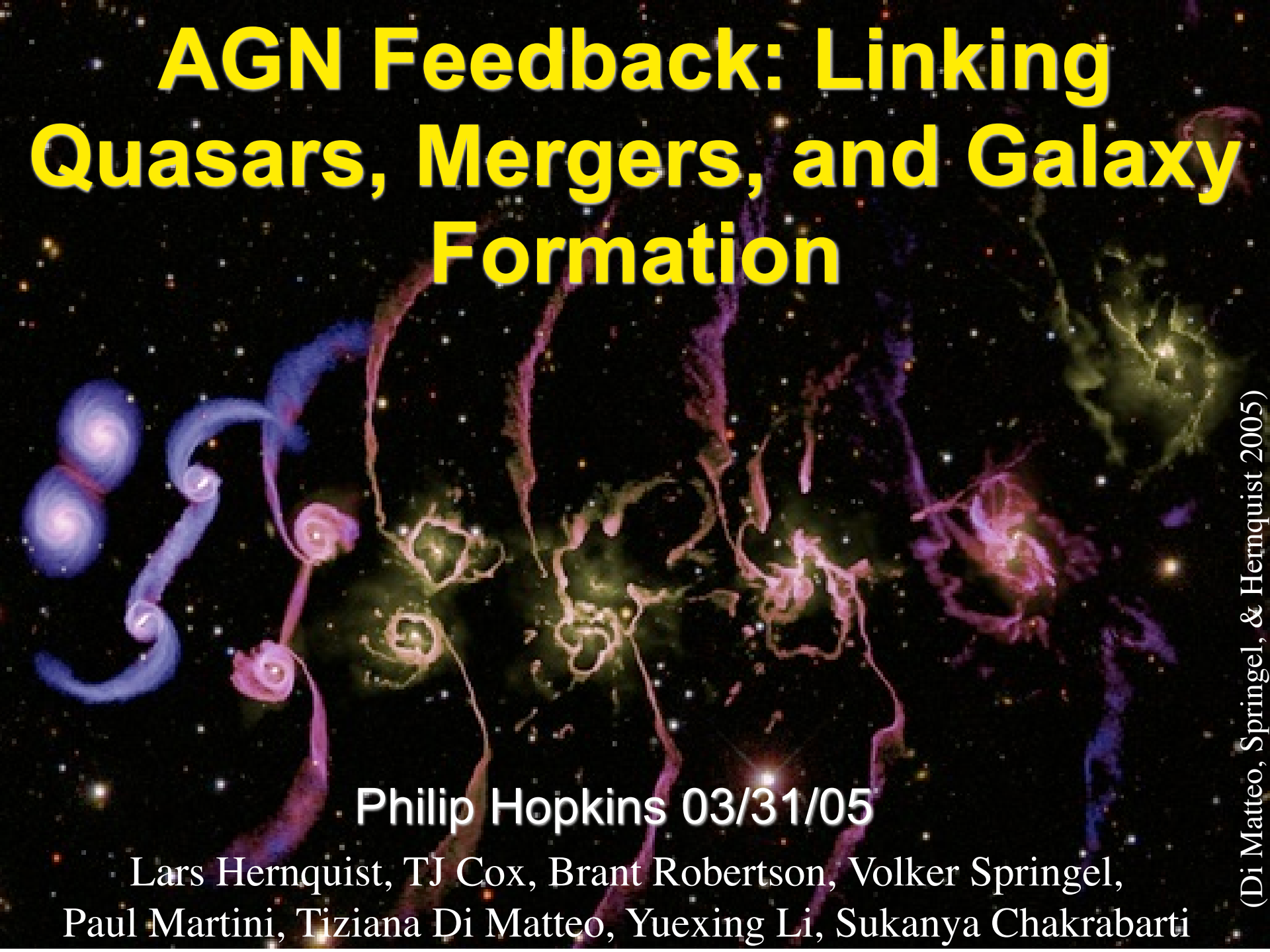
AGN Feedback: Linking Quasars, Mergers, and Galaxy Formation



(Di Matteo, Springel, & Hernquist 2005)

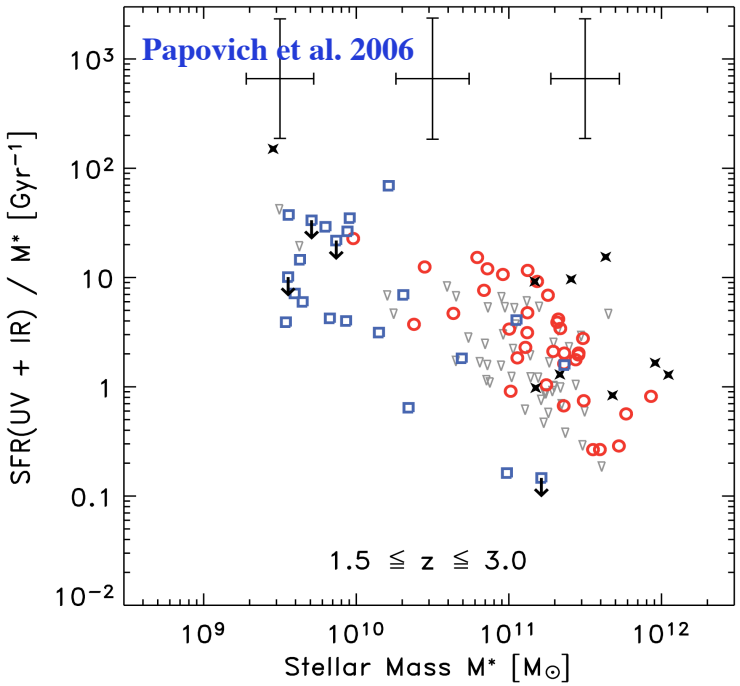
Philip Hopkins 03/31/05

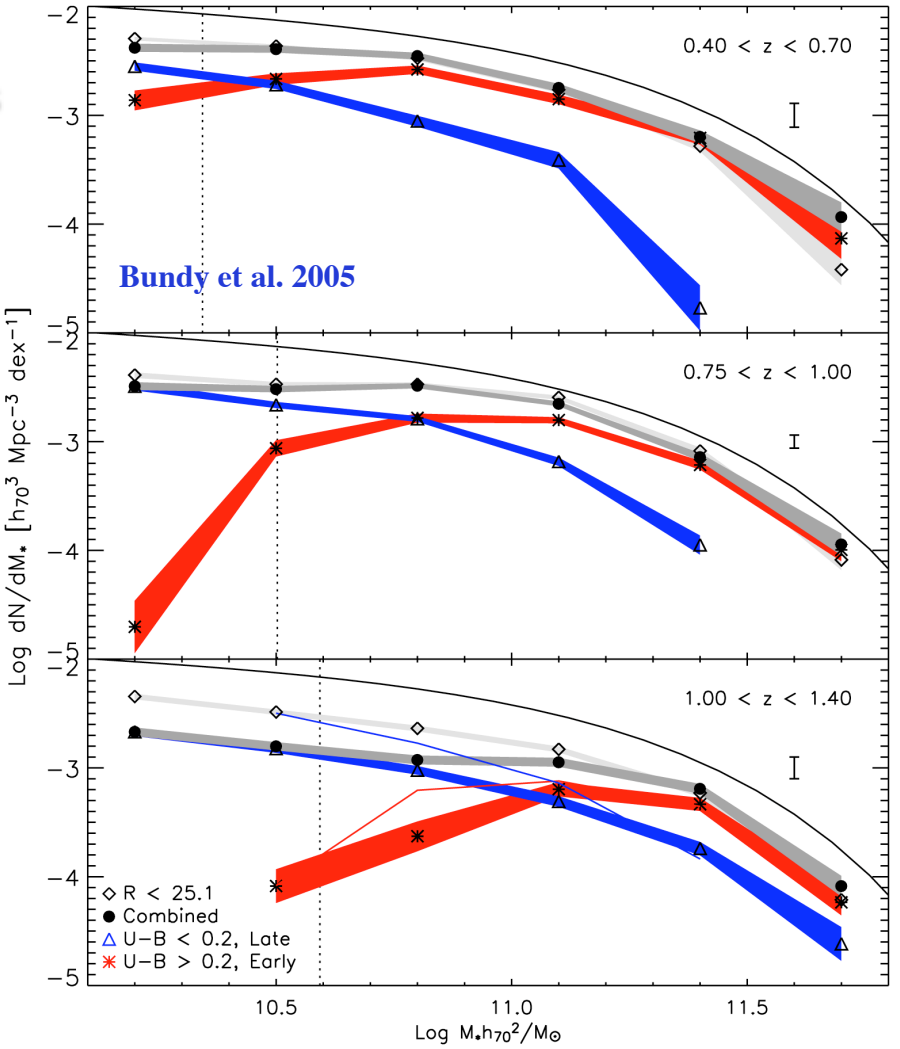
Lars Hernquist, TJ Cox, Brant Robertson, Volker Springel,
Paul Martini, Tiziana Di Matteo, Yuexing Li, Sukanya Chakrabarti

We've measured the cosmological parameters to 10% or better, so…

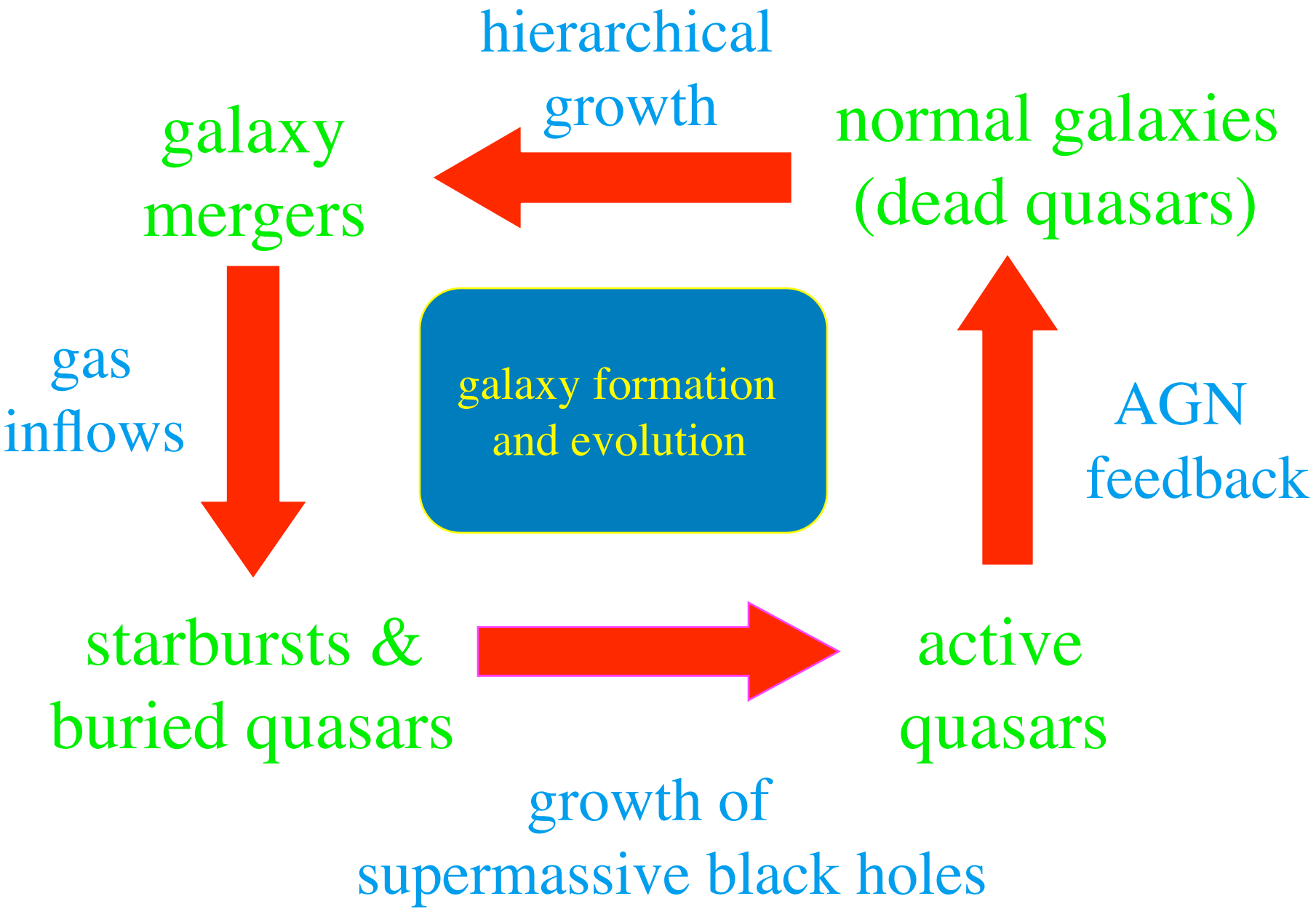
What don't we understand?

- Galaxy Formation!
  - **Bimodality**
  - Mergers? Interactions? Harassment? Secular Evolution?
  - **"Cosmic Downsizing"**
  - Dissipationless vs. Gas-Rich Mergers
  - Assembly vs. Formation Time
- Quasar Formation/Triggering
- How are the two connected?





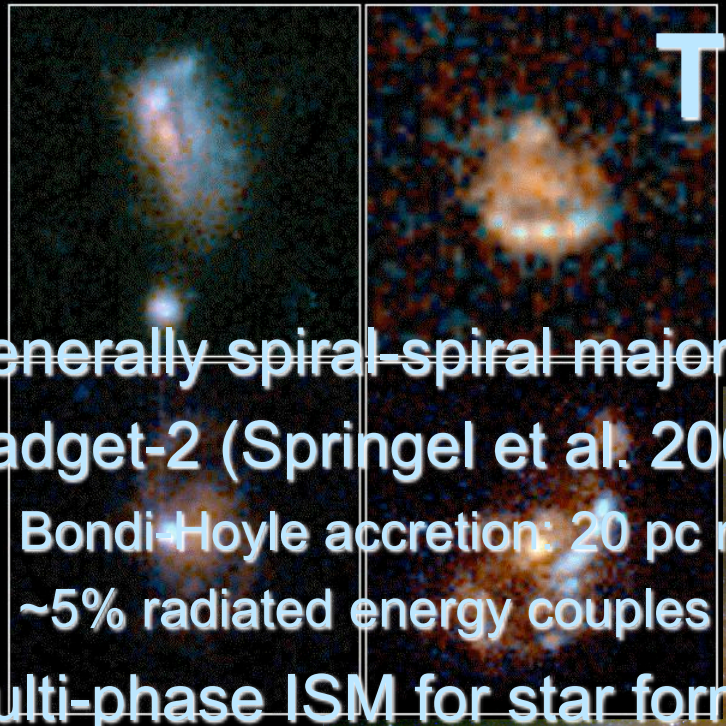
Cosmic Cycle



The Big Picture

- Are the statistics of quasars/BHs/mergers/spheroids/starbursts/etc. self-consistent?
  - Much work has gone into individual properties (e.g. Sanders et al., Bahcall et al. Rothberg & Joseph, Gebhardt et al., Kauffmann et al., and many others)
- What is the role and importance of AGN feedback?
  - What are the important physics?: light curves, lifetimes, and obscuration
- What can we learn about red galaxies and mergers from quasars? (and vice versa)
- Need detailed simulations
  - Torquing (strongly non-symmetric), star formation, gas cooling, supernova feedback, BH accretion, BH feedback, shocks, metal enrichment
  - Huge range of initial conditions, different physics, etc.

NASA, H. Ford (JHU), G. Illingworth (USCS/LO), M. Clampin (STScI), G. Hartig (STScI), and the ACS Science Team



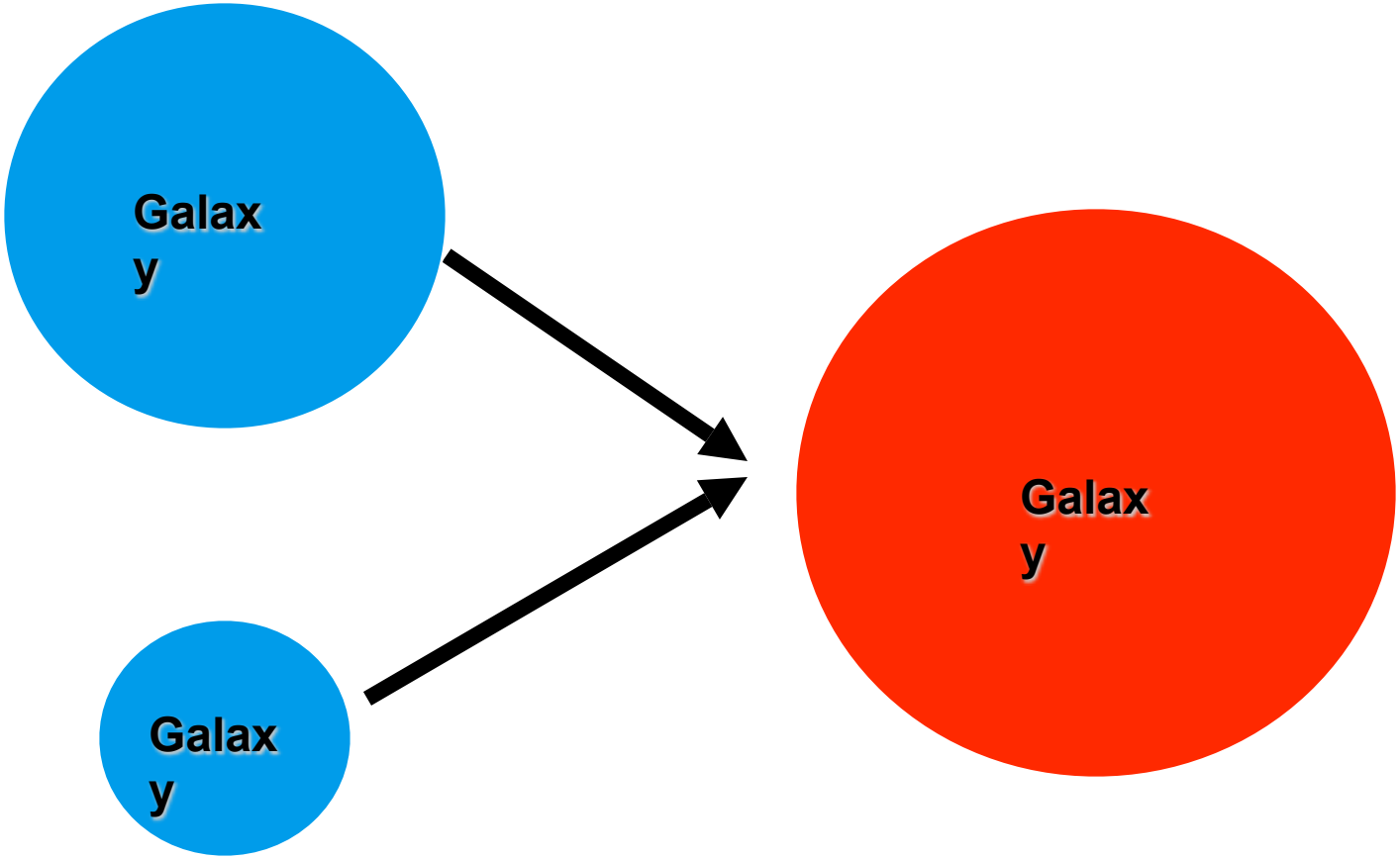
The Simulations

- Generally spiral-spiral major mergers
- Gadget-2 (Springel et al. 2005)
  - Bondi-Hoyle accretion: 20 pc resolution
  - ~5% radiated energy couples to local ISM
- Multi-phase ISM for star formation (Springel & Hernquist 2003)
  - Variable equation of state: increase/decrease thermal impact of SF feedback
  - +/- Stellar winds
- Several hundred simulations (Robertson et al. 2005, Cox 2004):
  - Progenitor masses, velocities, orbits, orientations, redshifts, gas fractions, ISM EOS, mass ratios, feedback coupling, bulge fractions, gas physics

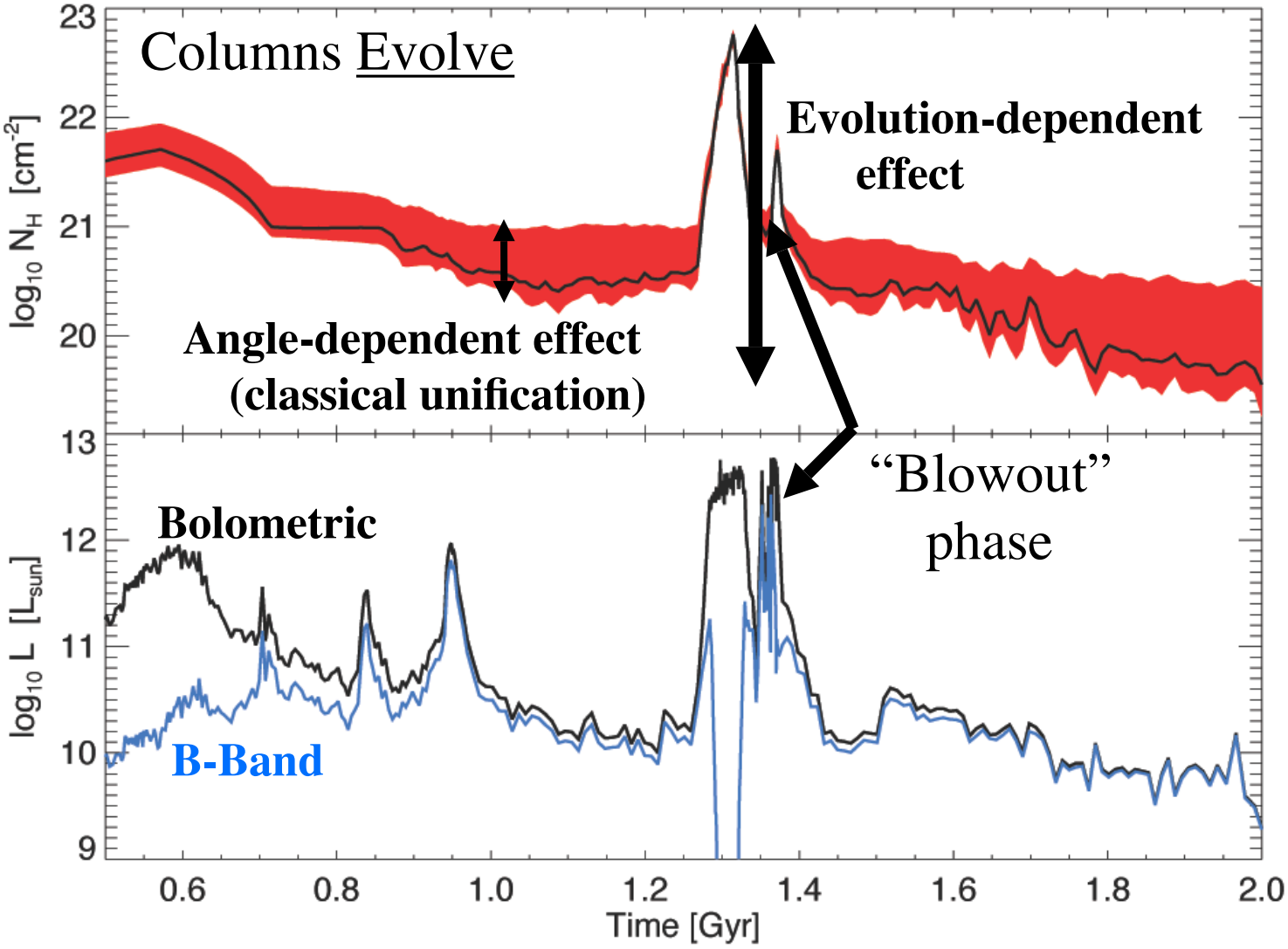

T = 0 Myr
Gas

The Semi-Analytic Approach

(e.g., Kauffmann & Haehnelt; Cole et al.; Somerville et al.; Volonteri et al; Wyithe & Loeb; Granato et al.; Baugh et al.; Croton et al.; & others)



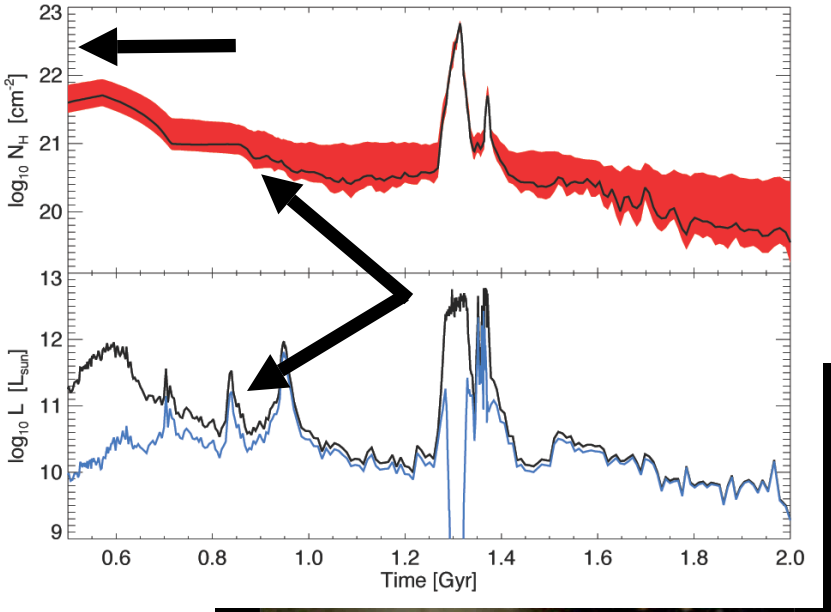
Quasar Lightcurves:



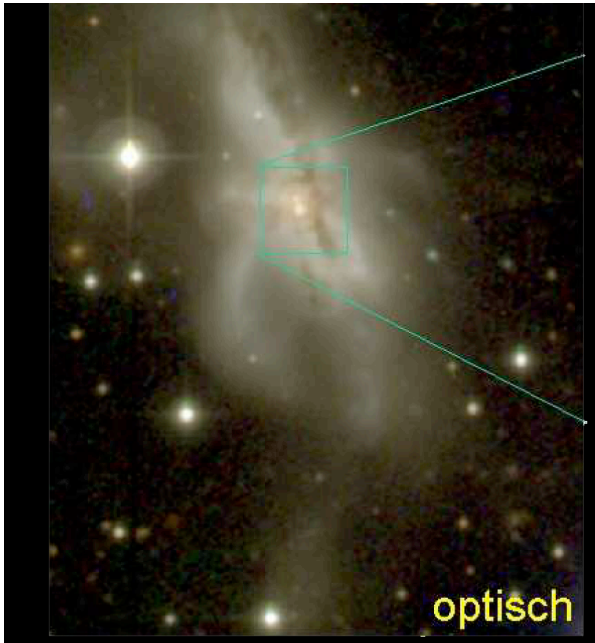
- Multi-phase ISM decomposition: gas+dust+metal columns

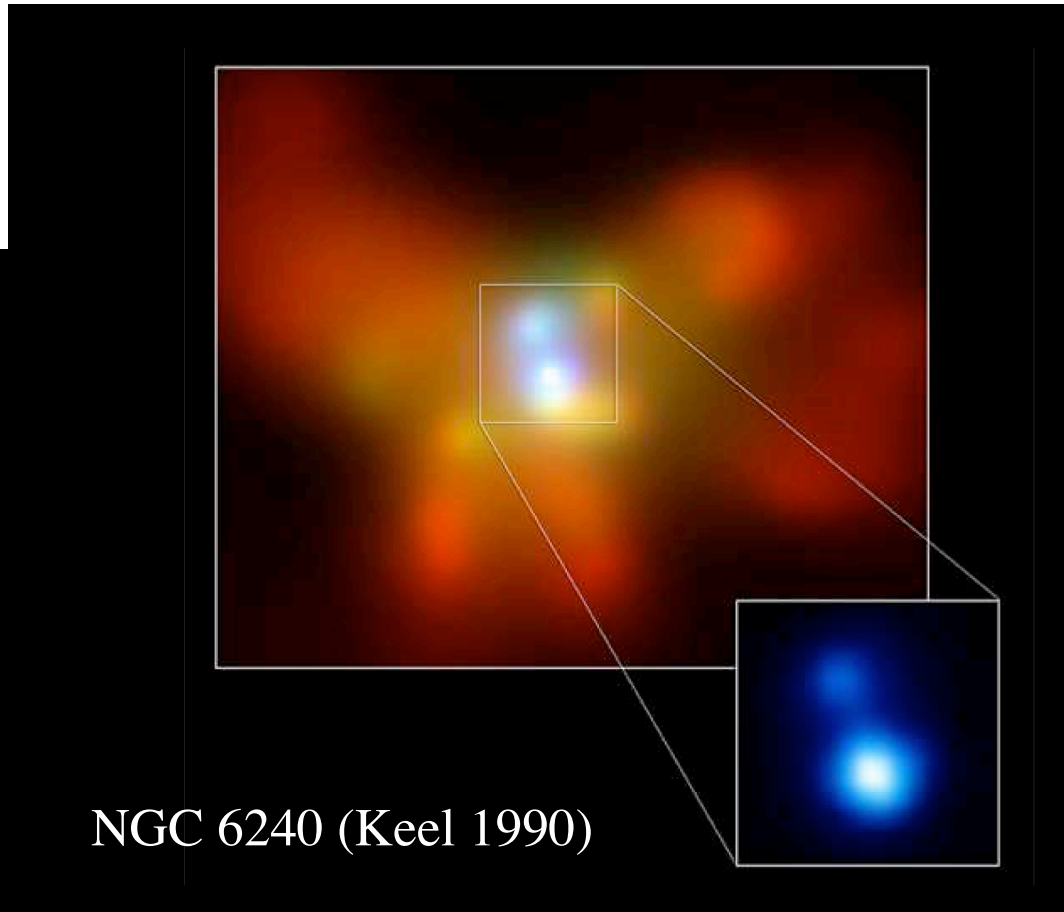
Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

GAS DENSITIES, COLUMNS, STAR FORMATION RATES CHANGE RAPIDLY



- Obscured growth associated w. starburst
  (e.g. Sanders; Fabian; Alexander,Chapman,Borys et al.)

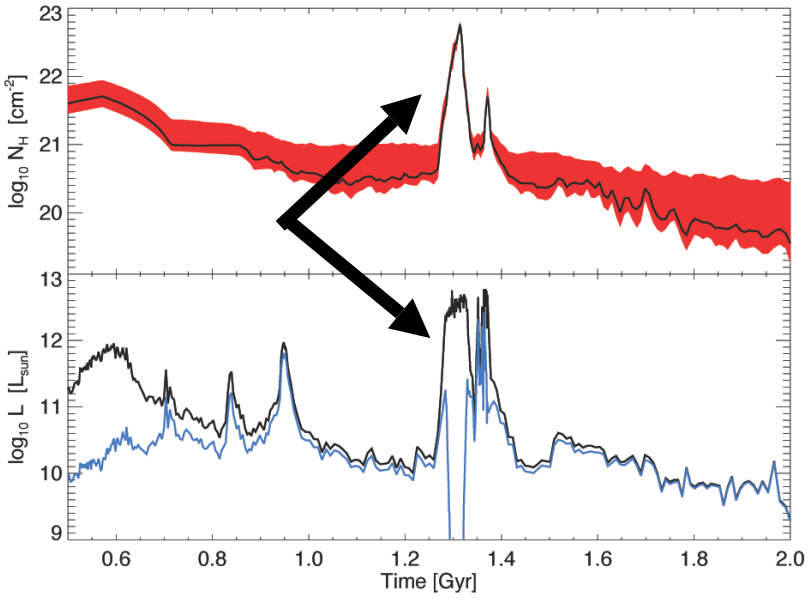


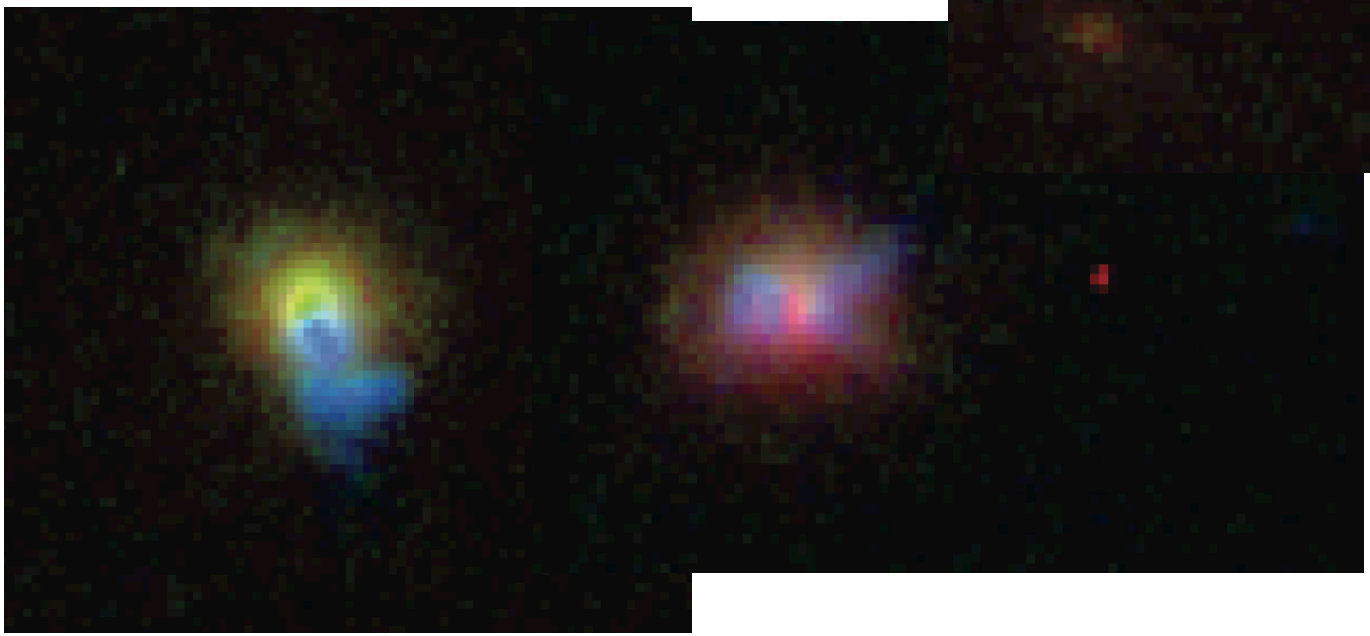


NGC 6240 (Keel 1990)

Columns Evolve Heavily, Even In Declining Starburst

LARGE SCALE GAS STRUCTURES IMPORTANT

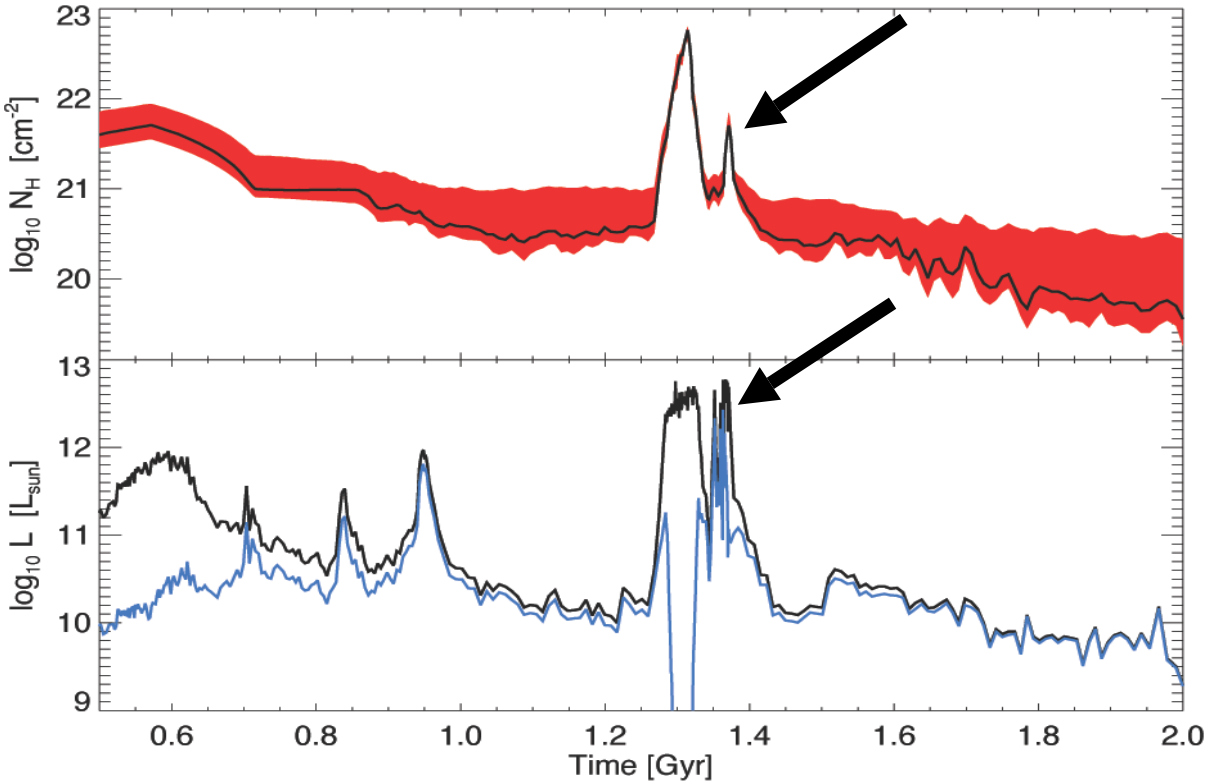




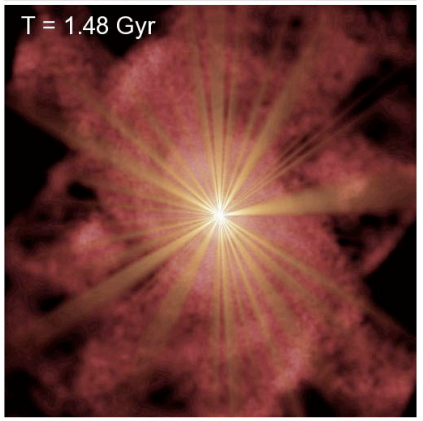
- Bright, Type II or reddened quasars with large (galaxy-scale) obscuration **(Zakamska et al., Gregg et al., Urrutia et al.)**

Feedback Is Necessary to Reveal the Brightest Quasars

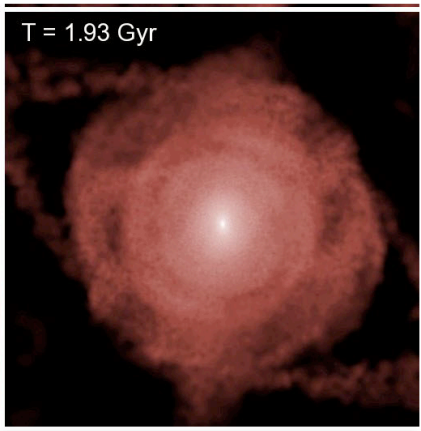
GAS IS HEATED AND EXPELLED IN BLOWOUT, REVEALING A BRIEF, BRIGHT QUASAR



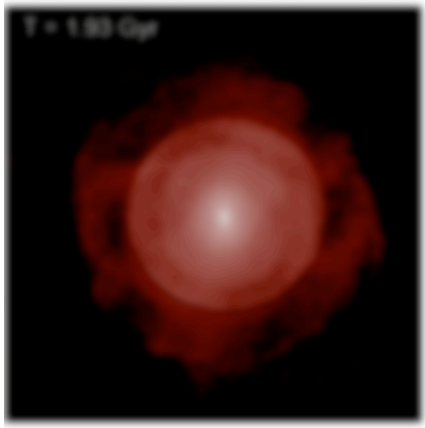
QSO = 1000xHost



QSO = Host



QSO = 0.1xHost

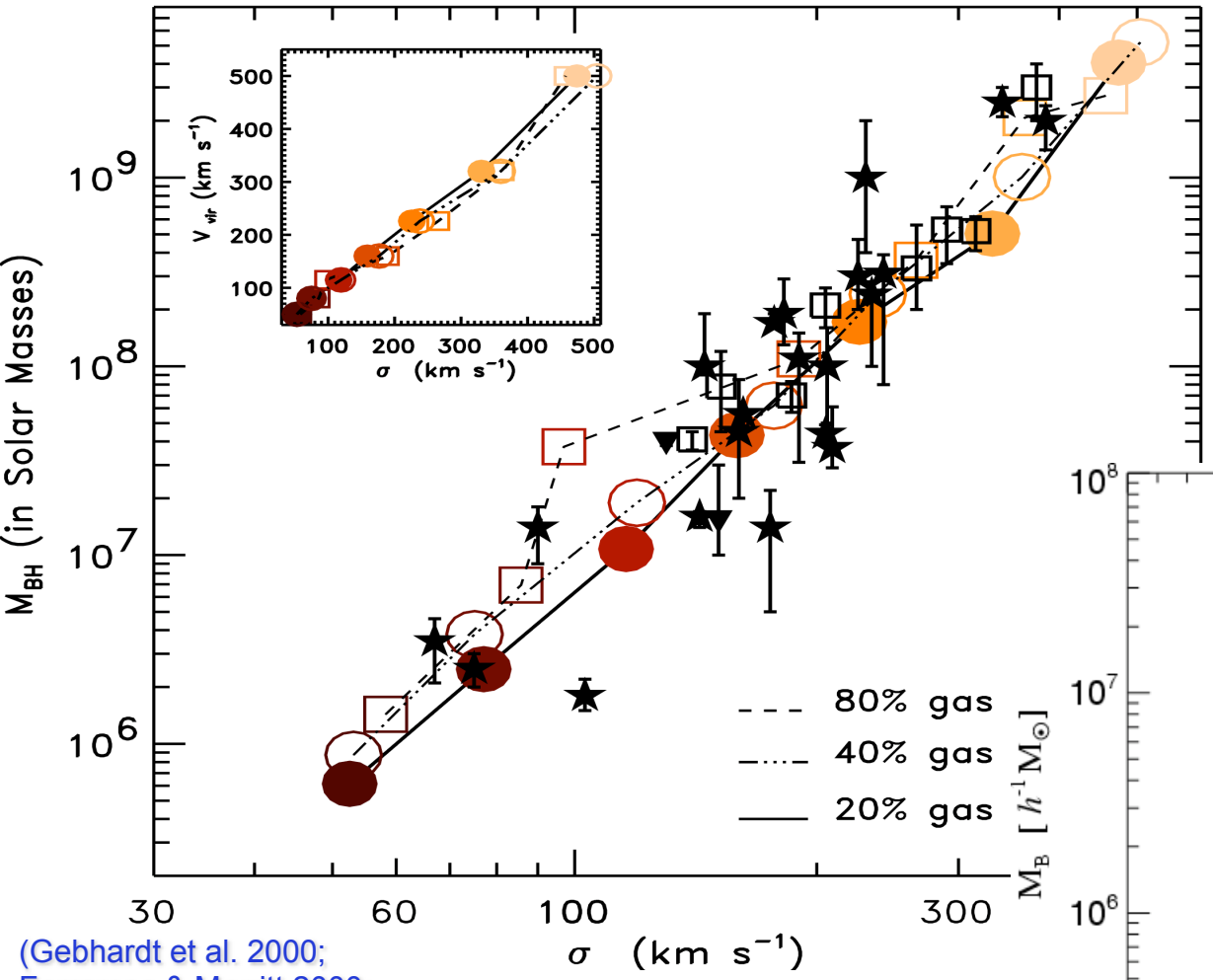


- Evolutionary Processes : NOT necessarily physical to "extrapolate" local, quiescent objects
- Eddington ratios vs. host properties (size, luminosity, morphology, redshift)
- Active BH mass functions

Hopkins et al. 2005e

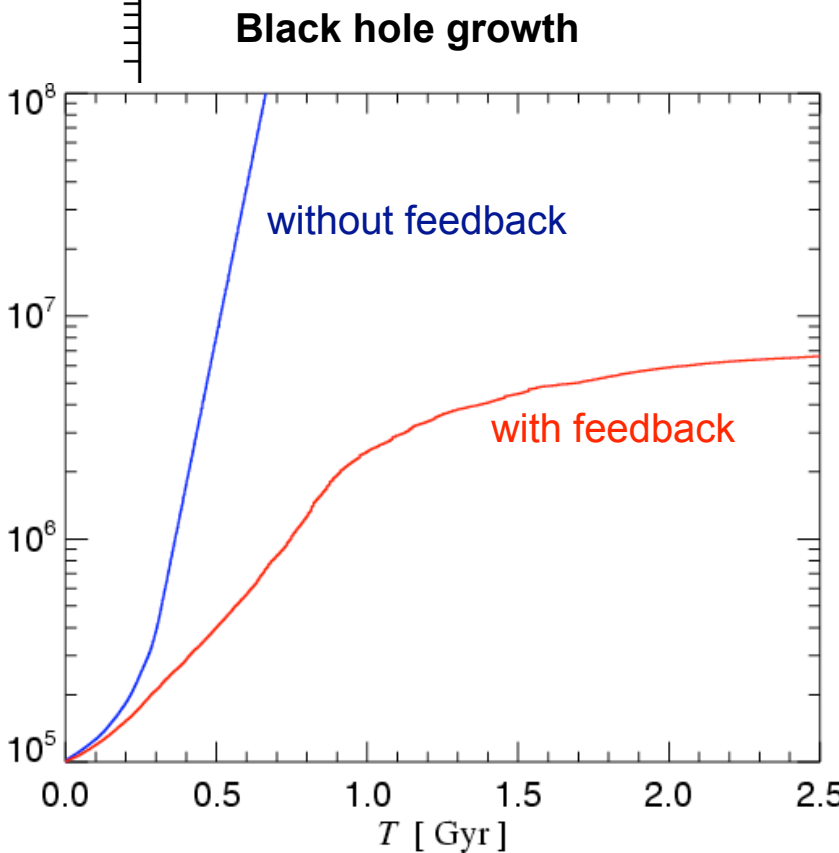
Feedback-driven "Blowout" Gives M-sigma Relation

PREVENTS RUNAWAY BLACK HOLE GROWTH



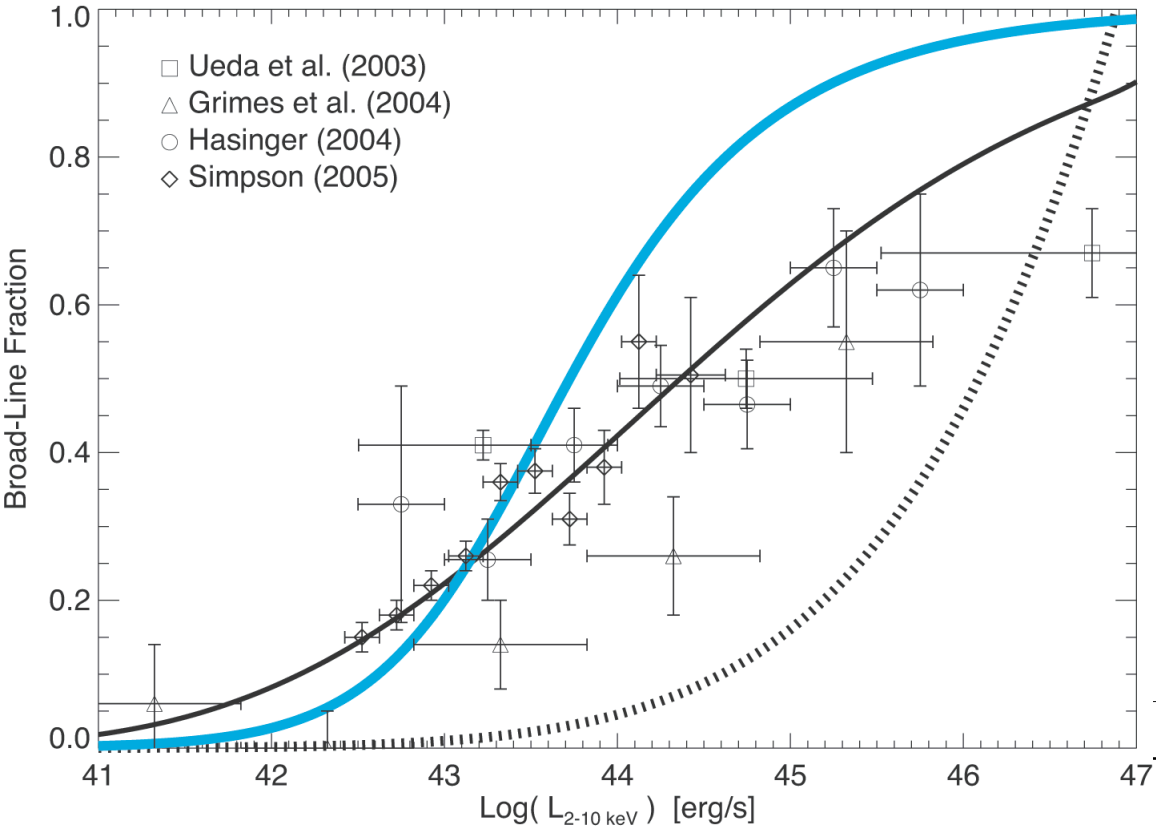
(Gebhardt et al. 2000;
Ferrarese & Merritt 2000;
Tremaine et al. 2002)

Di Matteo et al. 2005



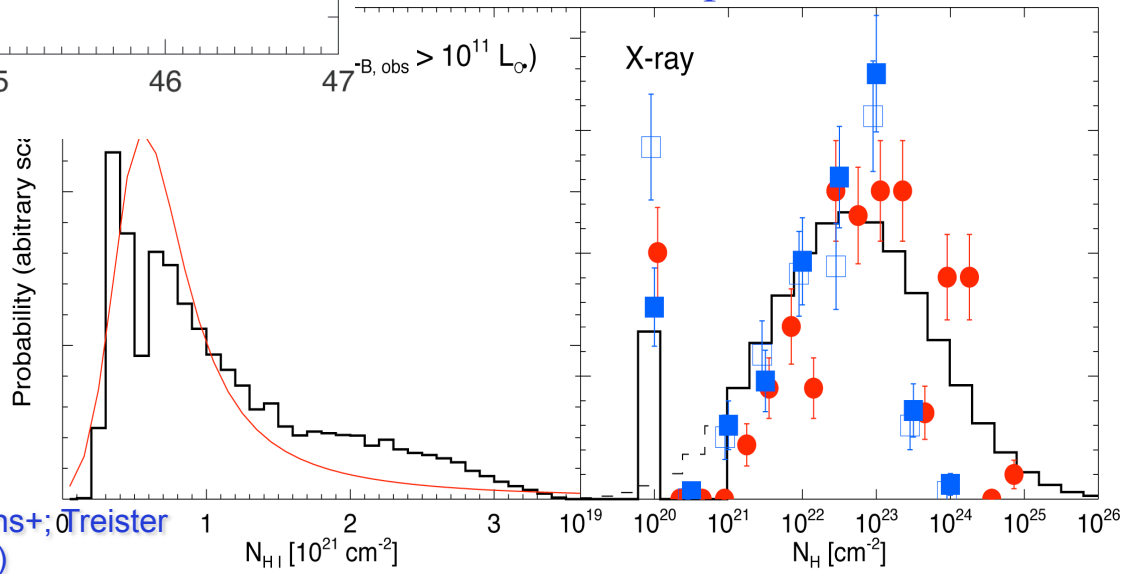
Springel et al. 2004

Other Tests of How Host & Quasar Impact one Another



- At Higher Luminosities, More Quasars are Near-Peak (i.e. Blowout)
  - Different relation to host than "Receding Torus"
  - Evolution with Redshift

Hopkins et al. 2005e

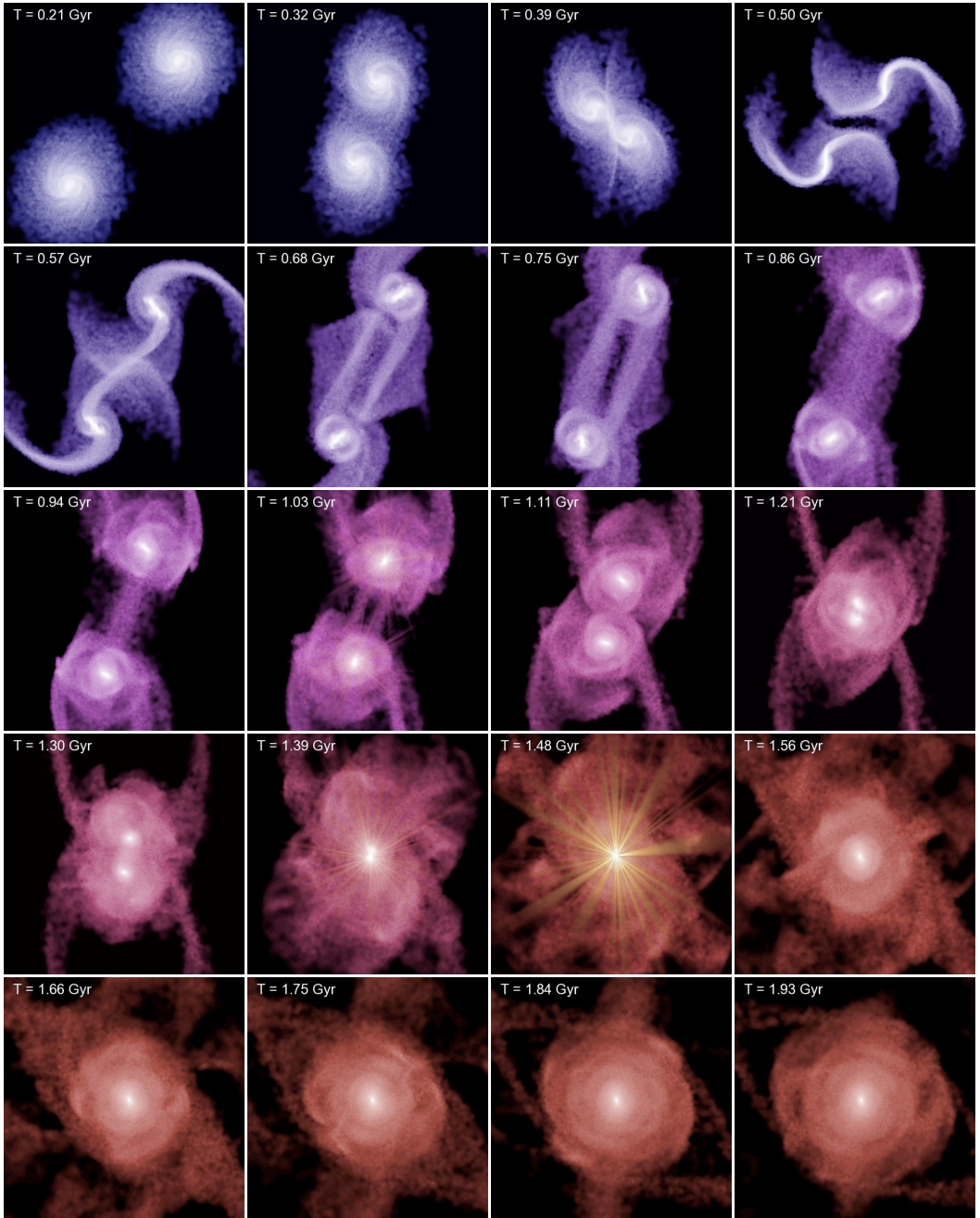


- Combined: Predict Columns and Obscured Fractions
  - X-ray Background

(obs: Hopkins+; Treister +; Mainieri+)

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME



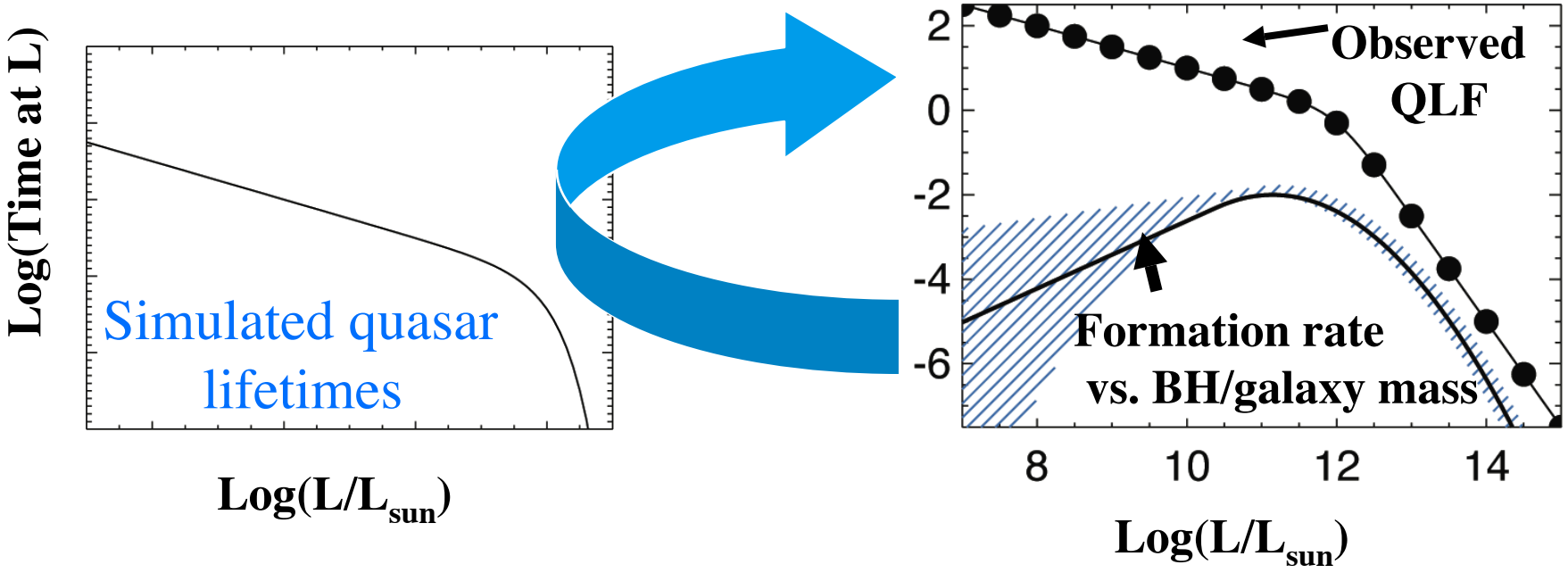
- Simulation: Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)
- "Quasar Lifetime" : a conditional, luminosity-dependent distribution

Hopkins et al. 2005e

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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

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

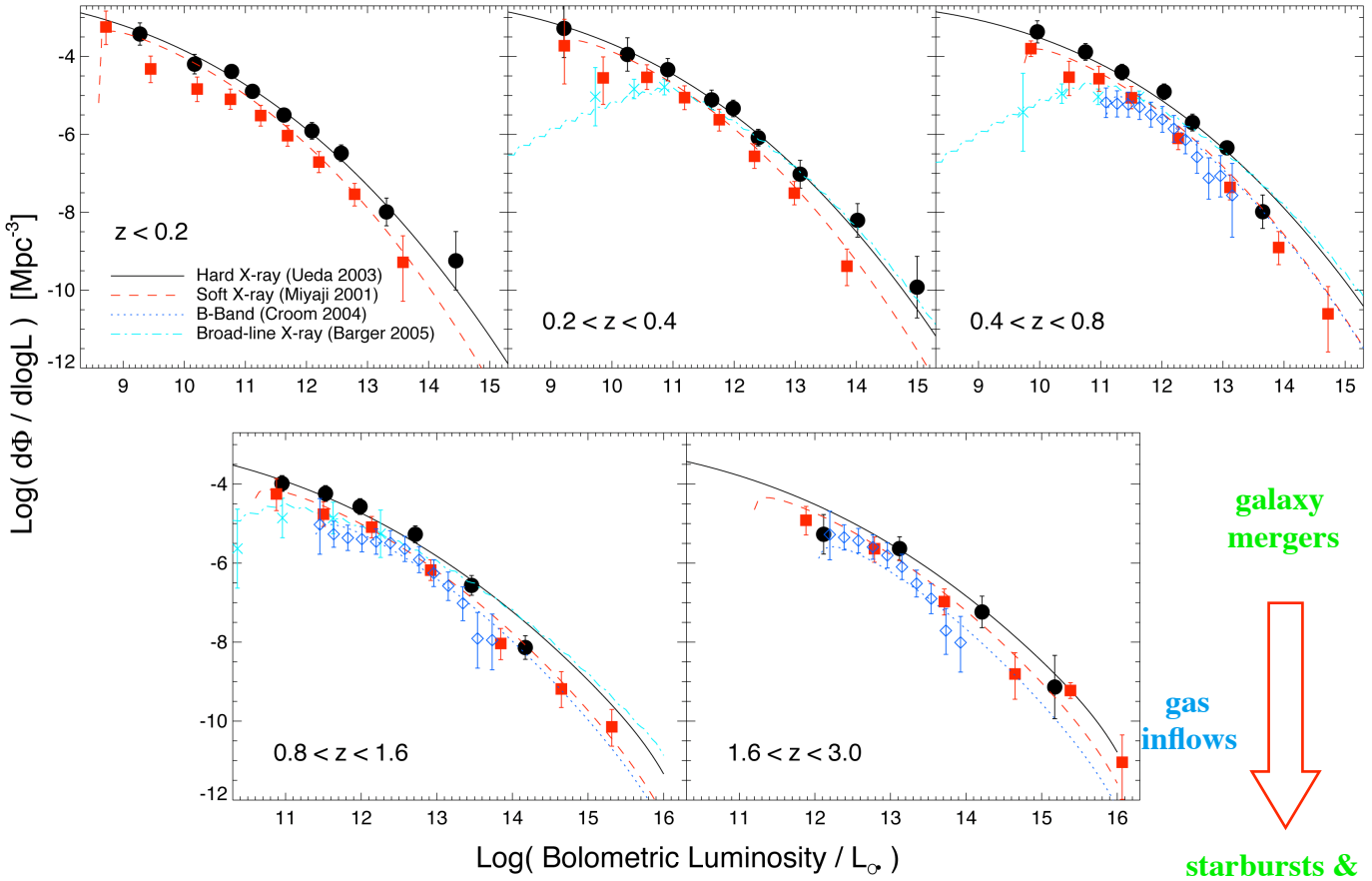


- Feedback-regulated lifetime drives a given QSO to lower L after blowout, and spends more time at low-L
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts
- In short: simulate every observed quasar & predict everything else!

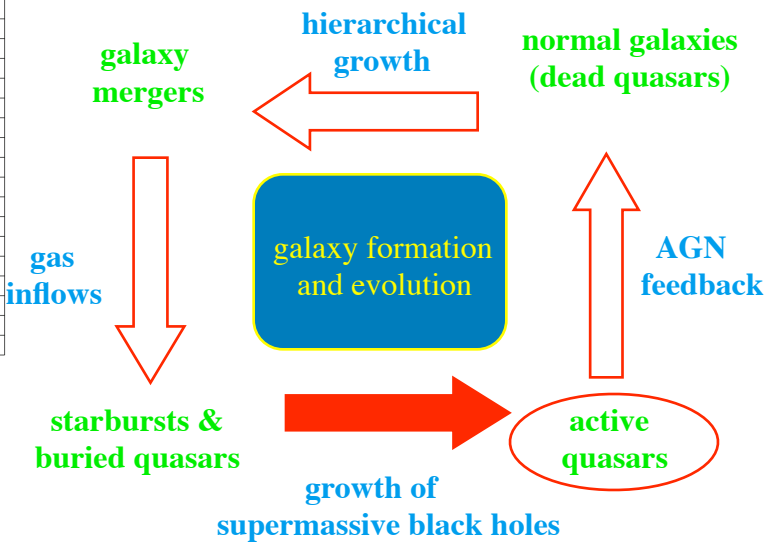
Given this Deconvolution, A Number of Predictions are Possible

THE QLF EMPIRICAL CONSTRAINT AT ONE FREQUENCY IS SUFFICIENT TO FIX THE MODEL

- Comparison with Observed QLFs:
  - hard & soft X-ray, B-band, UV, near & mid-IR
  - Type I & II; reddening & obscuration vs. luminosity
  - Z = 0 - 6



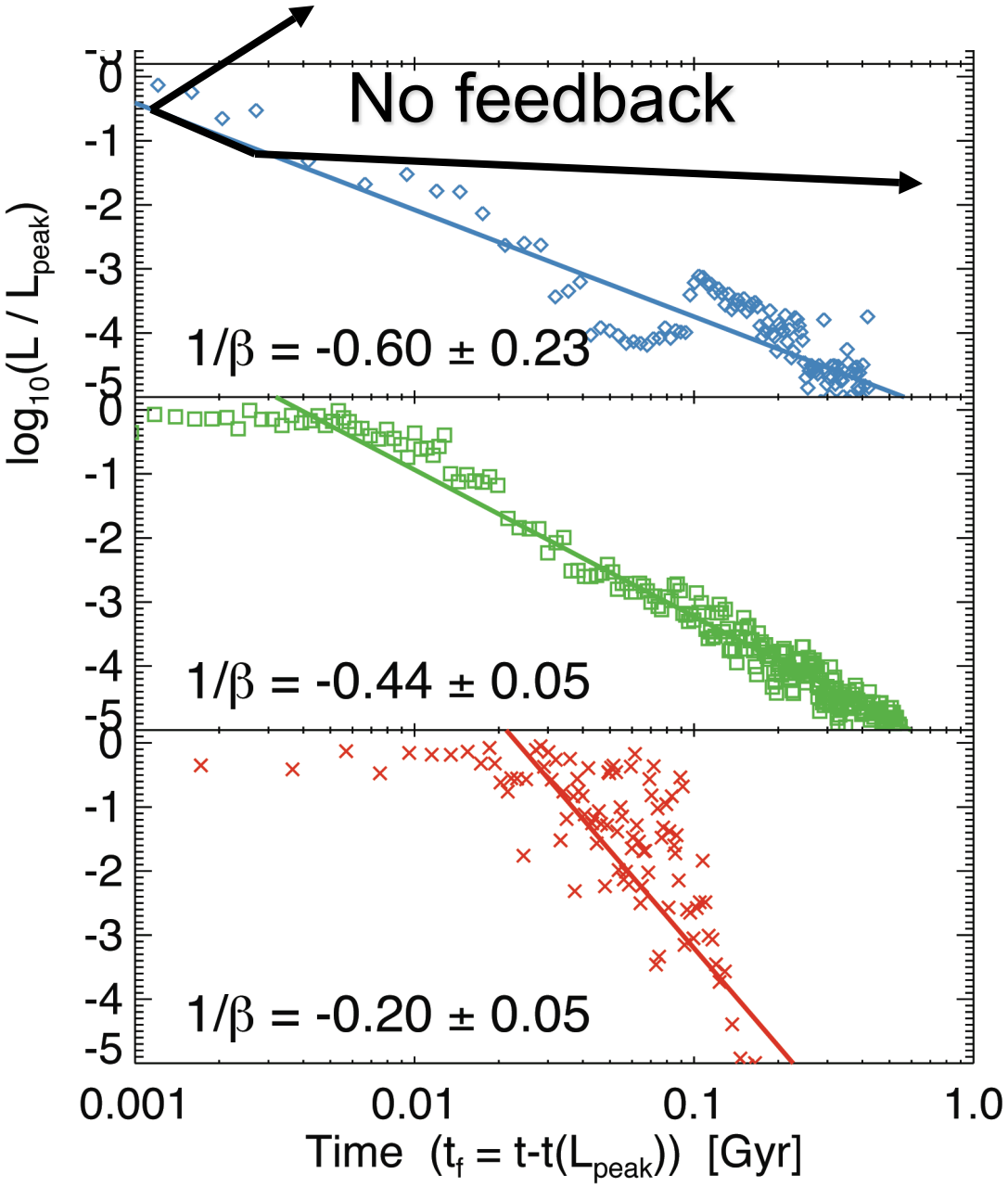
(Ueda+; Richards+; Croom+; Barger+; Hasinger+; Miyaji+; LaFranca+; Brown+; Matute+; Nandra+; Cristiani+; Hunt+; Wolf+; Fan+; & others)



Hopkins et al. 2005e

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
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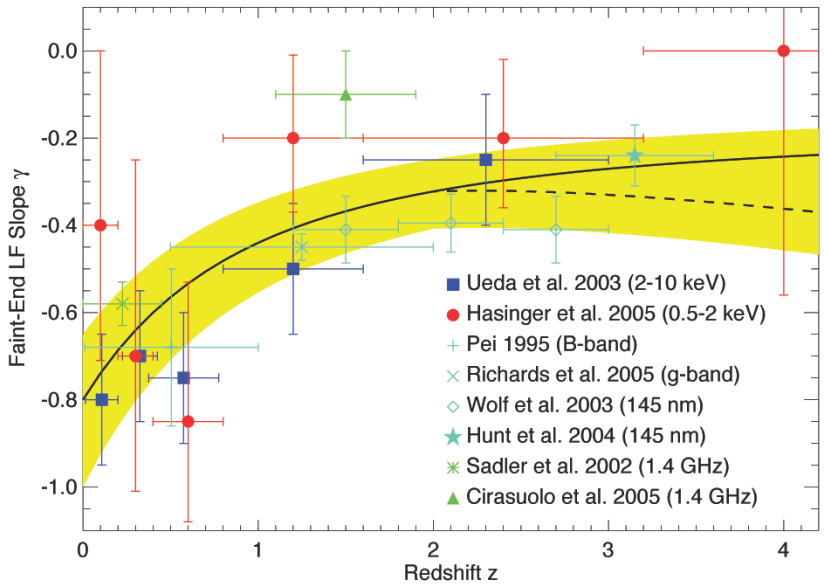
  - "Plateau" as run out of gas but can't expel it (extended step function)
- "Quasar Lifetime" : a conditional, luminosity-dependent distribution

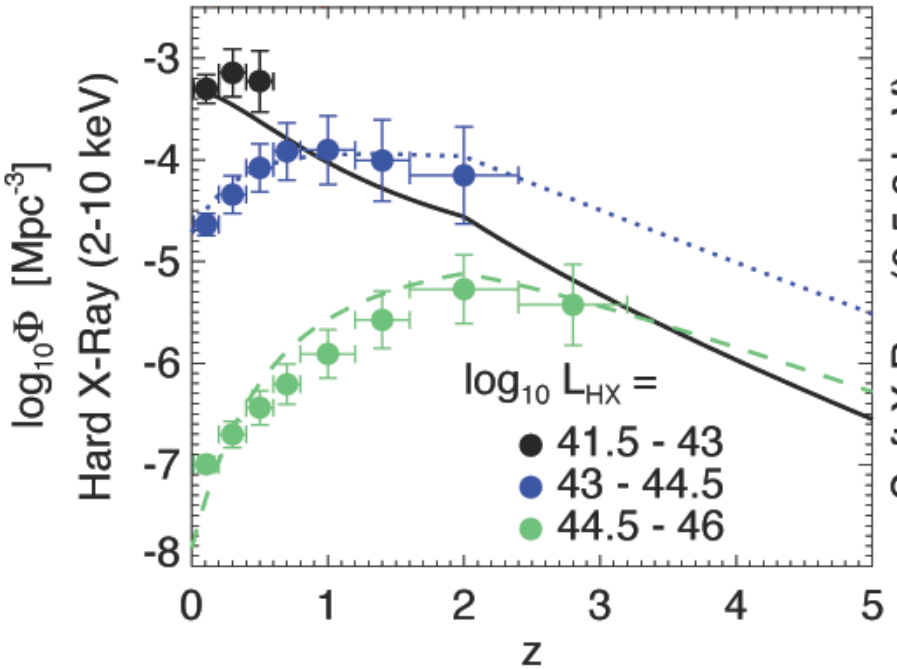
Hopkins et al. 2006a

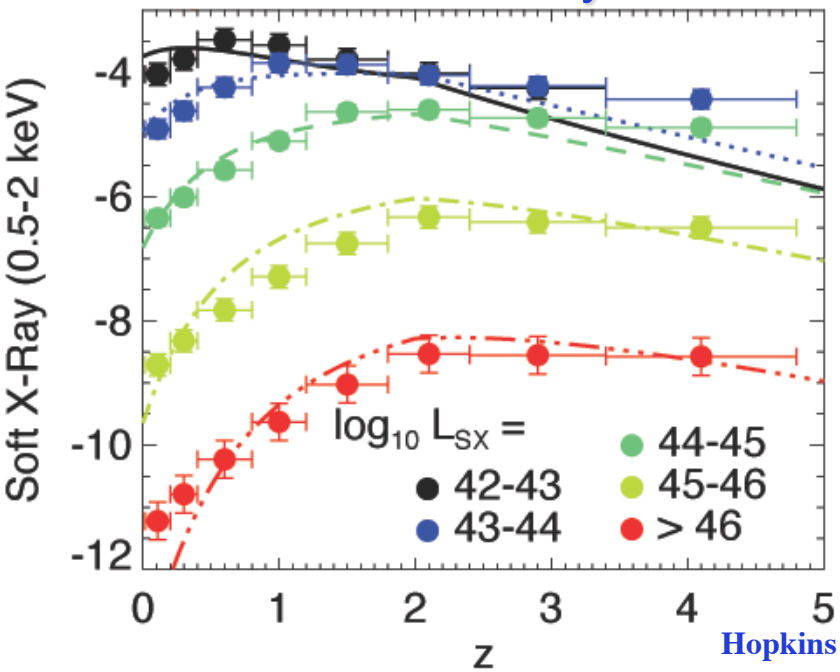
Faint-End Slope of QLF is Determined by Faint-End Quasar Lifetime

FAINT QSOs ARE DECAYING - LIFETIME DETERMINES HOW MANY SEEN



- Dependence on peak luminosity gives dependence on z
- Values inform feedback: e.g. steady wind vs. injection vs. steady "unfueled" disk
- Luminosity-dependent density evolution

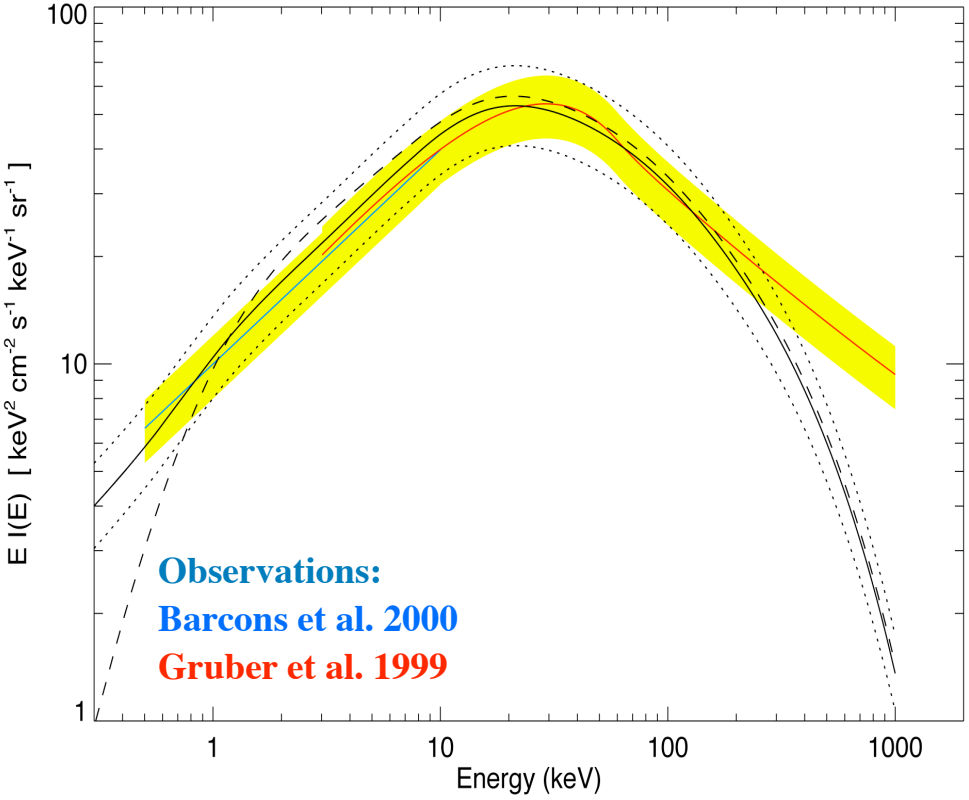




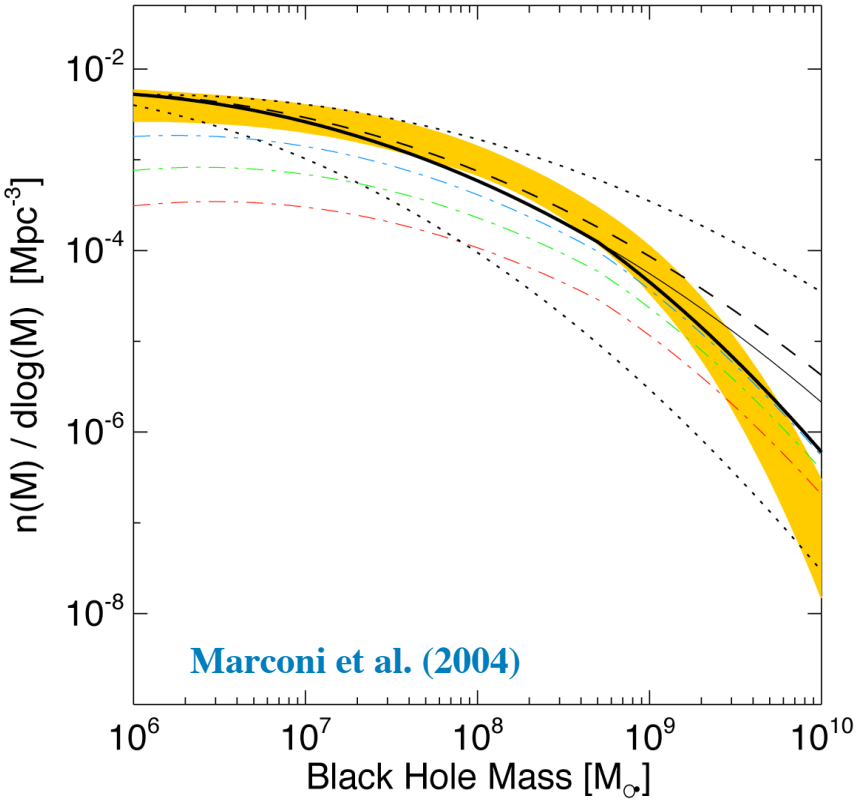
Hopkins et al. 2006a

Comparison with Observations:

- X-ray background spectrum



- Black hole mass functions

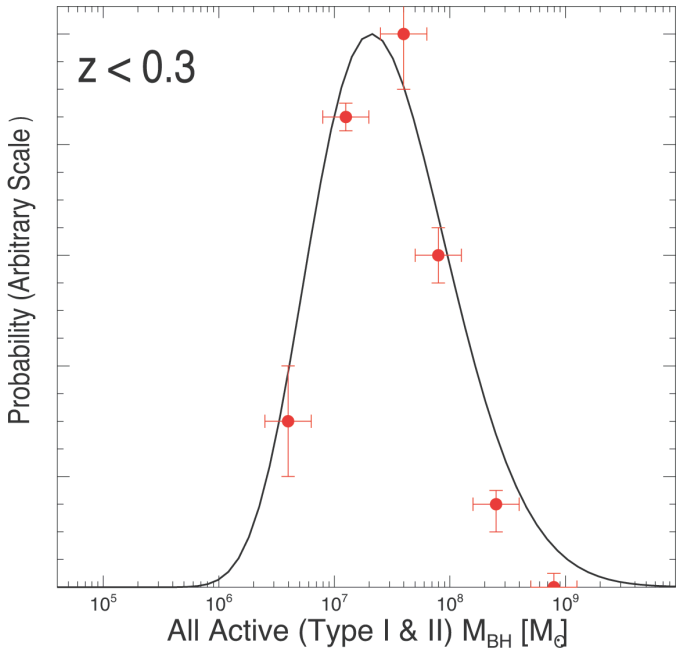


- No need to posit large missing/obscured population or strong obscured fraction evolution

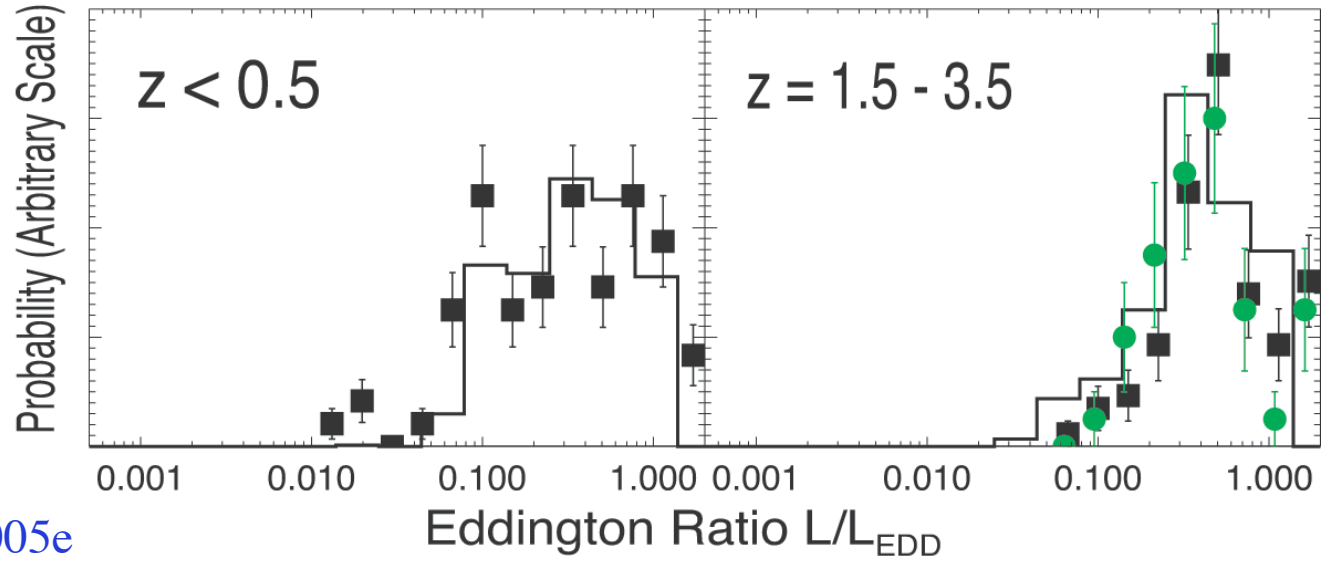
Hopkins et al. 2005e

Eddington Ratio Distributions and Active Black Hole Mass Functions

REFLECT TURNOVER IN FORMATION/MERGER RATE



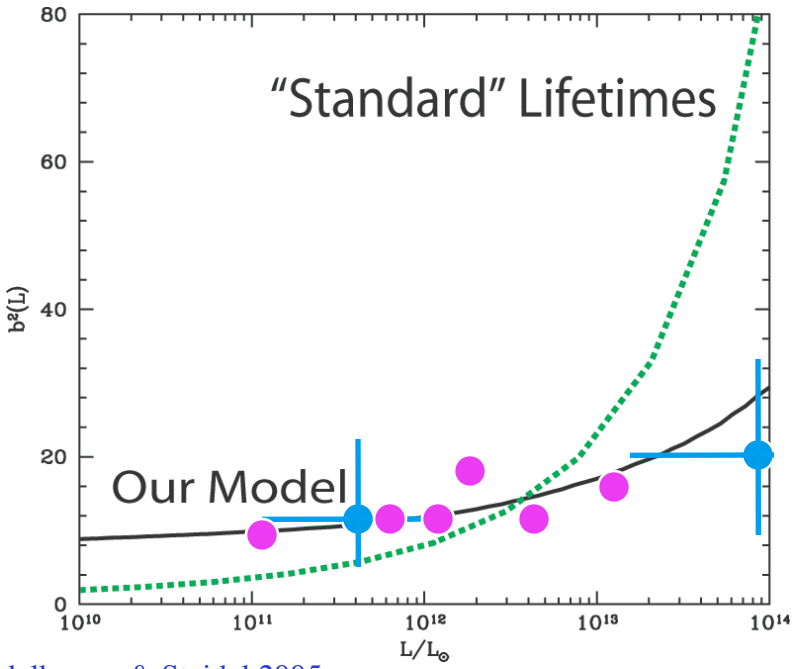
- QLF below break as Eddington ratio sequence
  - (Vestergaard+, Marchesini+, Woo & Urry, Hao+)
- Active BHMF similar in shape to formation rate
  - (Heckman+,Ho+, McLure & Dunlop)



Hopkins et al. 2005e

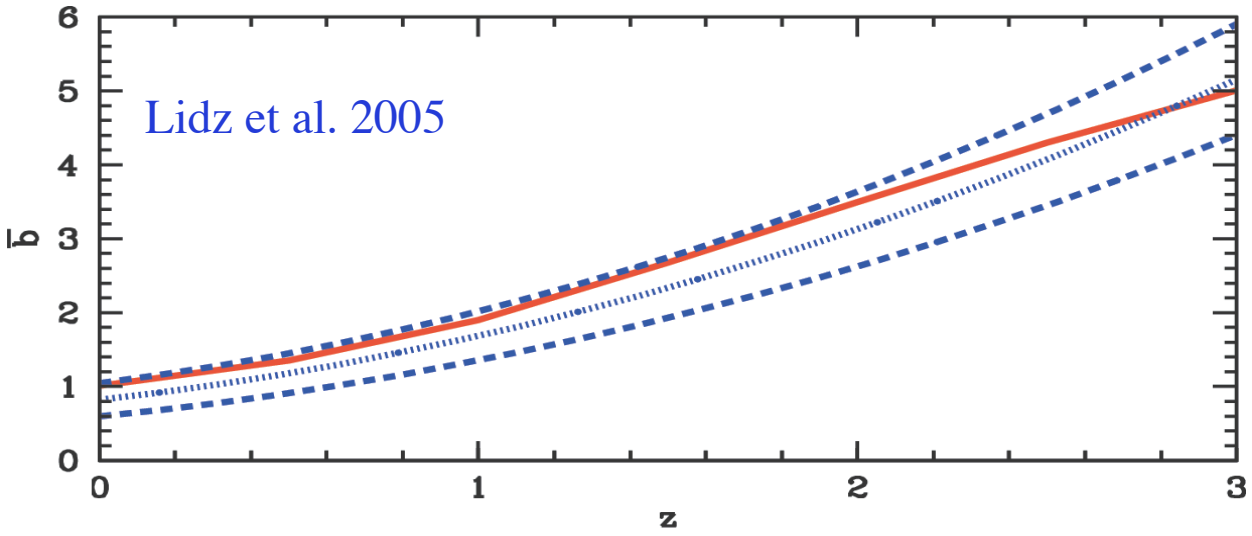
Quasar Clustering is a Strong Test of this Model

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



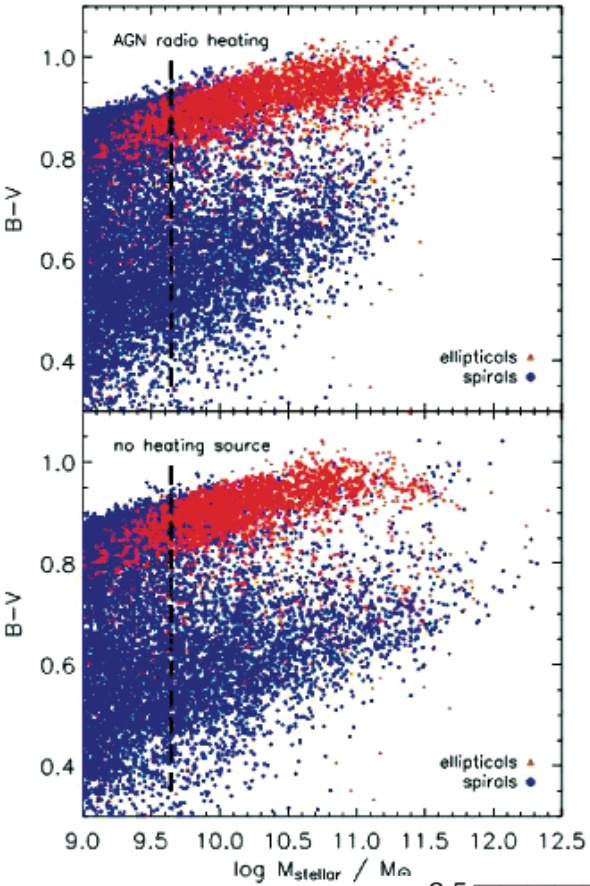
- Weak dependence of clustering on observed luminosity
  - (Croom et al. 2005, Adelberger & Steidel 2005, Myers et al. 2005)
- Characteristic halo mass
  $M \sim 10^{13} M_{sun}$

Adelberger & Steidel 2005,
Myers et al. 2005

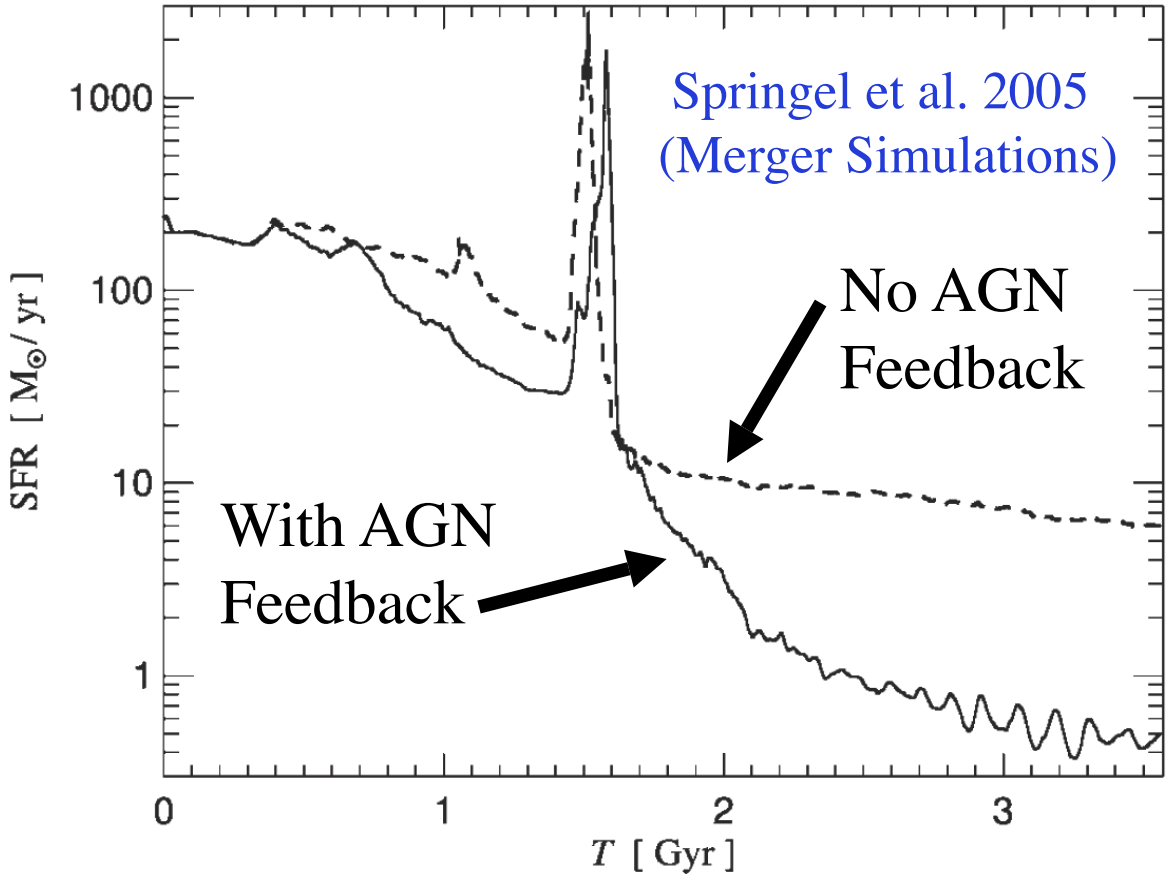


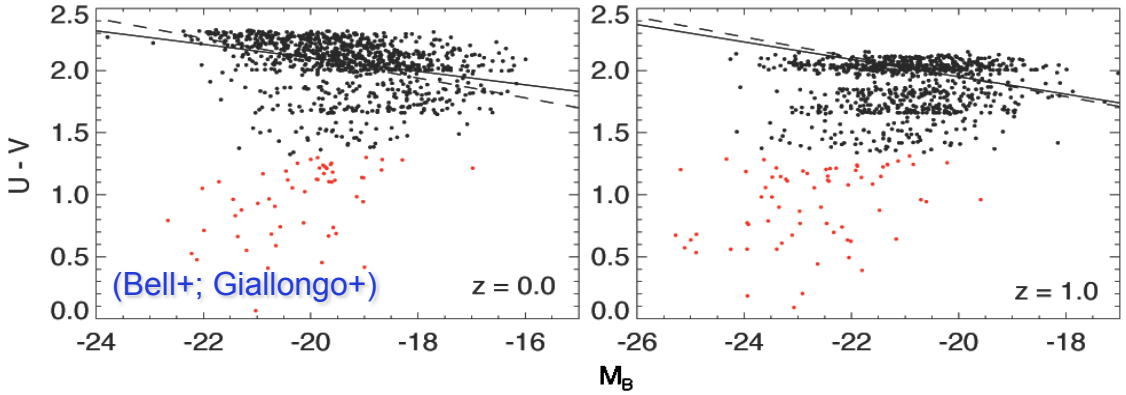
Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"



Croton et al. 2005 (SAMs)



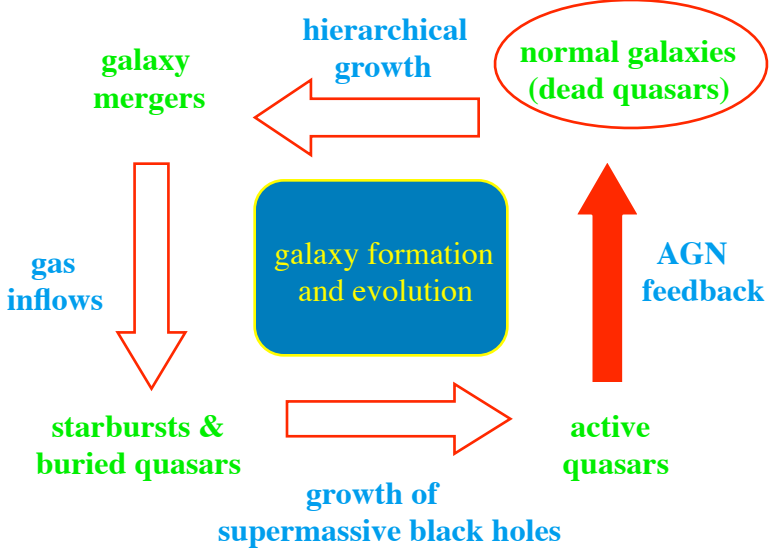


Hopkins et al. 2005f (Empirical+Sims)

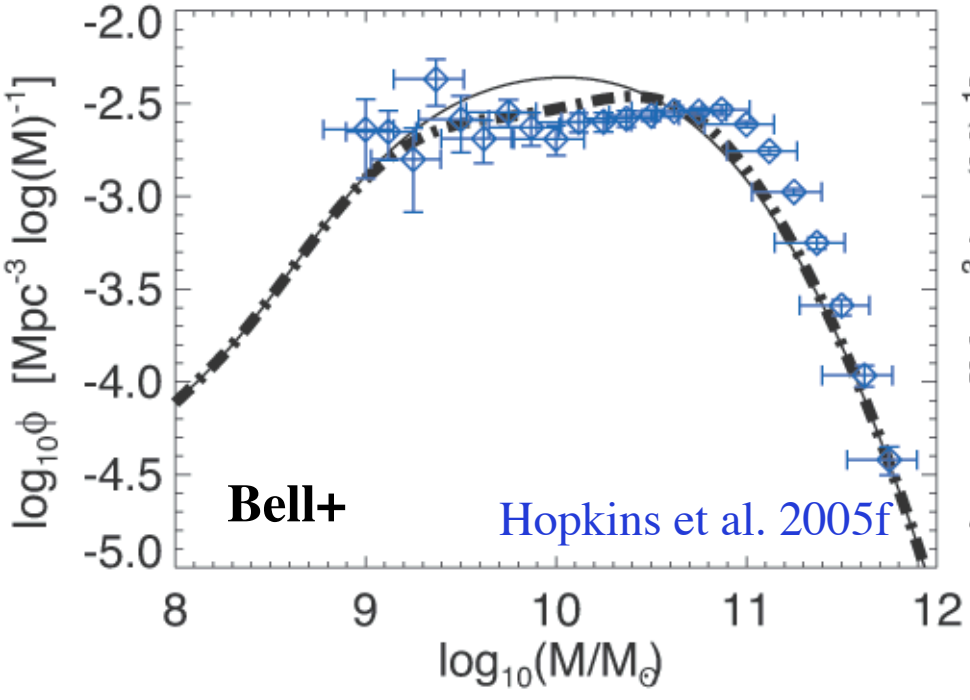
Every Quasar Has a Host

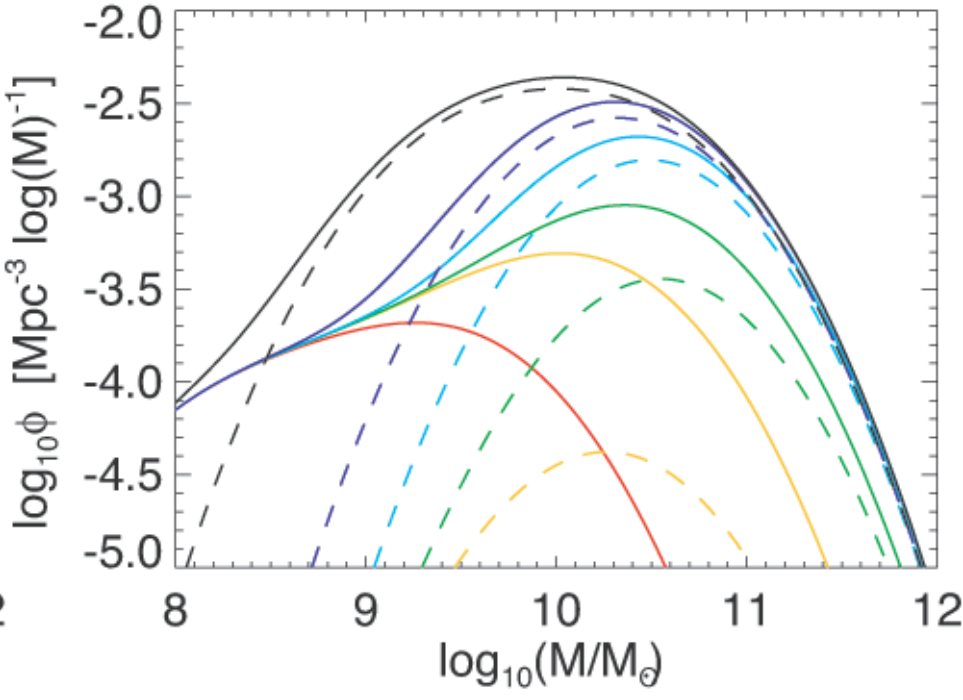
MAPPING BETWEEN MERGER DISTRIBUTIONS

- Spheroids + QSOs produced *together*
  - Hosts follow M-sigma (Di Matteo et al.), BH-bulge mass, Fundamental Plane (Robertson et al.), Kinematic/Morphological/Gas Properties (Cox et al.)
- Map each de-convolved *quasar* to

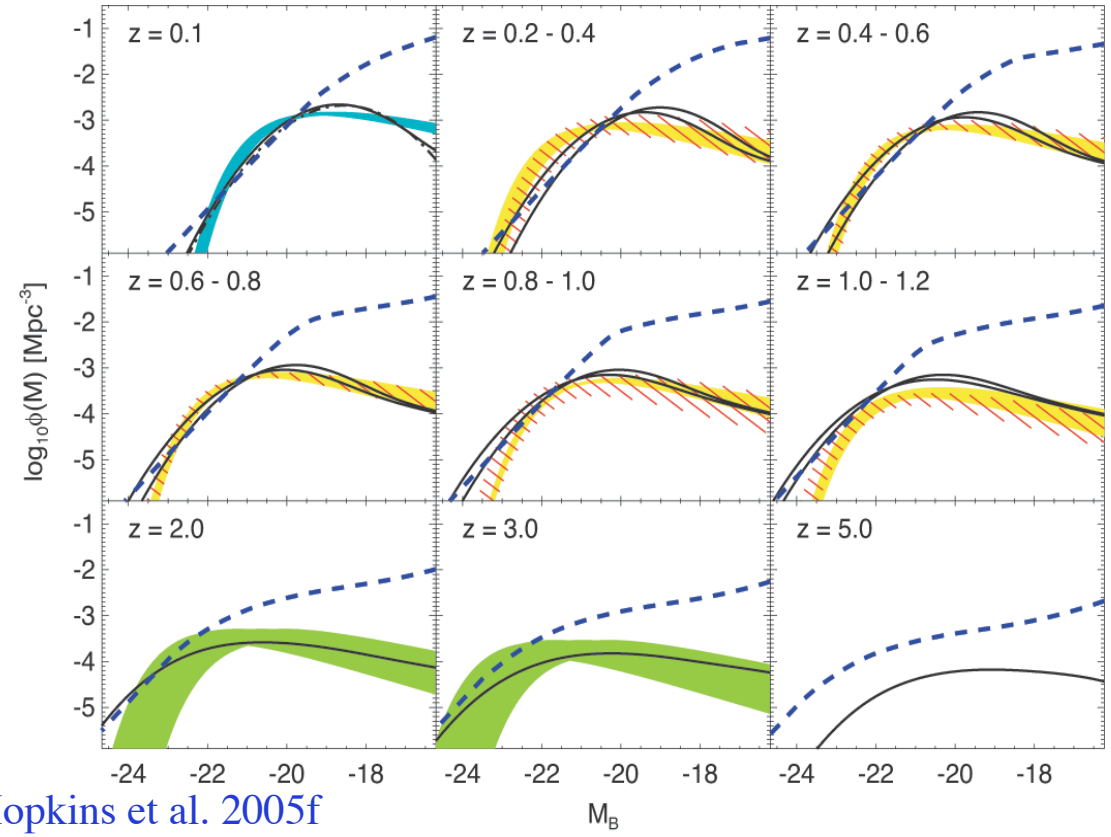


e.g. red galaxy mass function (dry mergers a small effect)



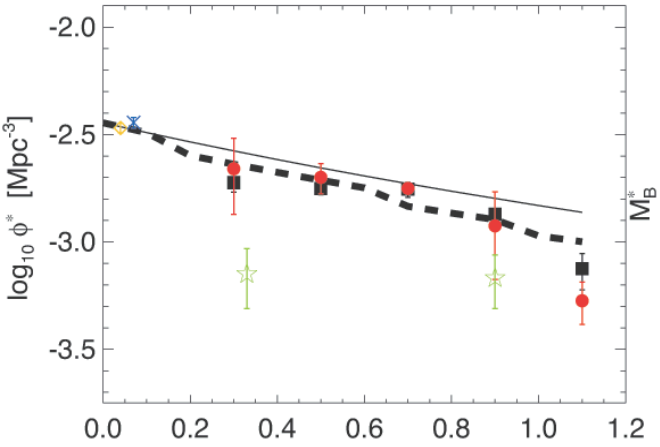


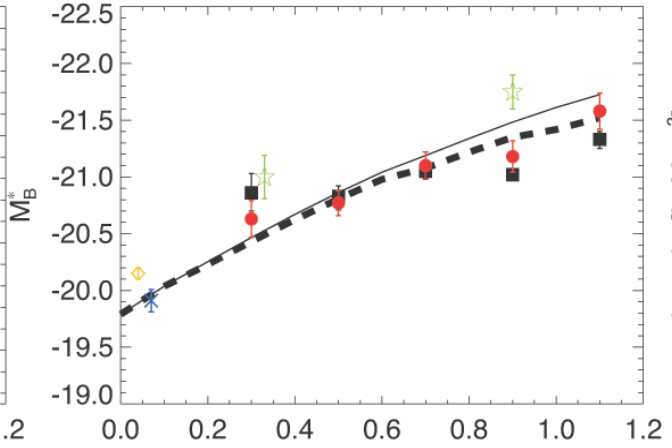
Luminosity Function (NUV,U,B,V,R,I,K; 0<z<6)

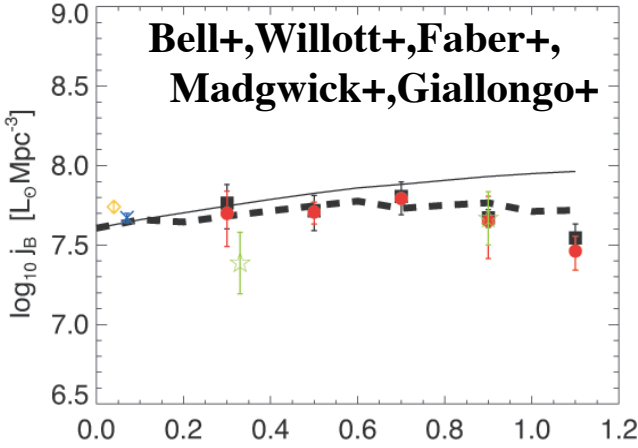


Hopkins et al. 2005f

- By z~1, significant post-merger but still reddening pop.
  - "Blue Spheroids" / E +A's

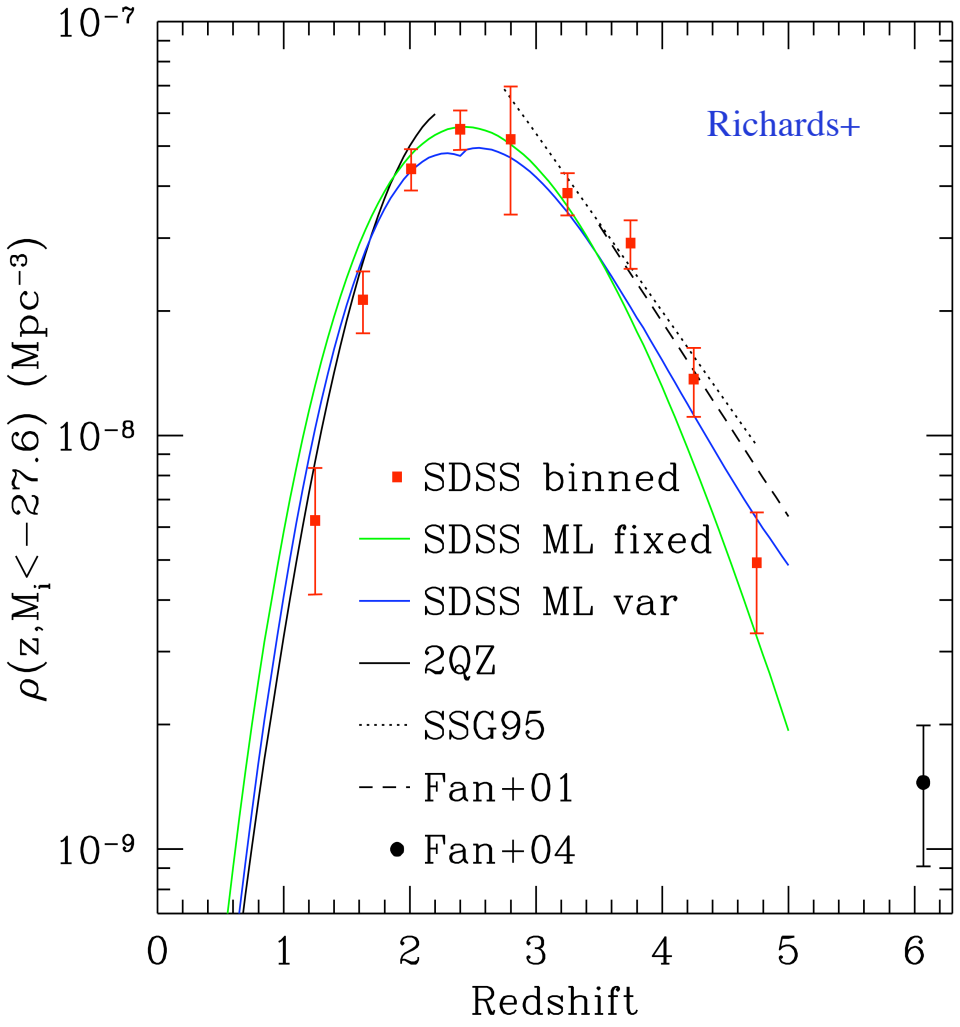


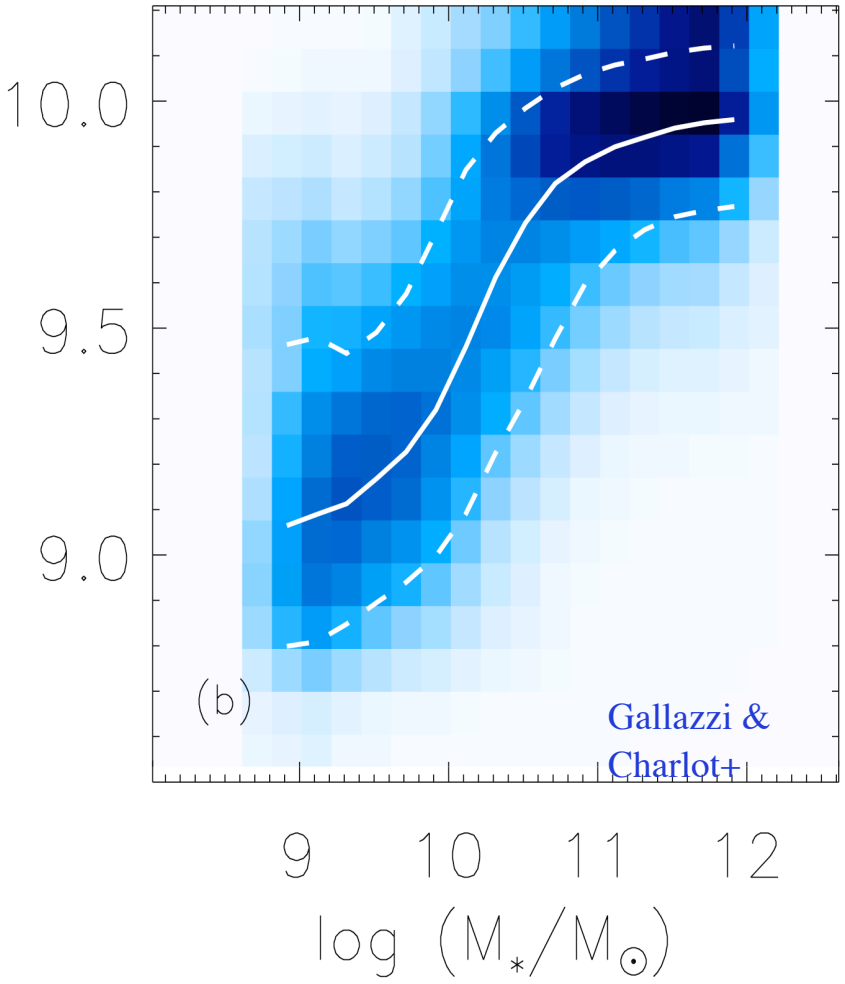




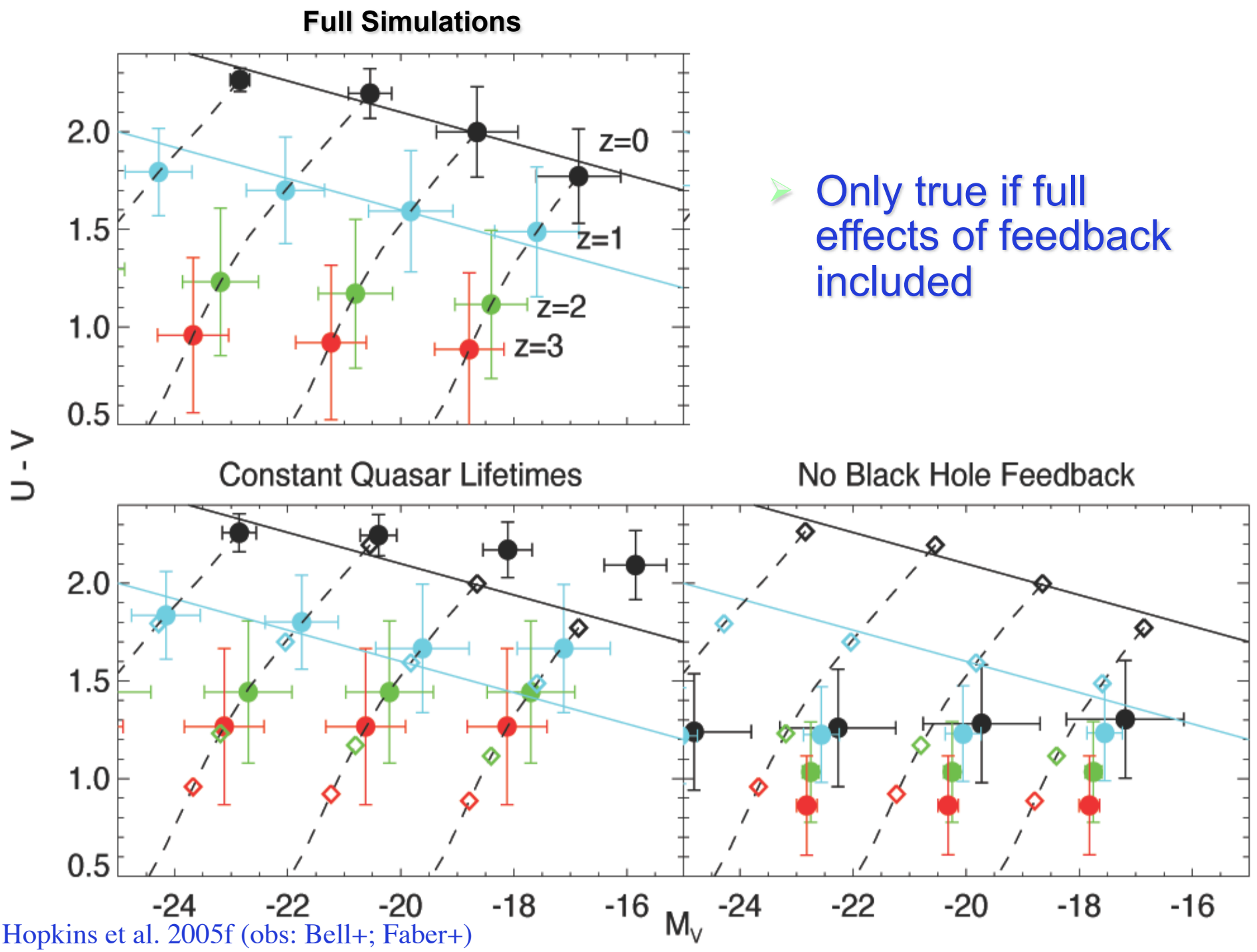
How Much Downsizing?

IS THE DOWNSIZING IN QUASAR AND GALAXY POPULATIONS THE SAME THING?





- Must be true in *any* model where AGN & SF are somehow coupled

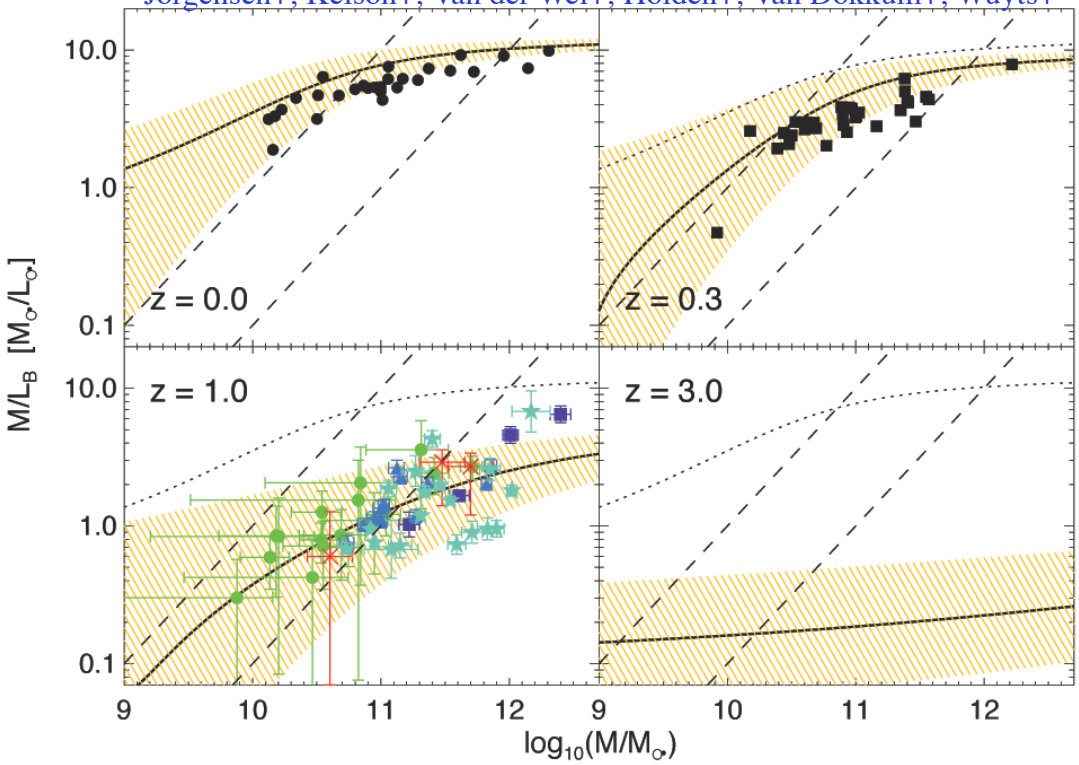


- Only true if full effects of feedback included

Hopkins et al. 2005f (obs: Bell+; Faber+)

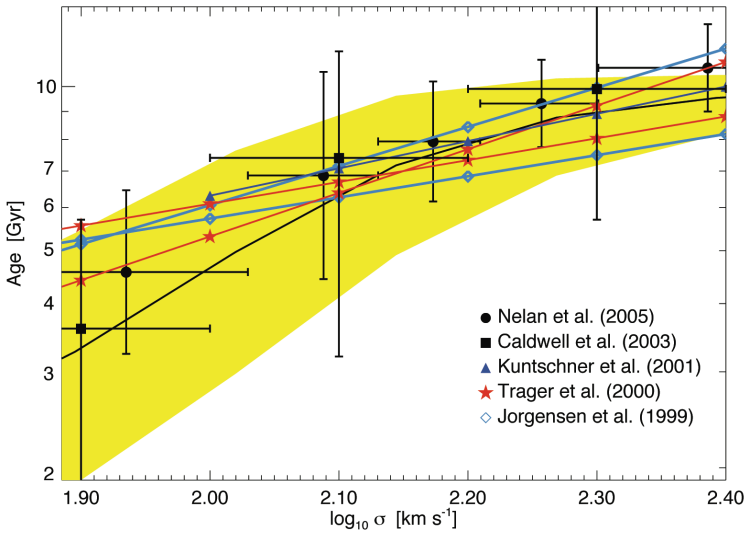
Multiple Age Measurements to Use as Checks

Jorgensen+; Kelson+; Van der Wel+; Holden+; Van Dokkum+; Wuyts+

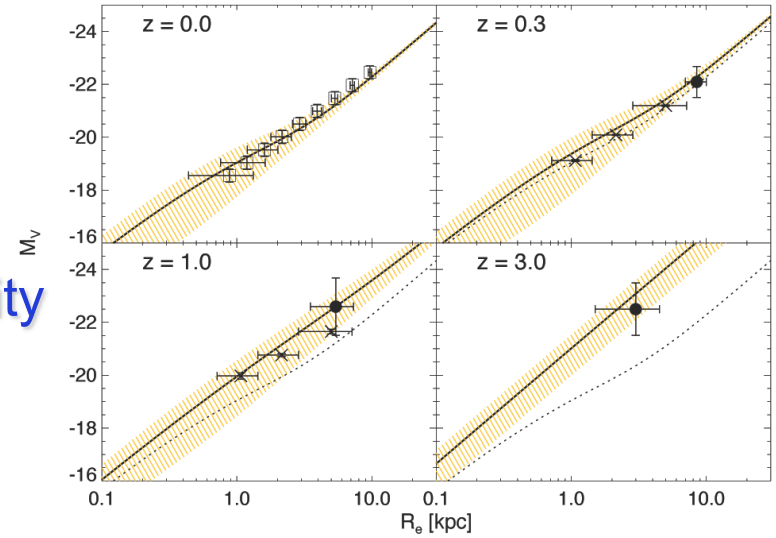


M/L Ratios

Age-sigma



Shen+; Trujillo+; McIntosh+

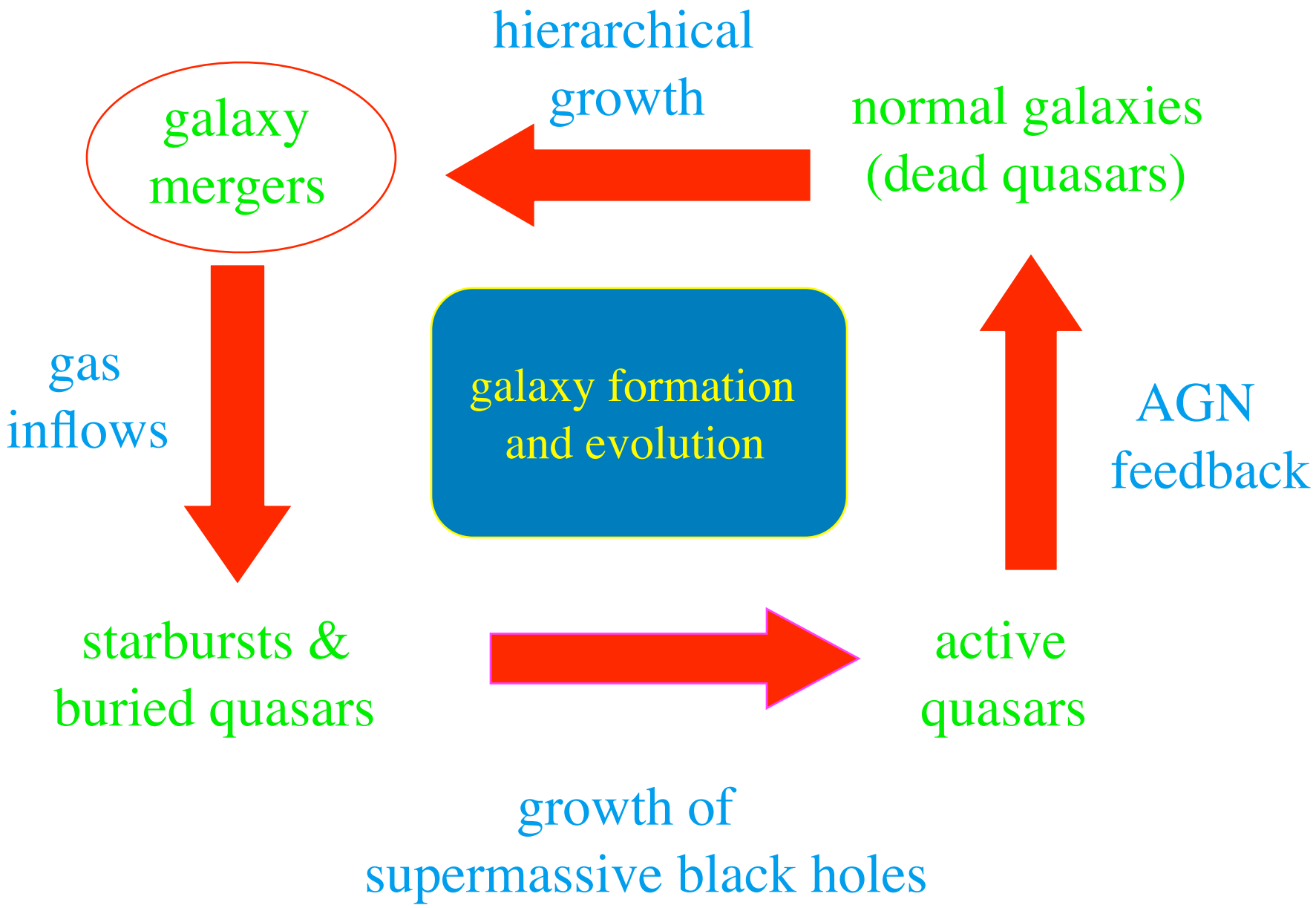


Size-Luminosity Relation

Hopkins et al. 2005f

Extend This Mapping to *Ongoing* Mergers

TEST STATISTICS OF QUASAR, RED GALAXY, & MERGER POPULATIONS



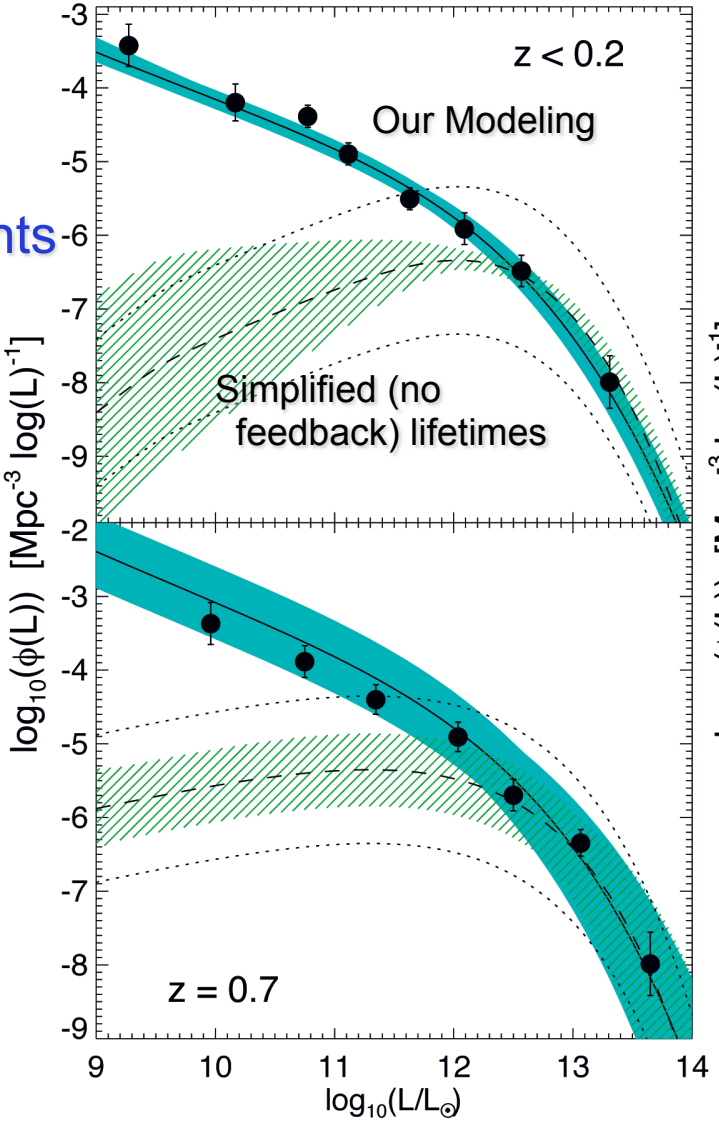
Extend This Mapping to *Ongoing* Mergers

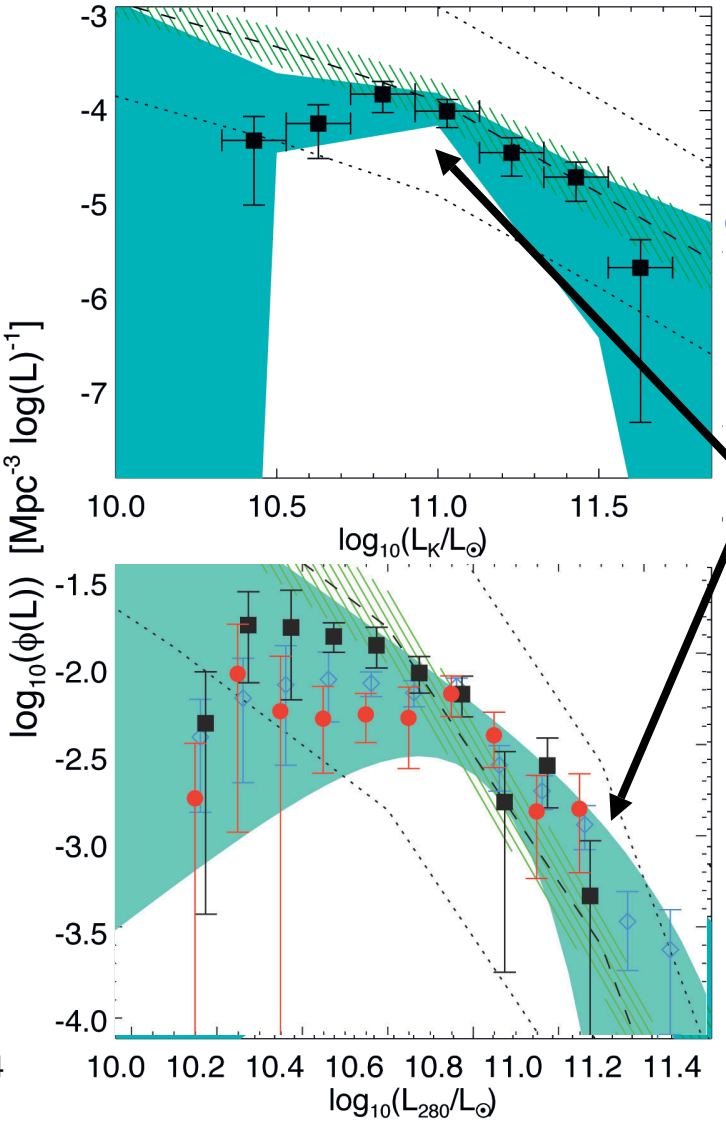
TEST STATISTICS OF QUASAR, RED GALAXY, & MERGER POPULATIONS

Merger LF → Quasar LF

Quasar LF → Merger LF

Tight constraints





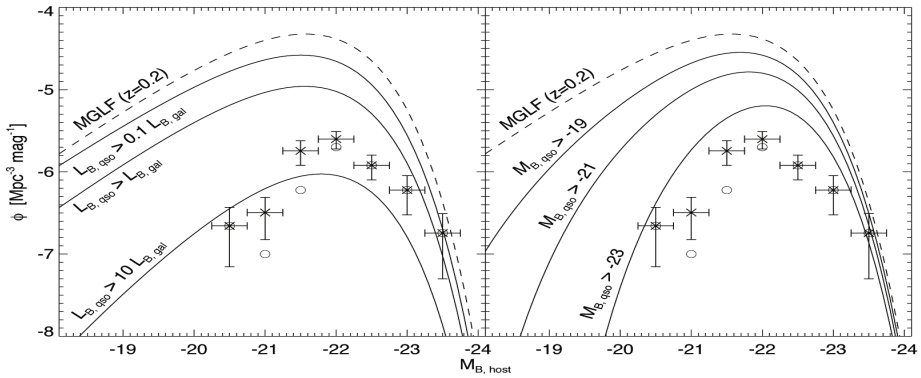
Loose constraints, but break (luminosity density) is tight

Xu+;Wolf+; Ueda+

Ongoing Mergers: Luminosity Density and Quasar Hosts

USE QUASARS TO PREDICT THE MERGER LUMINOSITY DENSITY AND HOST LF

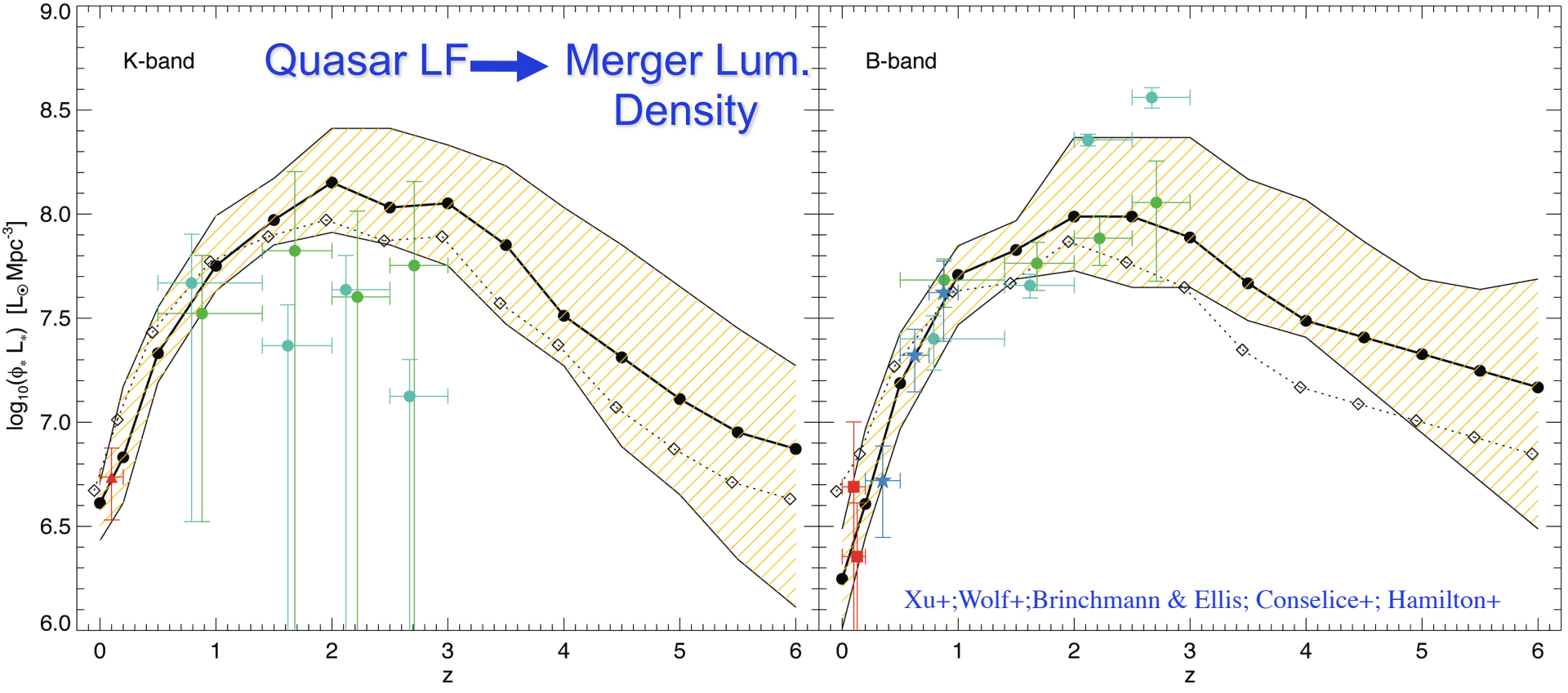
Quasar LF → Quasar Host LF



Also, e.g.:

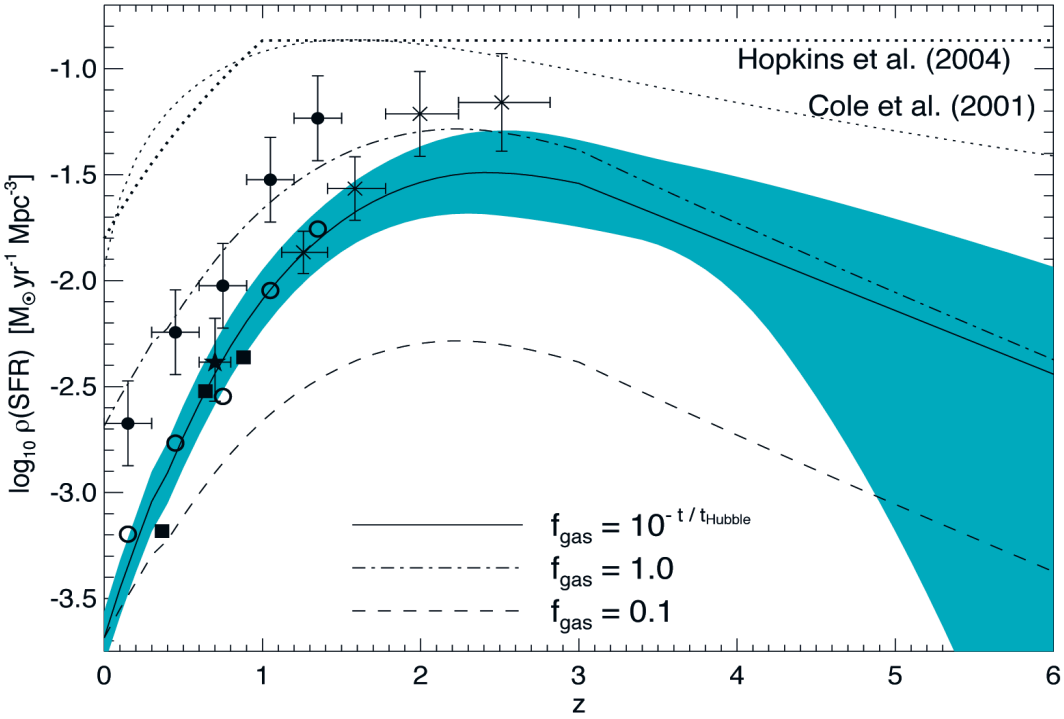
- number densities
- color-magnitude relations
- color-color relations
- dust distributions

Quasar LF → Merger Lum. Density

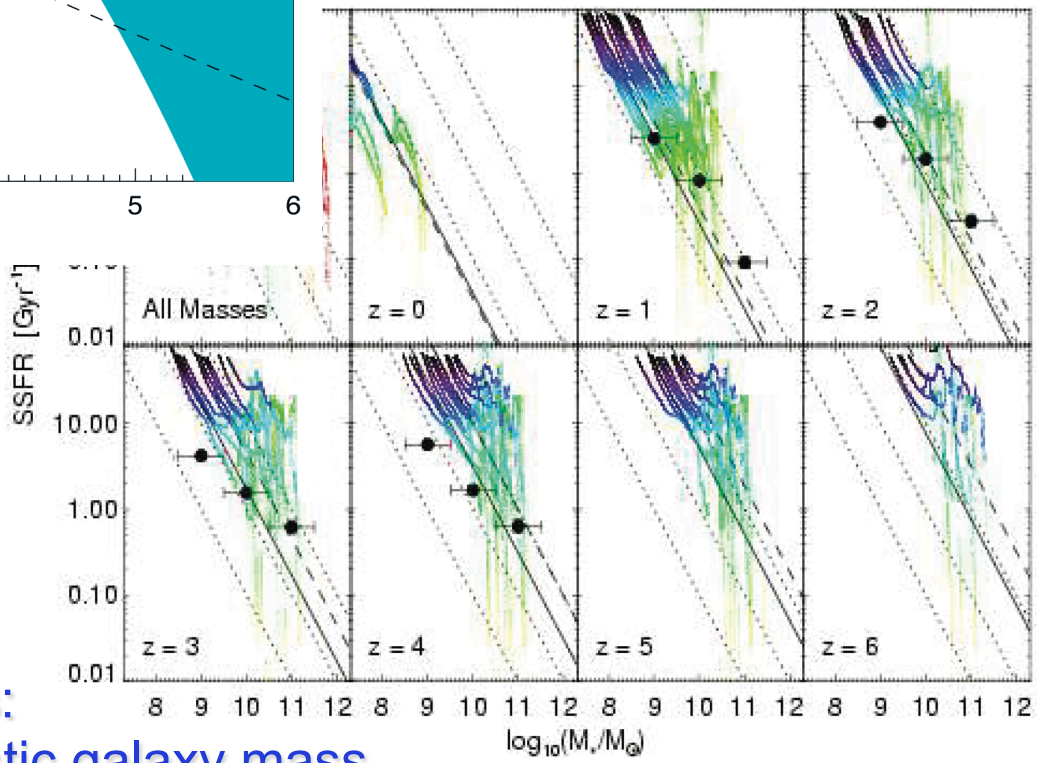


Ongoing Mergers: Merger-Induced Star Formation Rates

APPLY AN IDENTICAL FORMALISM TO THE SFR DISTRIBUTION TO MAP FROM QUASARS



(Hopkins et al. 2006)



SSFR/SFR Distributions: Increase w. characteristic galaxy mass

Bauer+; Feulner+; Perez-Gonzalez+

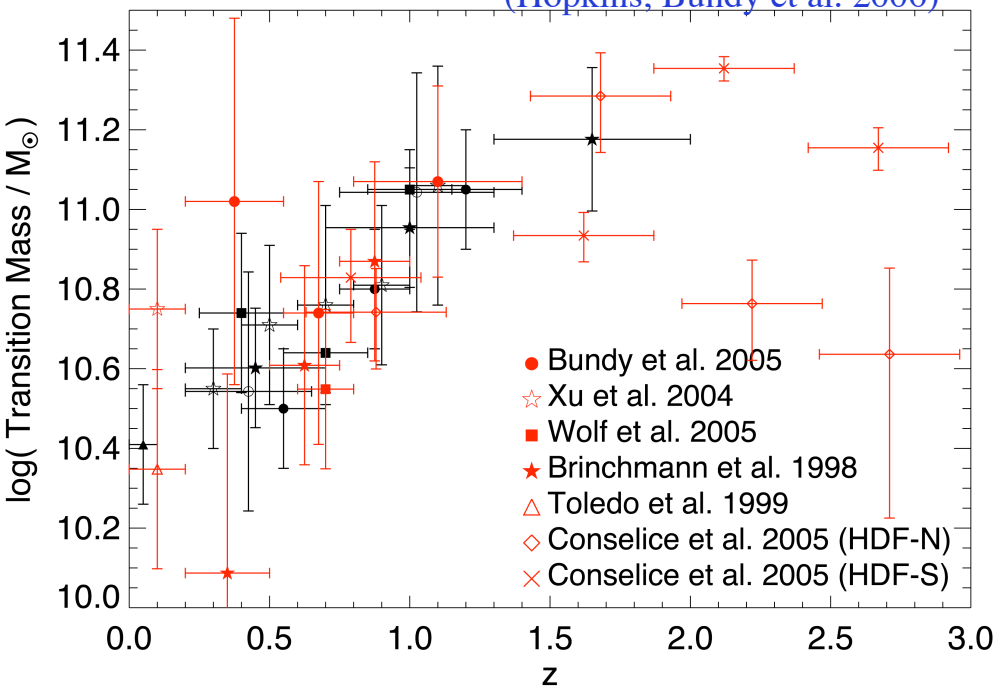
Independent Observational Tests:

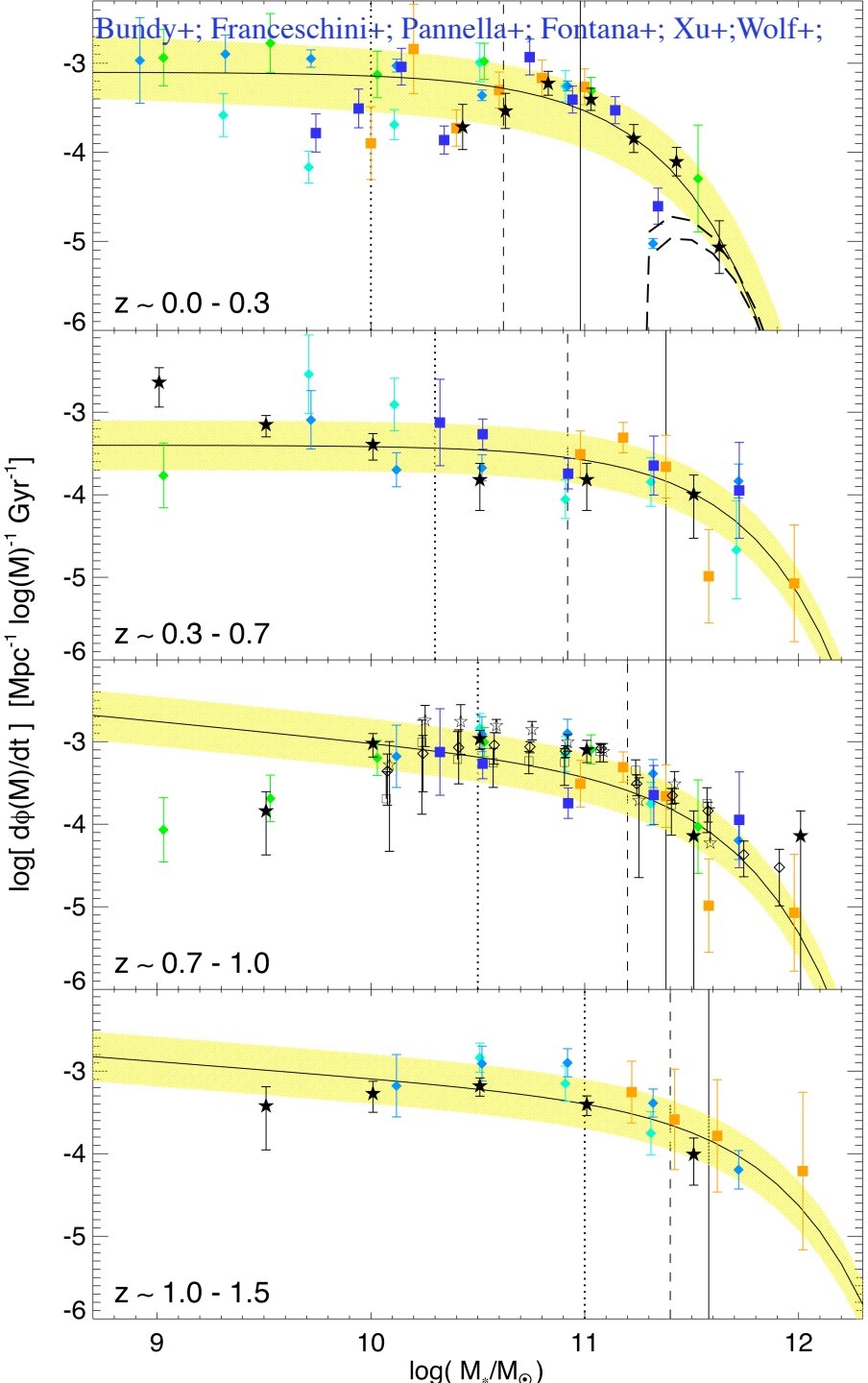
CAN WE TRACE THIS JUST FROM THE OBSERVATIONS?

Becoming possible:

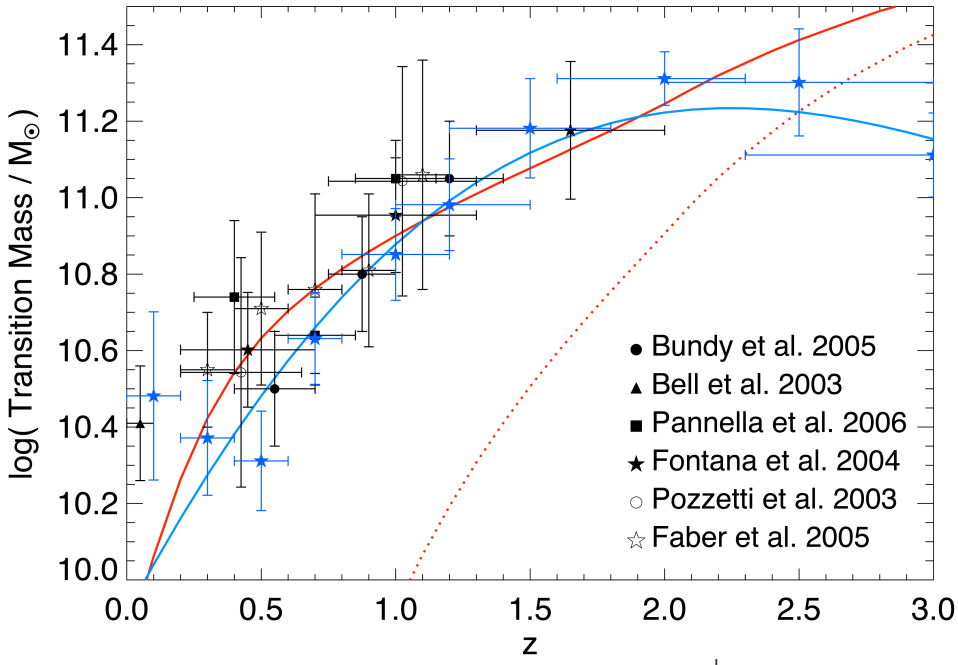
- morphologically separated mass & luminosity functions to z~1
- characteristic mass traced in "quenching" or "transition" mass (e.g. Bundy et al. 2005)

(Hopkins, Bundy et al. 2006)

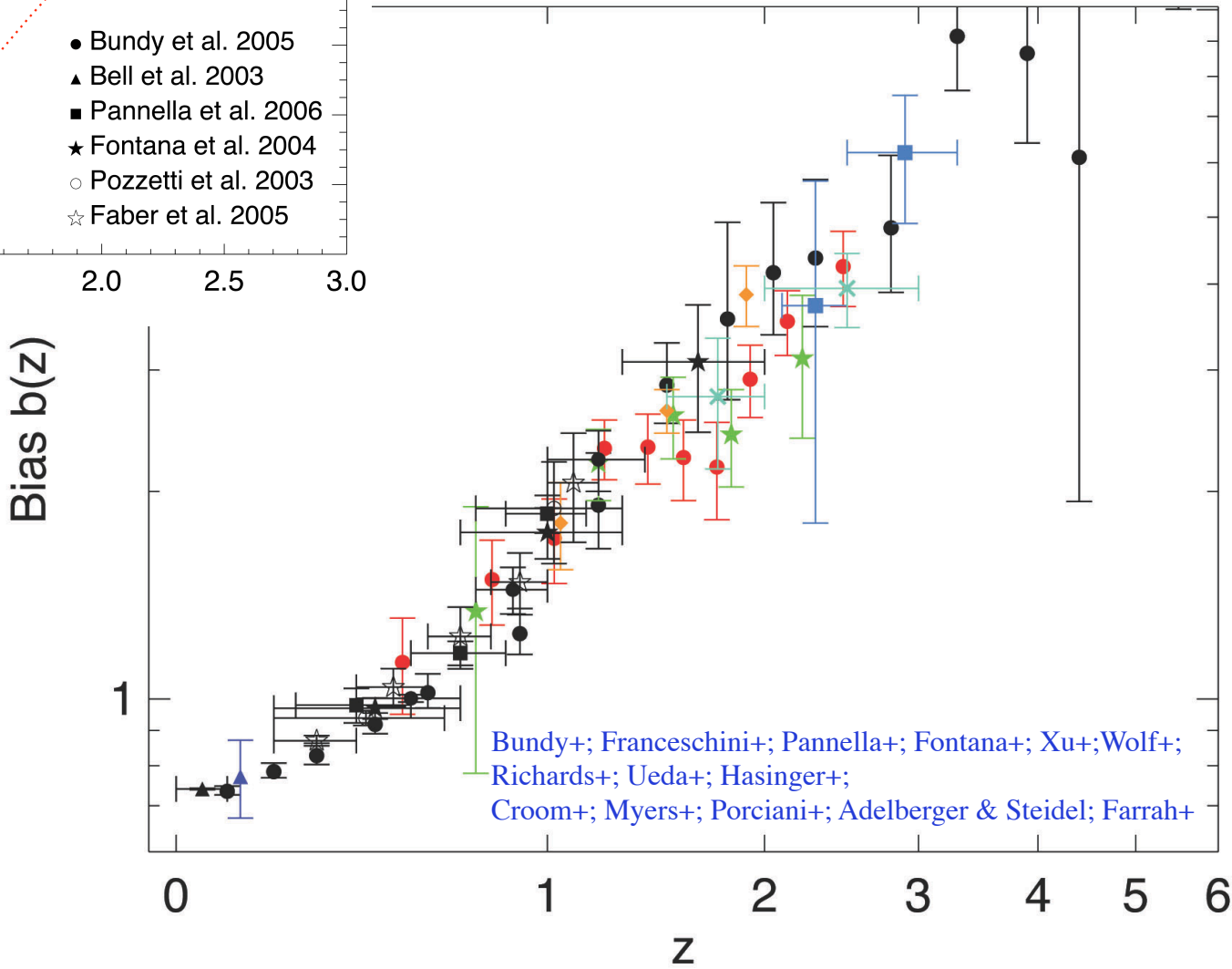




Same for quasars



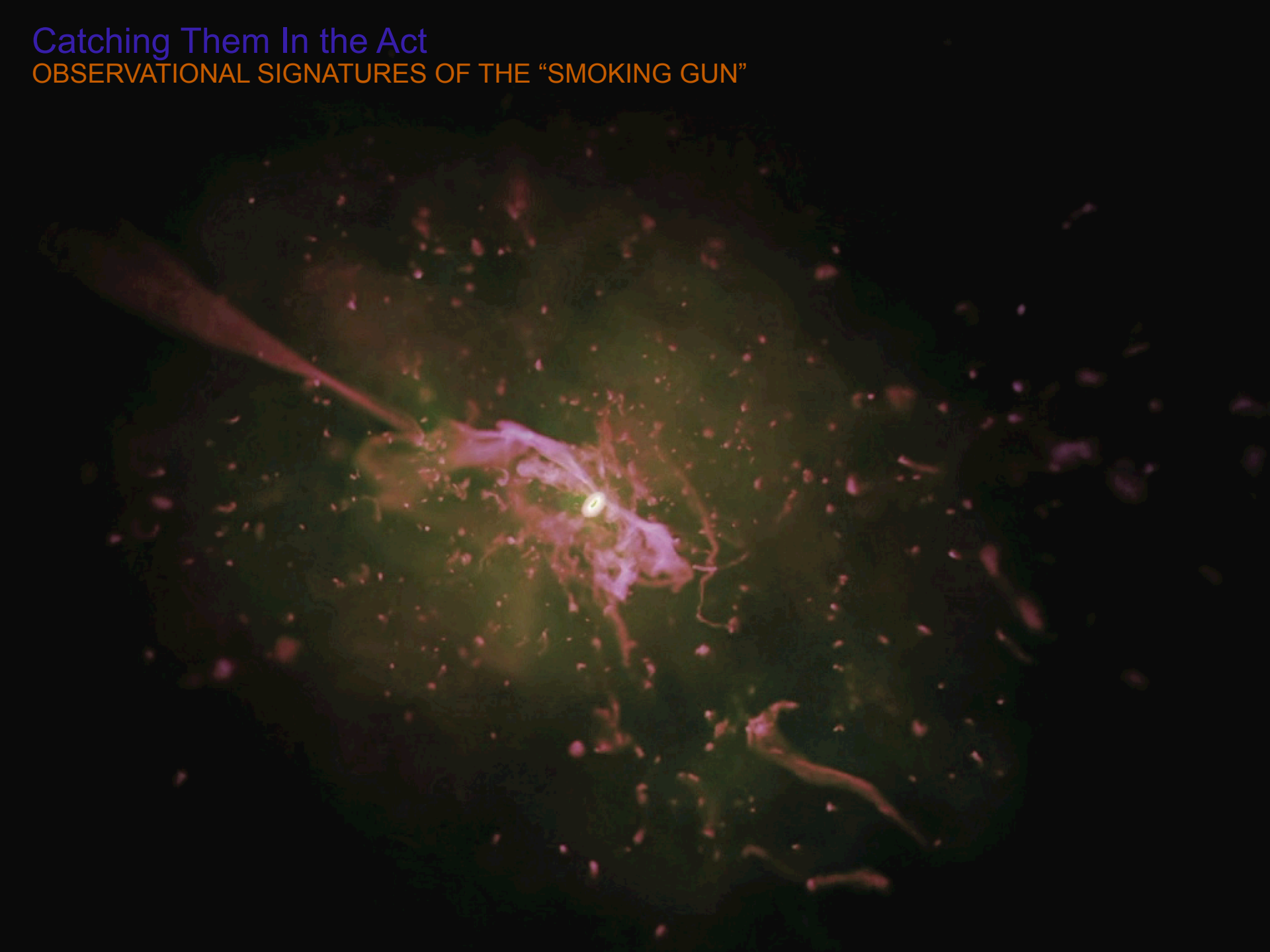
Independently, from clustering:



(Hopkins, Bundy et al. 2006)

Catching Them In the Act

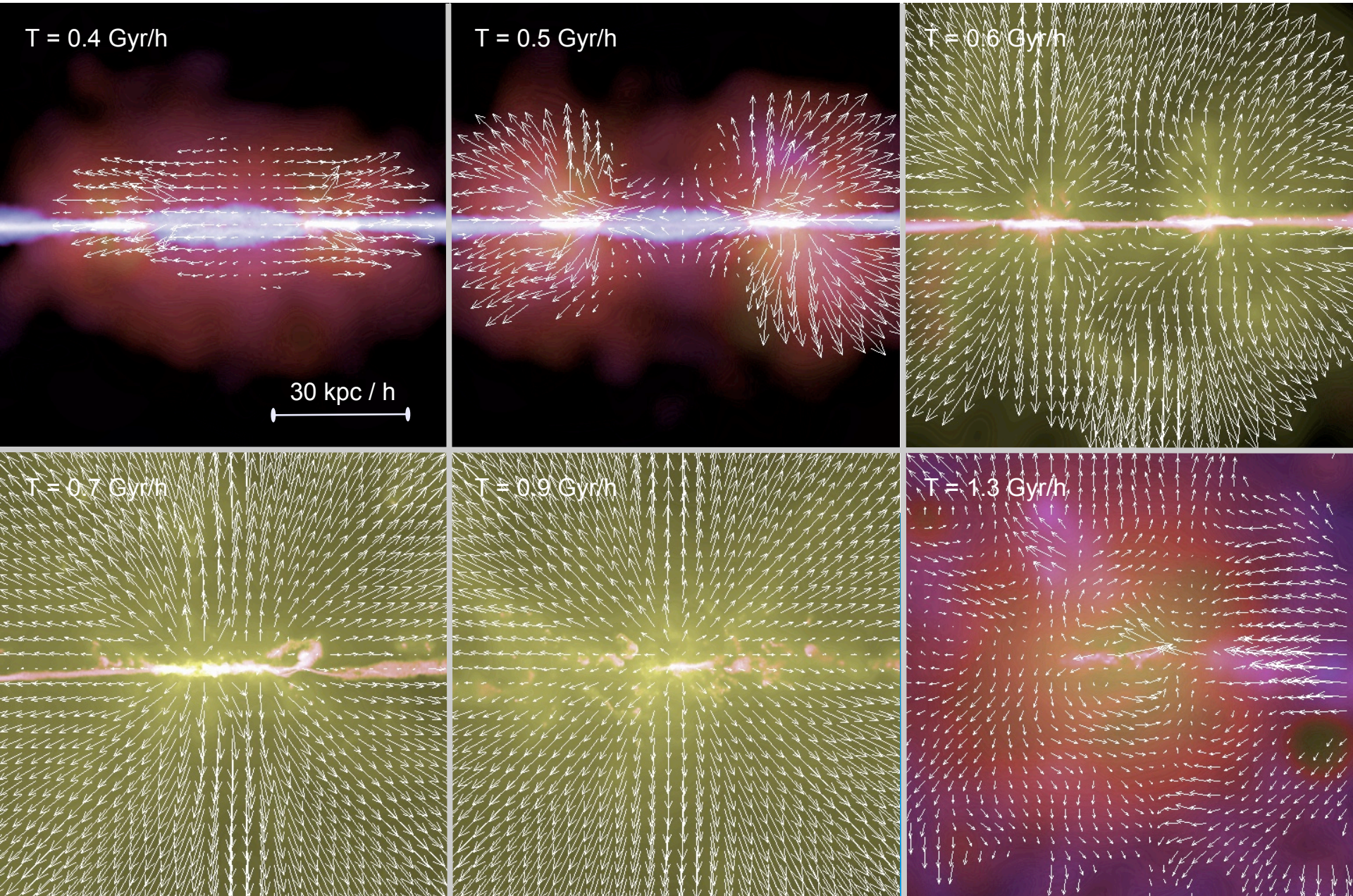
OBSERVATIONAL SIGNATURES OF THE “SMOKING GUN”



AGN Feedback Drives A Strong Wind

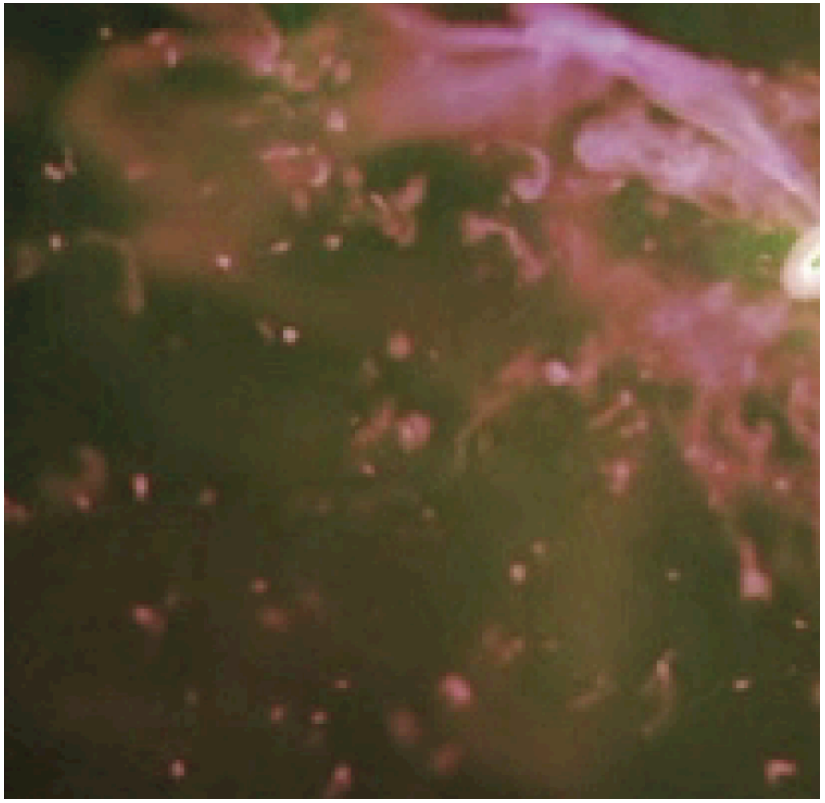
* **Outflow reaches speeds of up to ~2000 km/sec**

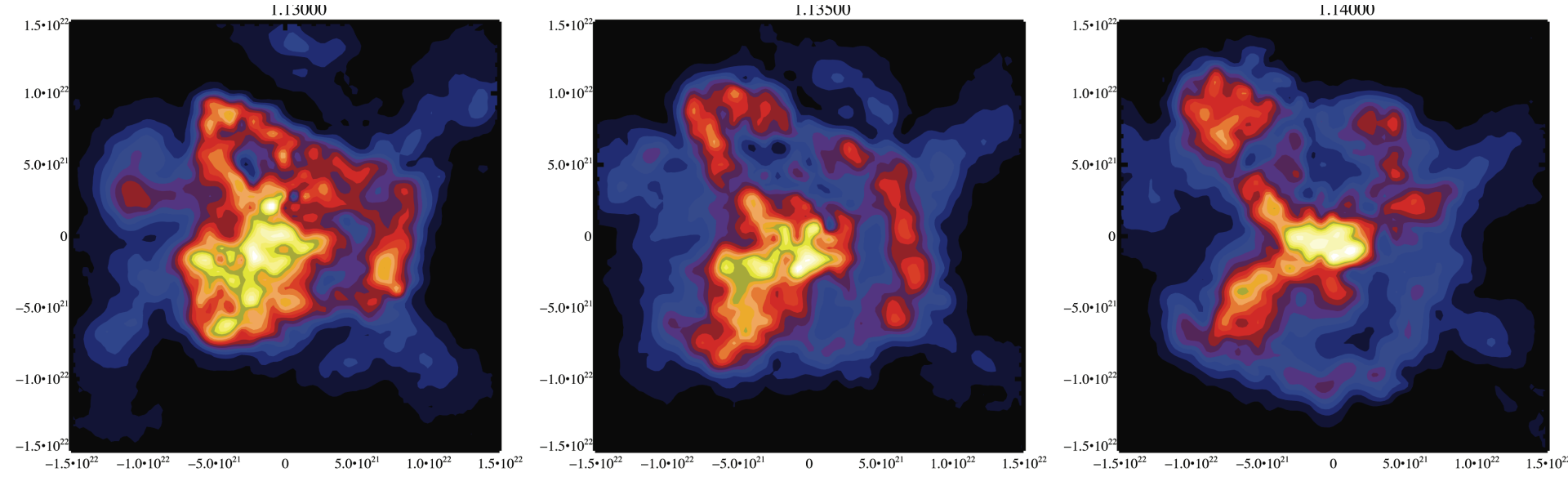
* **Measure velocity structure**



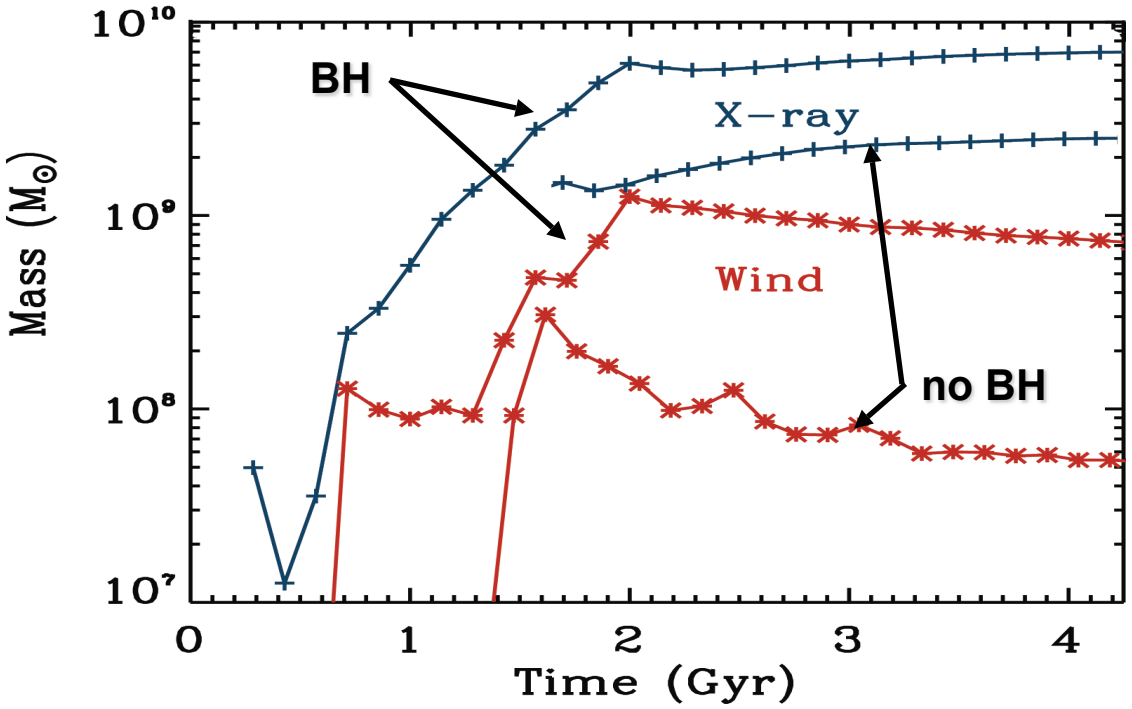
Outflows are Explosive and Clumpy

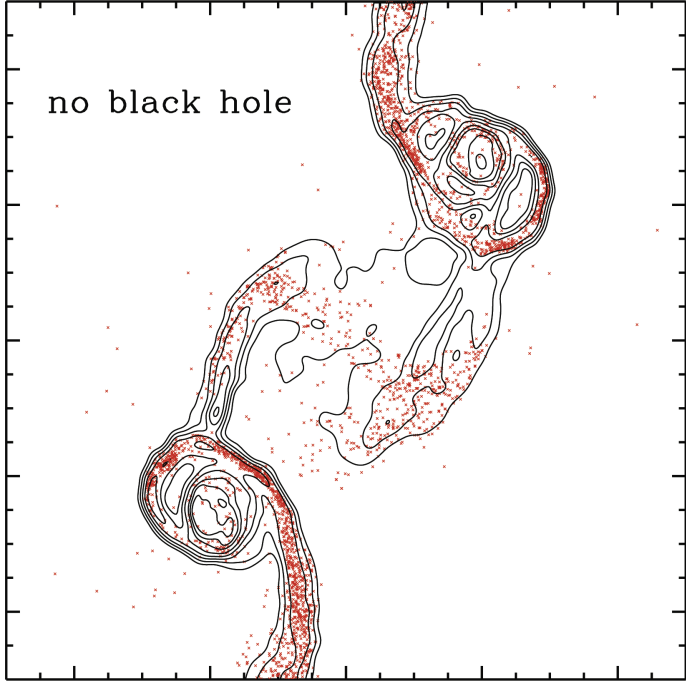
- Rapid BH growth => point-like injection
  - Explosion, independent of coupling
- Clumpy
  - ULIRG cold/warm transition (S. Chakrabarti)
  - CO outflows (D. Narayanan)

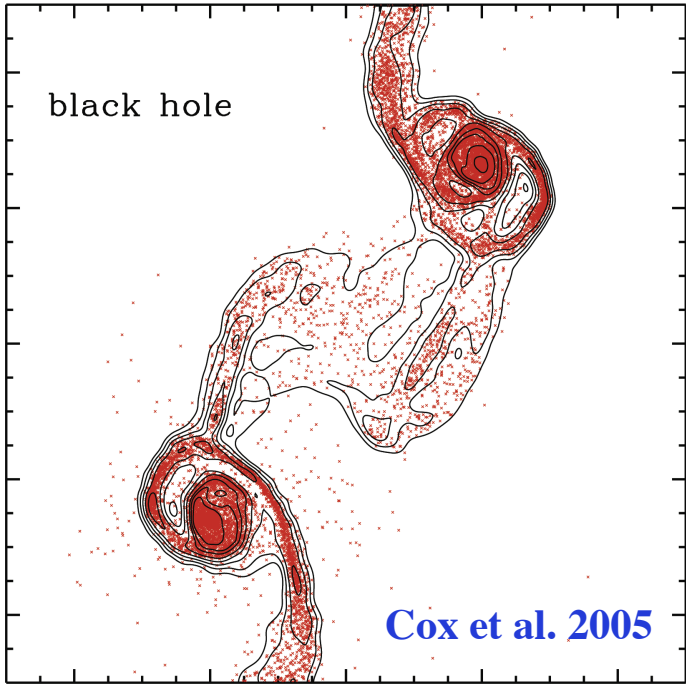


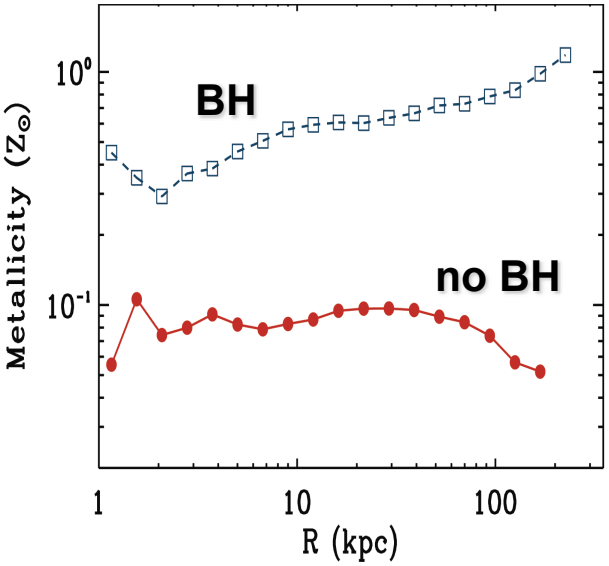


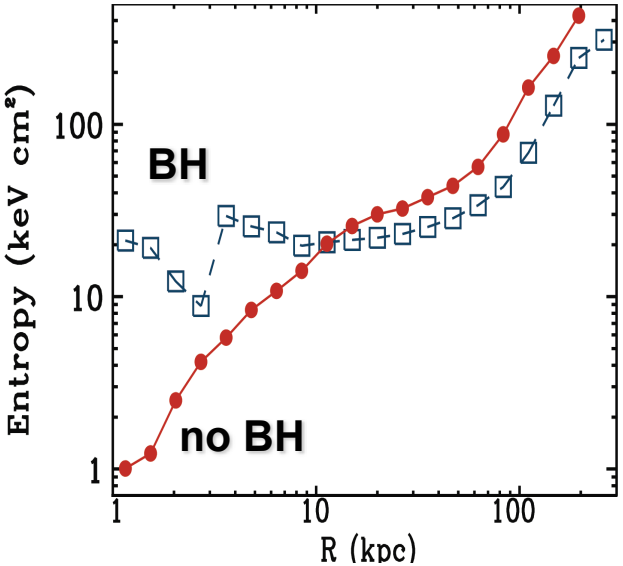
Expel Metal-Enriched Gas & Build Up X-Ray Halo











Summary

- Quasars do interesting things!
  - Quasar lifetime not one number:
    Luminosity-dependent lifetimes
    Increases at lower L
  - Obscuration evolves
- Feedback is key:
  - Gives the lifetime its form
  - Allows ellipticals to redden & build red sequence
- This allows a huge range of predictions
  galaxy & quasar populations and demographics become self-consistent
- Keep pushing until something gives:
  - Faint-end lifetimes: rapidly constrain feedback models
  - $n(L_{PEAK})$: formation histories, especially at high-z

Self-Consistentlv Predicts:

- Quasar Luminosity Functions
  - Optical, soft XR, hard XR, radio
- NH distribution in QSOs
  - Optical & X-ray
- Broad-line fraction vs. luminosity
- Clustering vs. luminosity
- SMBH mass function
- X-ray background spectrum
- Eddington ratio distribution
  - Vs. Luminosity
- Active SMBH mass function
  - Type I & Type II QSOs
- High-z radio source counts
- QLF faint-end slope
  - Luminosity-Dependent Density
- M-sigma relation
- Red Galaxy Populations
  - Fundamental Plane
  - Mass-size relation
  - Luminosity functions
    - NUV,U,B,V,R,I,K,u,g,r
    - M*,Phi*,j evolution
  - Mass function
  - Color-magnitude relations
    - U-V,U-B,R-K,u-g,u-r,B-V
    - Slope evolution & reddening
    - Bimodality
  - Mass-to-light vs. mass
  - Luminosity-size relations
  - Age distribution vs. luminosity/ mass
  - Velocity dispersion function
  - Young spheroid fraction vs. mass

No Feedback or Simplified Quasars:

- Quasar Luminosity Functions
  - Optical, soft XR, hard XR, radio
- NH distribution in QSOs
  - Optical & X-ray
- Broad-line fraction vs. luminosity
- Clustering vs. luminosity
- SMBH mass function
- X-ray background spectrum
- Eddington ratio distribution
  - Vs. Luminosity
- Active SMBH mass function
  - Type I & Type II QSOs
- High-z radio source counts
- QLF faint-end slope
  - Luminosity-Dependent Density Evolution

- M-sigma relation
- Red Galaxy Populations
  - Fundamental Plane
  - Mass-size relation
  - Luminosity functions
    - NUV,U,B,V,R,I,K,u,g,r
    - M*,Phi*,j evolution
  - Mass function
  - Color-magnitude relations
    - U-V,U-B,R-K,u-g,u-r,B-V
    - Slope evolution & reddening
    - Bimodality
  - Mass-to-light vs. mass
  - Luminosity-size relations
  - Age distribution vs. luminosity/ mass
  - Velocity dispersion function
  - Young spheroid fraction vs.

Where to From Here?

- Simulations/Theory:
  - Different coupling of AGN : how much can the answer change?
    - Radio mode & cD galaxies - Different modes altogether?
  - Role of Stellar Feedback
    - Tests for Outflow Origin? Structural signatures?
  - Incorporation with SAMs & Cosmological sims
    - Fully a priori predictions; feedback not “just another knob”
- Observations:
  - **Informing our Modeling:**
    - Break & faint-end slope of QLF at high redshift
    - Age distribution of low-mass spheroids
    - Coupling modes of AGN feedback : the local Seyfert (non-merger!) “lab”
  - **Predictions to Test:**
    - Clustering vs. luminosity
    - Obscuration vs. luminosity and *peak* luminosity (host properties)
    - Active BHMF & Eddington ratio distributions vs. L
    - Merger luminosity density (LFs) & SFR density at high-z
    - Buildup of early-type MF, “Blue Spheroid” population