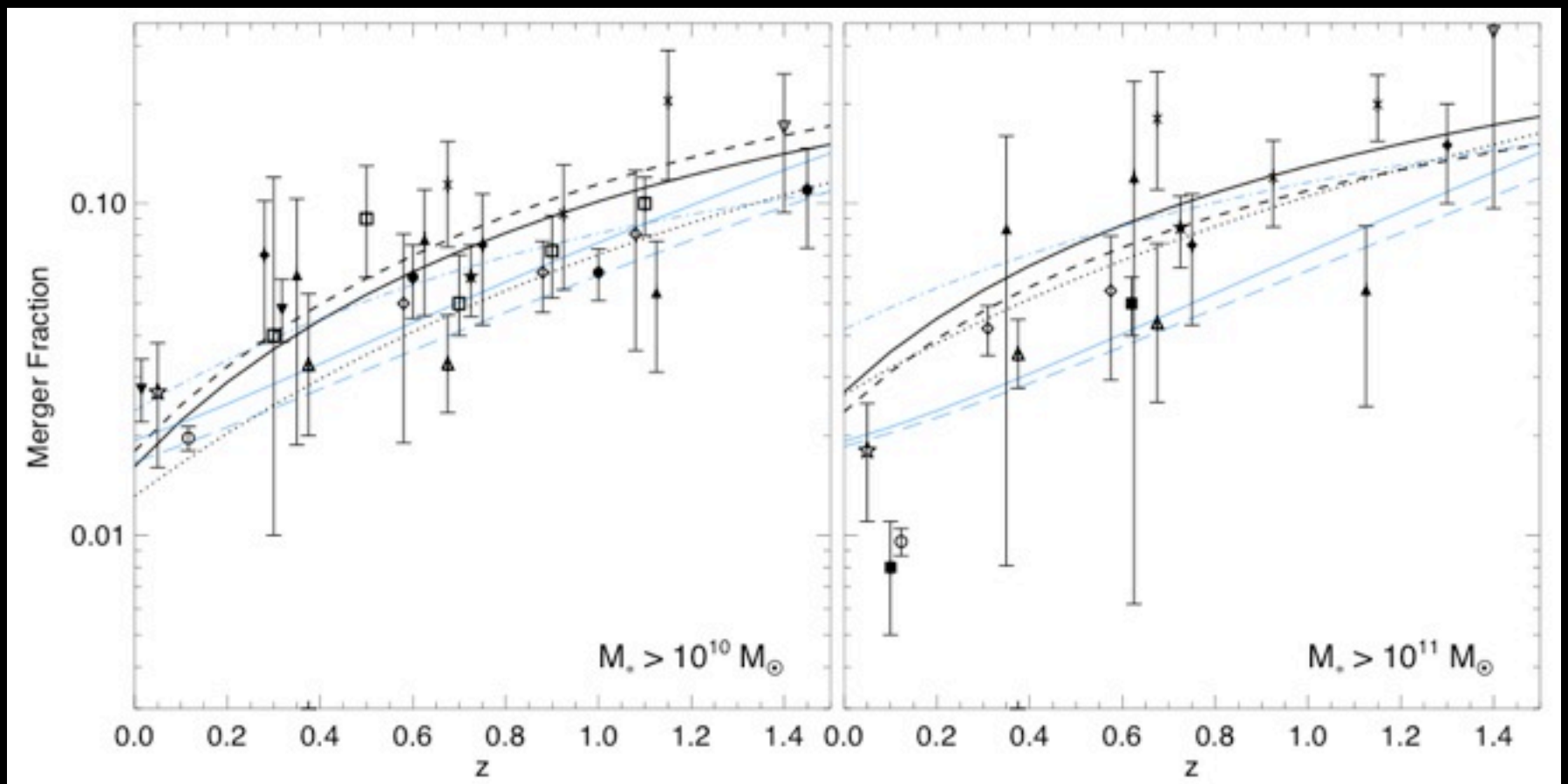
- Predicts the QLF vs. redshift, luminosity, wavelength



PH07

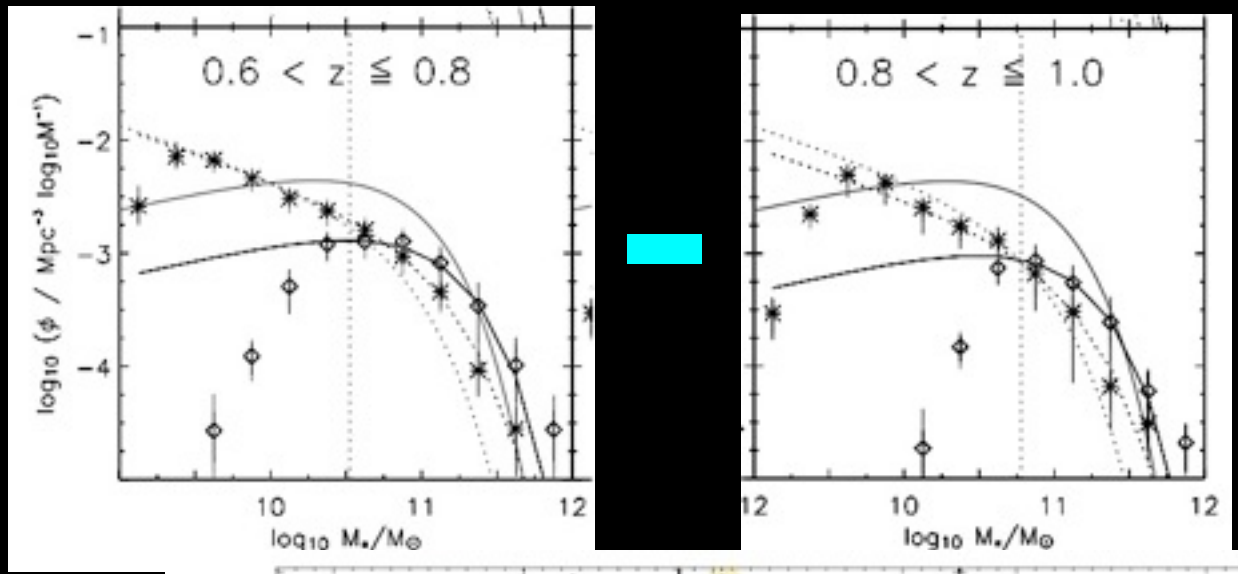
Predictions

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

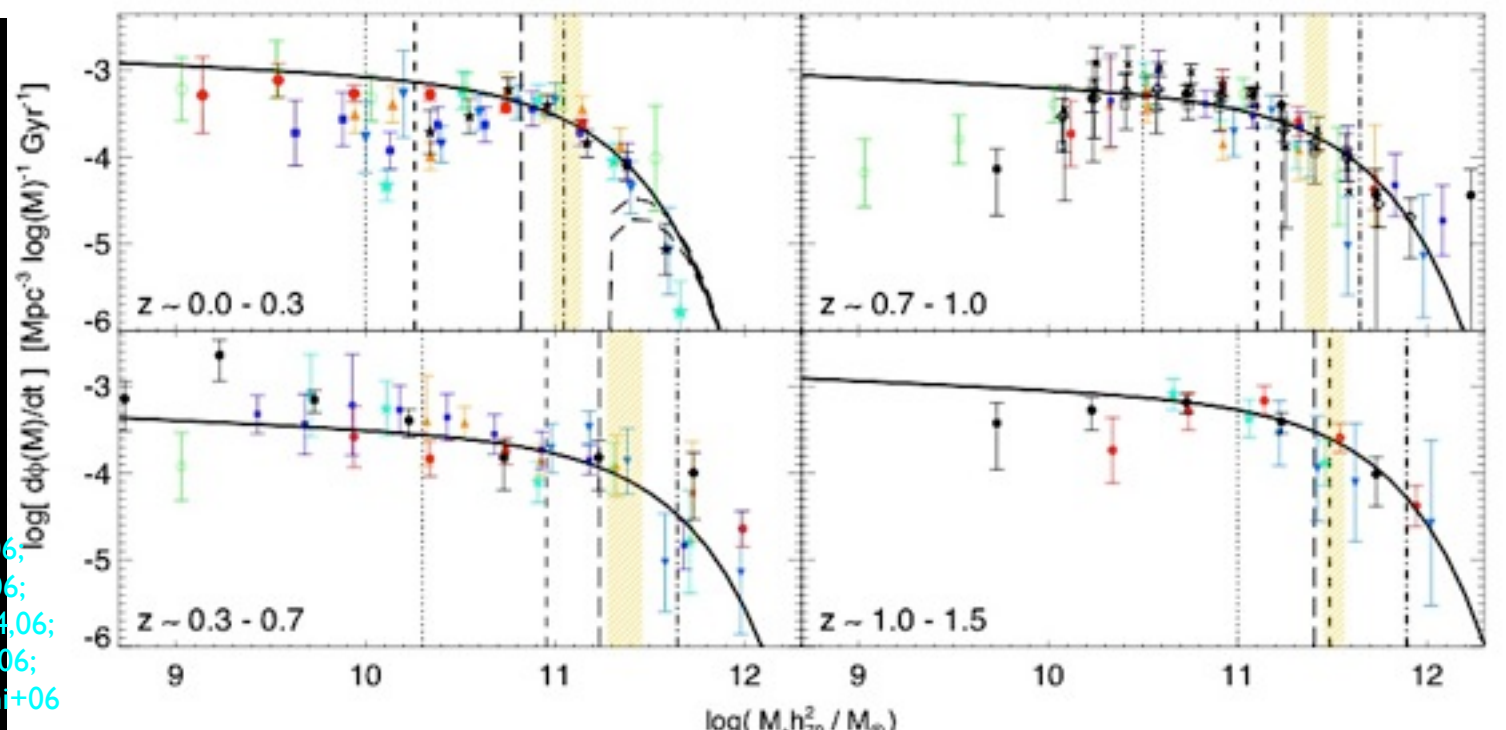


PH07

Predictions



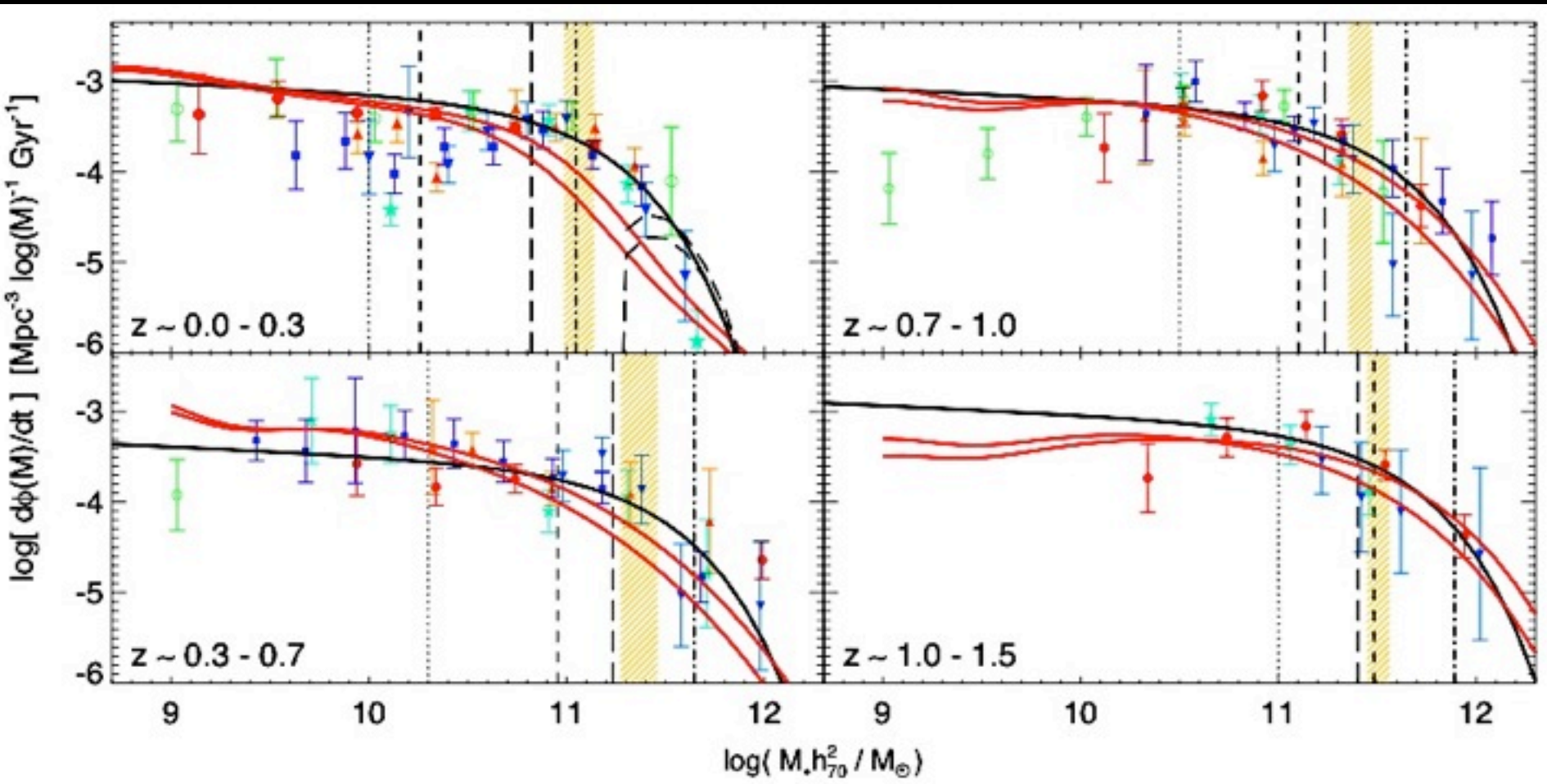
Hopkins, Bundy, Hernquist+ 06



Borch+06;
Bundy+06;
Fontana+04,06;
Pannella+06;
Franceschini+06

Predictions

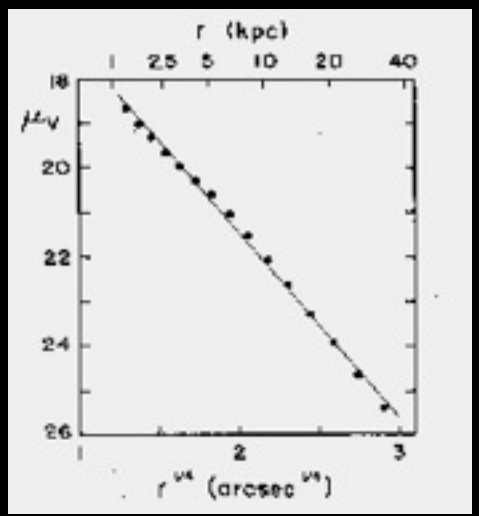
- Observed RS Buildup to z>~1 = Expectation if *all* new mass to the RS "transitions" in a quasar-producing merger

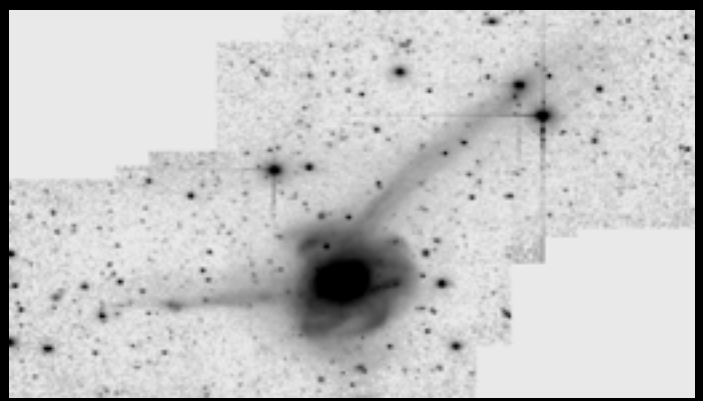


Hopkins, Bundy, Hernquist+ 06

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)



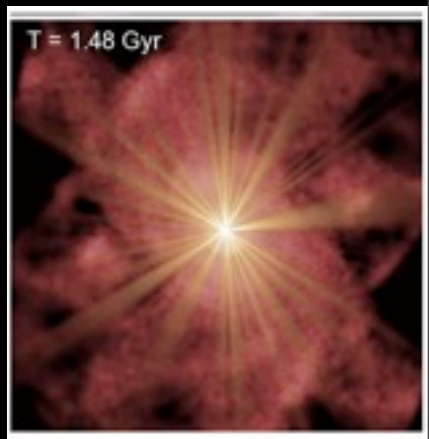


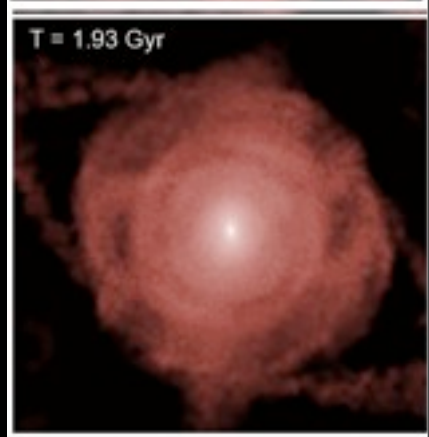
Schweizer (1982)

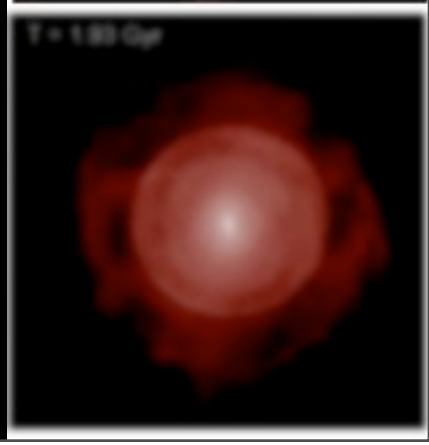
QSO = 1000xHost

QSO = Host

QSO = 0.1xHost

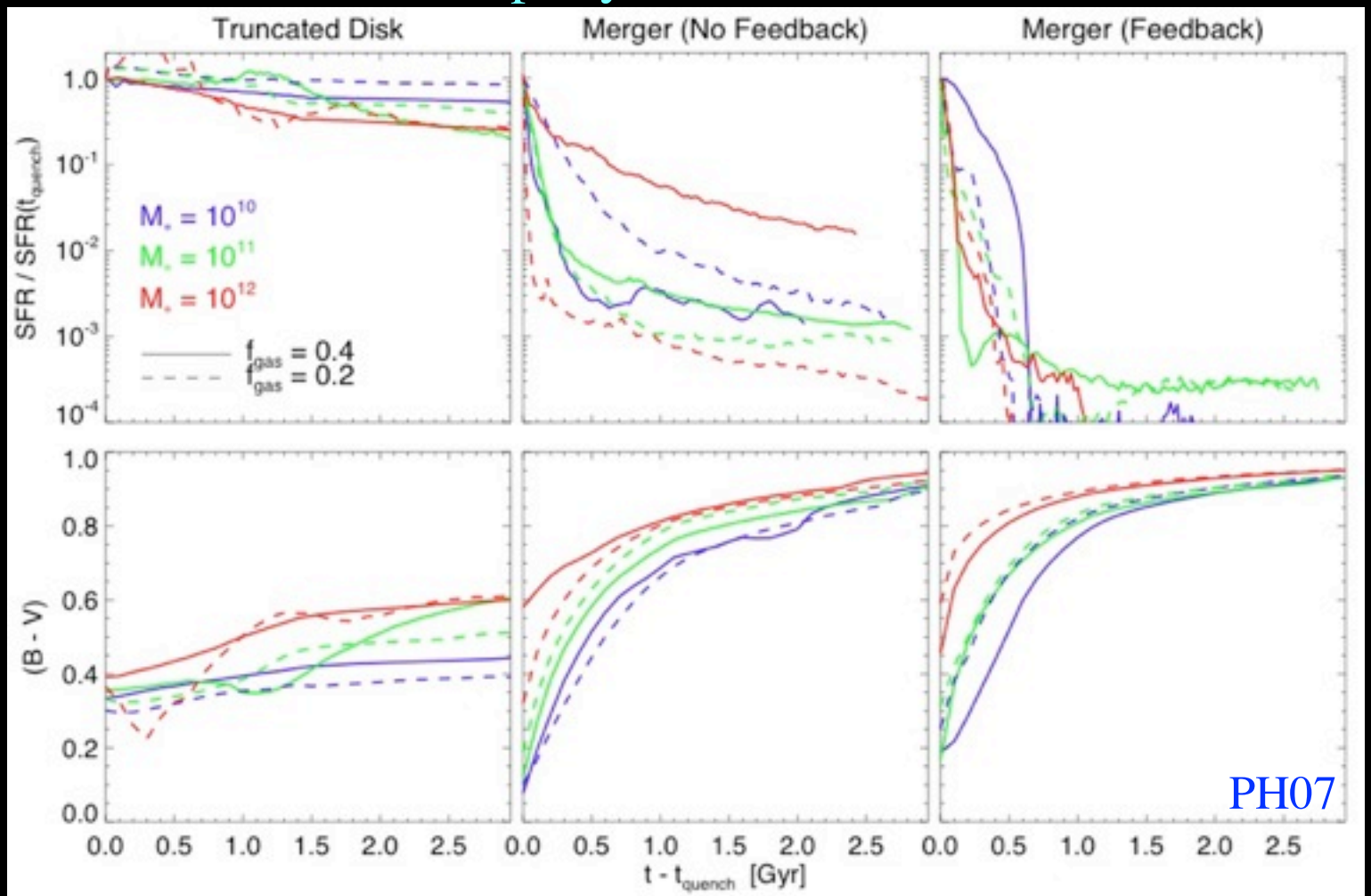






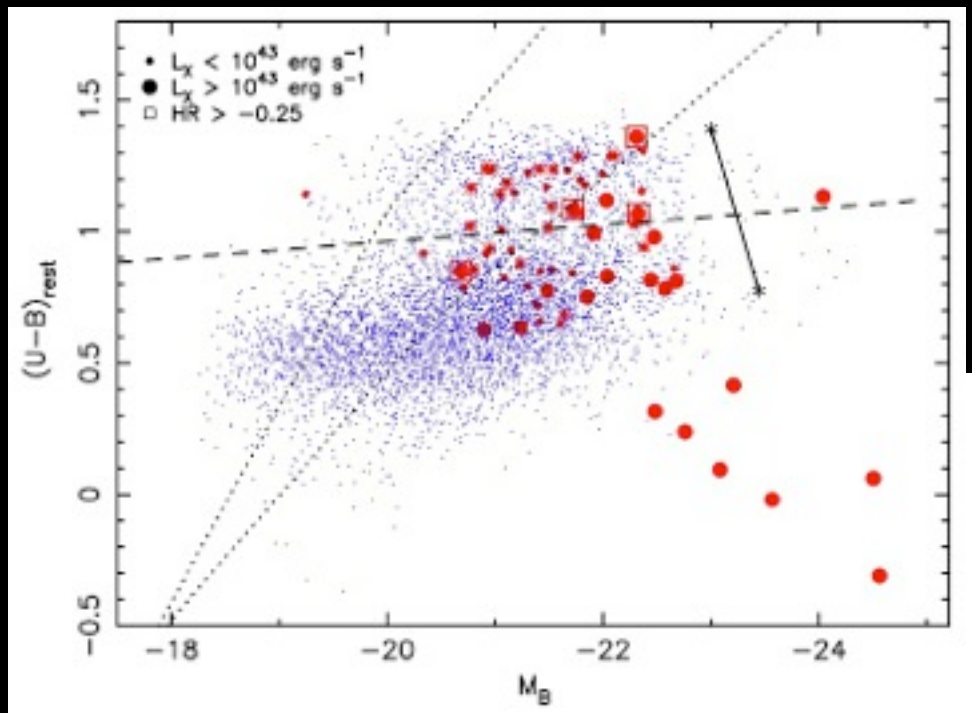
Color Evolution of Quasar Hosts

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

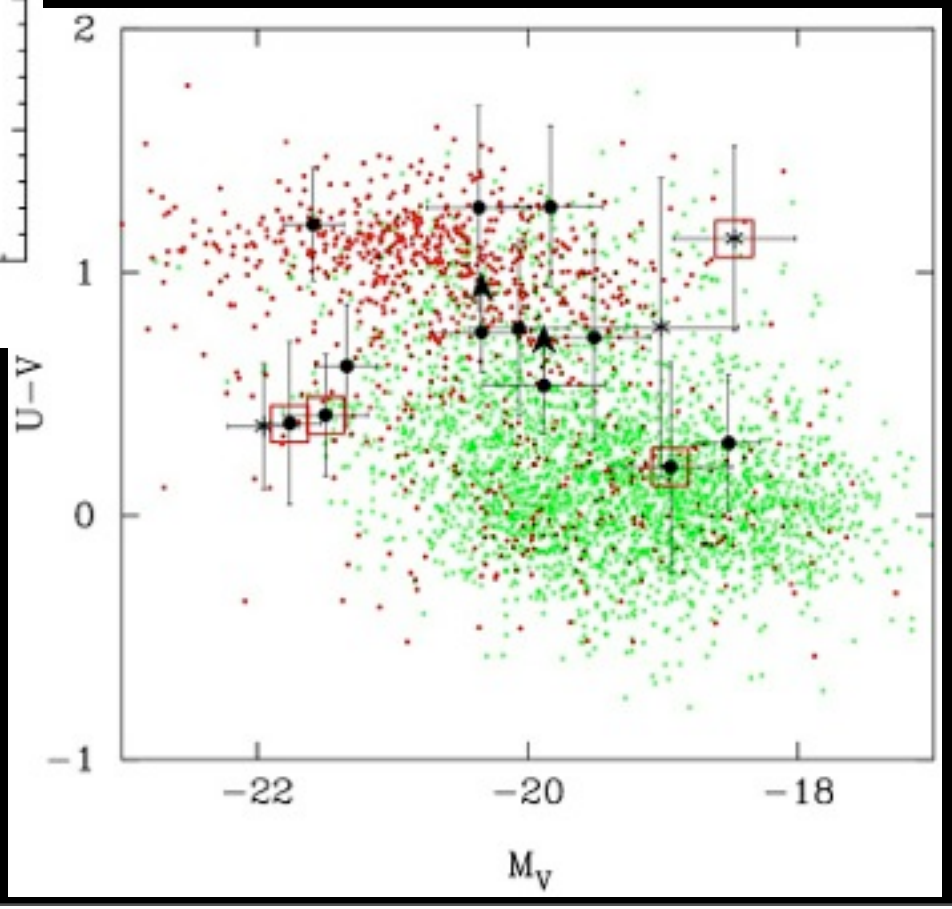


- Not true of secular evolution/pseudobulges (observed too)

Color Evolution of Quasar Hosts

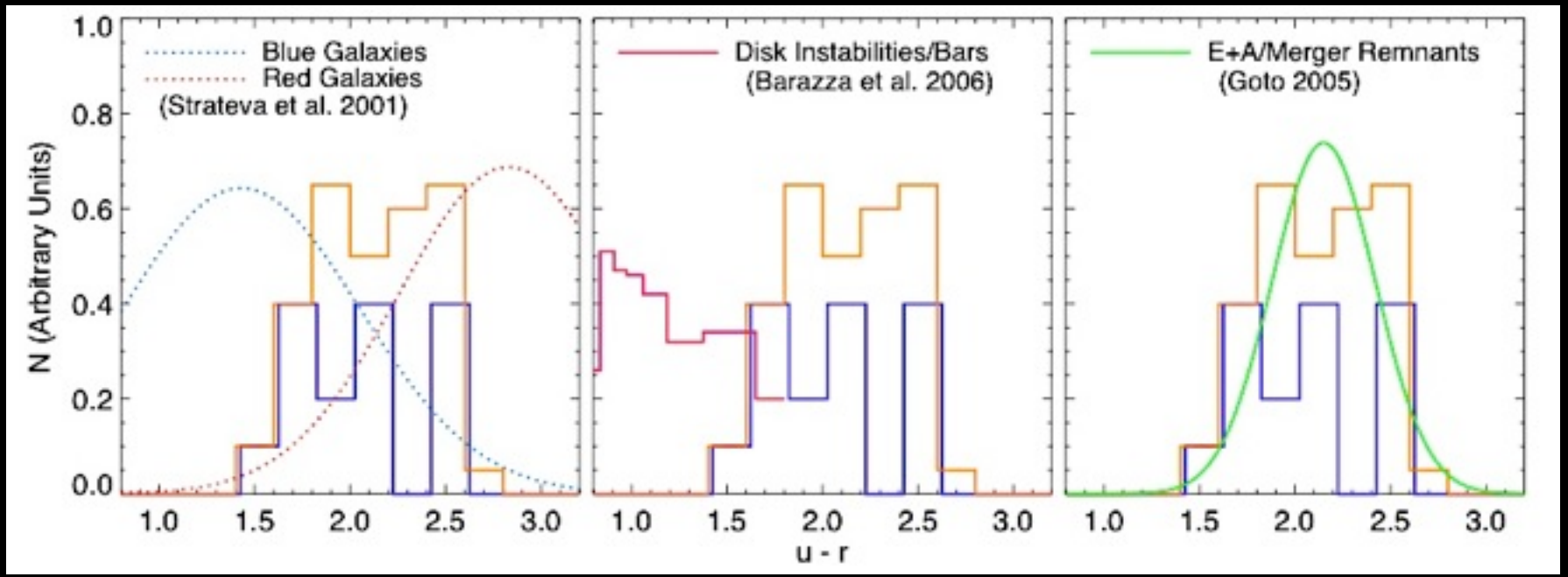


Sanchez+ '05
GEMS
$0.5 < z < 1.1$
Optical QSOs



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

Color Evolution of Quasar Hosts

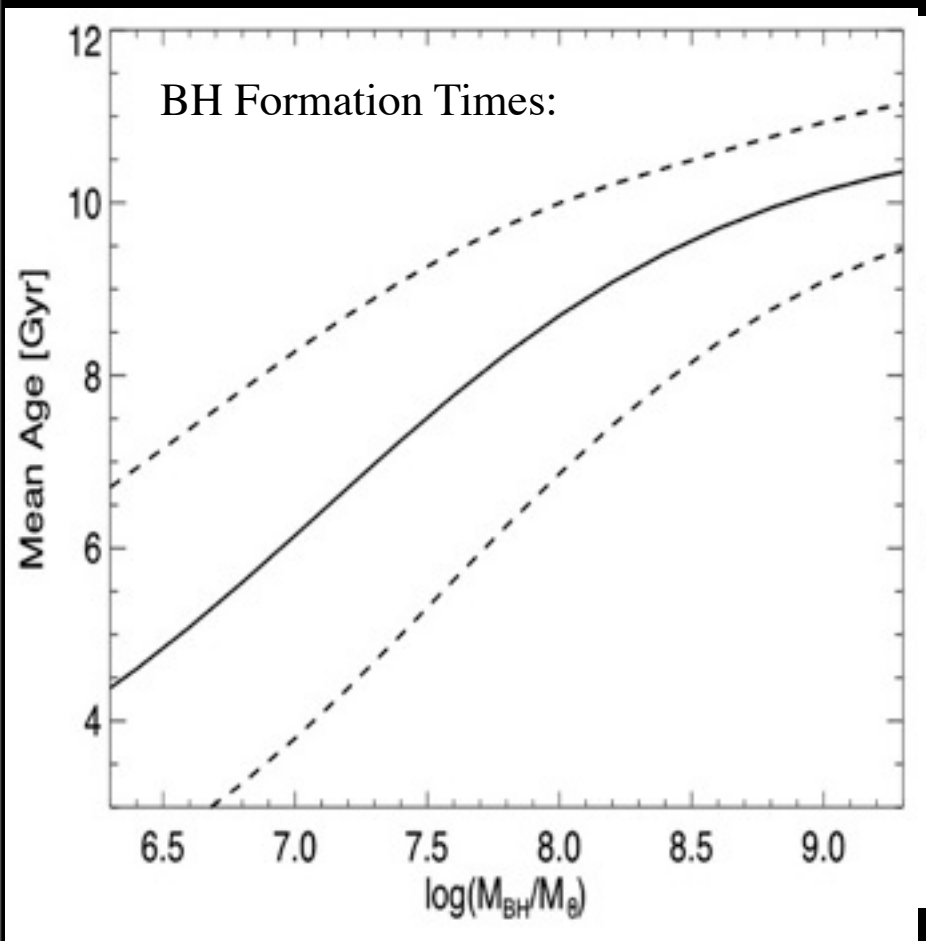


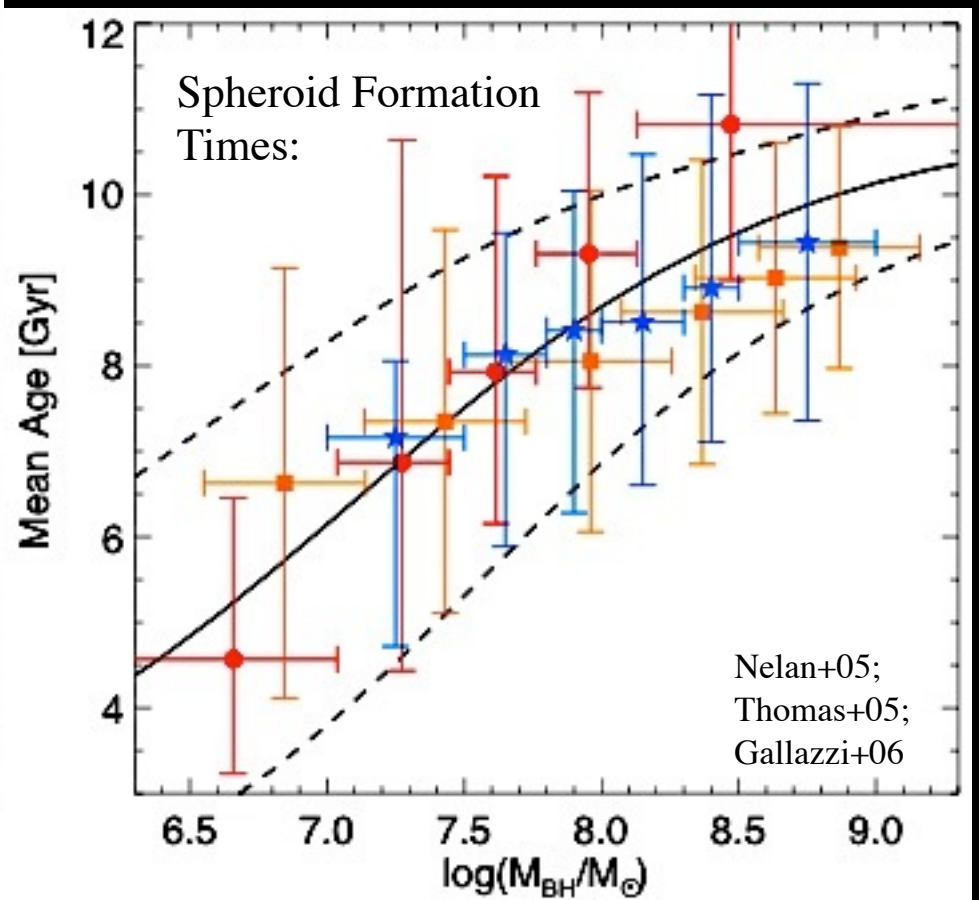
PH07

- Need to go to next level: full stellar populations - are these really post-SB?
- Examine the time/redshift dependence

Color Evolution of Quasar Hosts

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



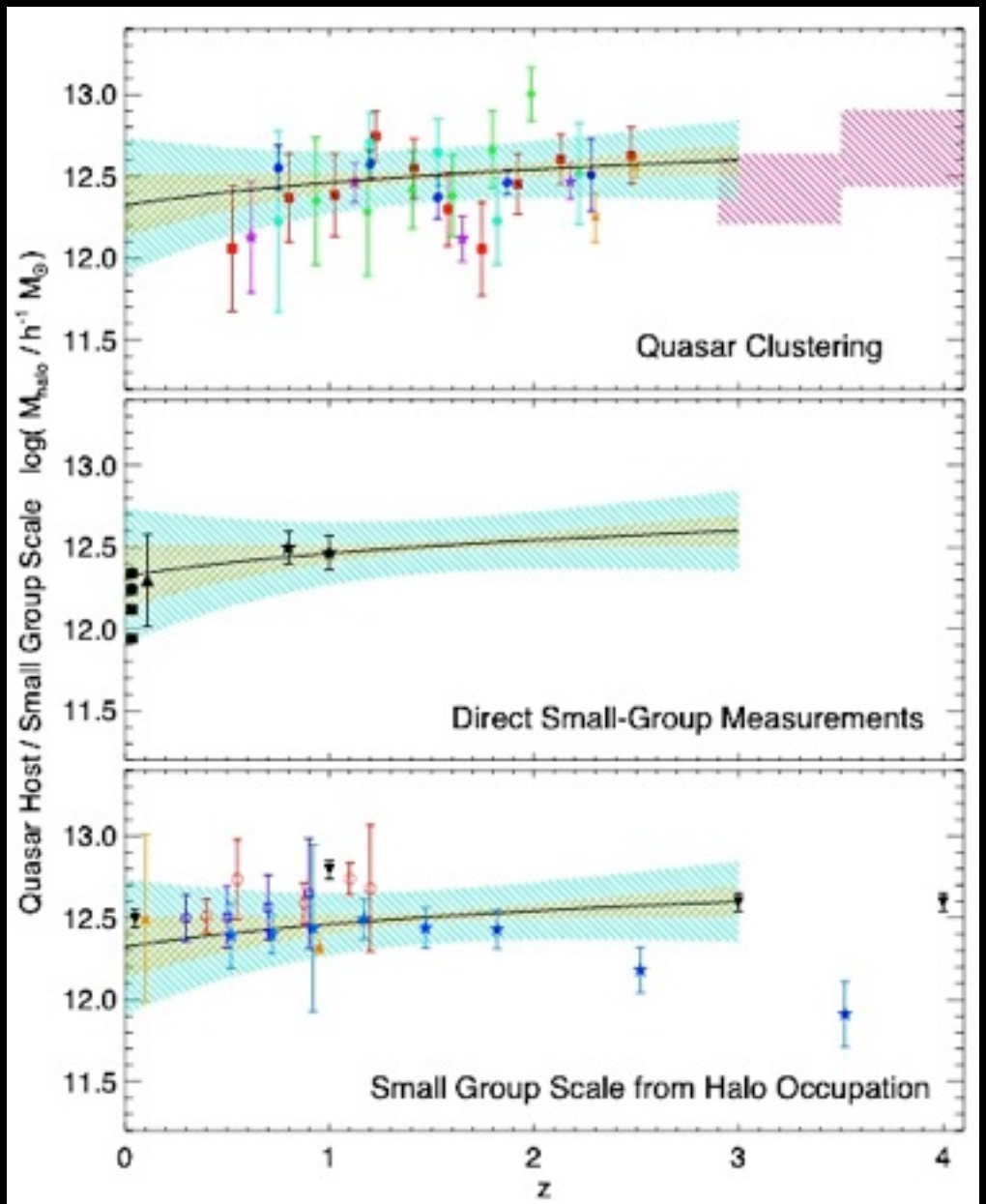


Hopkins, Lidz, Hernquist, Coil, et al. 2007

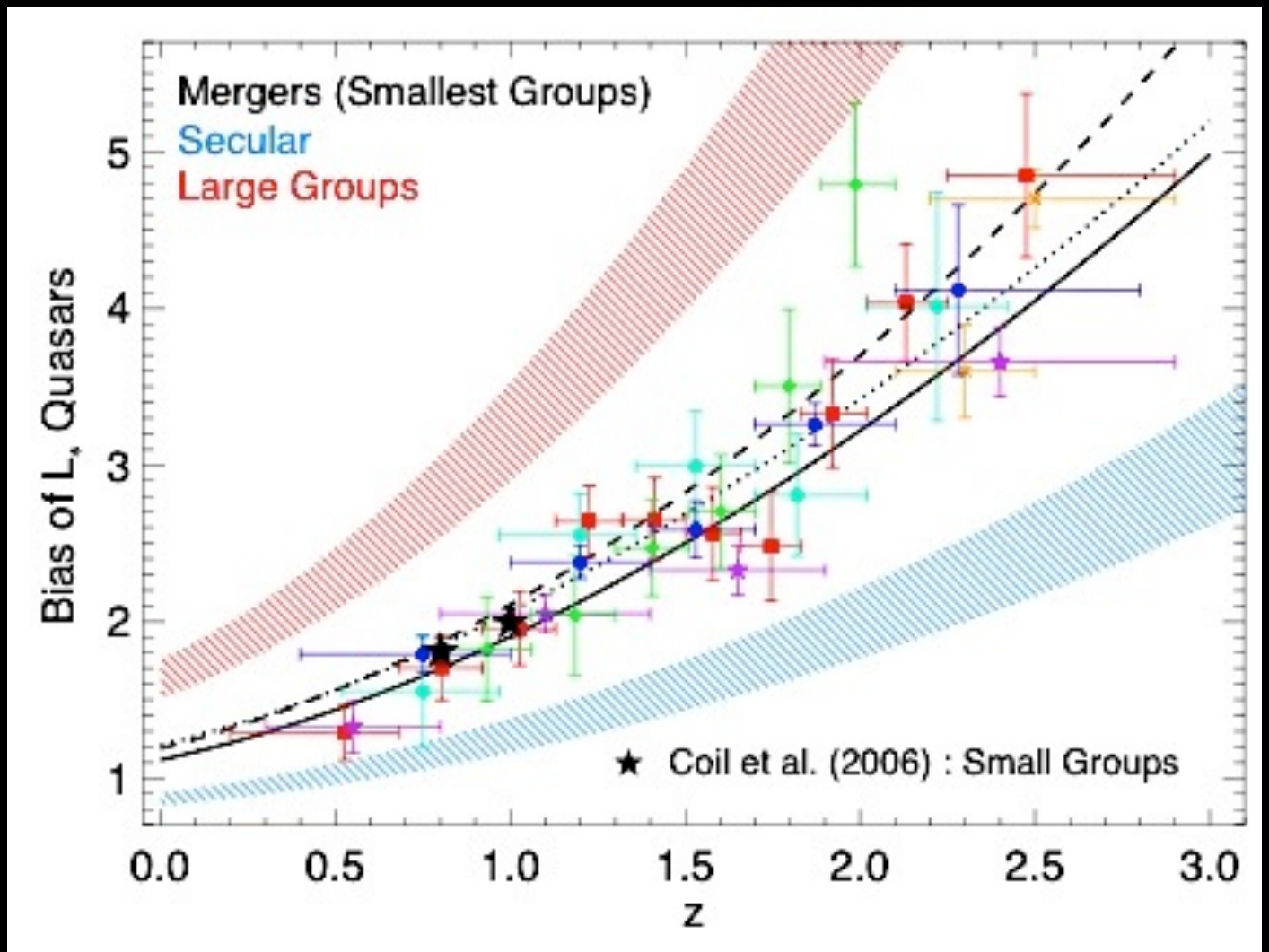
Where Quasars Are Born

PH07

- Croom et al. (2005) (+others): from 2dF QSO survey
  - M_{halo}(QSO host) ~ $3.0 \pm 1.6\ h^{-1}\ M_{solar}$ 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

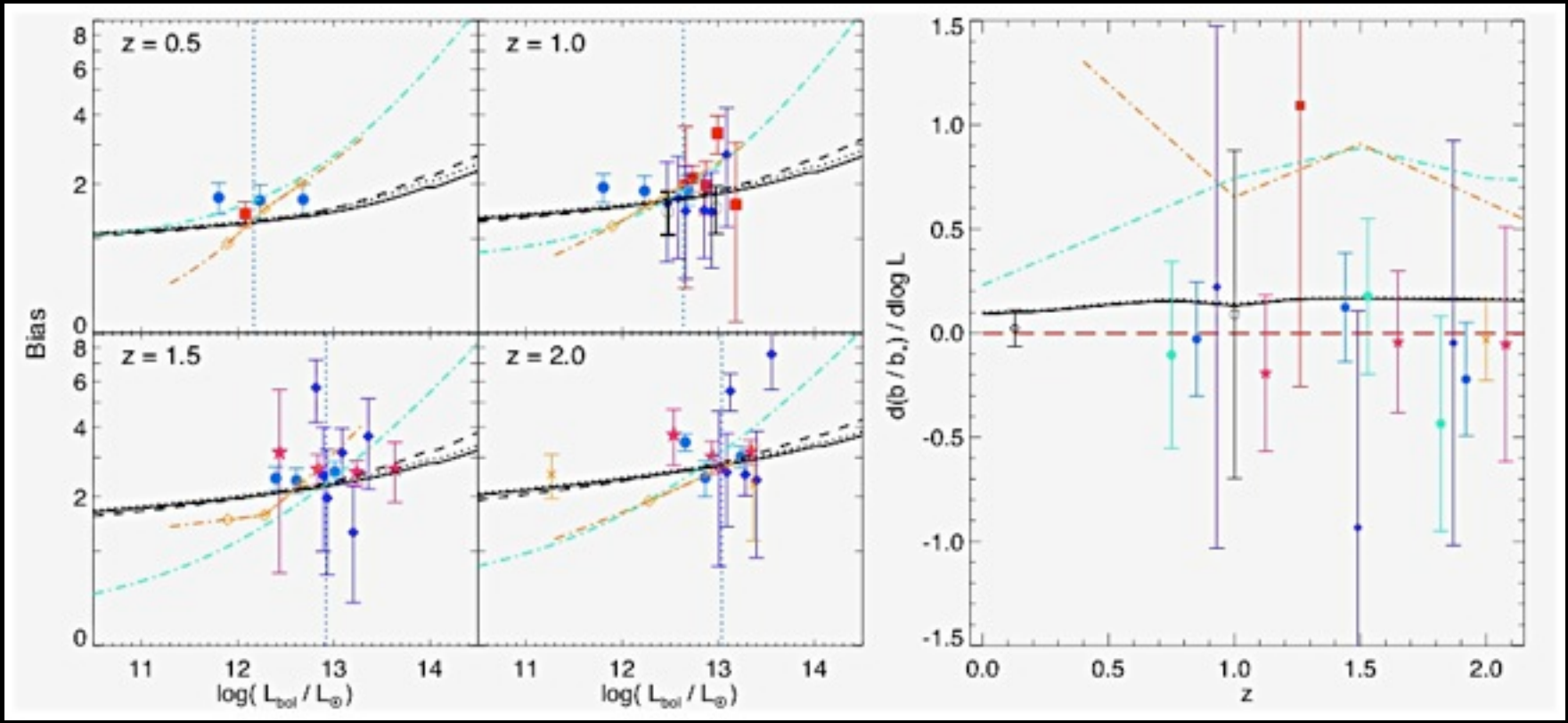


PH07

- Clustering of ~L* quasars is different from ~L* disks (secular expectation)

Where Quasars Are Born

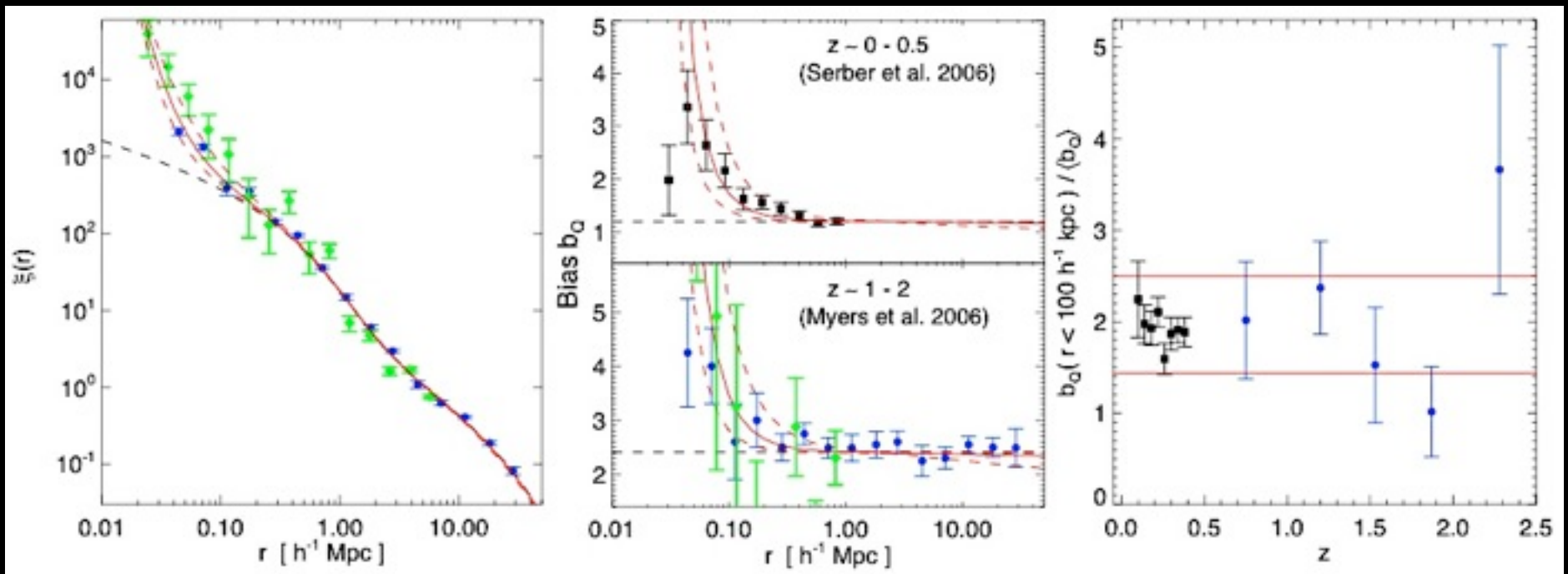
- Weak luminosity dependence: same ~L* galaxy merger goes through evolution in different luminosities



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



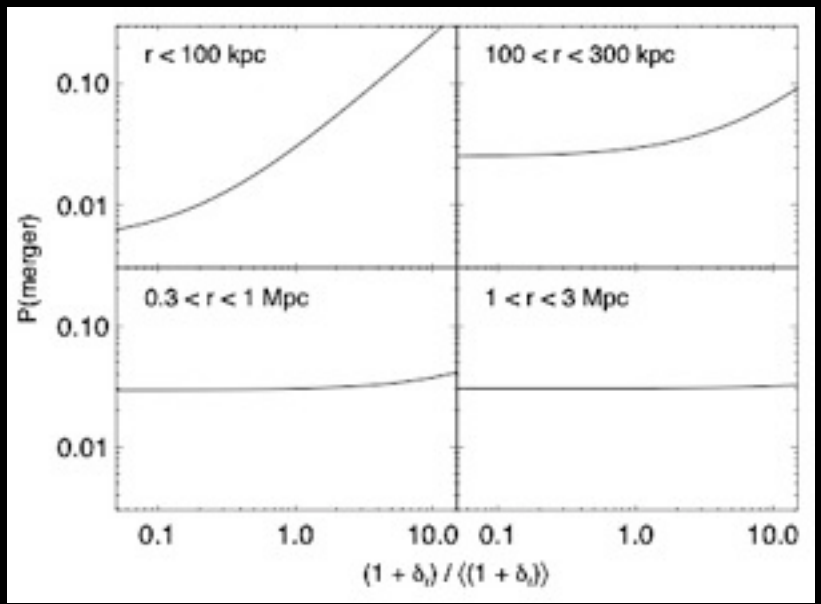
- Predicted by merger models

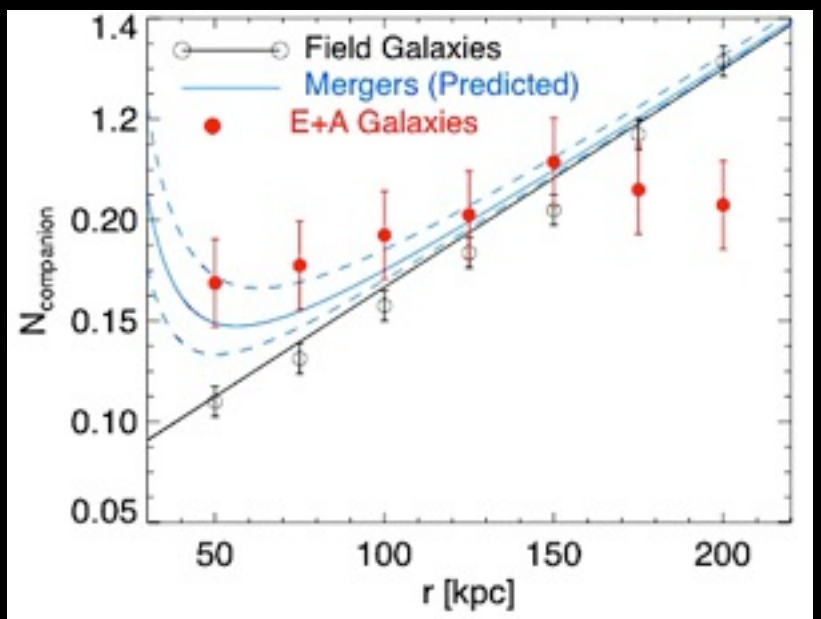
PH07

Where Quasars Are Born

PH07

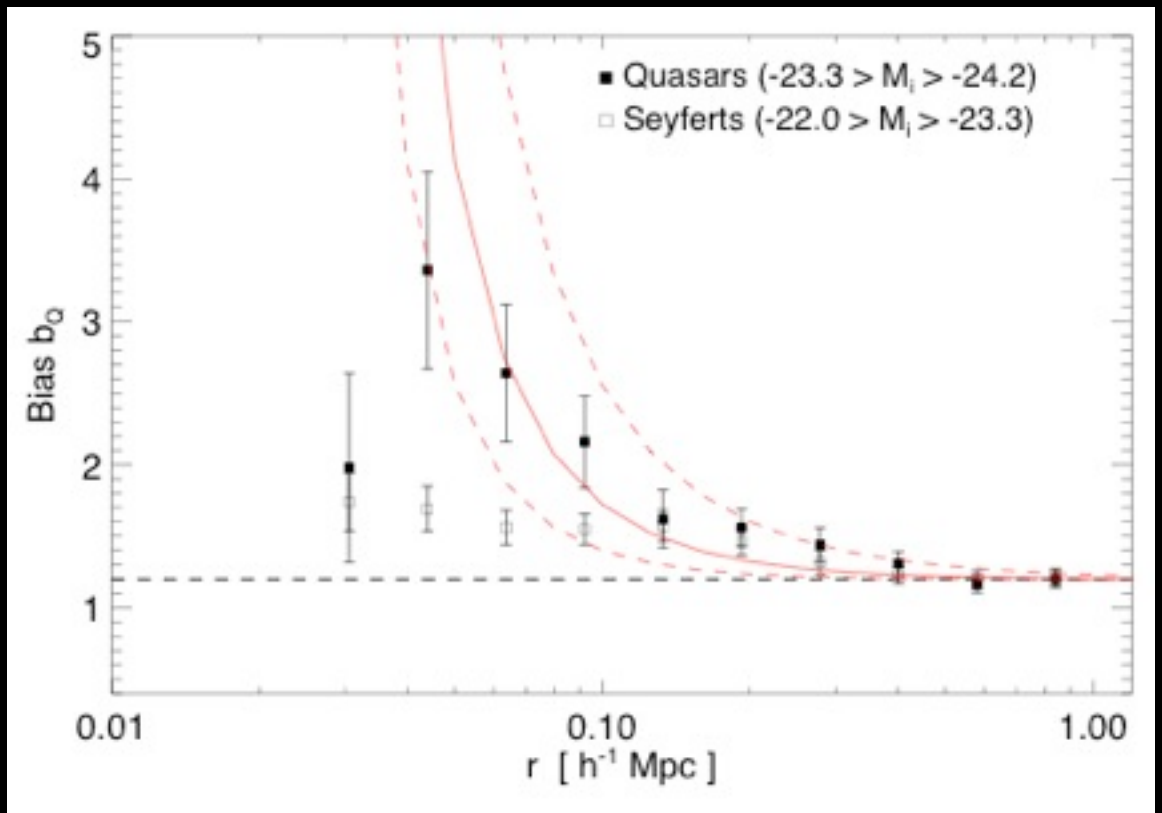
- Small-Scale Excess:
  - Predicted in merger models
    - Mergers biased to regions with *small-scale* overdensities
    - Seen in cosmological simulations (Thacker et al.)
    - Seen in merger remnants! (Goto et al.; Hogg et al.)
  - *Not* expected in secular/instability, cooling flow, stellar mass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





Where Quasars Are Born

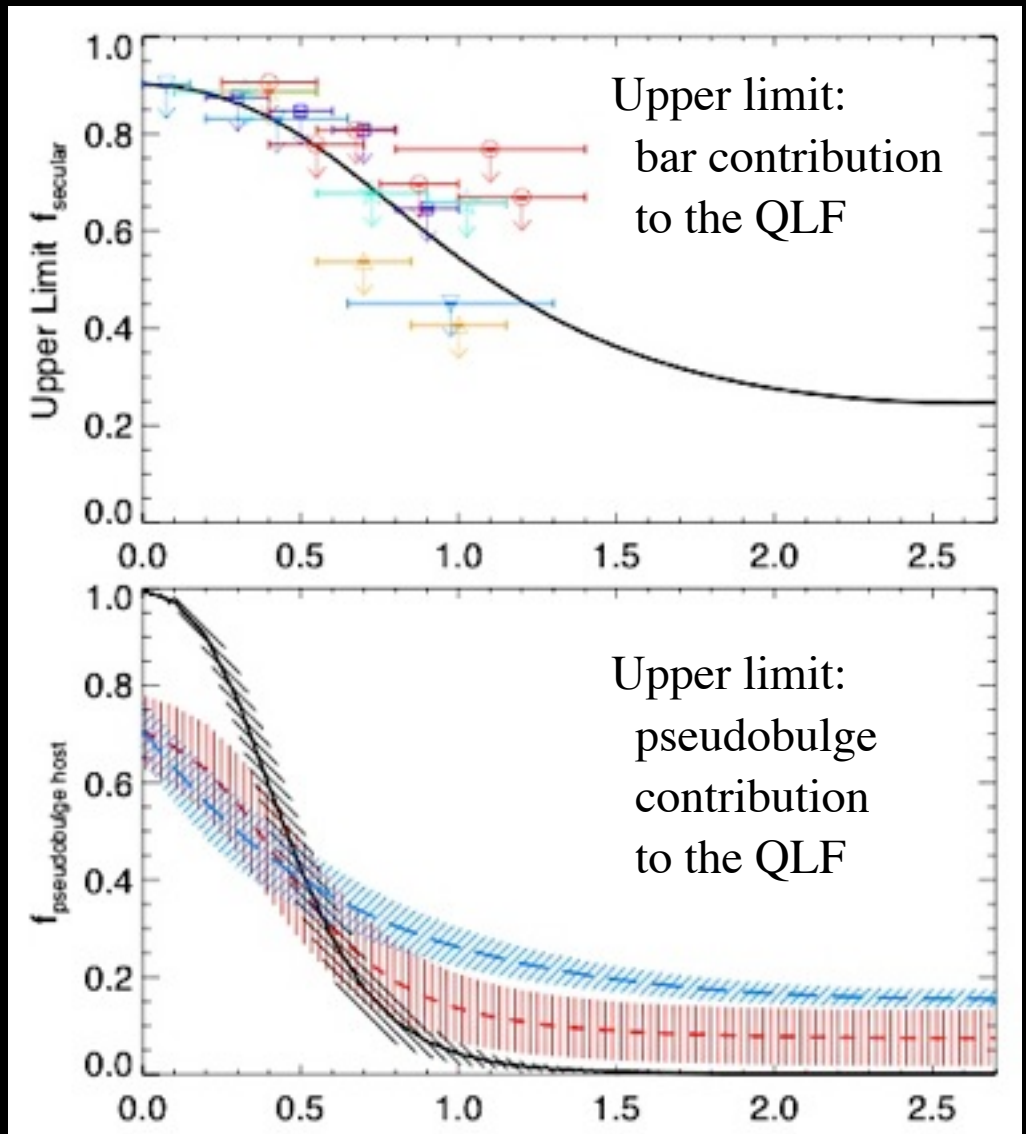
- Small-Scale Excess:
  - Not seen in Seyferts:
    - Suggests different processes dominate fueling below M_B ~ -23 (M_bh ~ 10^7)?



Serber et al. 2006

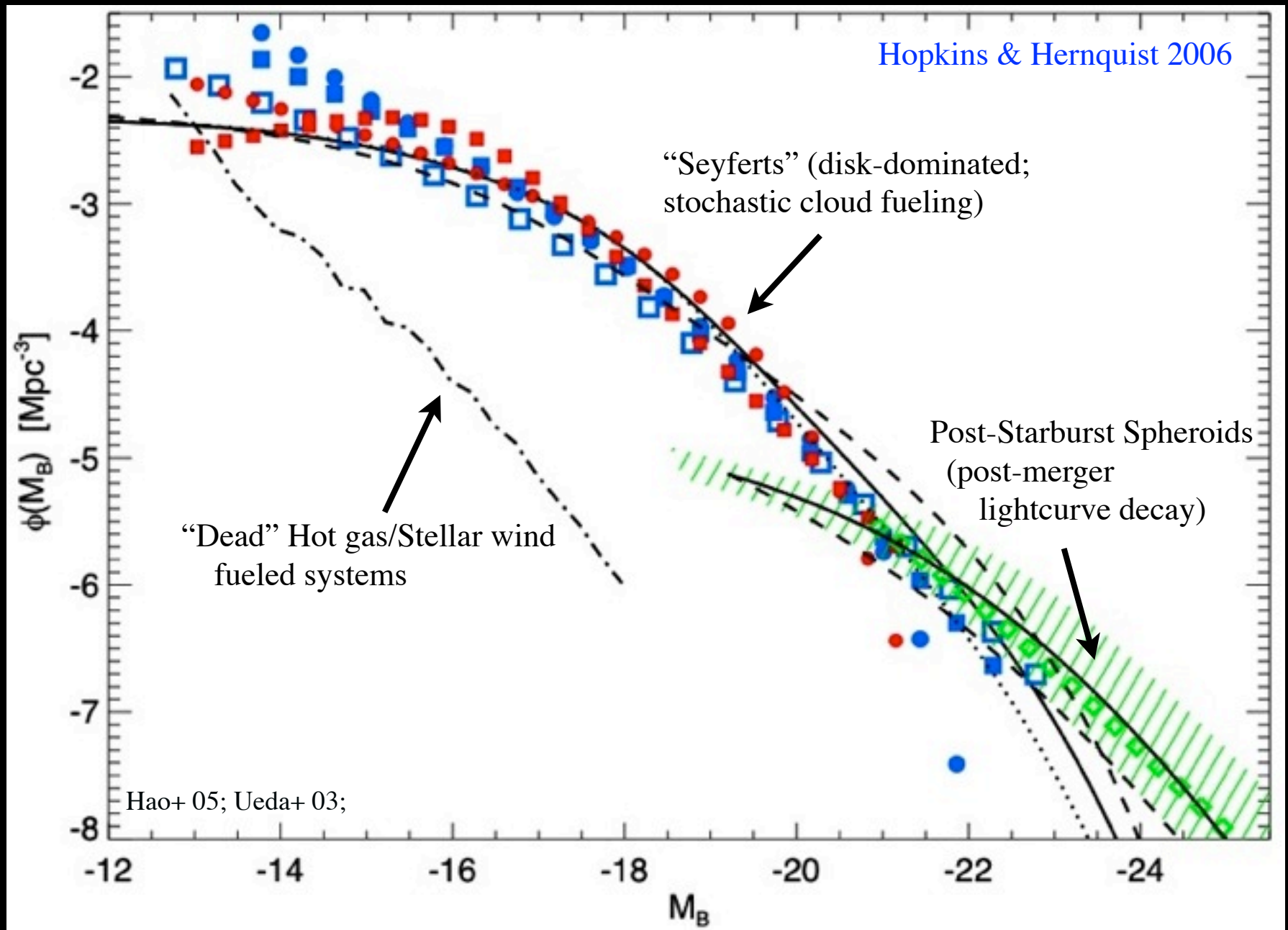
Morphology of Quasar Hosts

- 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

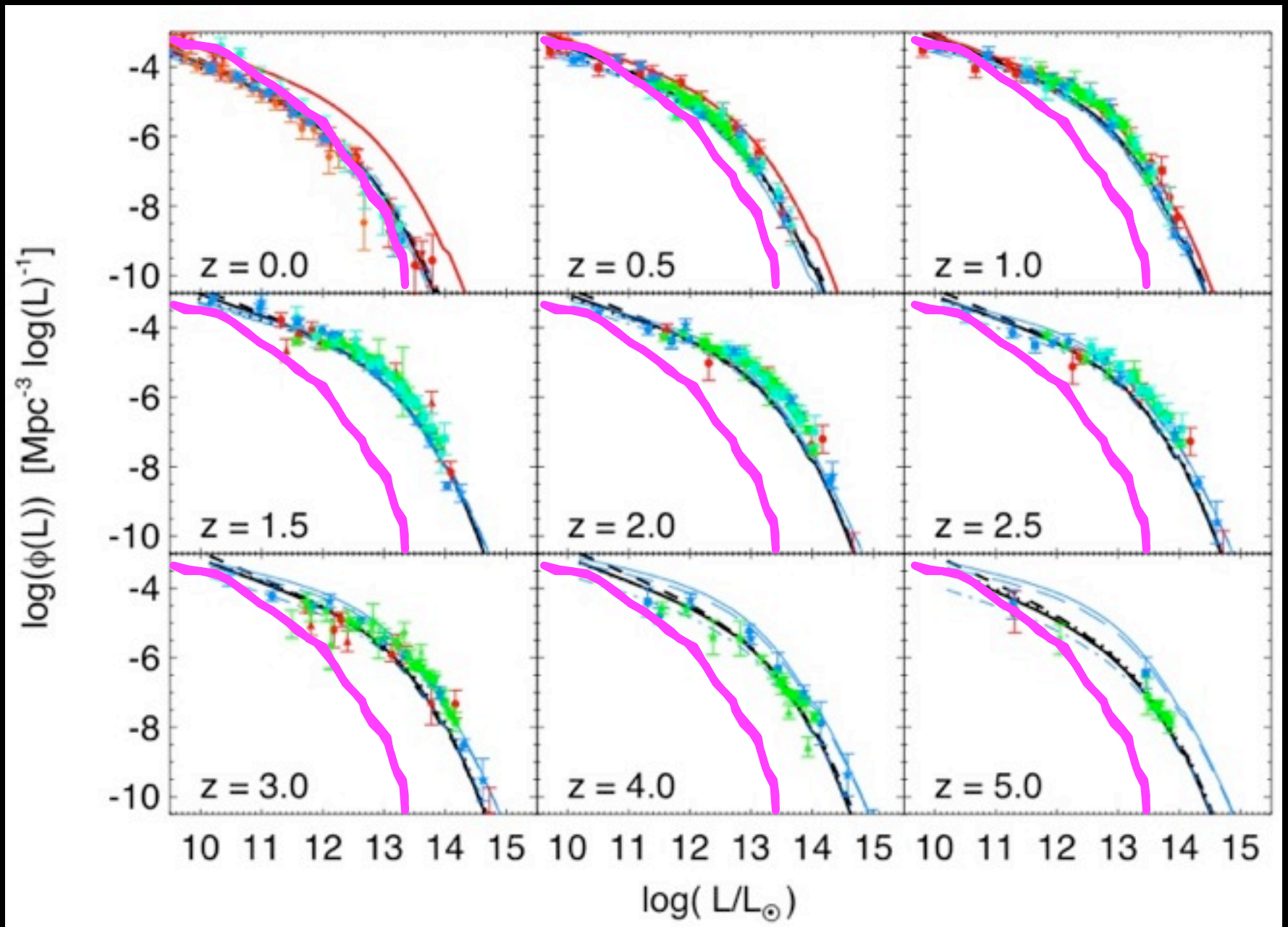


PH07

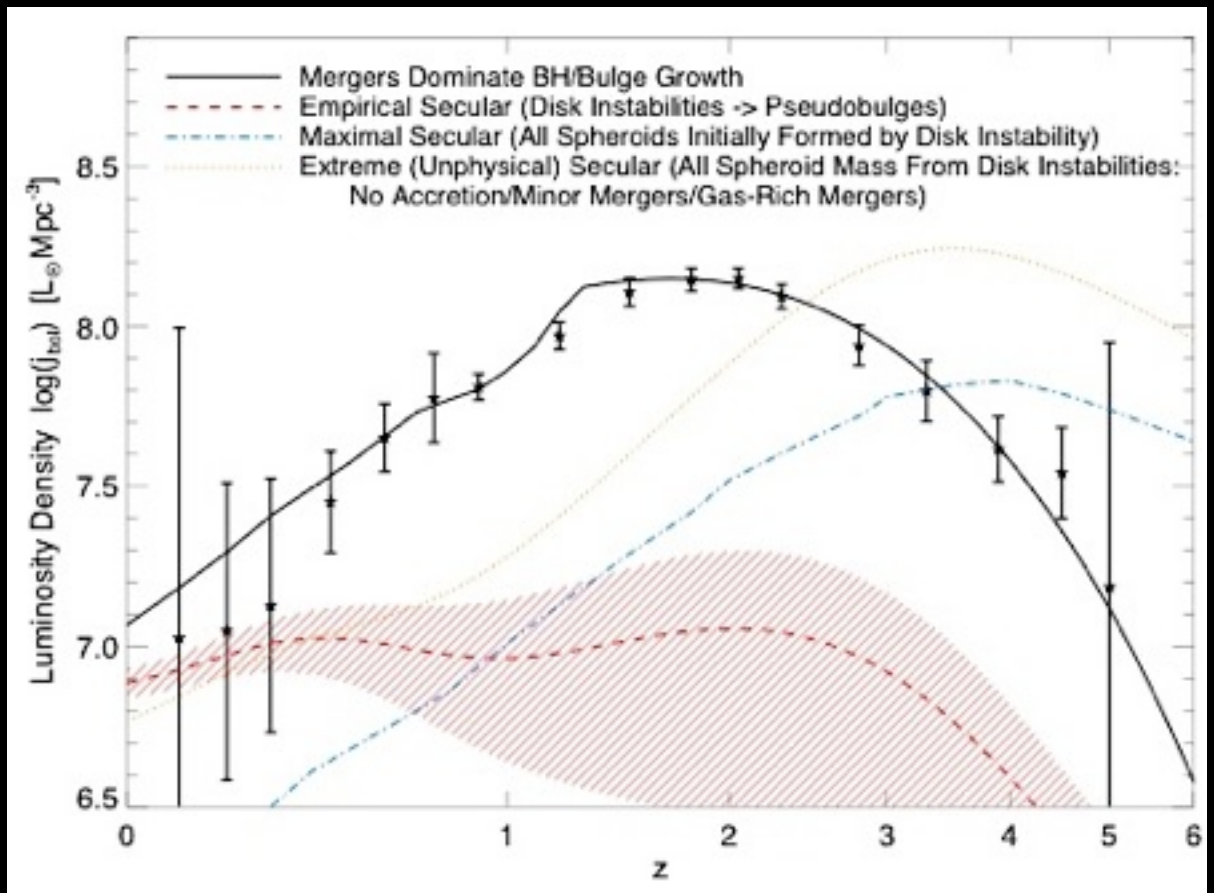
Morphology of Quasar Hosts: Local



Morphology of Quasar Hosts: Evolution



Morphology of Quasar Hosts: Evolution



PH07

- Even ignoring the kinematics: mergers are inevitable
  - Secular fueling (if it did dominate) would have to happen before
  - Predicts QSOs decaying by z~3-4

Conclusions

- picture for quasar evolution:
  - complex, evolving lightcurves, lifetimes
  - evolving pattern of obscuration: increases with luminosity, drops during blowout
- self-consistent model for quasar population, cosmic X-ray background, supermassive black hole & galaxy spheroid population
- description of quasar clustering & explanation for "universal" quasar host halo mass

- new tests for quasar origins: clustering vs. scale, host stellar populations, host kinematics
- new questions: