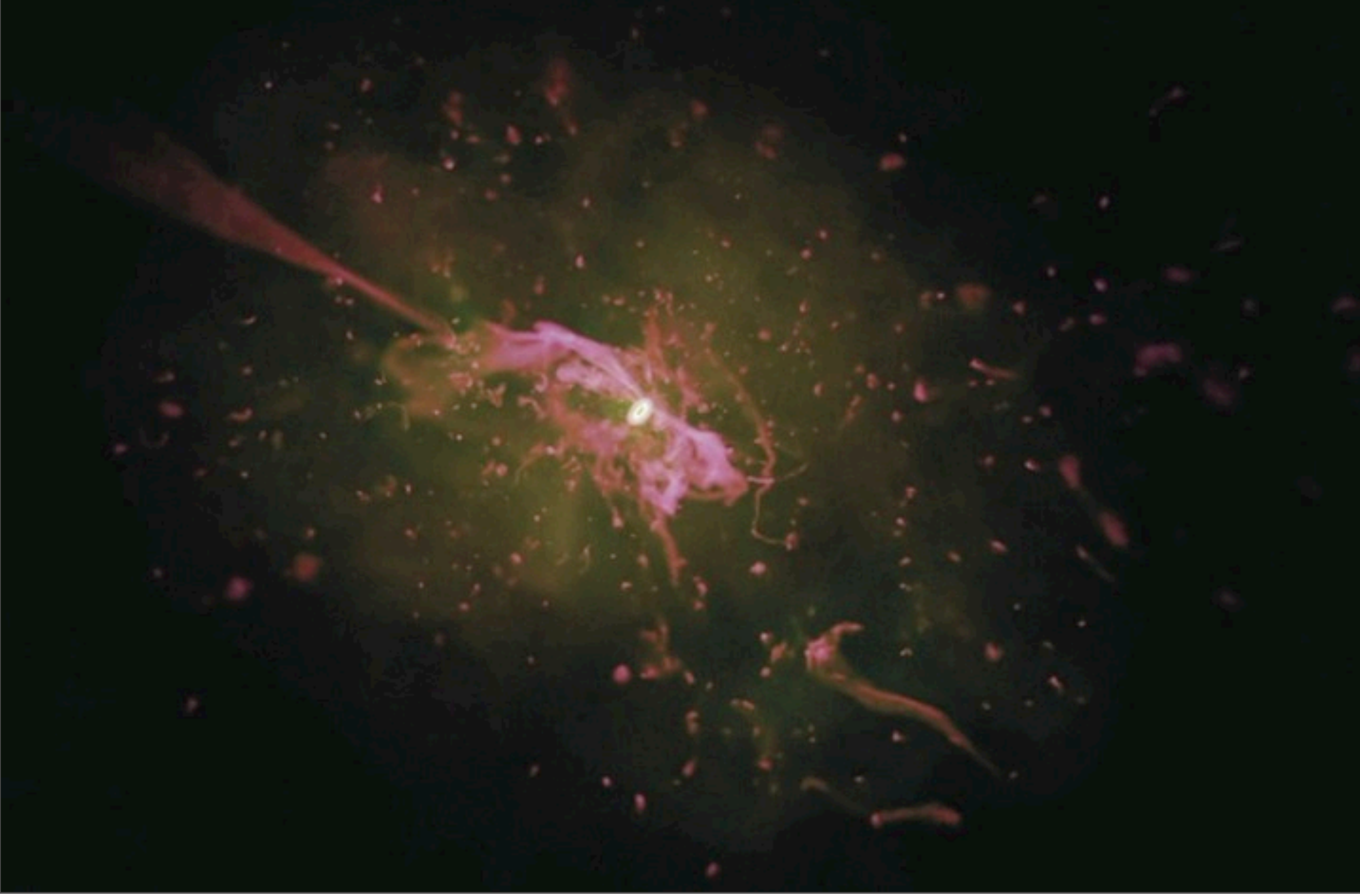
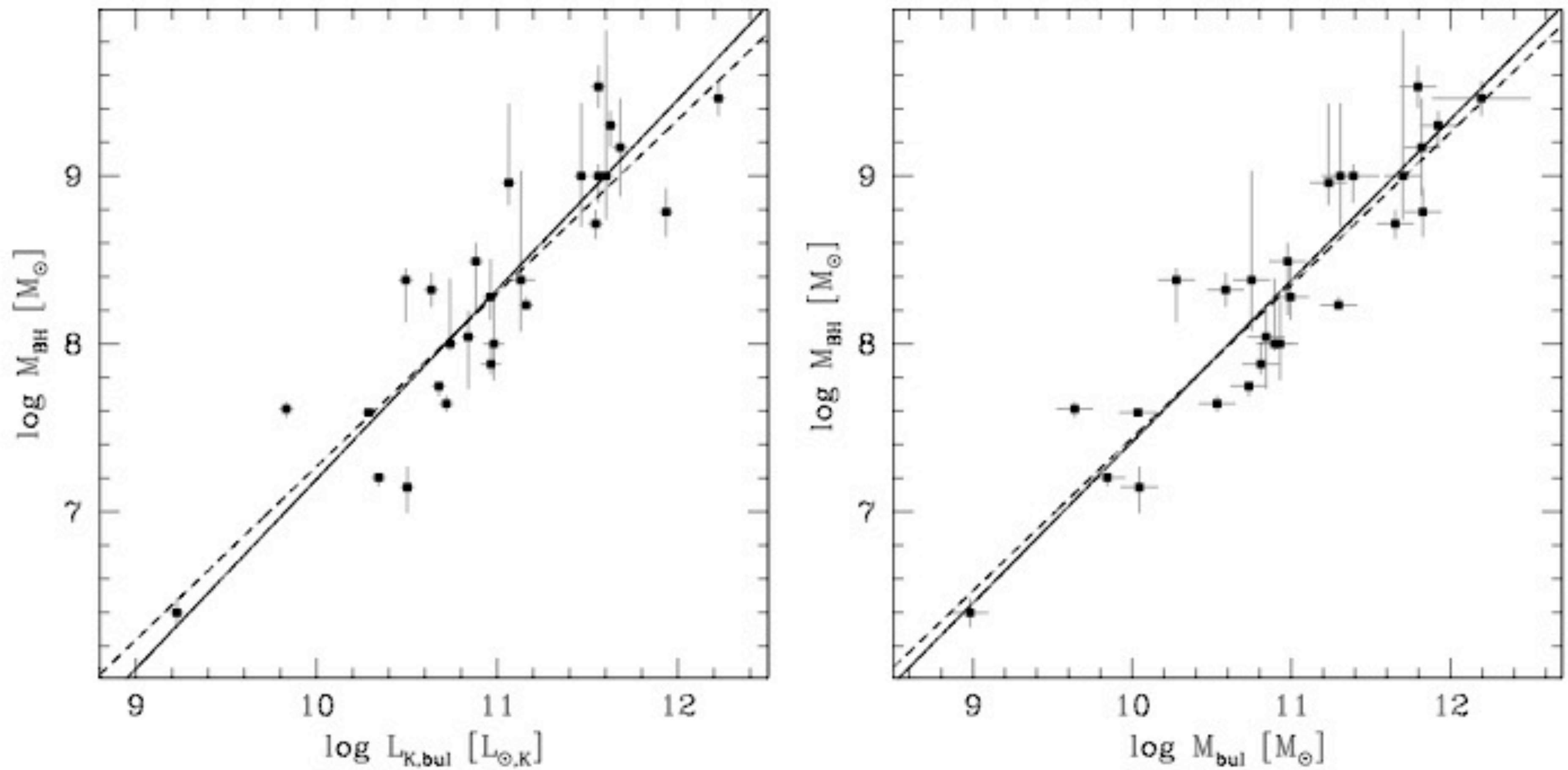
Beyond M_{BH}-S



Kormendy et al. (1995) & Magorrian (1998)

BH mass – galaxy luminosity / mass correlation



Marconi & Hunt (2003)

Black Holes

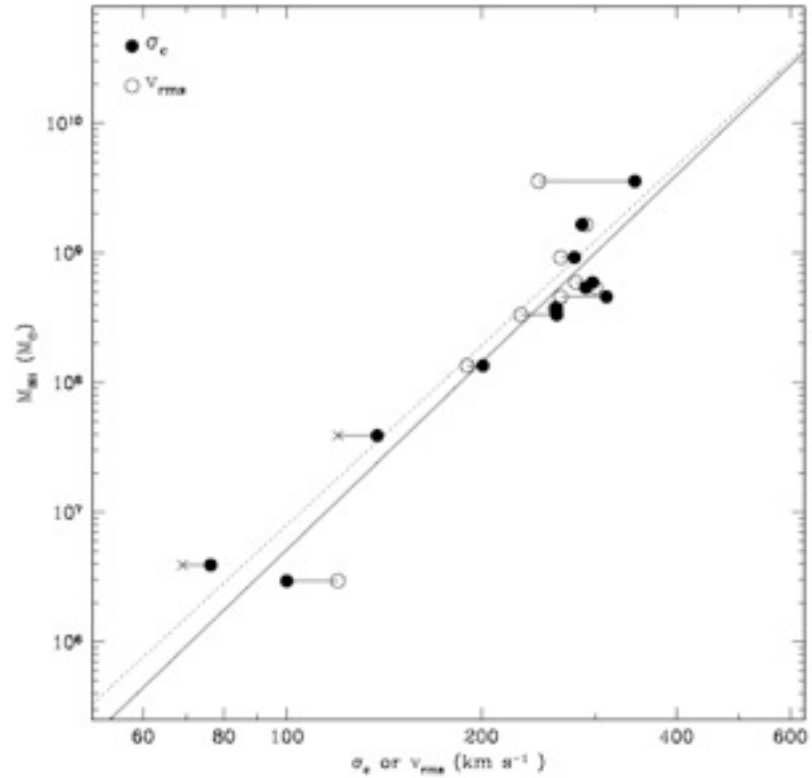
NEWCOMERS TO THE CORRELATIONS

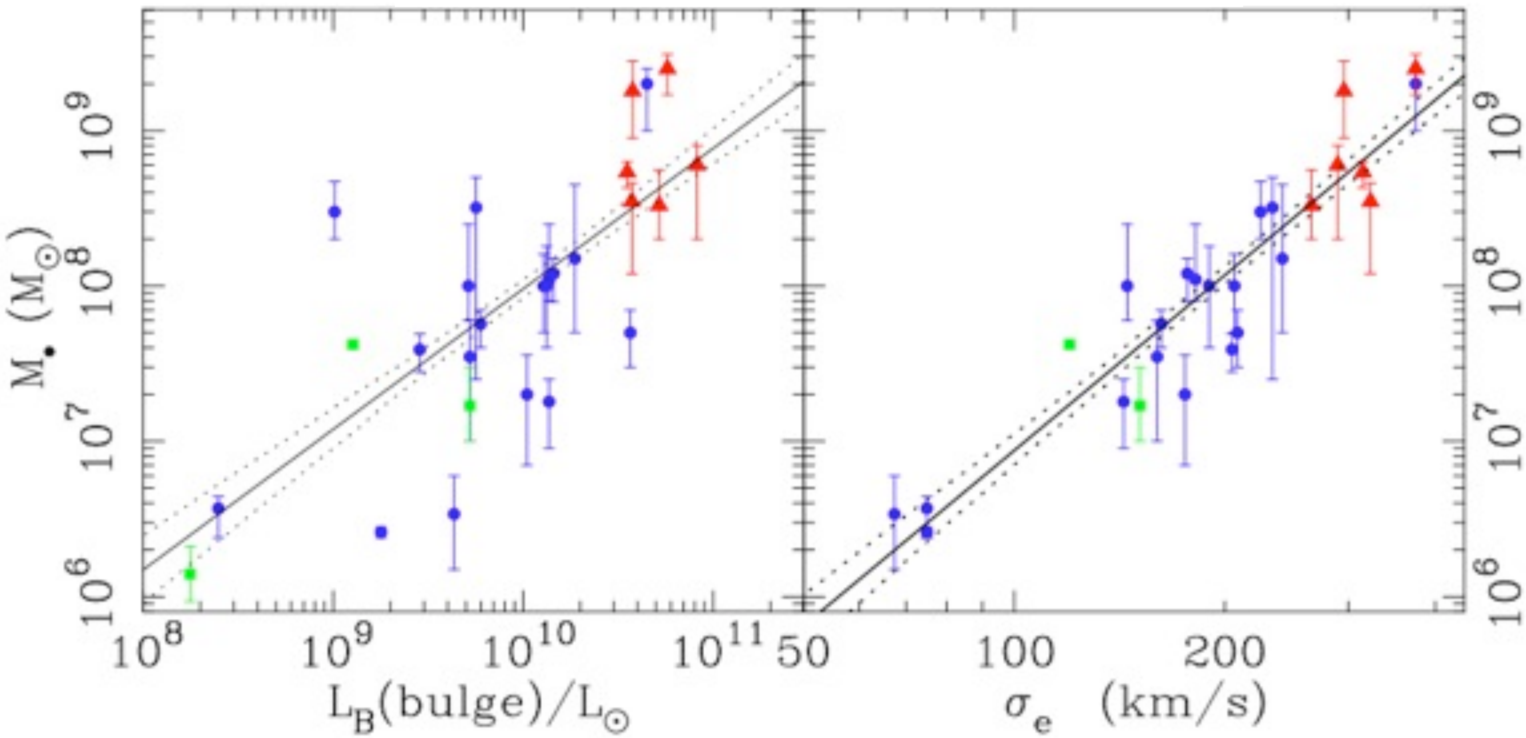
Ferrarese & Merritt (2000)

and

Gebhardt et al. 2000:

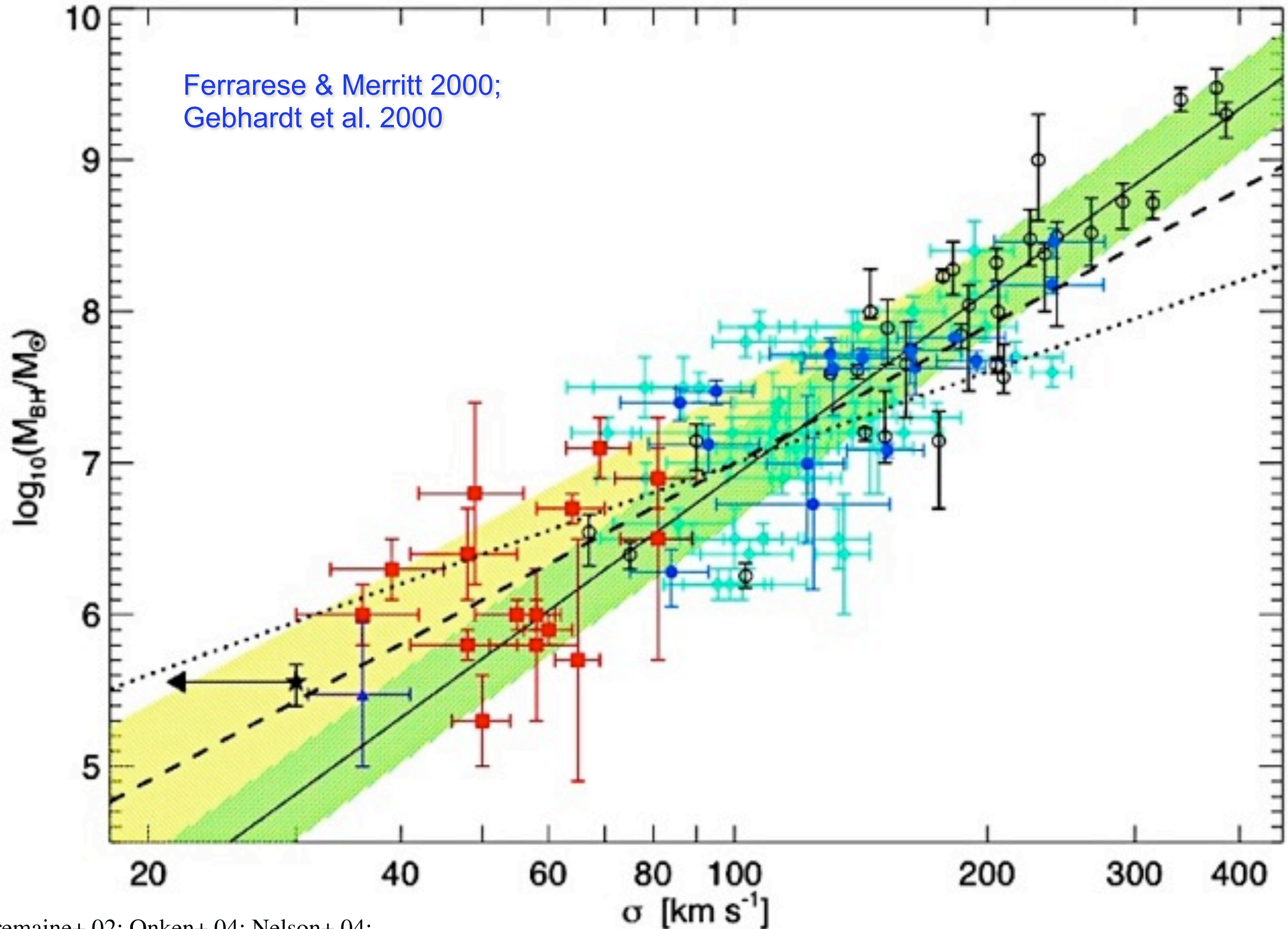
Mbh ~ sigma^4.x



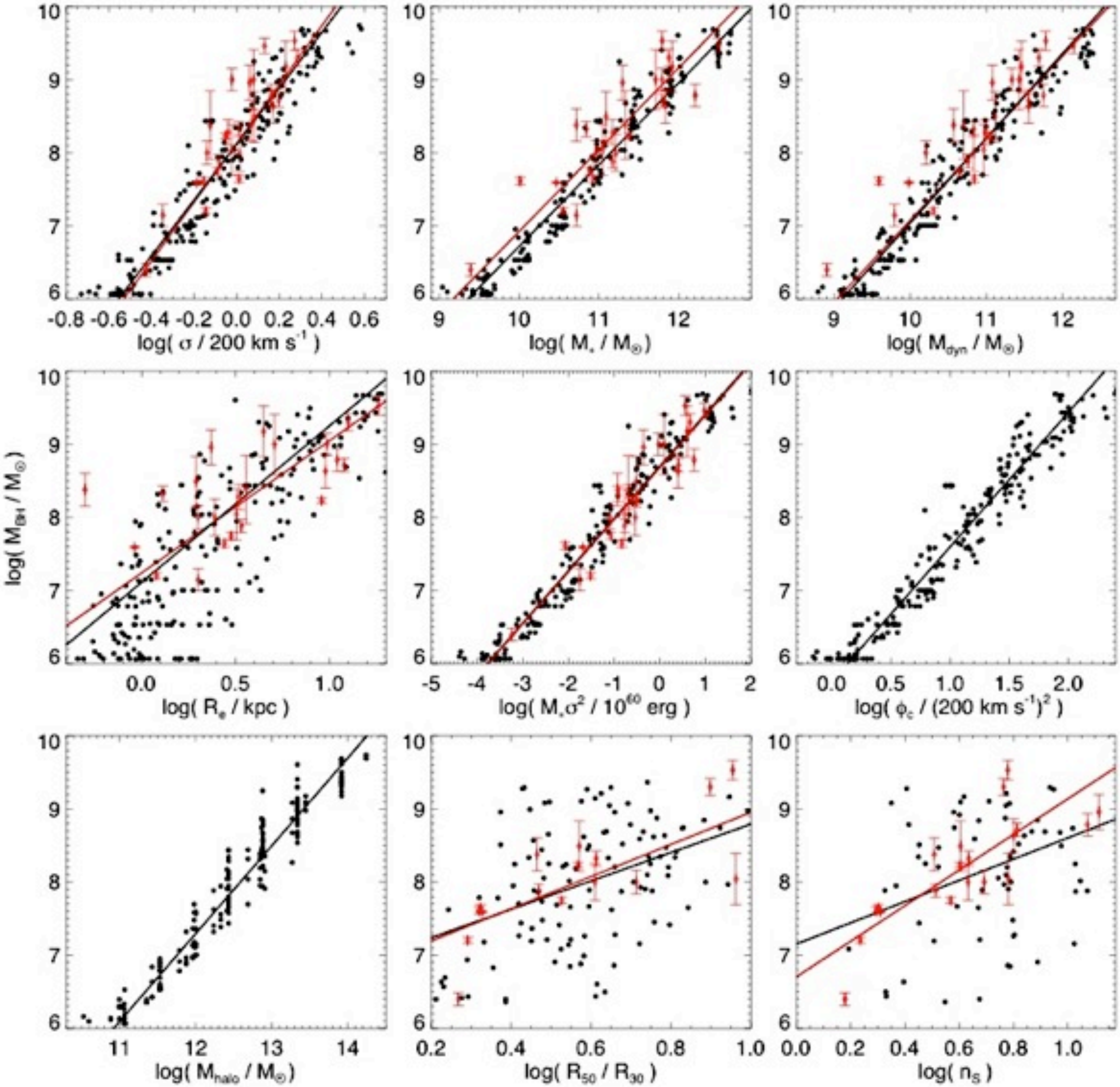


M-sigma Relation Is Now Canonical

BHs & BULGEs CO-EVOLVE IN SOME SENSE



Tremaine+ 02; Onken+ 04; Nelson+ 04;
Peterson+ 04, 05; Barth+ 04, 05;
Greene & Ho 05



log(σ / 200 km s⁻¹)
log(M* / M⊙)
log(Mdyn / M⊙)
log(MBH / M⊙)
log(Re / kpc)
log(M*σ² / 10⁶⁰ erg)
log(φc / (200 km s⁻¹)²)
log(Mhalo / M⊙)
log(R50 / R90)
log(nS)

Origins of M-sigma

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 & Reese 1998)

Sink-particles and a simple parameterization of the accretion rate are used to model the growth of black holes

THE IMPLEMENTED BLACK HOLE ACCRETION MODEL

Growth of Black Holes

Bondi-Hoyle-Lyttleton type accretion rate parameterization:

$$\dot{M}_{\rm B} = \alpha \times 4\pi R_{\rm B}^2 \, \rho \, c_s \simeq \frac{4\pi\alpha G^2 M_\bullet^2 \, \rho}{(c_s^2 + v^2)^{3/2}}$$

Limitation by the Eddington rate:

$$\dot{M}_\bullet = \min(\dot{M}_{\rm B}, \dot{M}_{\rm Edd})$$

Feedback by Black Holes

Standard radiative efficiency:

$$L_{\rm bol} = 0.1 \times \dot{M}_\bullet \, c^2$$

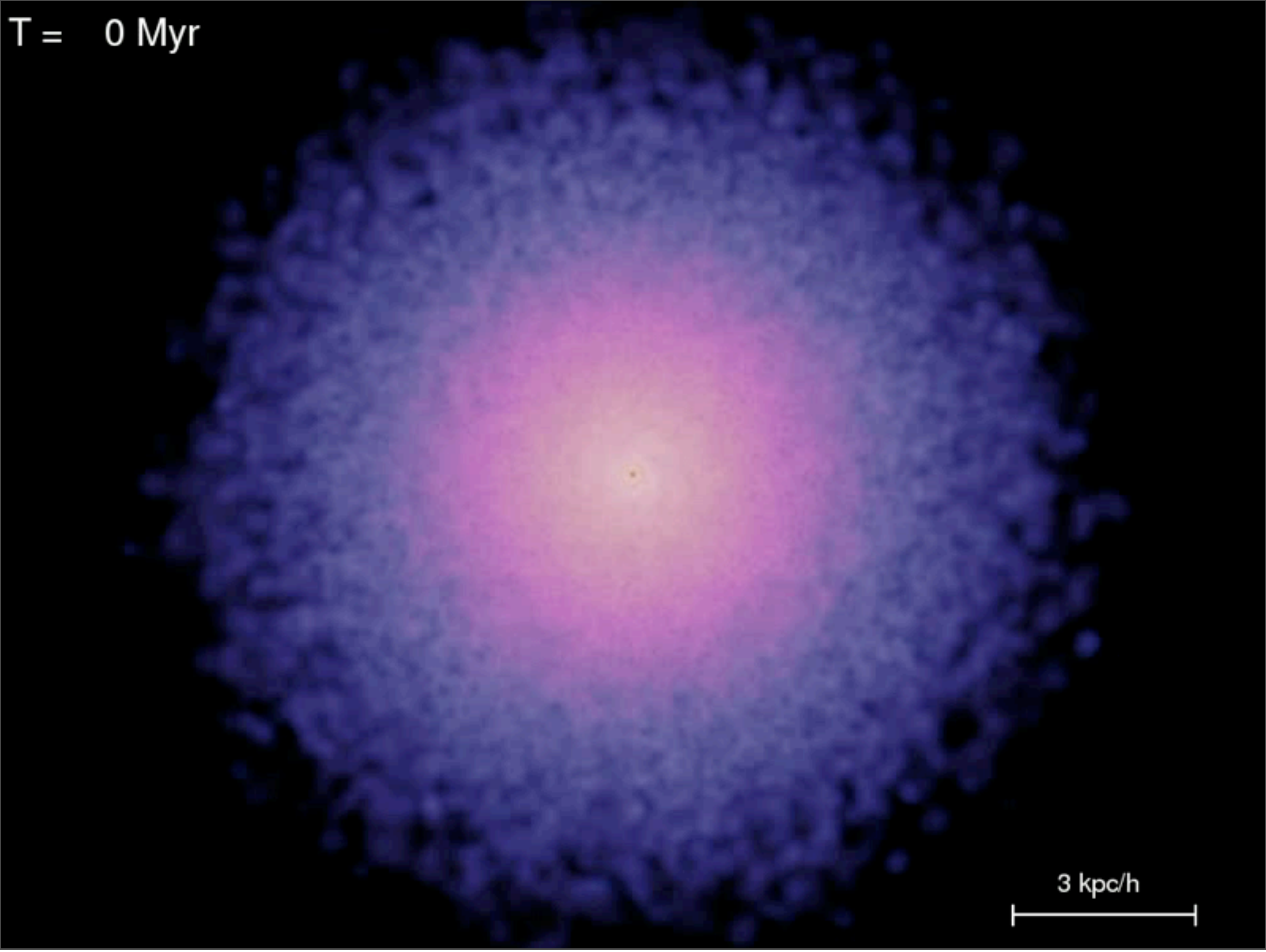
Thermal coupling of some fraction of the energy output to the ambient gas:

$$\dot{E}_{\rm feedback} = f \times L_{\rm bol} \qquad f \simeq 5\%$$

Implementation in SPH simulation code

Additions in the parallel GADGET-2 code:

- BH sink particles swallow gas stochastically from their local neighbourhoods, in accordance with the estimated BH accretion rate
- Feedback energy is injected locally into the thermal reservoir of gas
- On-the-fly FOF halo finder detects emerging galaxies and provides them with a seed black hole
- BHs are merged if they reach small separations and low enough relative speeds


T = 0 Myr
3 kpc/h

Growth rate of black holes in isolated galaxies

THREE PHASES OF BLACK HOLE GROWTH

Bondi-growth:

$$\dot{M}(t) = \frac{M_0}{1 - 4\pi\alpha\rho G^2 M_0 t / c^3}$$

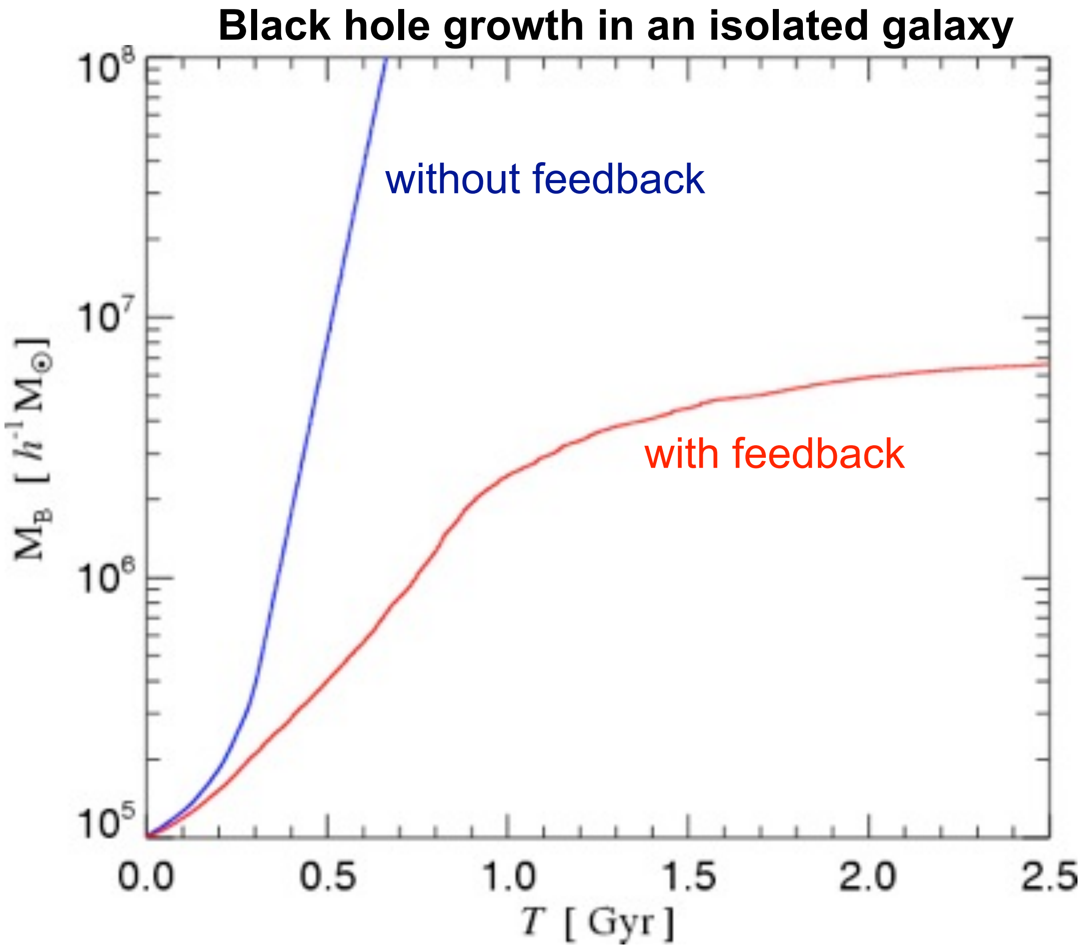
Eddington-growth:

$$\dot{M}(t) = M_0 \exp\left(\frac{t}{t_S}\right)$$

Slow, feedback regulated growth:

$$\frac{\mathrm{d}E_{\rm cool}}{\mathrm{d}t} = \Lambda(T)\,\rho\,M_{\rm gas}$$

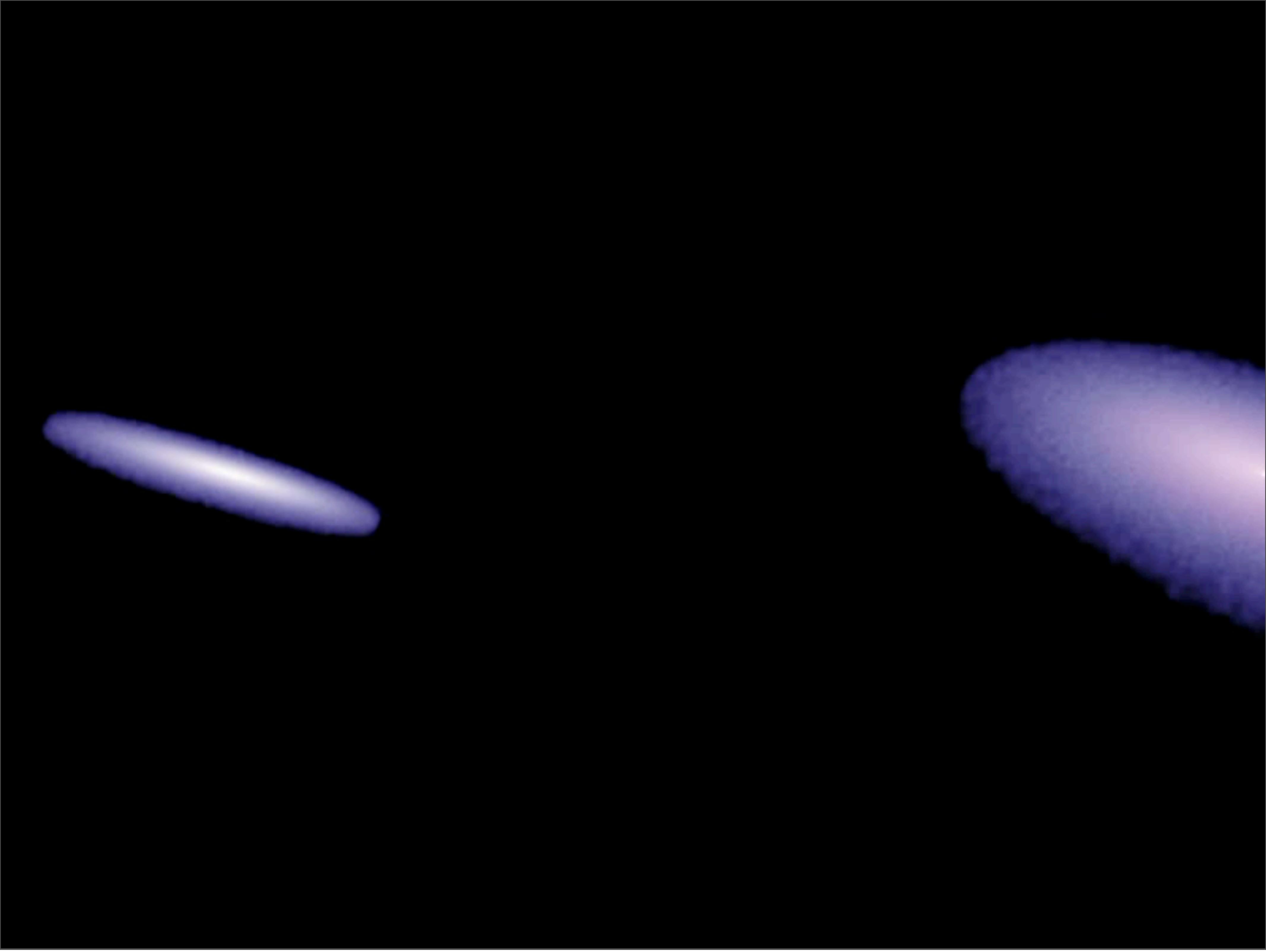
$$\frac{\mathrm{d}E_{\rm heat}}{\mathrm{d}t} = 0.1 f \dot{M} c^2 \propto \frac{\rho M_{\rm B}^2}{T^{3/2}}$$



- $T_{\rm equal}$ independent of density
- for: $T_{\rm equal} \simeq T_{\rm vir}$, $M_{\rm gas} \propto M_{\rm halo}$

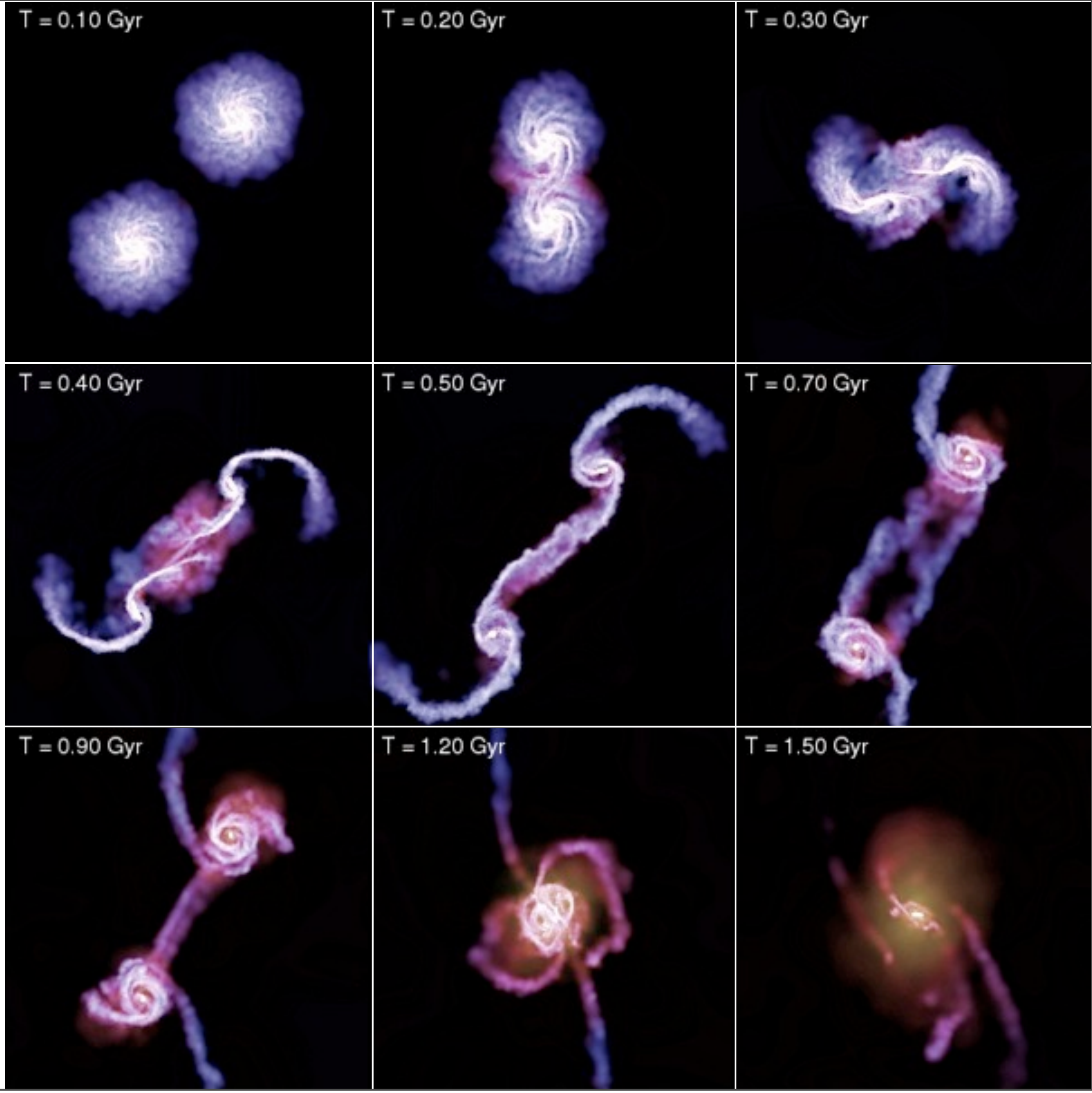
$$M_{\rm B} \propto V_{\rm vir}^{7/2}$$

- If $T_{\rm equal} >> T_{\rm vir}$, the hole is too big for the halo. It can blow gas out until there is (almost) none left.



In major-mergers between two disk galaxies, tidal torques extract angular momentum from cold gas, providing fuel for nuclear starbursts and BH growth

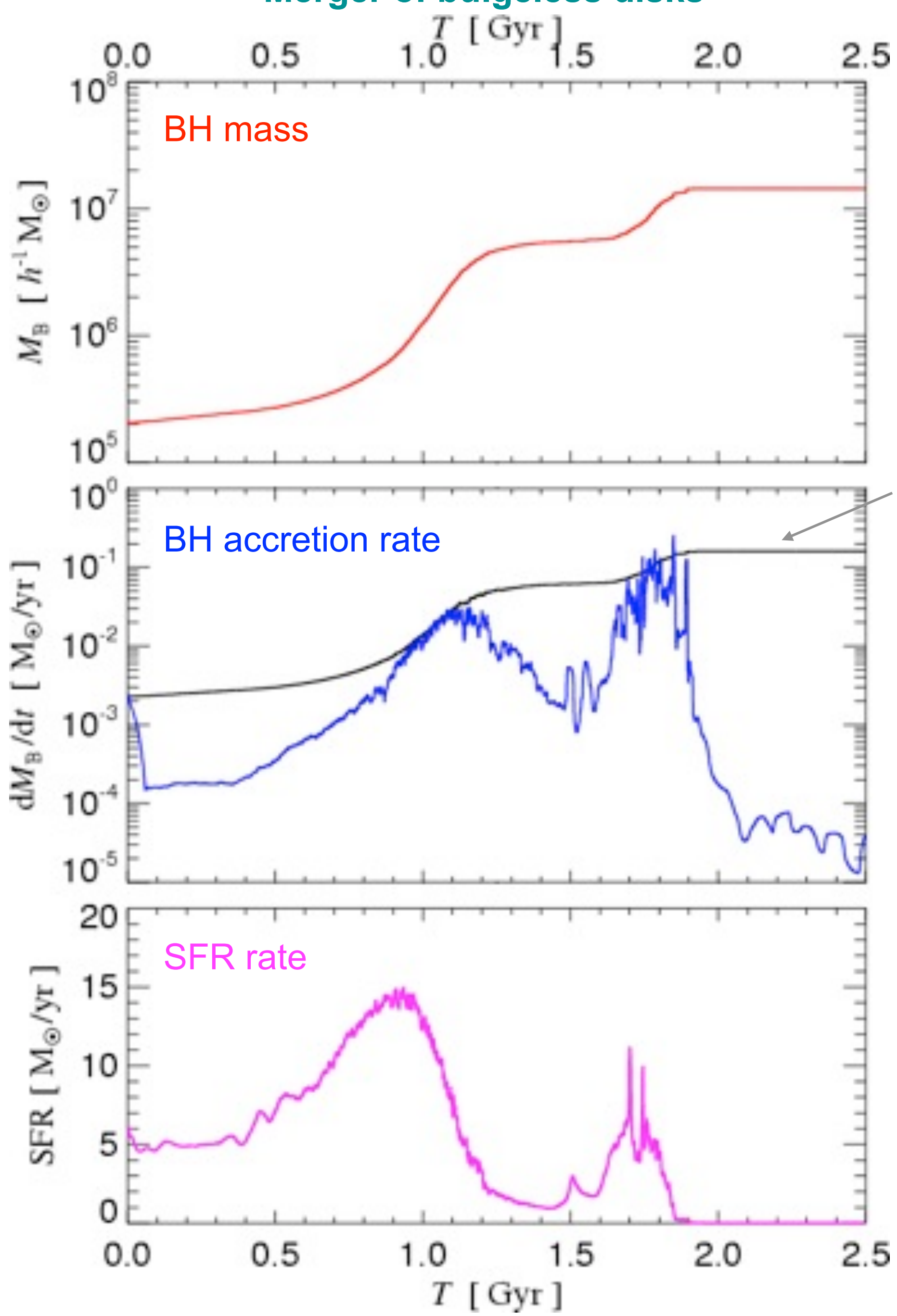
TIME EVOLUTION OF A PROGRADE MAJOR MERGER



Mergers of disk galaxies trigger starburts and ignite central AGN activity

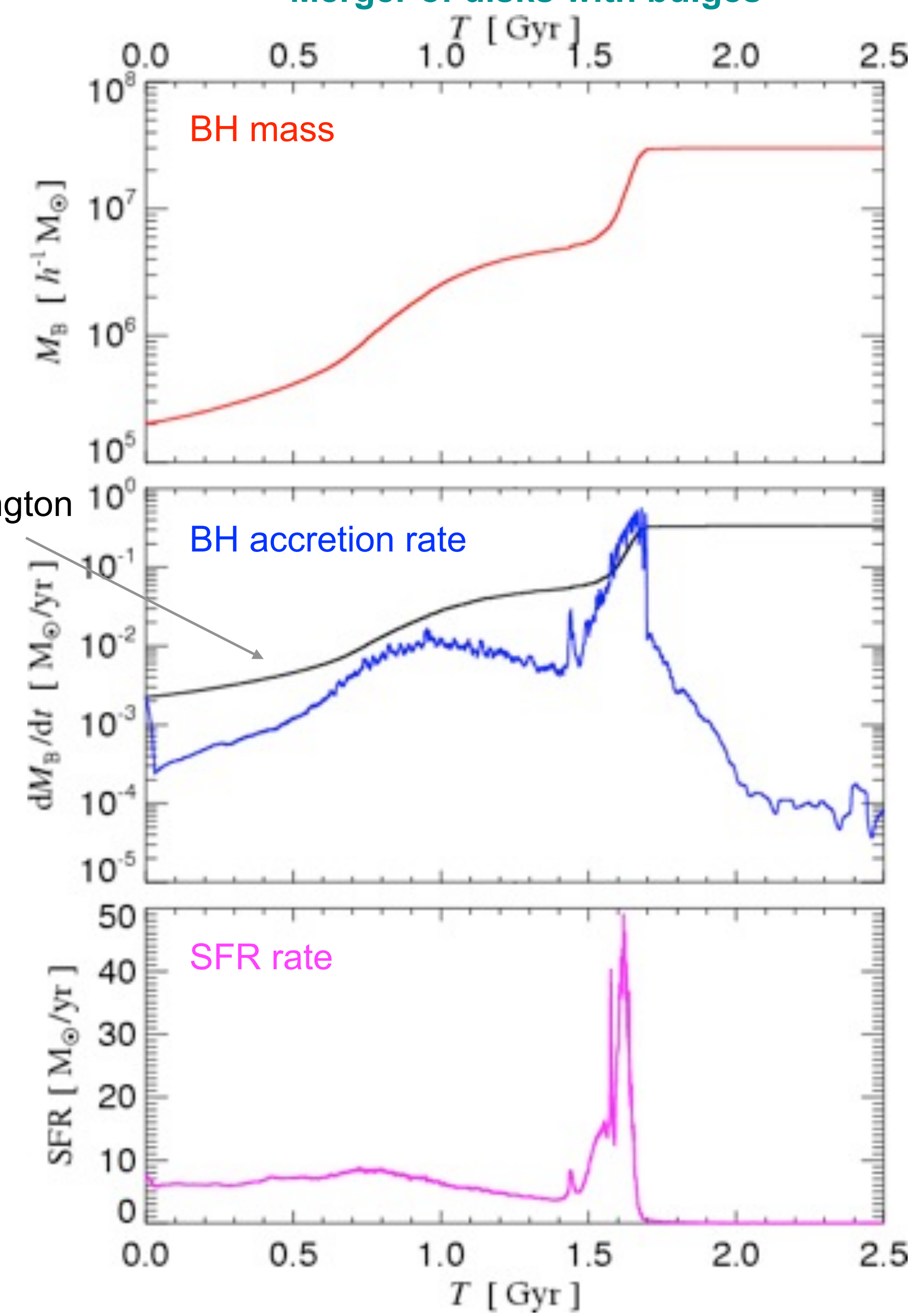
TIME EVOLUTION OF STAR FORMATION RATE AND BLACK HOLE GROWTH IN A MERGER

Merger of bulgeless disks

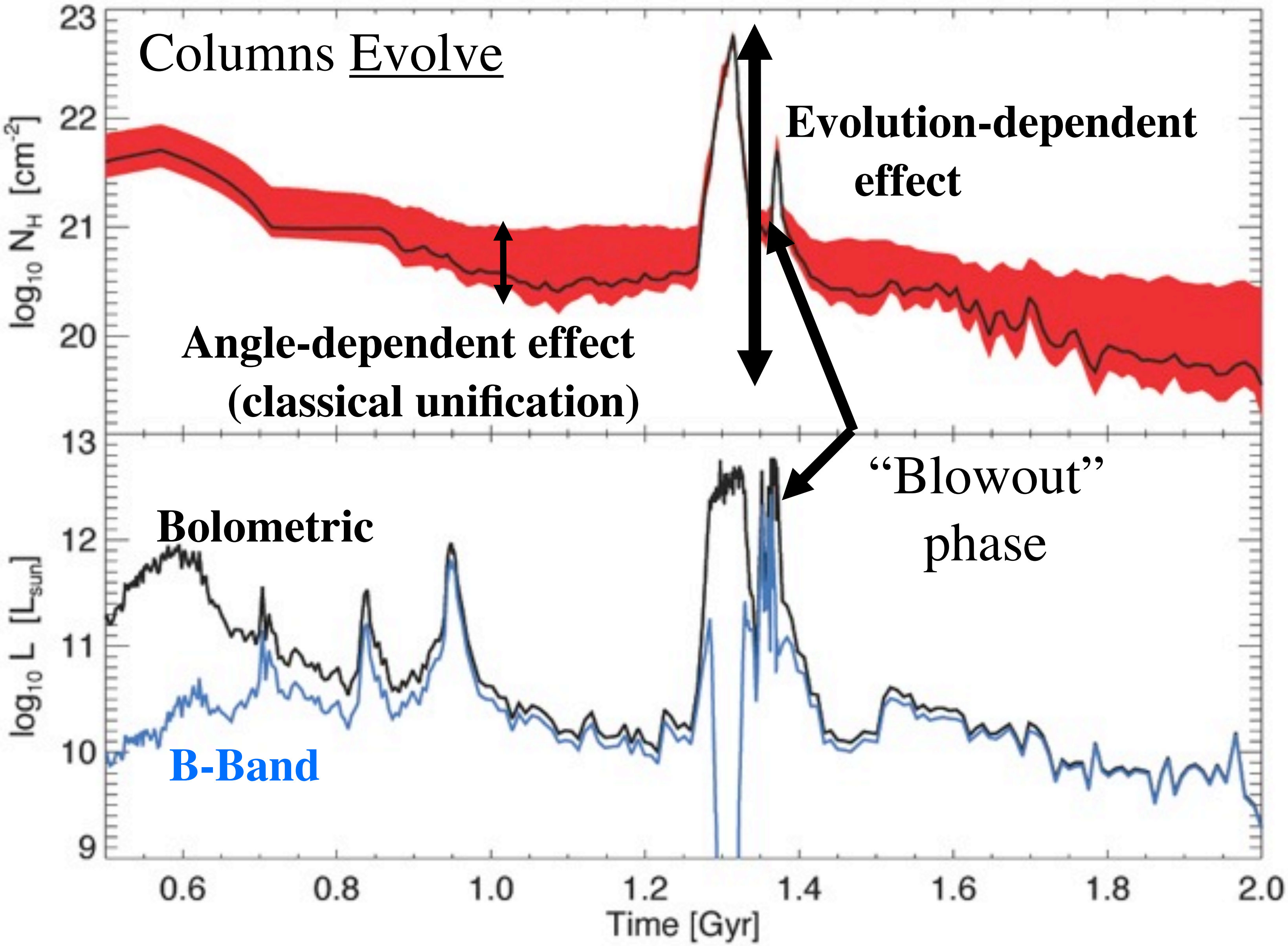


50%
Eddington
rate

Merger of disks with bulges



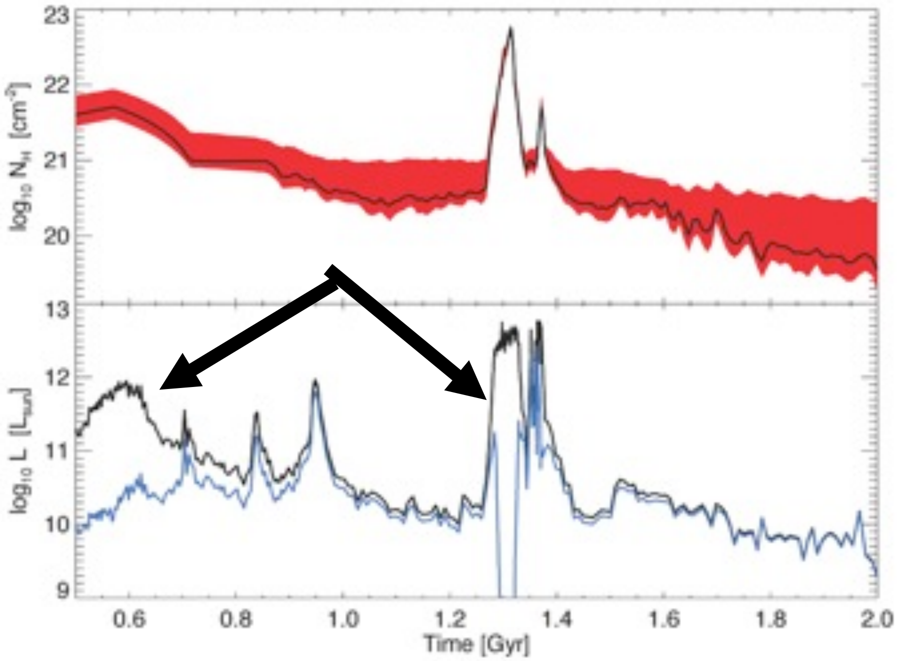
Quasar Lightcurves:



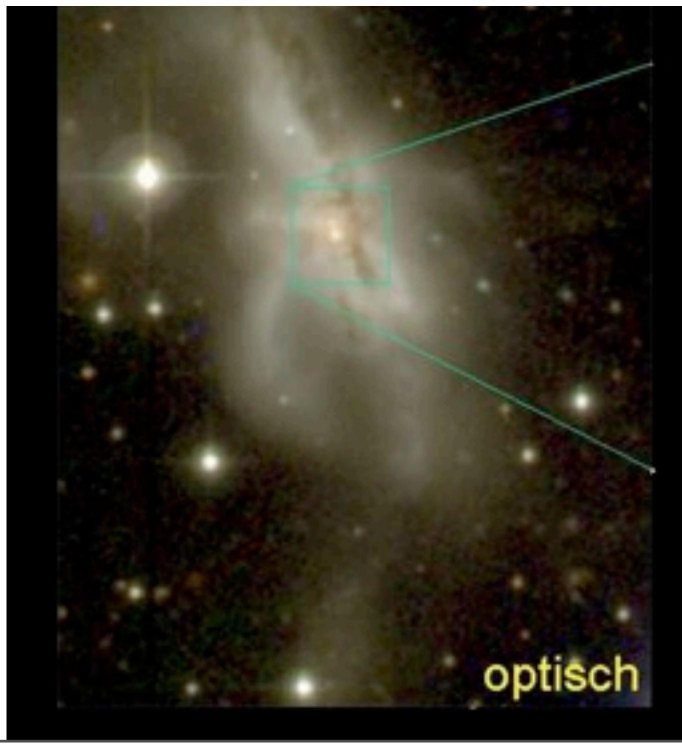
- Multi-phase ISM decomposition: gas+dust+metal columns

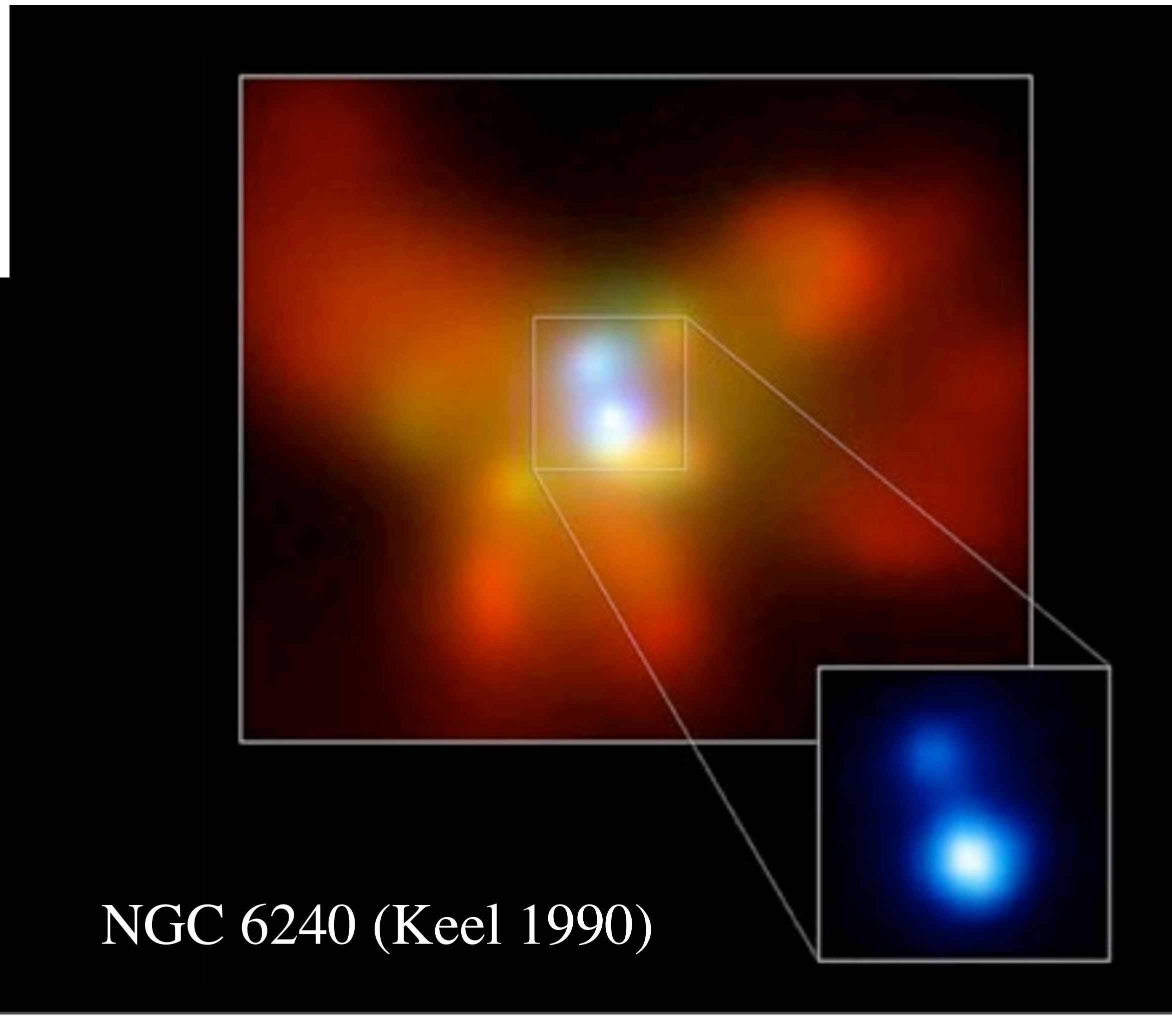
Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

GAS DENSITIES, COLUMNS, STAR FORMATION RATES CHANGE RAPIDLY



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

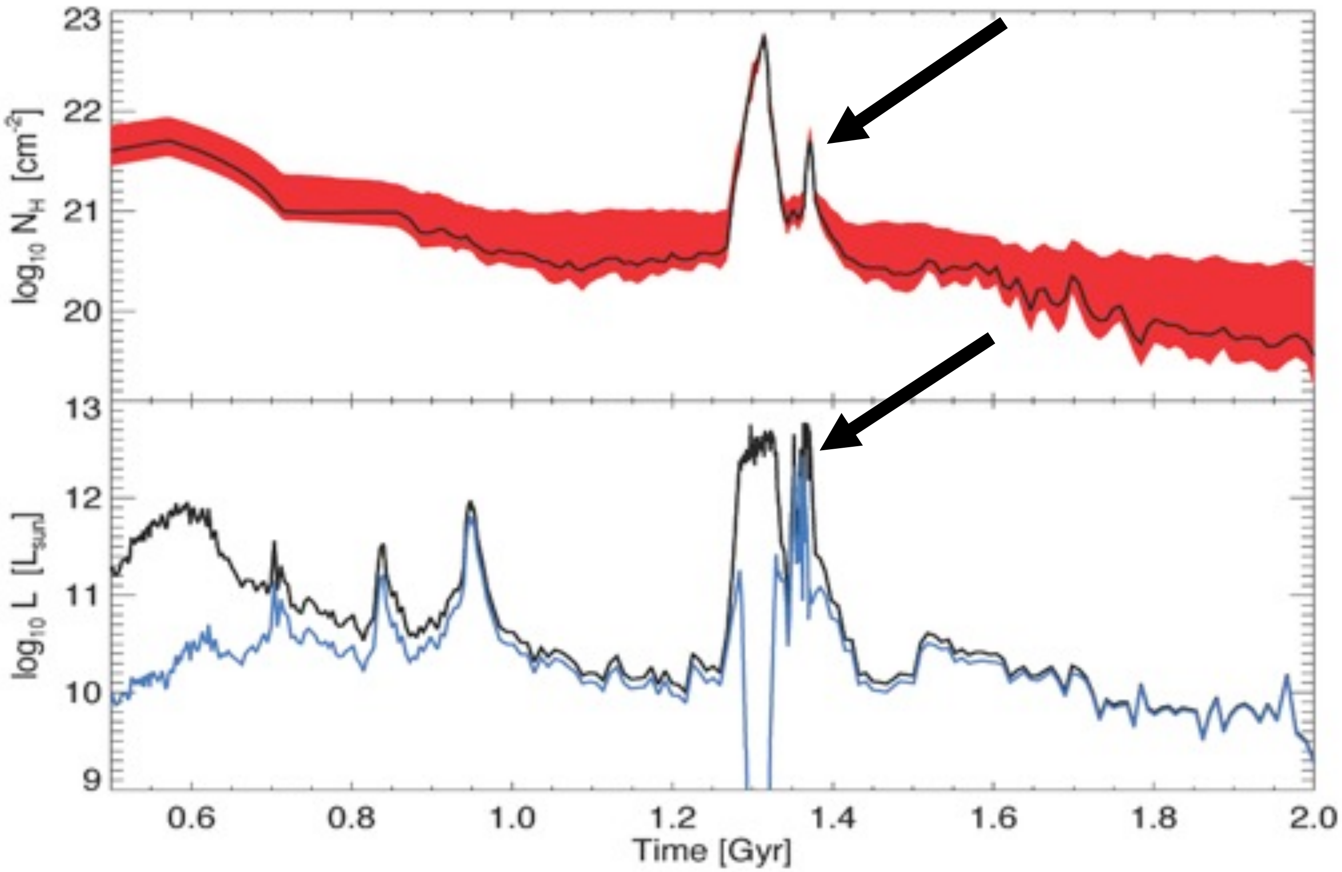




NGC 6240 (Keel 1990)

Feedback Is Necessary to Reveal the Brightest Quasars

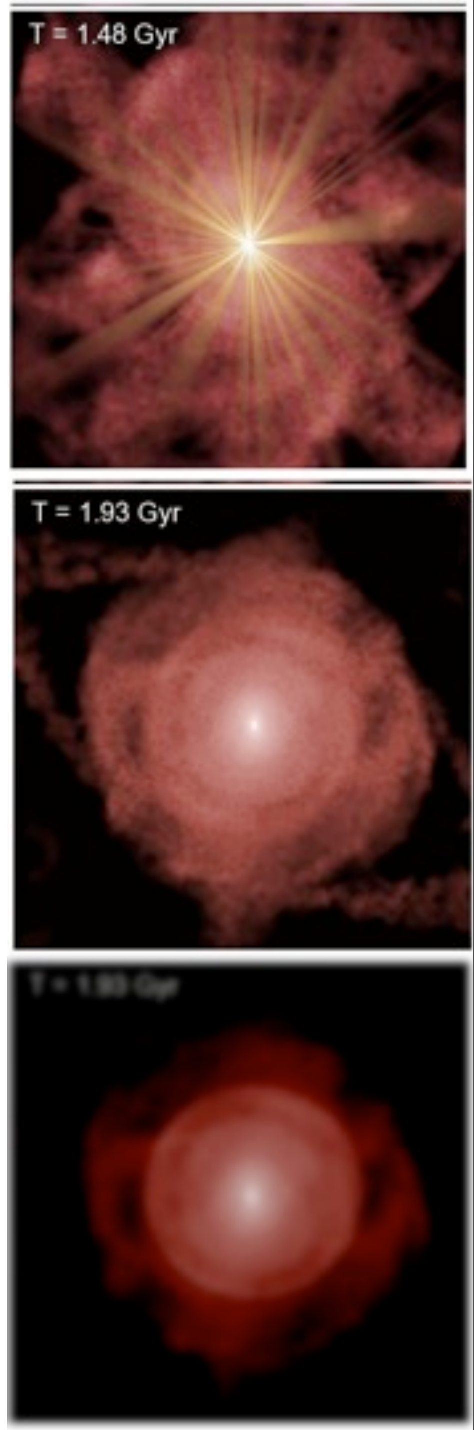
GAS IS HEATED AND EXPELLED IN BLOWOUT, REVEALING A BRIEF, BRIGHT QUASAR



QSO = 1000xHost

QSO = Host

QSO = 0.1xHost



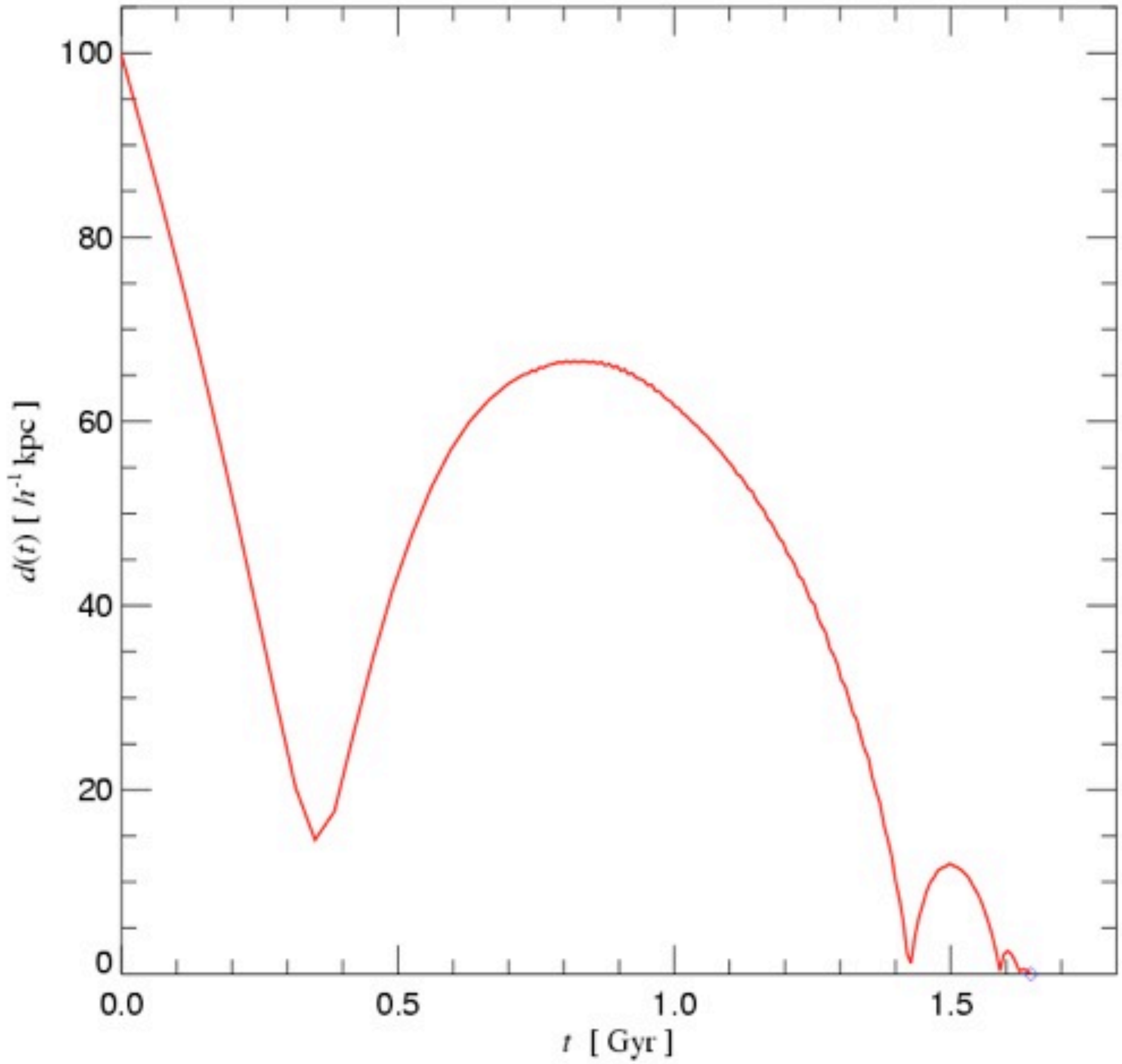
- Evolutionary Processes : NOT necessarily physical to “extrapolate” the local, quiescent torus
- Eddington ratios vs. host properties (size, luminosity, morphology, redshift)
- Active BH mass functions

Hopkins et al. 2005e

Galaxy mergers bring their central supermassive black holes quickly to separations less than ~100 pc

APPROACH OF THE BLACK HOLES IN MERGER SIMULATIONS

Note: The actual formation of a black hole binary, and the hardening of it, cannot presently be addressed by our simulations in an adequate way, due to lack of spatial dynamic range.



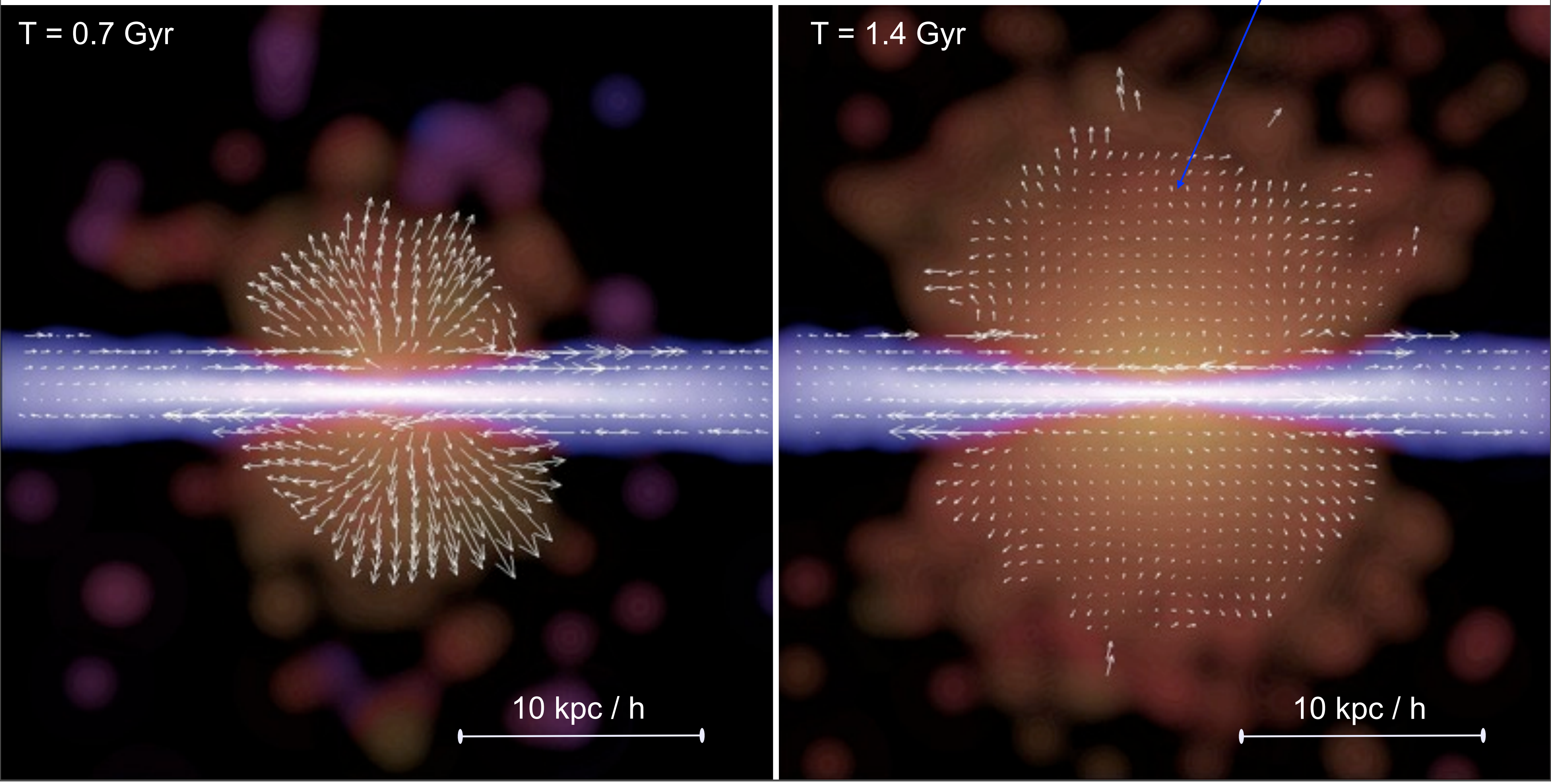
At low accretion rates, feedback by the central black hole activity may blow a weak wind into the halo

GAS FLOW INTO THE HALO

Isolated disk galaxy with bulge

Generated hot halos hold 1-2% of the gas

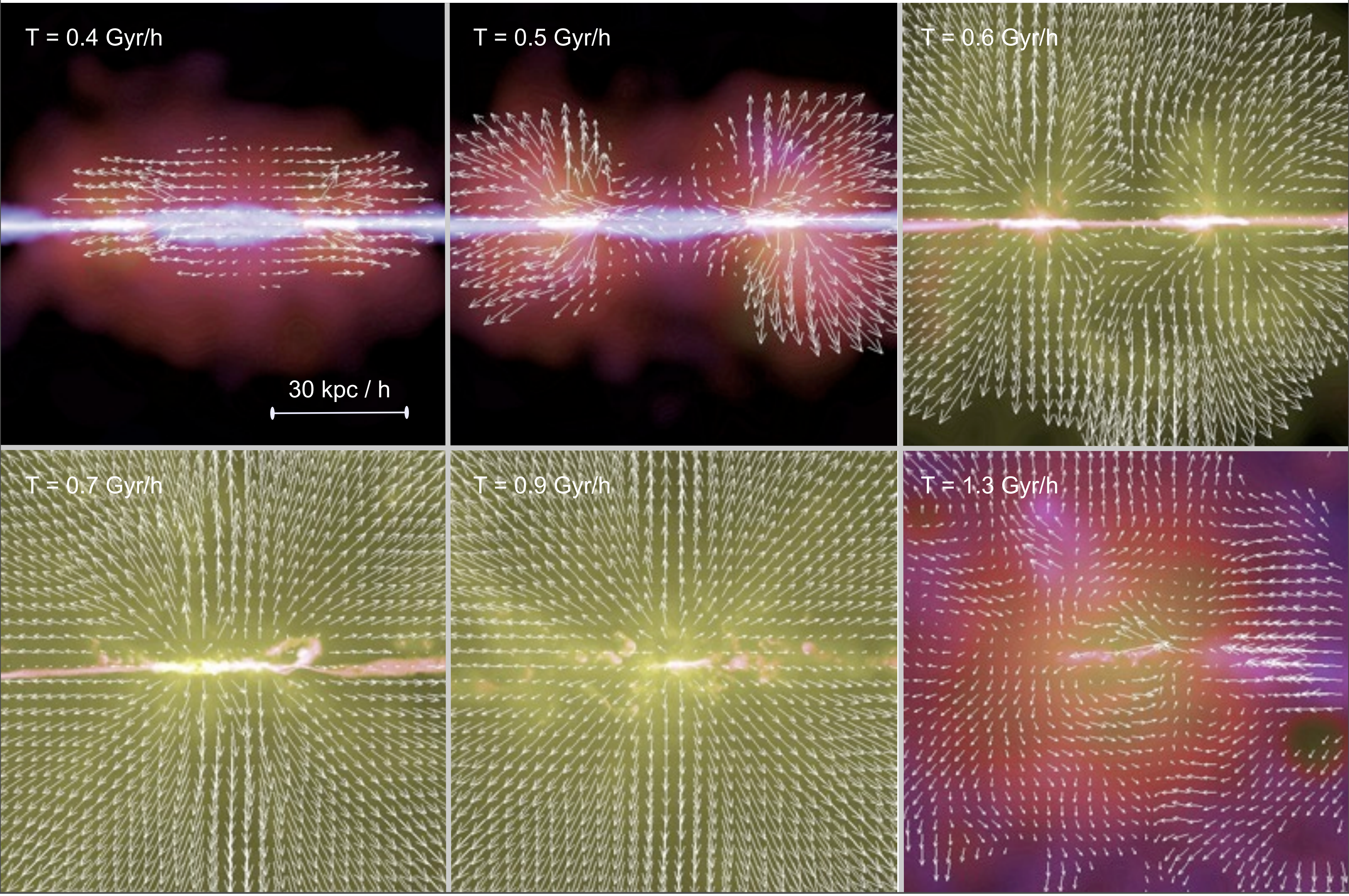
(dynamic range in gas surface density ~10^6)



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

GAS OUTFLOW BY AGN FEEDBACK

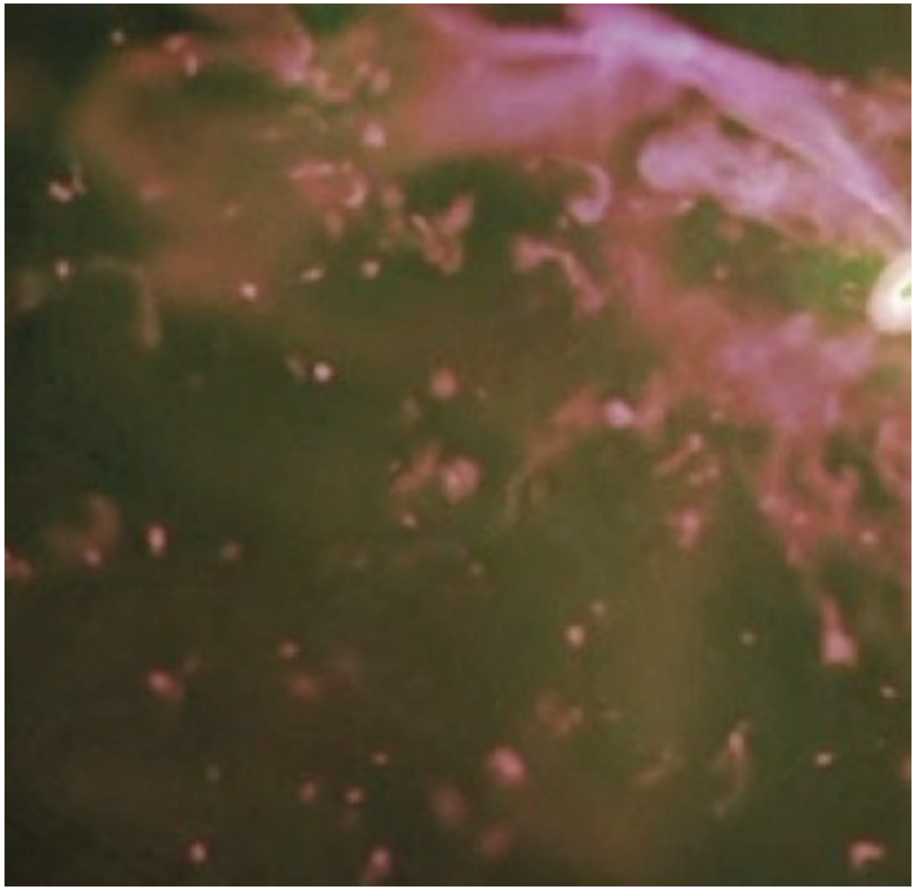
(outflow reaches speeds of up to ~1800 km/sec)

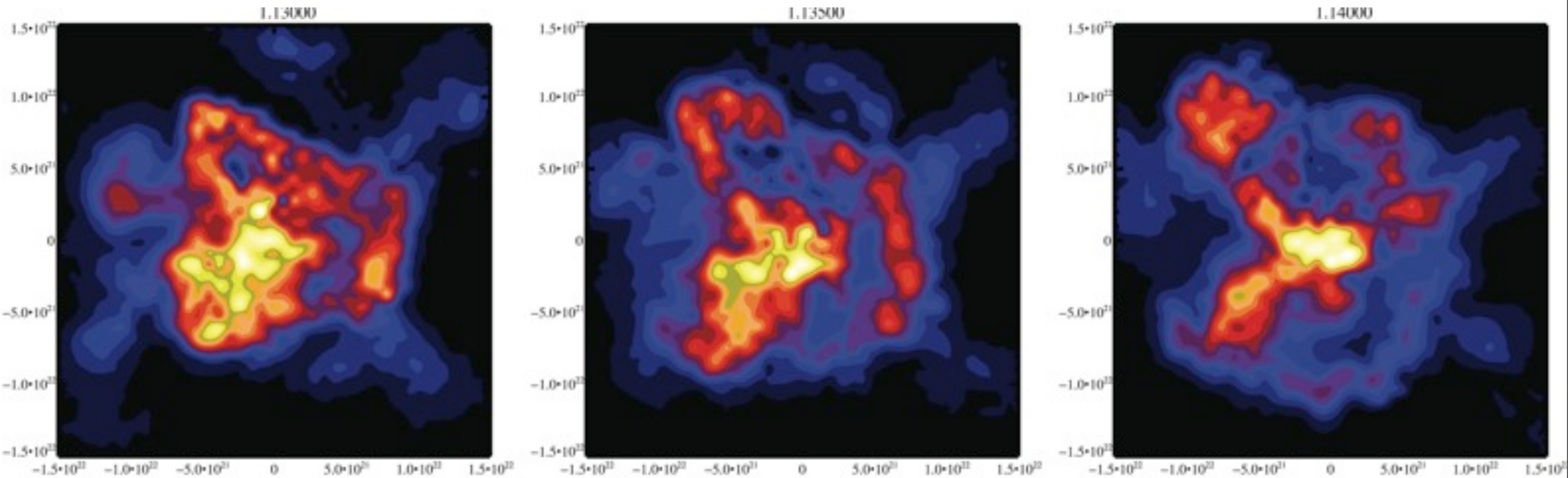


Outflows are Explosive and Clumpy

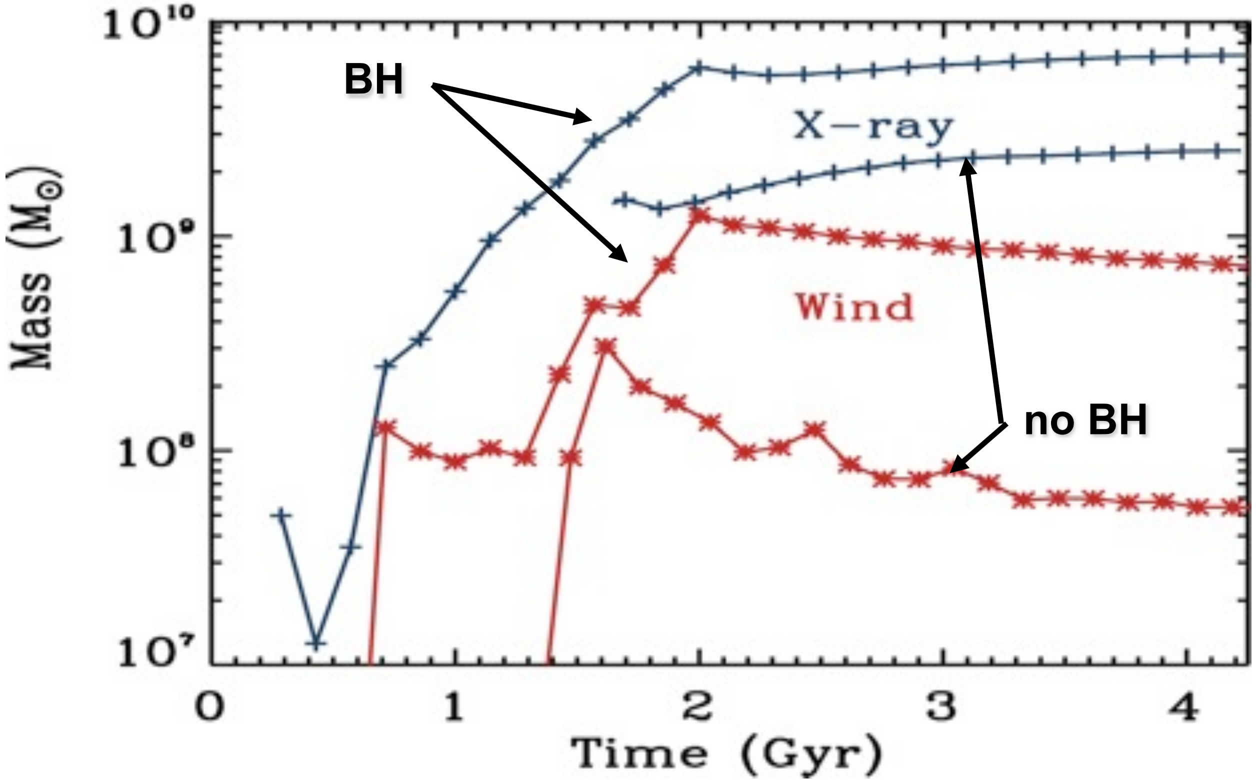
- Rapid BH growth => point-like injection
  - Explosion, independent of coupling

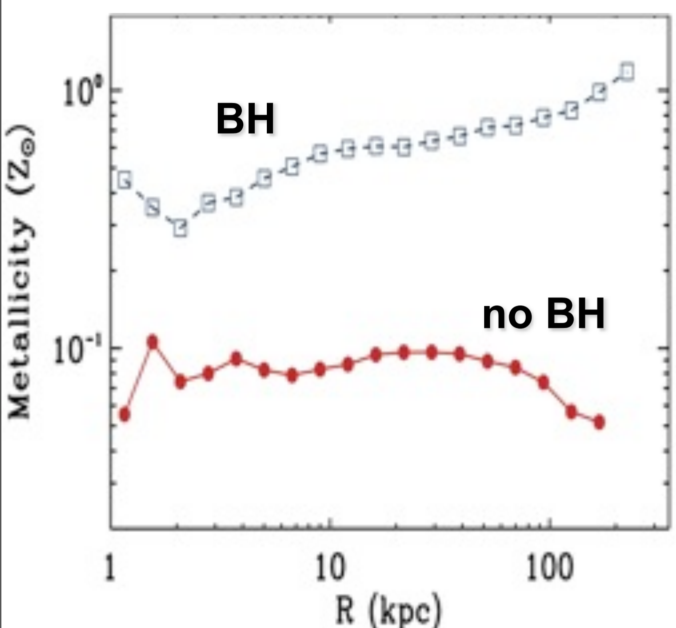
- Clumpy
  - ULIRG cold/warm transition (S. Chakrabarti)
  - CO outflows (D. Narayanan)

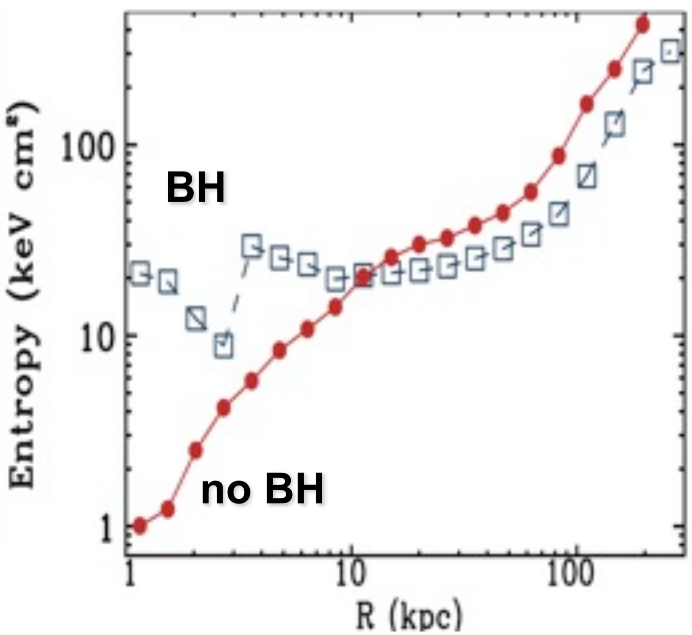


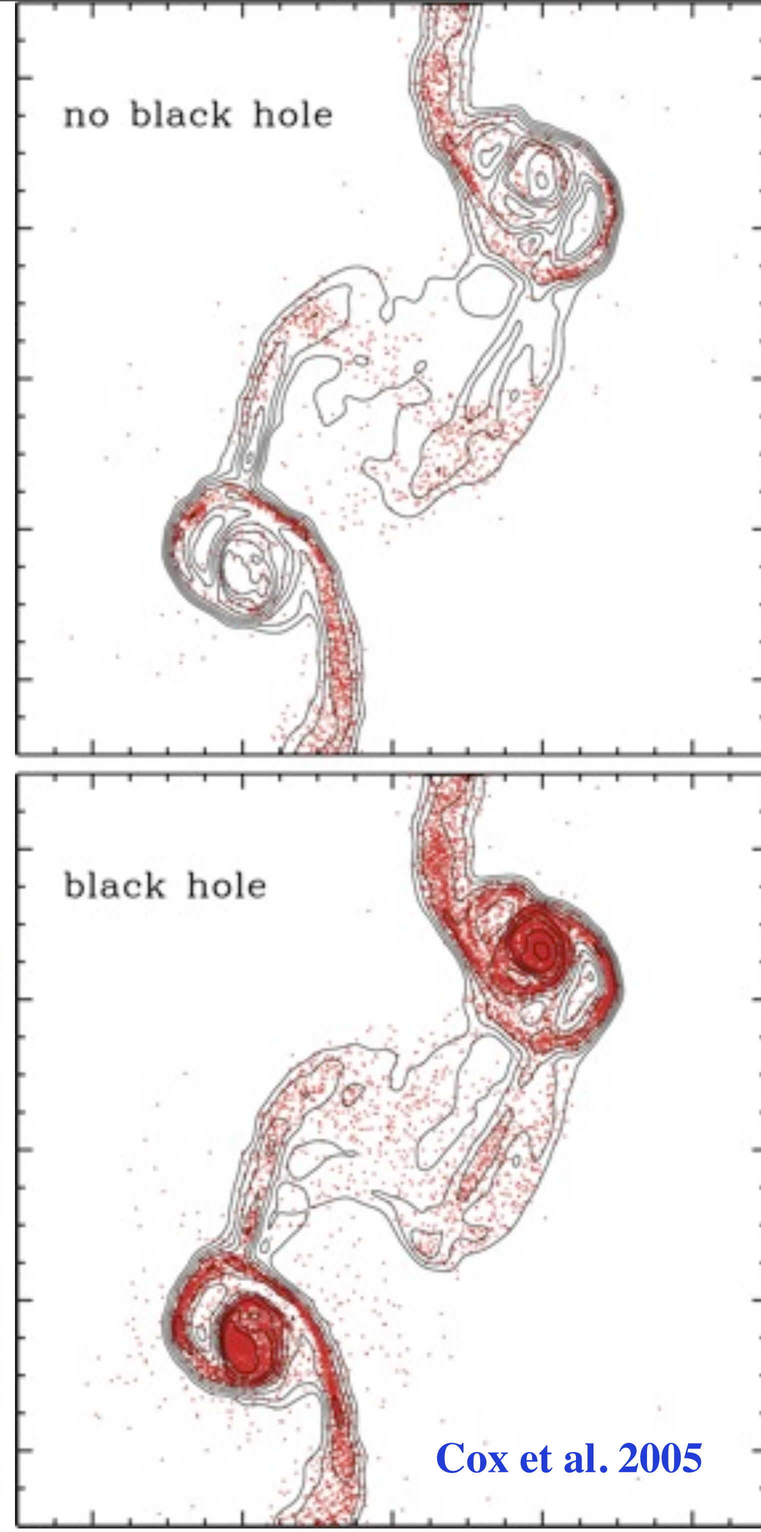


Expel Metal-Enriched Gas & Build Up X-Ray Halo









The properties of merger remnants are altered by the AGN activity

THE FATE OF THE GAS IN A MERGER WITH AND WITHOUT BLACK HOLES

Merger without black hole:

initial gas mass: $1.56 \times 10^{10}\ h^{-1} M_{\odot}$

- 89.0% turned into stars
- 0.05% expelled from halo
- 1.2% cold, star forming gas
- 9.8% diffuse gas in halo

X-ray luminosity

$\sim 9.5 \times 10^{39}$ erg s^{-1}

Residual star formation rate

$\sim 0.13\ M_{\odot} yr^{-1}$

(1 Gyr after galaxy coalesence)

Merger with black hole:

initial gas mass: $1.56 \times 10^{10}\ h^{-1} M_{\odot}$

- 51.9% turned into stars
- 35.3% expelled from halo
- 0% cold, star forming gas
- 11.1% diffuse gas in halo
- 1.6% swallowed by BH(s)

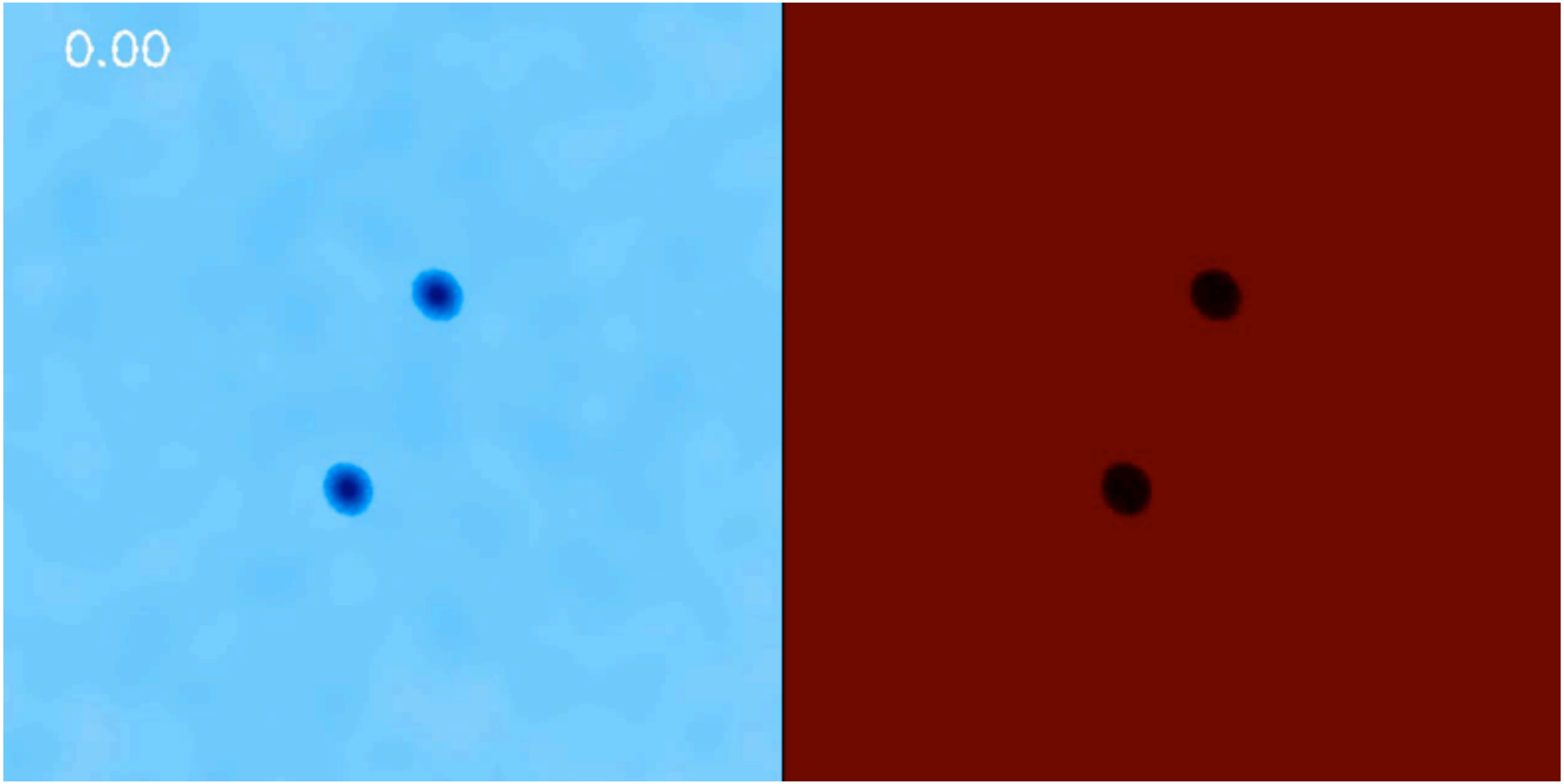
X-ray luminosity

$\sim 4.8 \times 10^{38}$ erg s^{-1}

Residual star formation rate

$0\ M_{\odot} yr^{-1}$

(1 Gyr after galaxy coalesence)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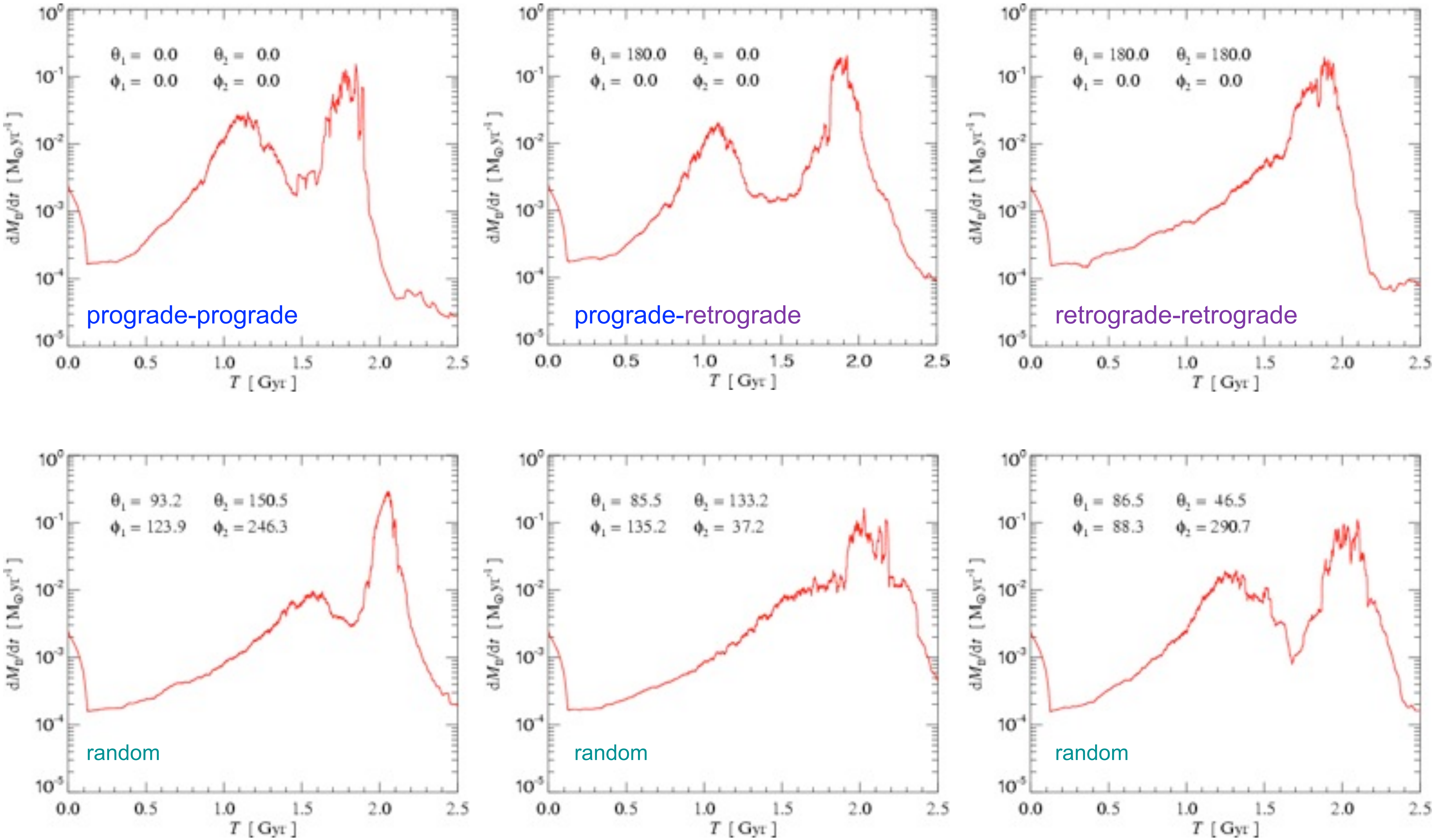
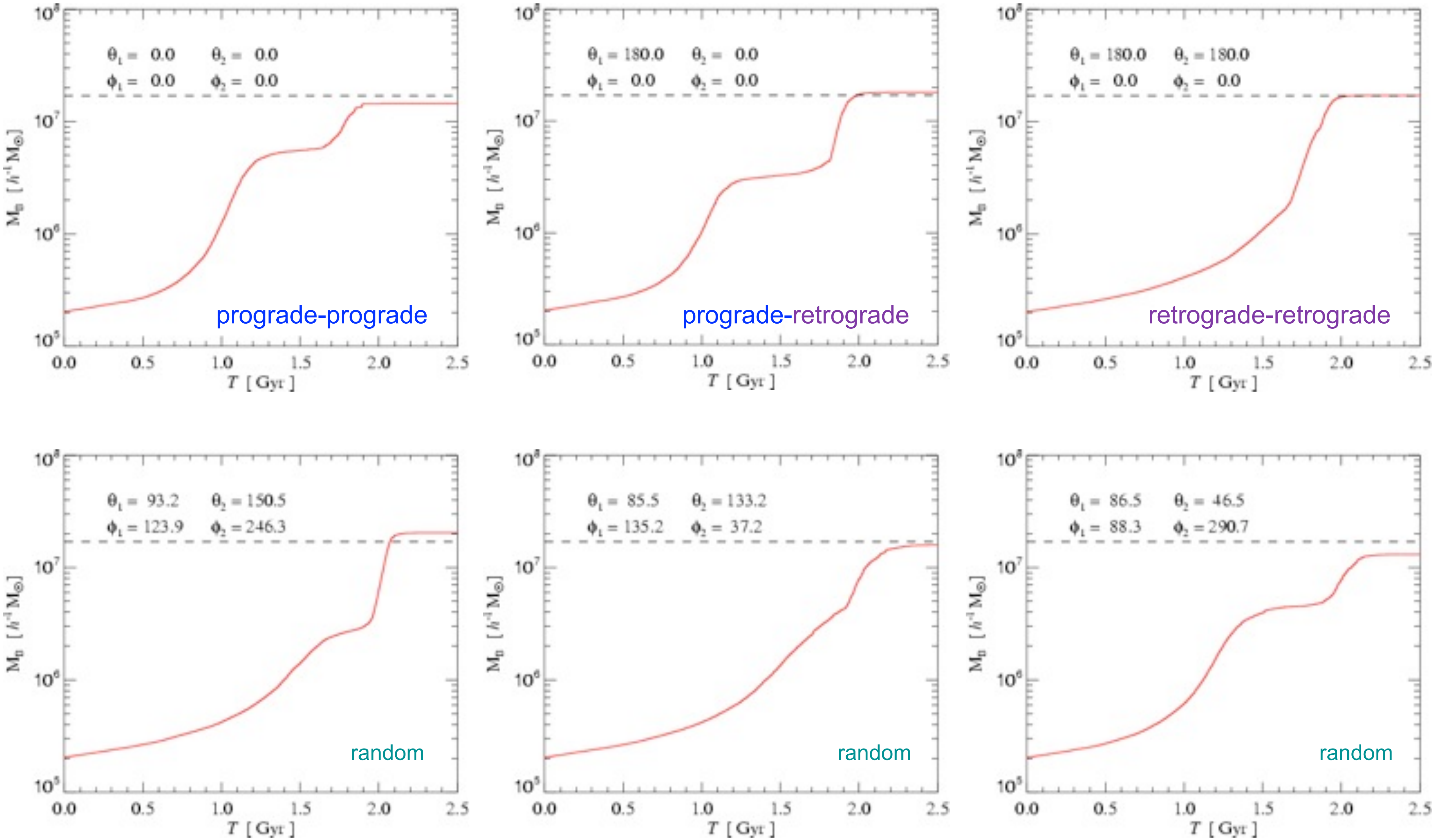
The orientation of the galaxies in the merger affects the accretion pattern

BLACK HOLE ACCRETION RATE FOR DIFFERENT GALAXY ORIENTATIONS



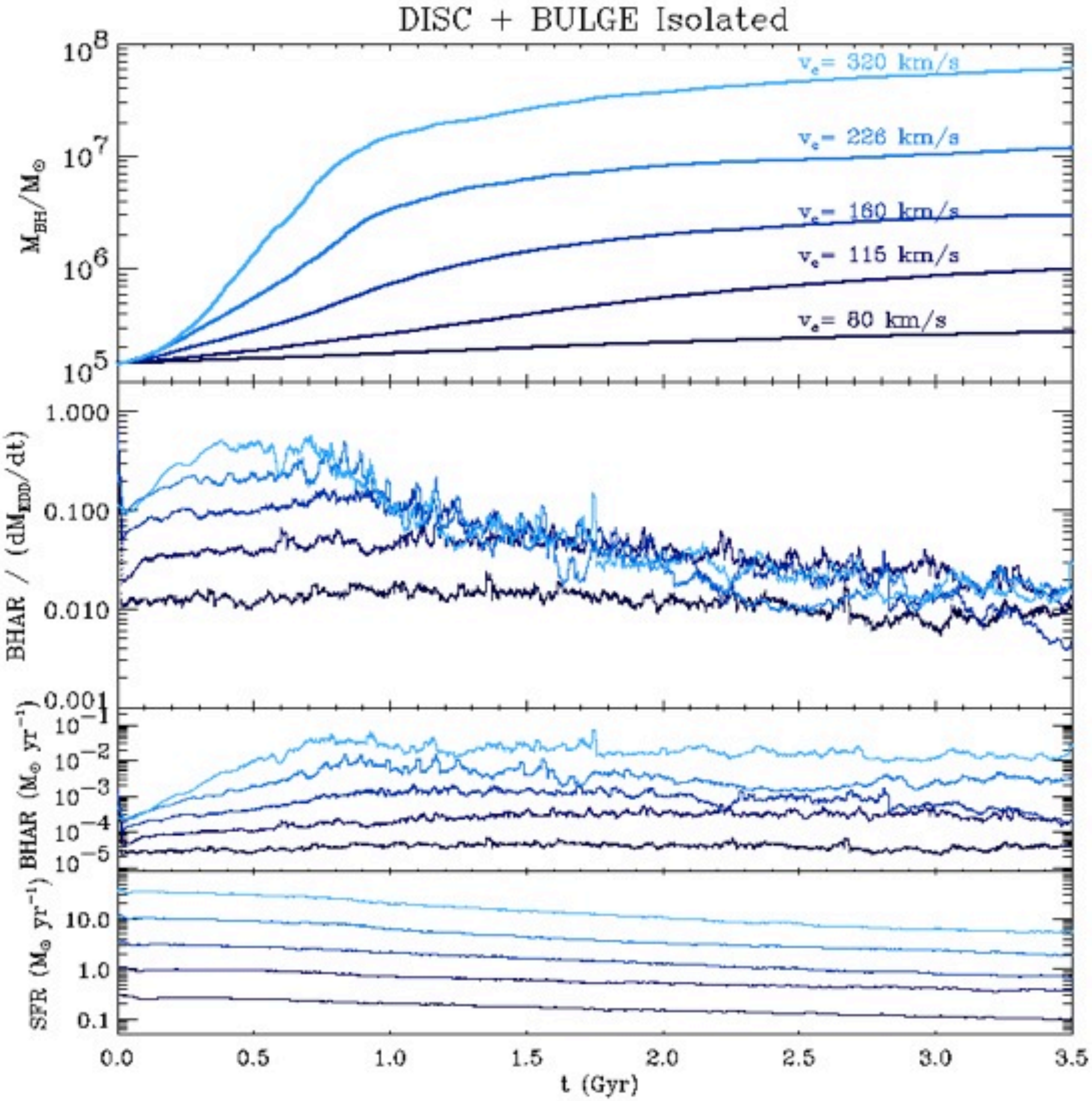
The final black hole mass in the merger remnant is not very sensitive to details of the orbit of the collision

BLACK HOLE MASS FOR DIFFERENT GALAXY ORIENTATIONS



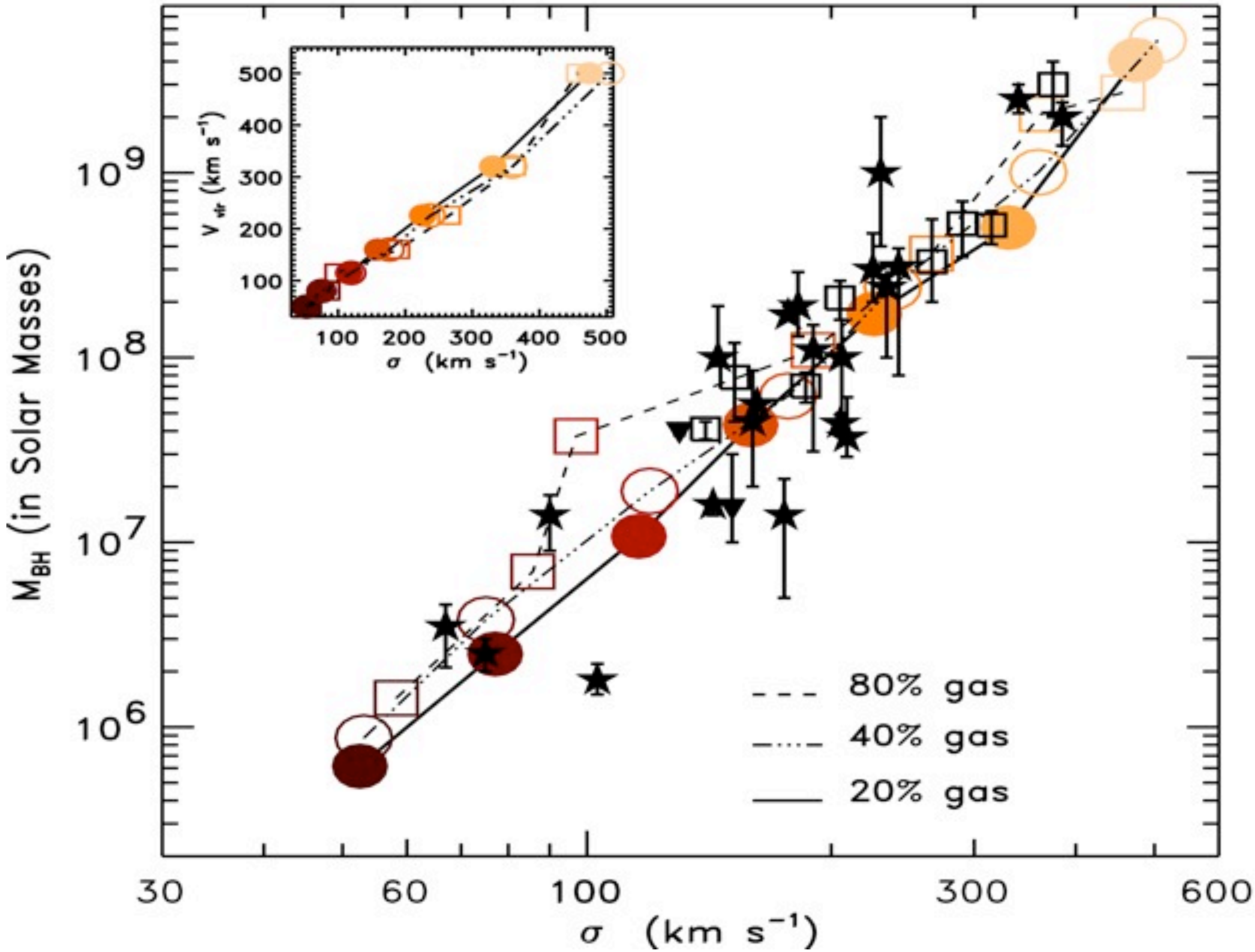
In larger galaxies, black holes grow to progressively larger sizes before feedback throttles the growth rate

GROWTH OF BLACK HOLES IN ISOLATED GALAXIES AS A FUNCTION OF GALAXY SIZE



Feedback-driven “Blowout” Gives M-sigma Relation

PREVENTS RUNAWAY BLACK HOLE GROWTH

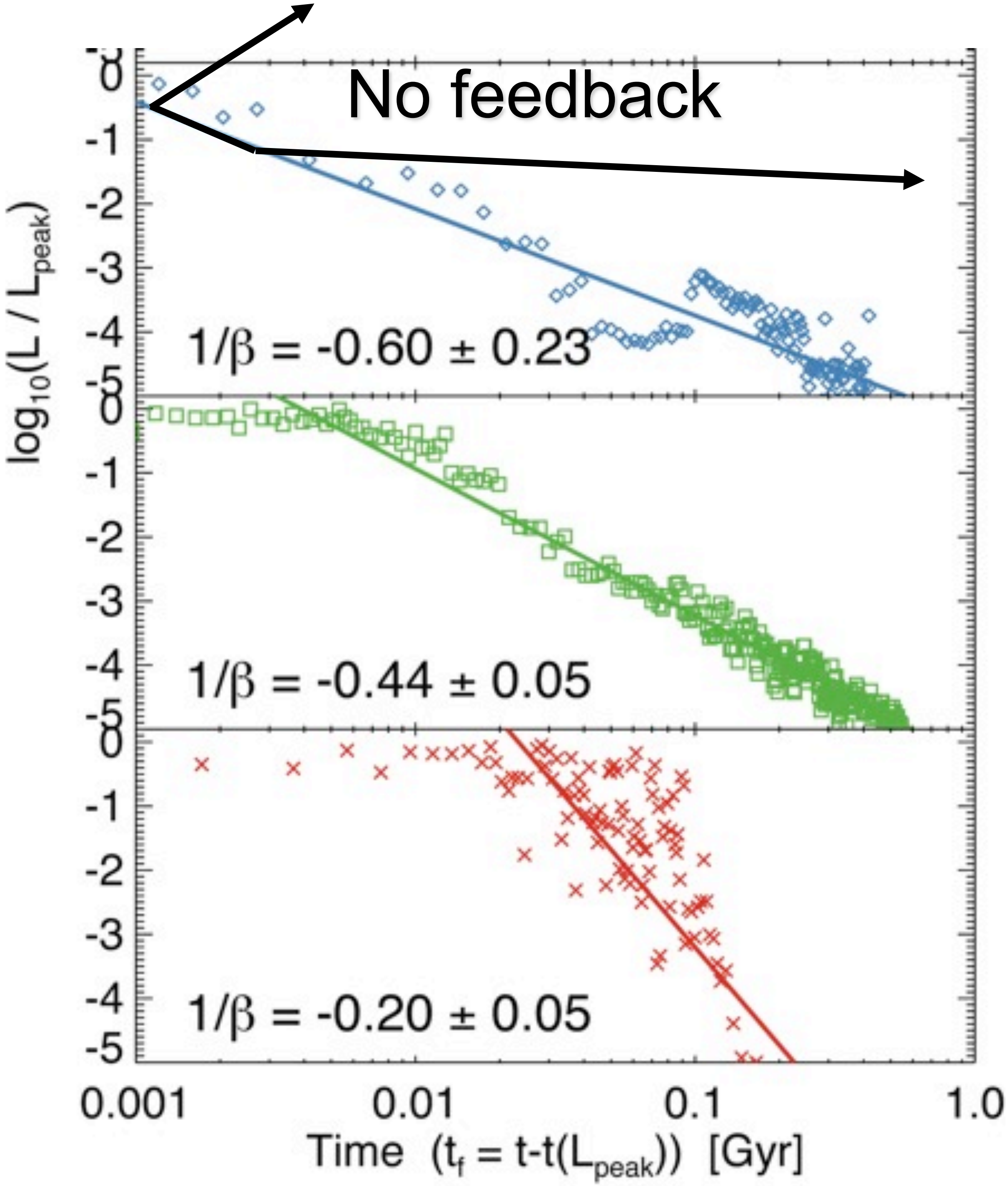


(Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002)

Di Matteo et al. 2005

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

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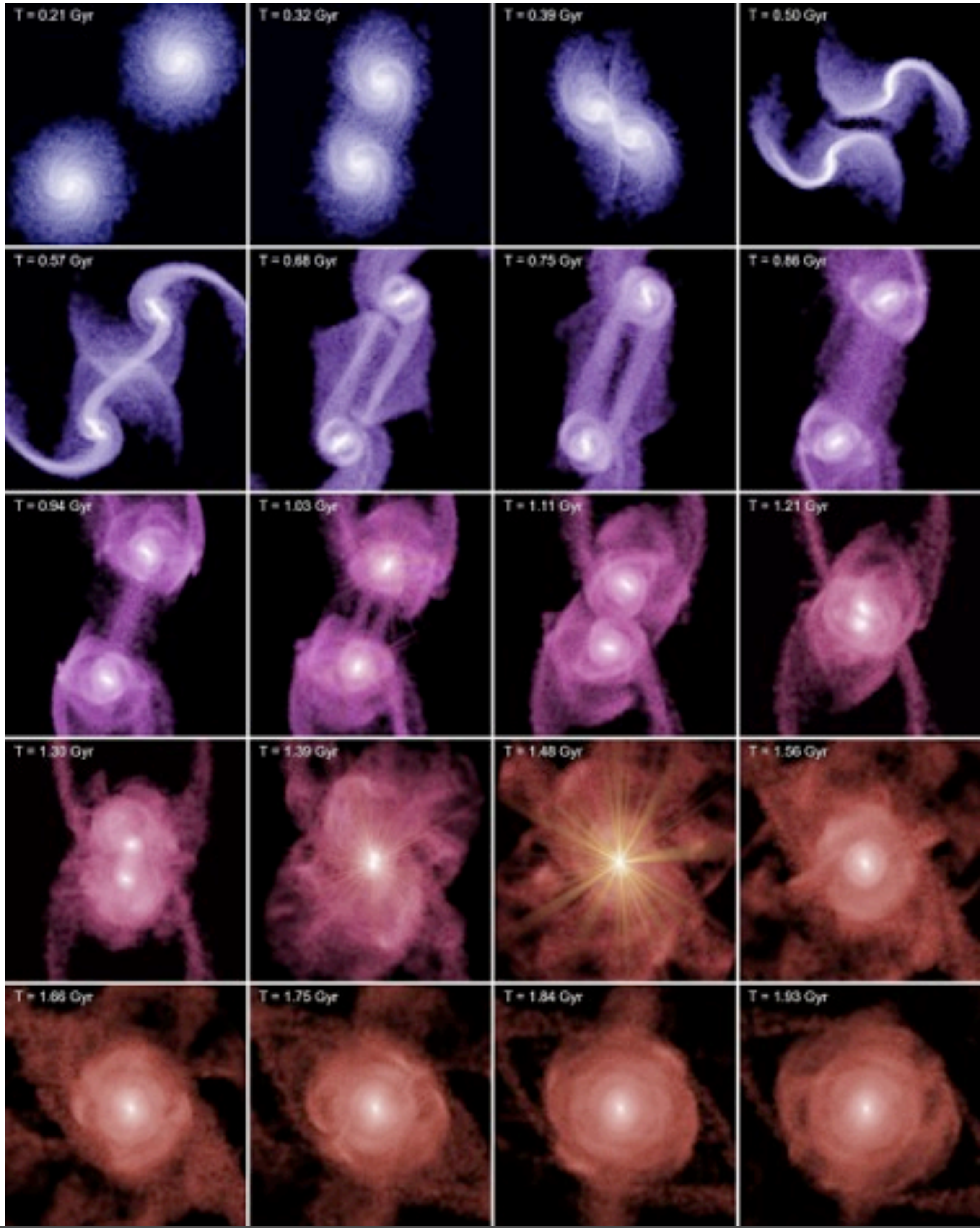

- "Quasar Lifetime" : a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity
    - General solution depends just on energy injection

Hopkins et al. 2006b

Feedback Determines the Decay of the Quasar Light Curve

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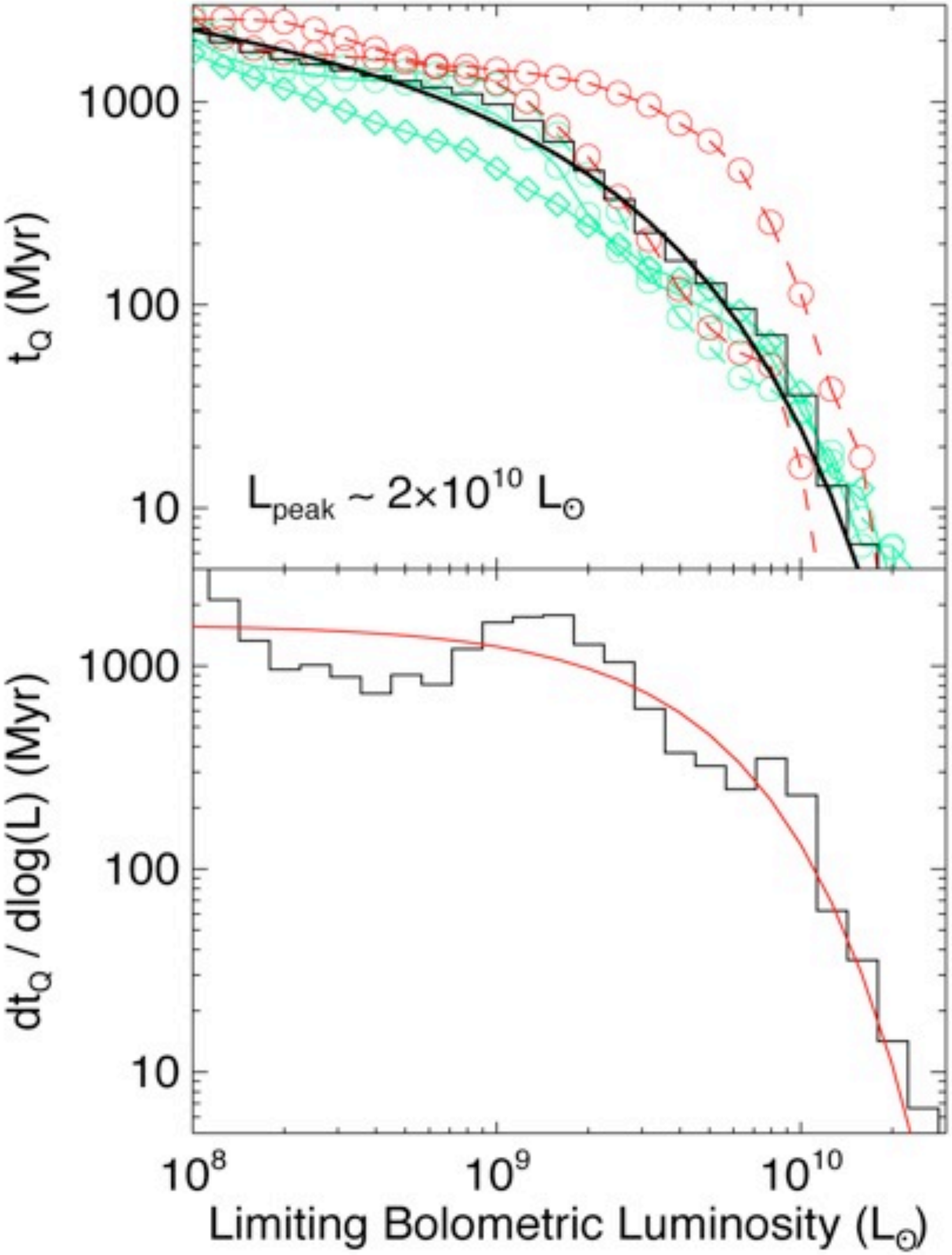

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Hopkins et al. 2006b

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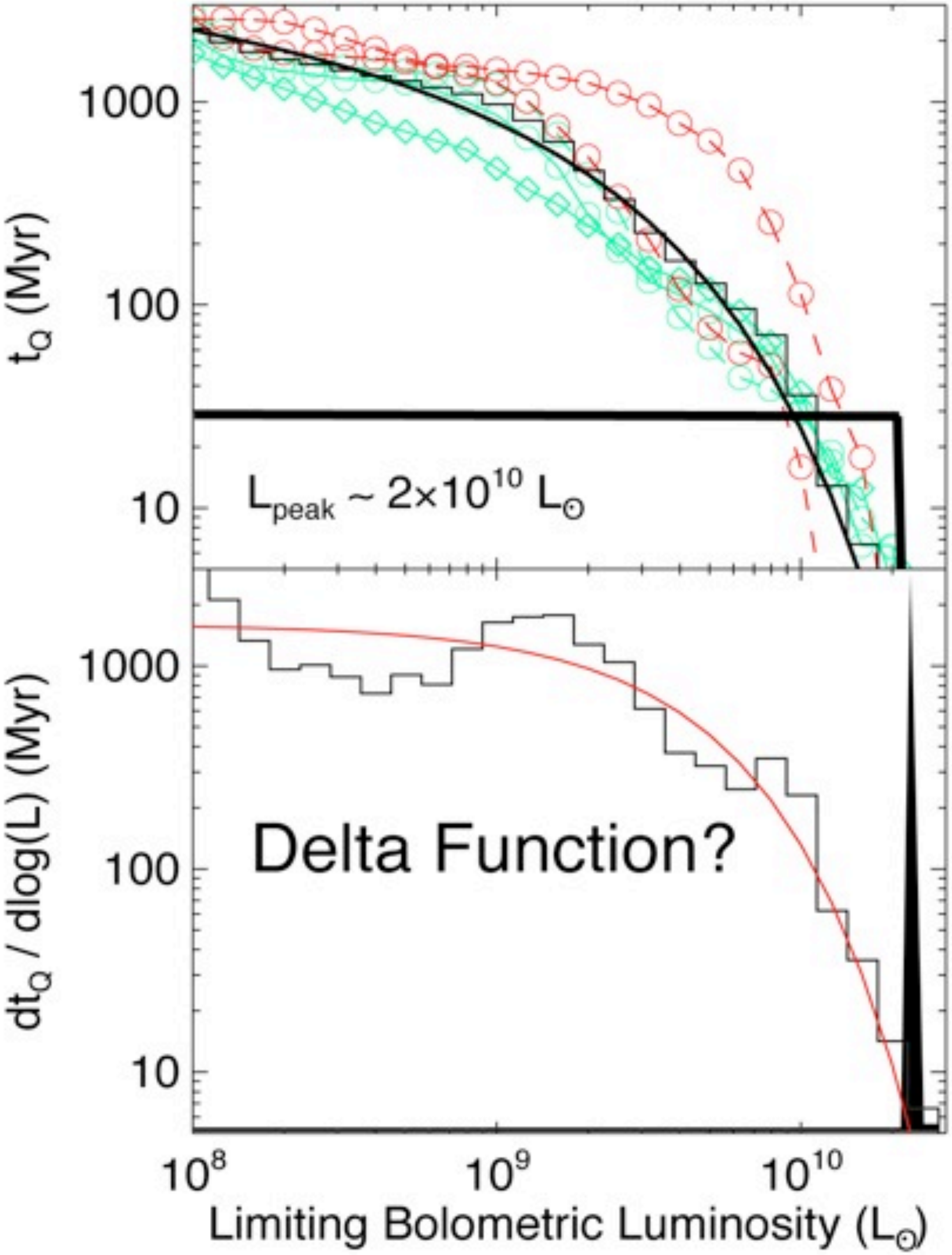

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Hopkins et al. 2006b

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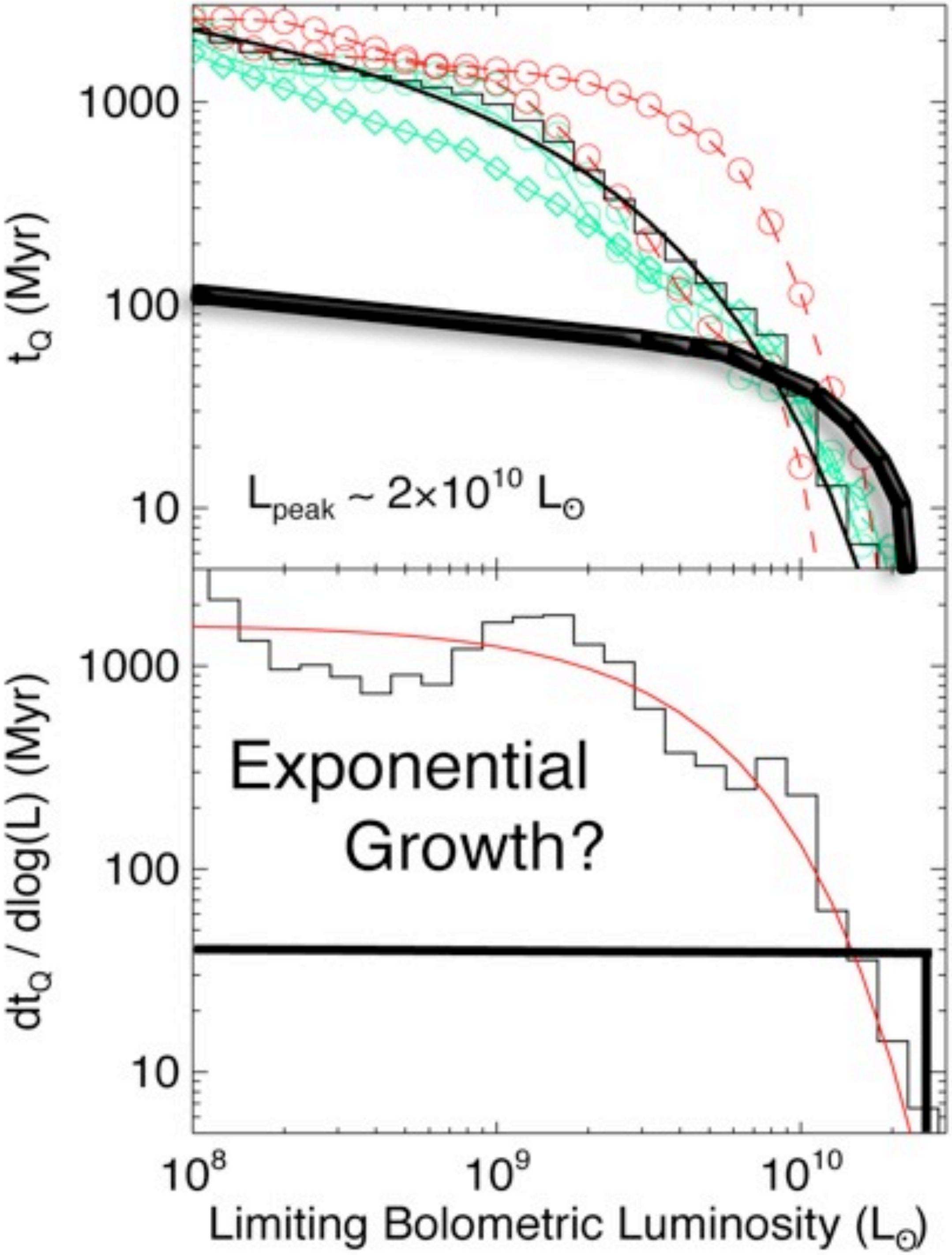

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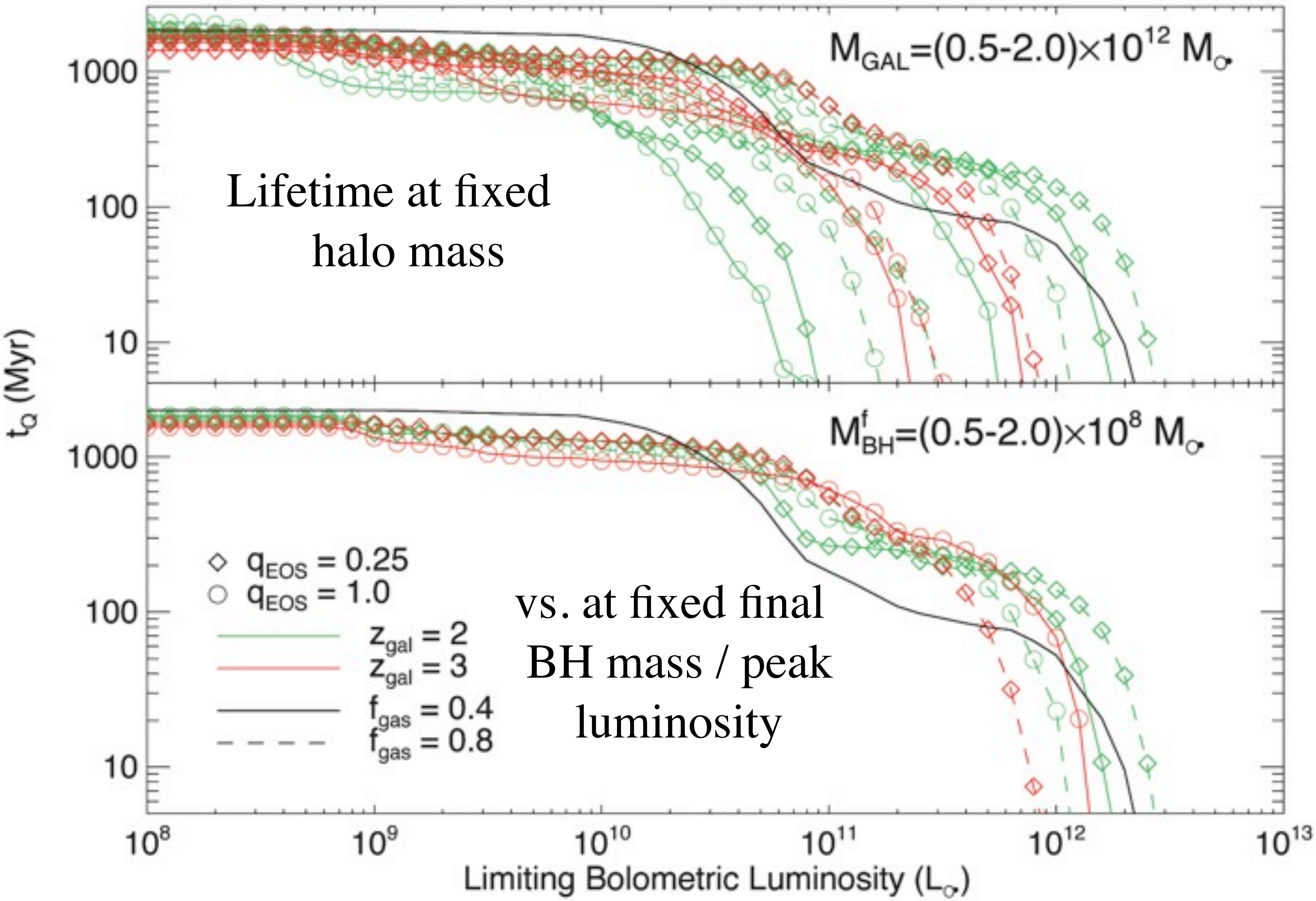
Hopkins et al. 2006b

Robustness of Quasar Lifetimes

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

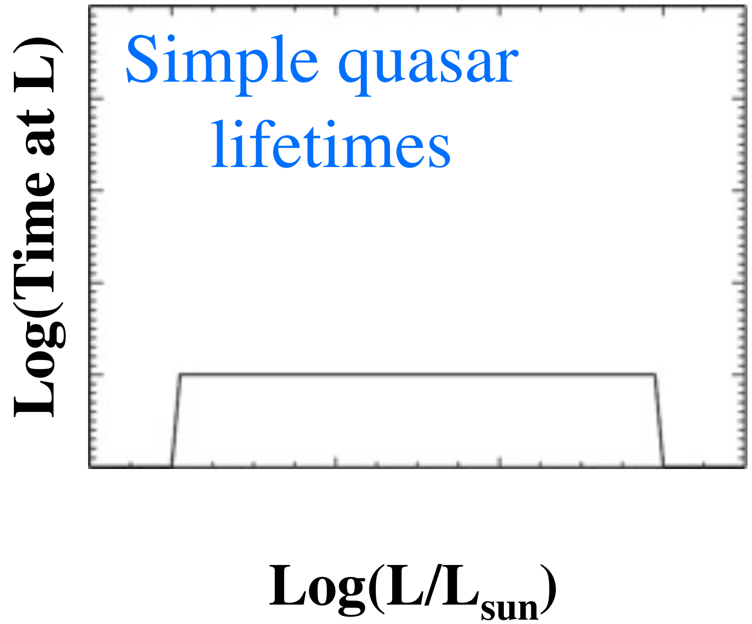


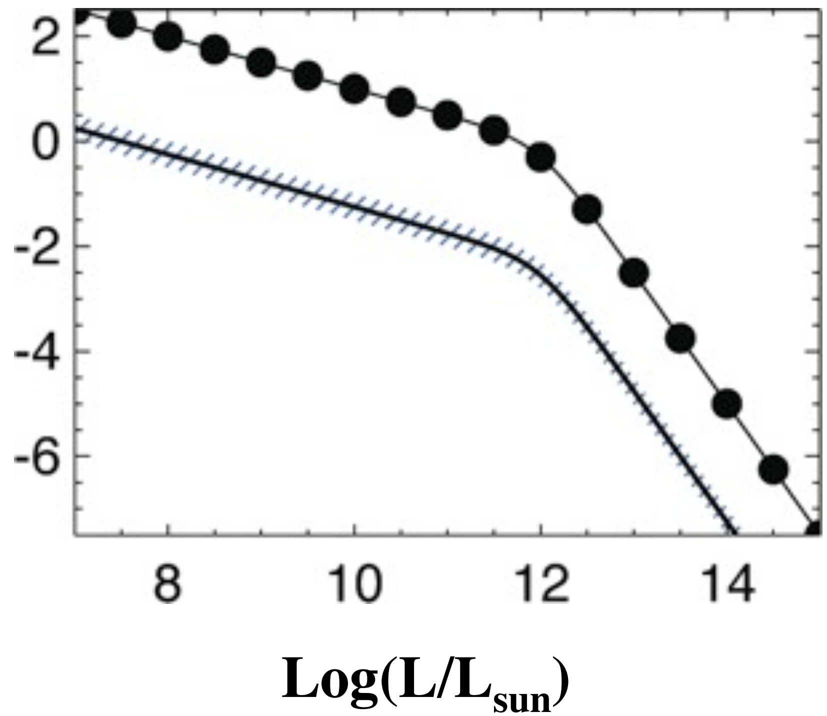
Hopkins et al. 2006b

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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

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





- 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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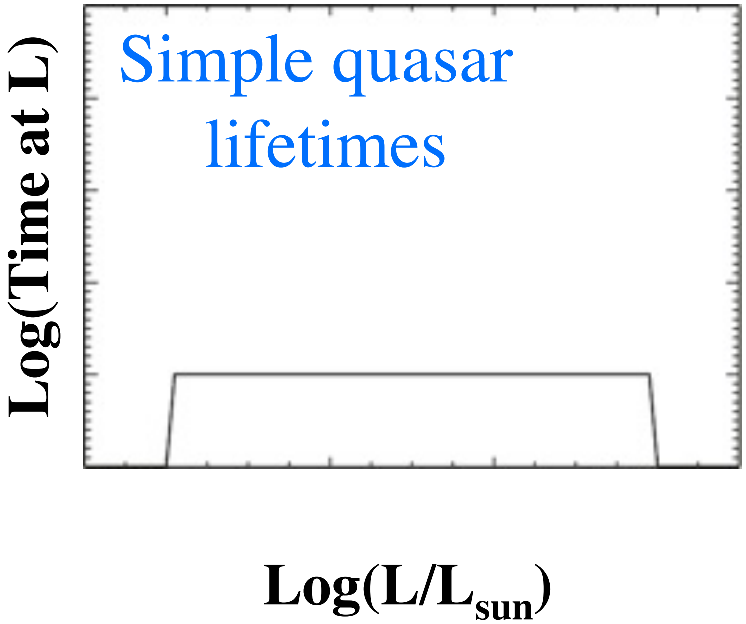

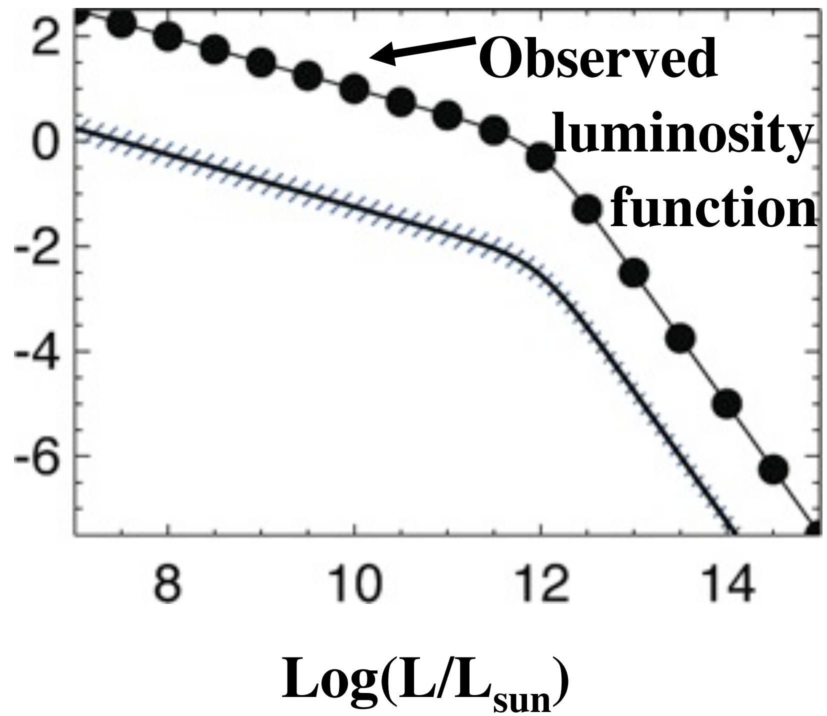

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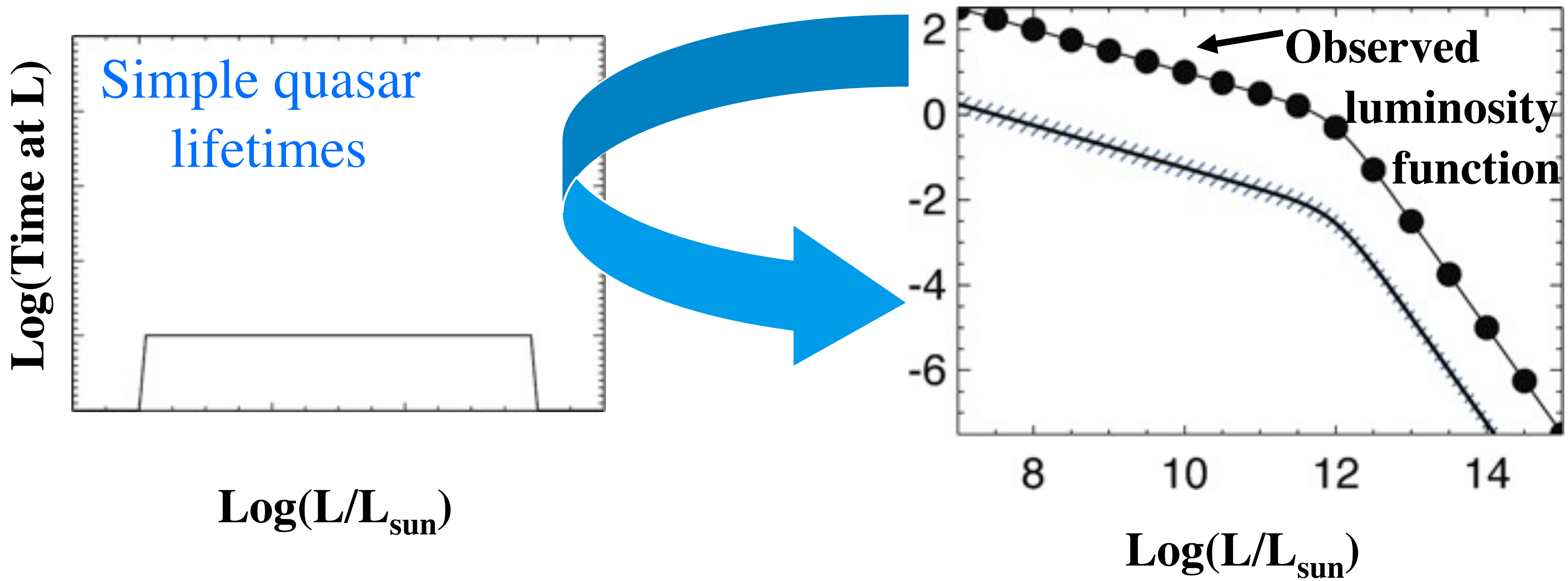

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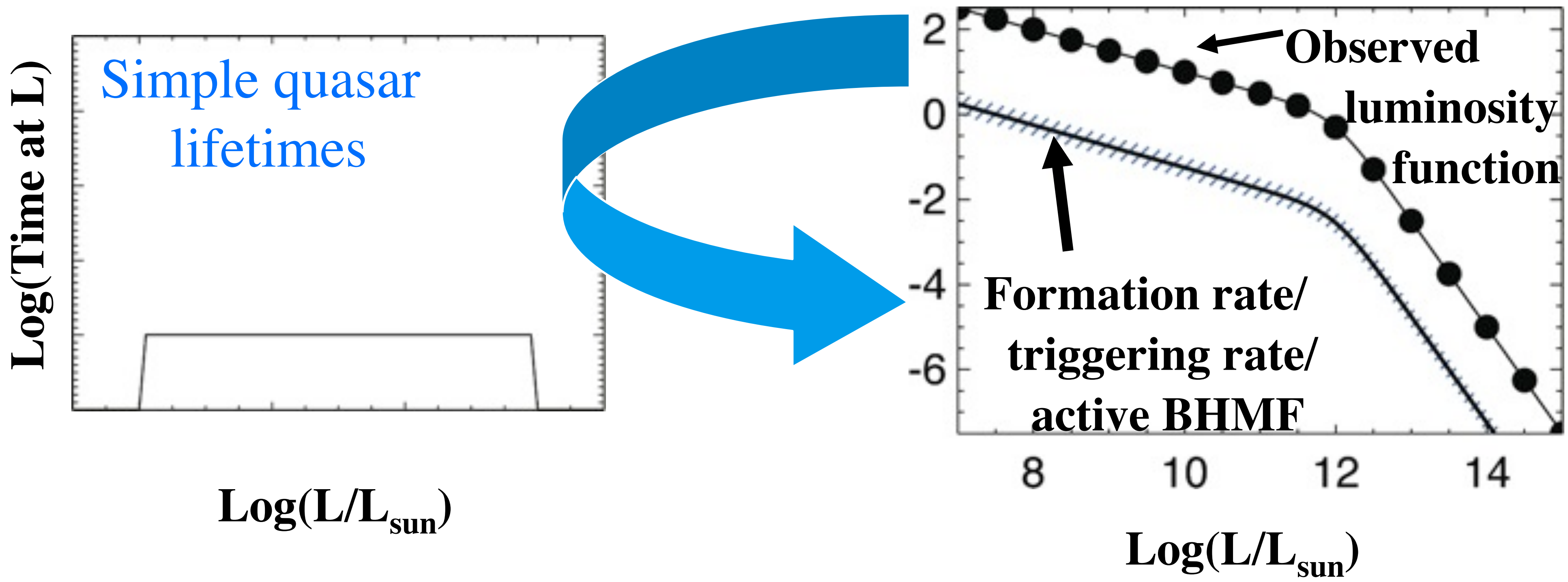
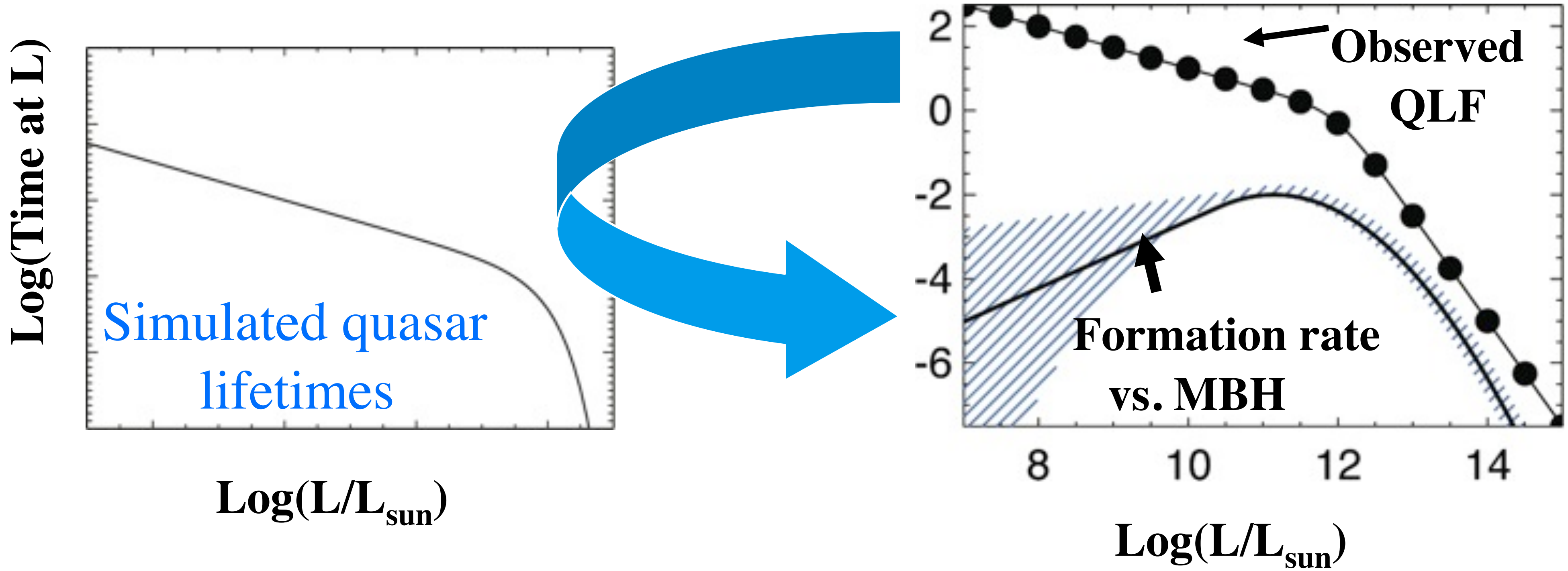


- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF

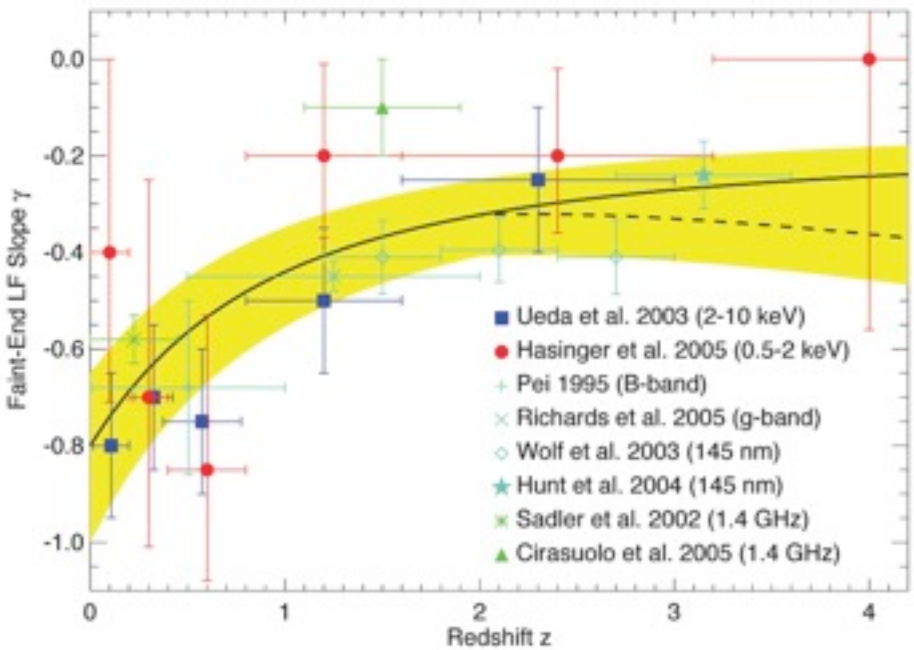
$$\phi(L) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\log L}(L) = \int \frac{\mathrm{d}t(L, L_{\rm peak})}{\mathrm{d}\log(L)}\,\dot{n}(L_{\rm peak})\,\mathrm{d}\log(L_{\rm peak}).$$



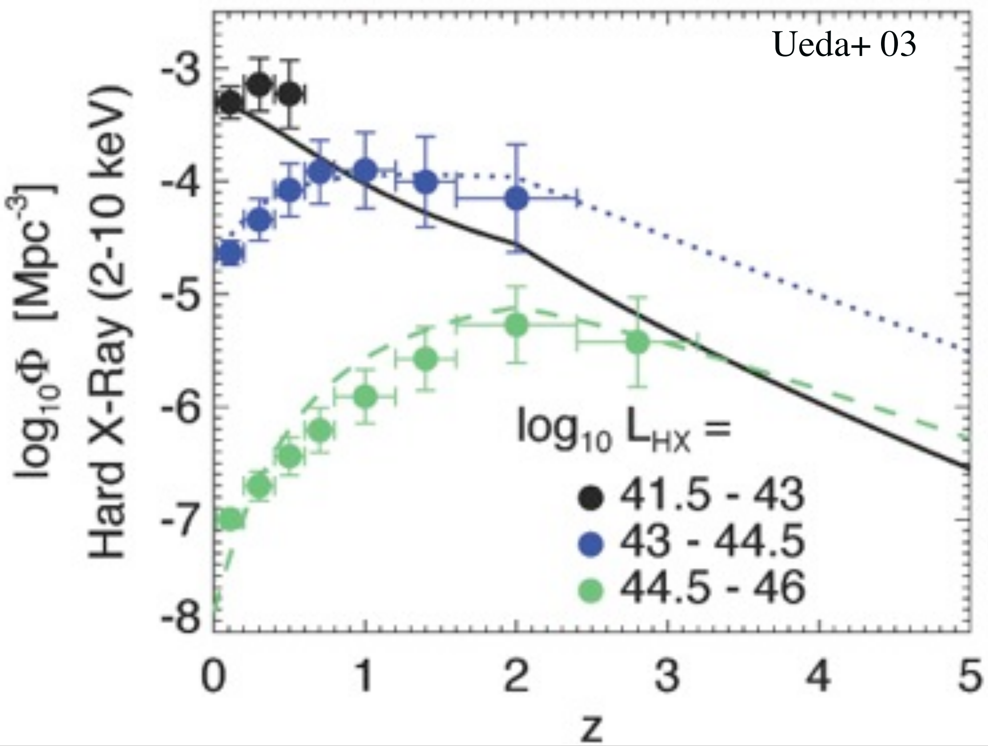
- Feedback-regulated lifetime drives a given QSO to lower L after blowout, and spends more time at low-L
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts

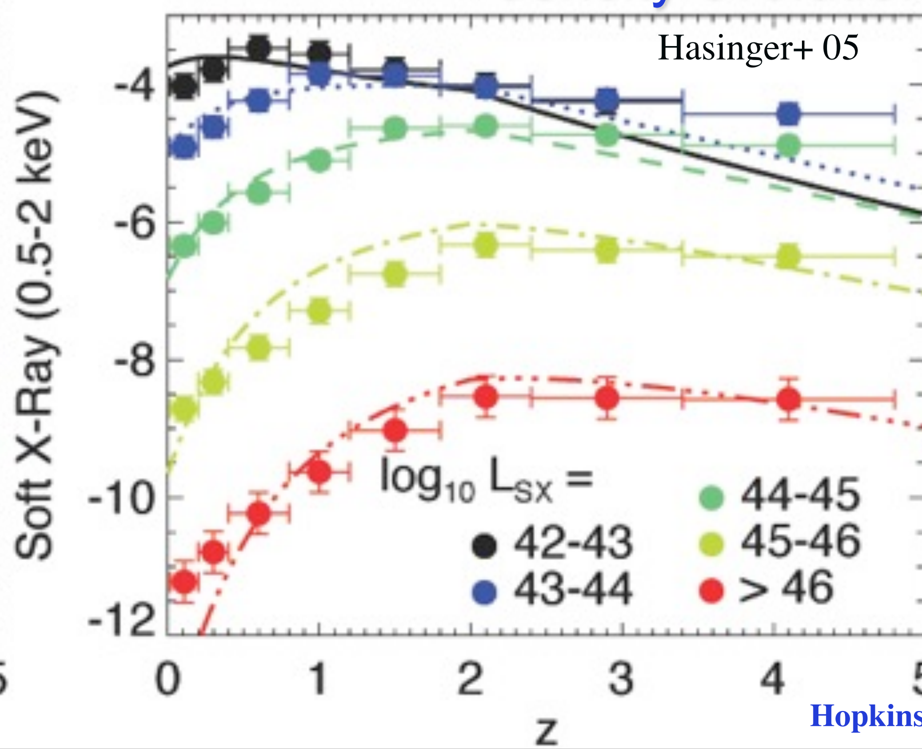
Faint-End Slope of QLF is Determined by Faint-End Quasar Lifetime

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

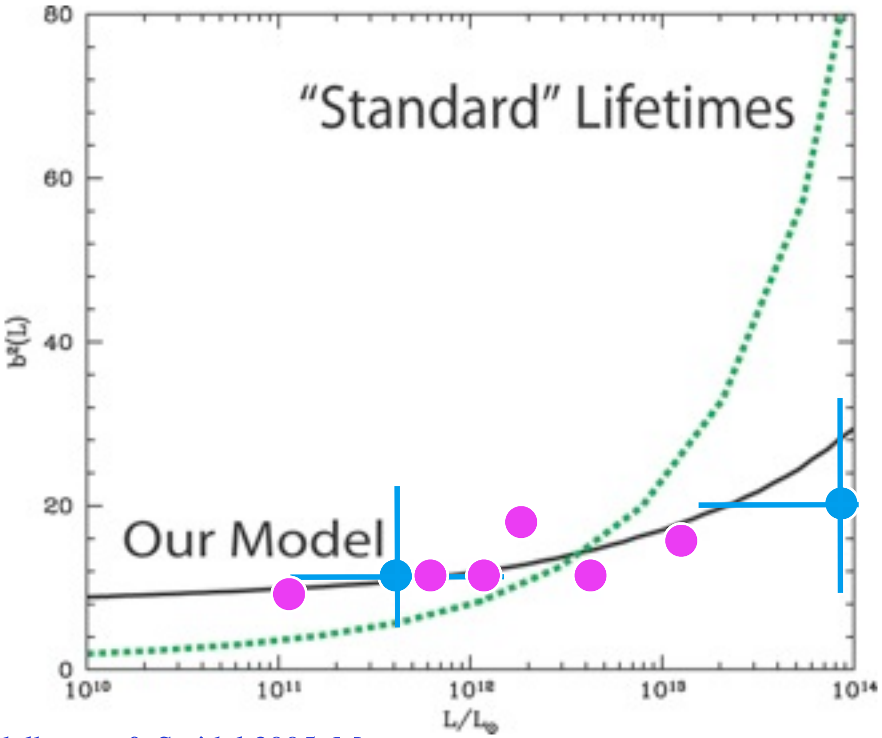




Hopkins et al. 2006a

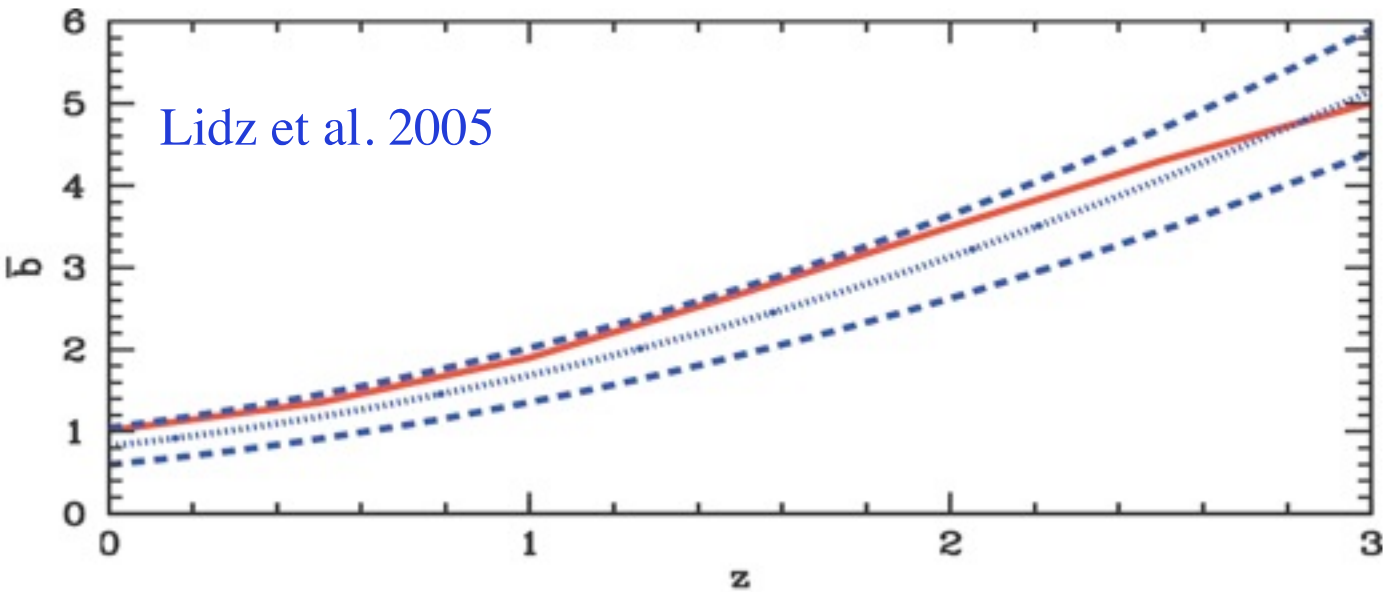
Quasar Clustering is a Strong Test of this Model

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



Adelberger & Steidel 2005, Myers et al. 2005

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



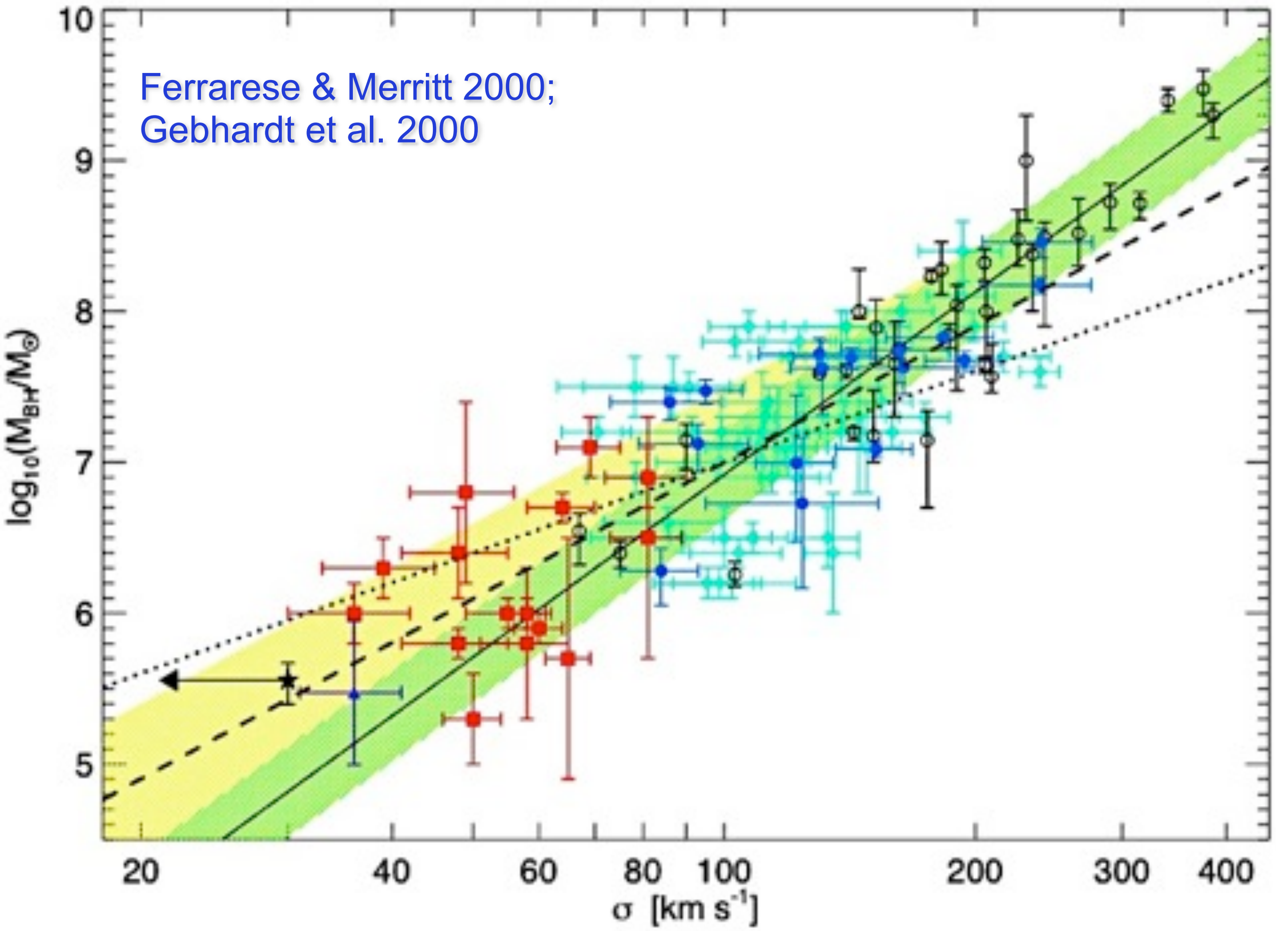
Summary

- Feedback can explain the Mbh-sigma relation
  - Naturally arises from energetics: when BH comparable to the host, get strong feedback

- Feedback has dramatic effects on the shape & interpretation of the QLF:
  - Quasar lifetime not one number:
    Luminosity-dependent lifetimes
    Increases at lower L
  - Evolution of slopes & LDDE
  - "Cosmic Downsizing" as manifest in QSOs

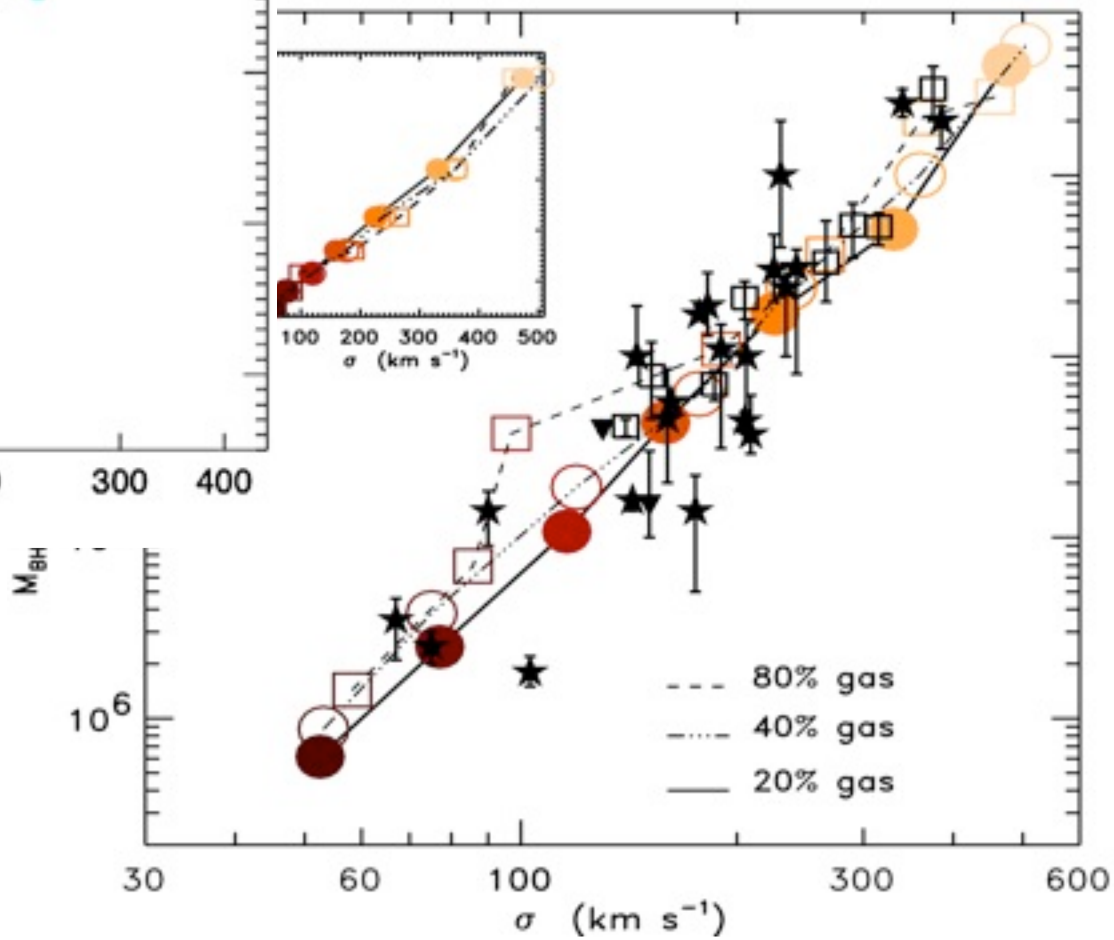
M-sigma Relation Is Now Canonical

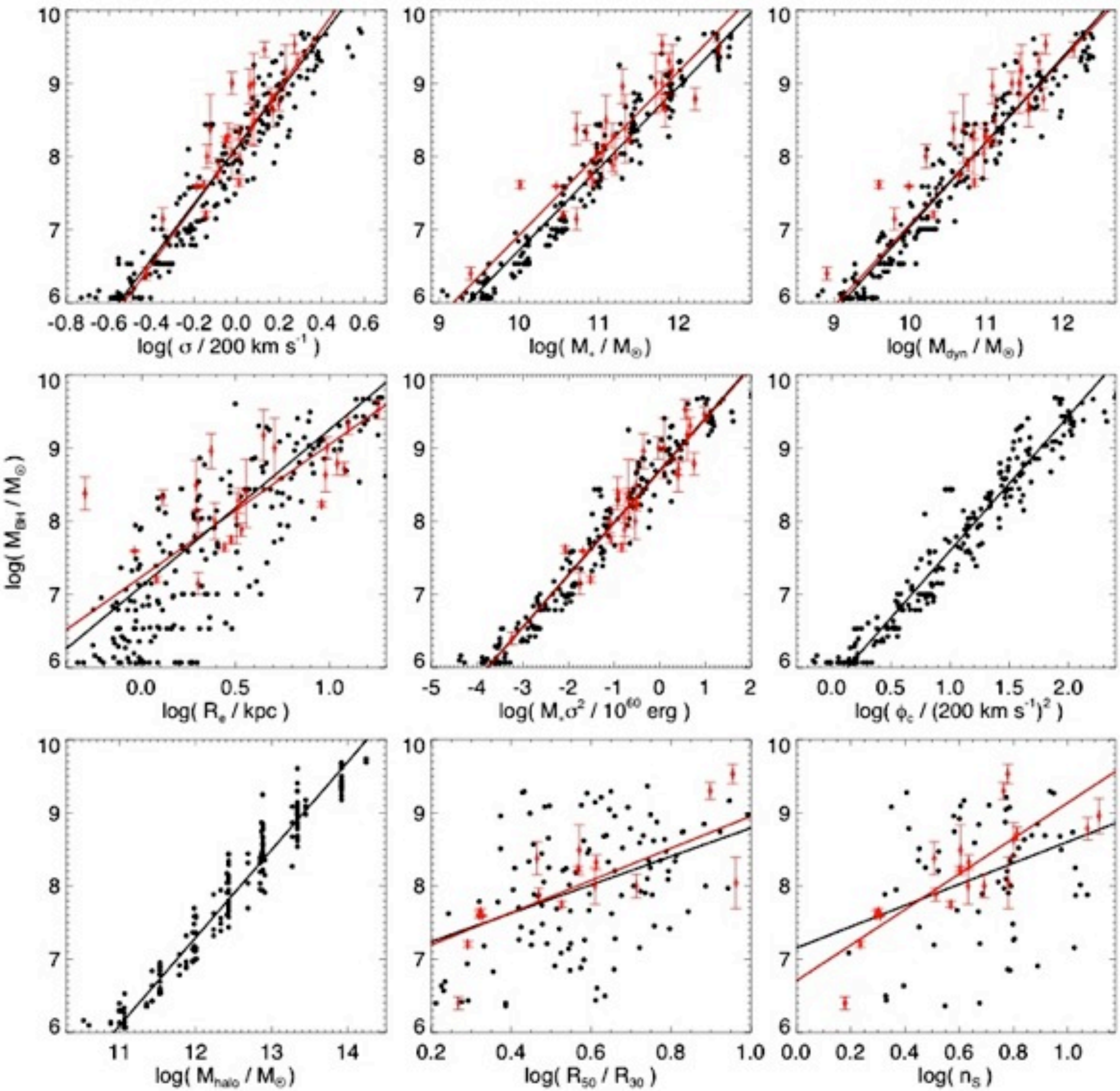
BHs & BULGEs CO-EVOLVE IN SOME SENSE



Tremaine+ 02; Onken+ 04; Nelson+ 04;
Peterson+ 04, 05; Barth+ 04, 05;
Greene & Ho 05

Di Matteo et al. 2005

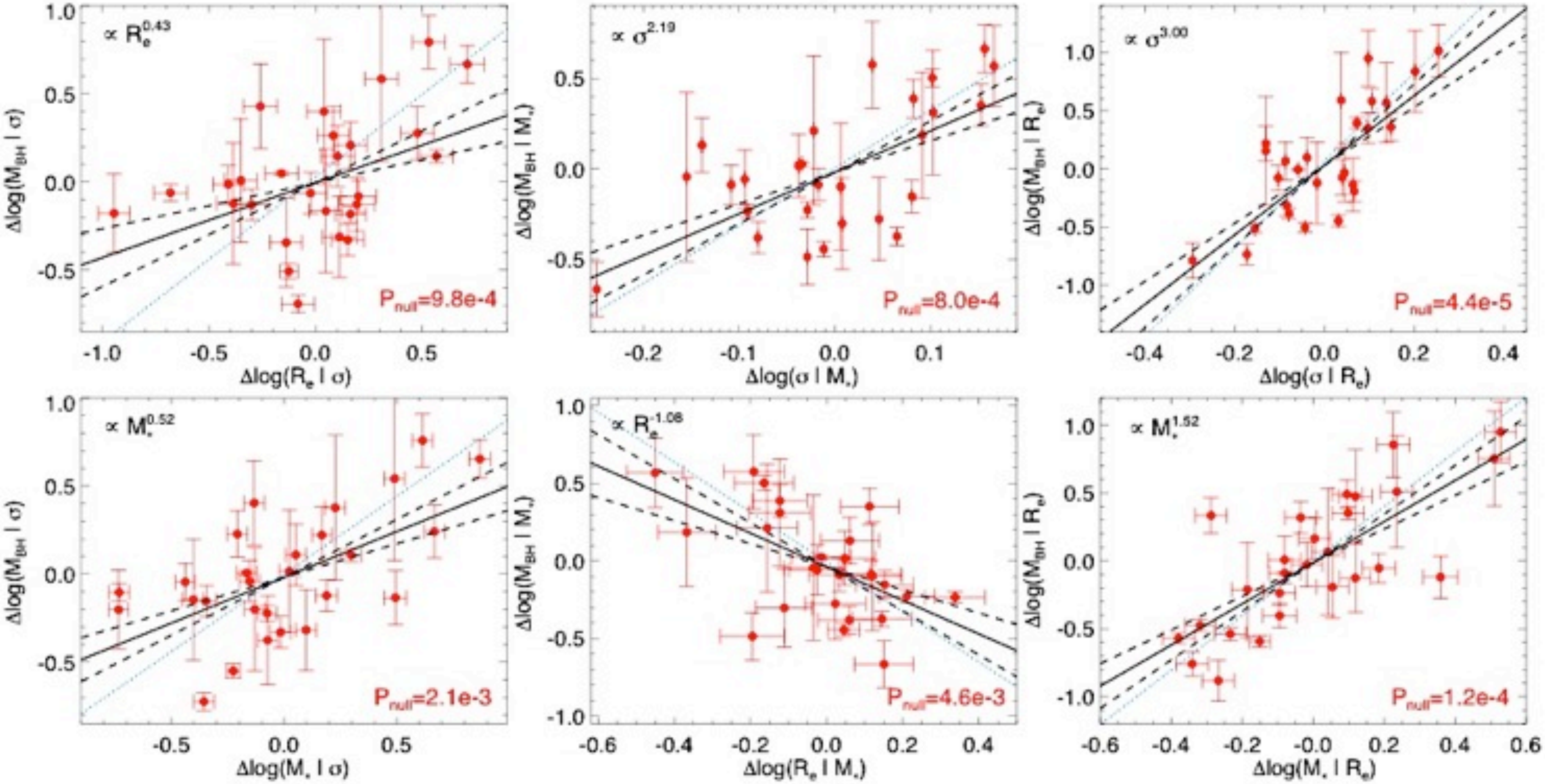



log(σ / 200 km s⁻¹)
log(M* / M⊙)
log(M_dyn / M⊙)
log(M_BH / M⊙)
log(R_e / kpc)
log(M*σ² / 10⁶⁰ erg)
log(φ_c / (200 km s⁻¹)²)
log(M_halo / M⊙)
log(R_50 / R_90)
log(n_S)

Which Correlation Is "Most Fundamental"?

COMPARE RESIDUALS

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

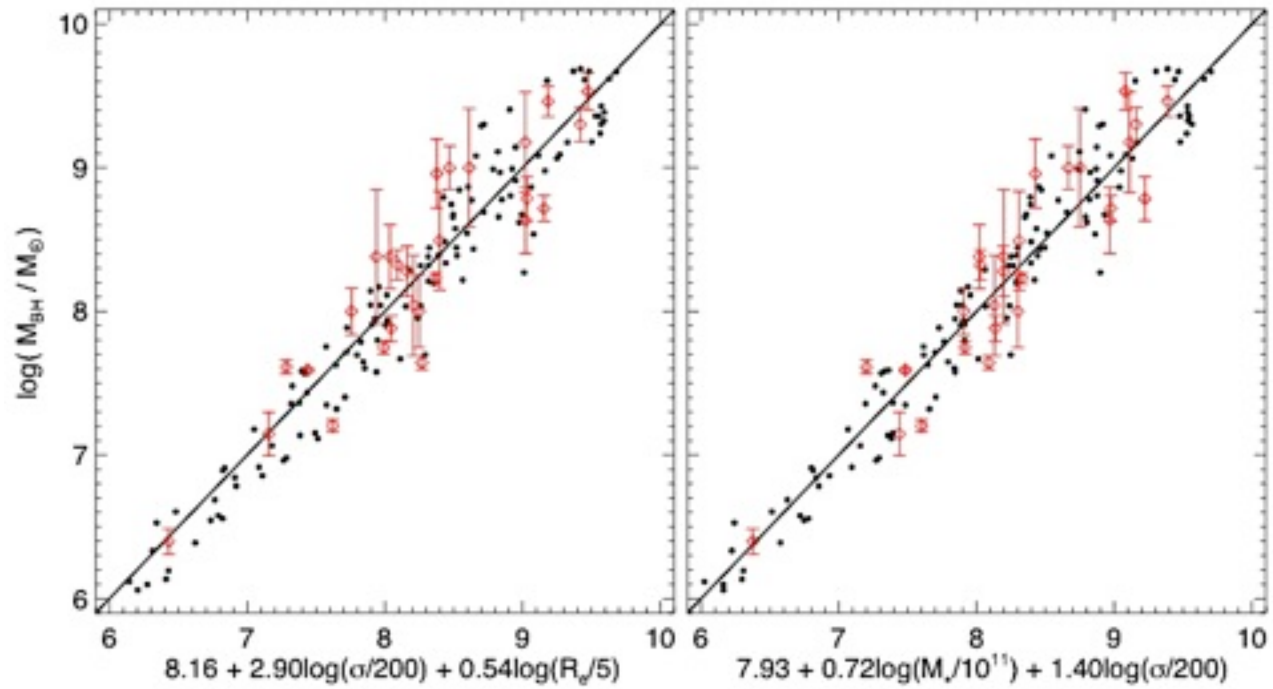


~3s significant residual trend with respect to ANY single variable correlation!

Which Correlation Is “Most Fundamental”?

WHAT ELIMINATES THE SECONDARY VARIABLES?

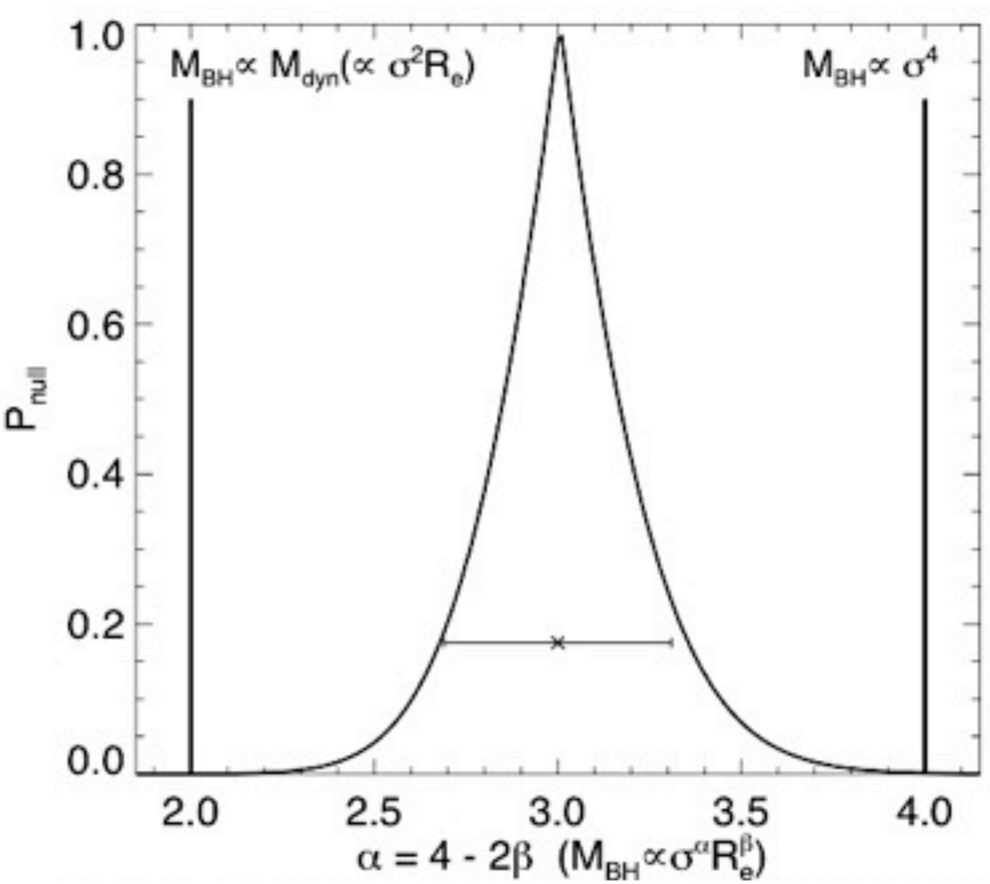
- Find a FP-like correlation:
  - $M_{bh} \sim M_{bul}^{a}\ s^{b}$
  - $M_{bh} \sim R_{e}^{a}\ s^{b}$
  - $M_{bh} \sim M_{bul}^{a}\ R_{e}^{b}$

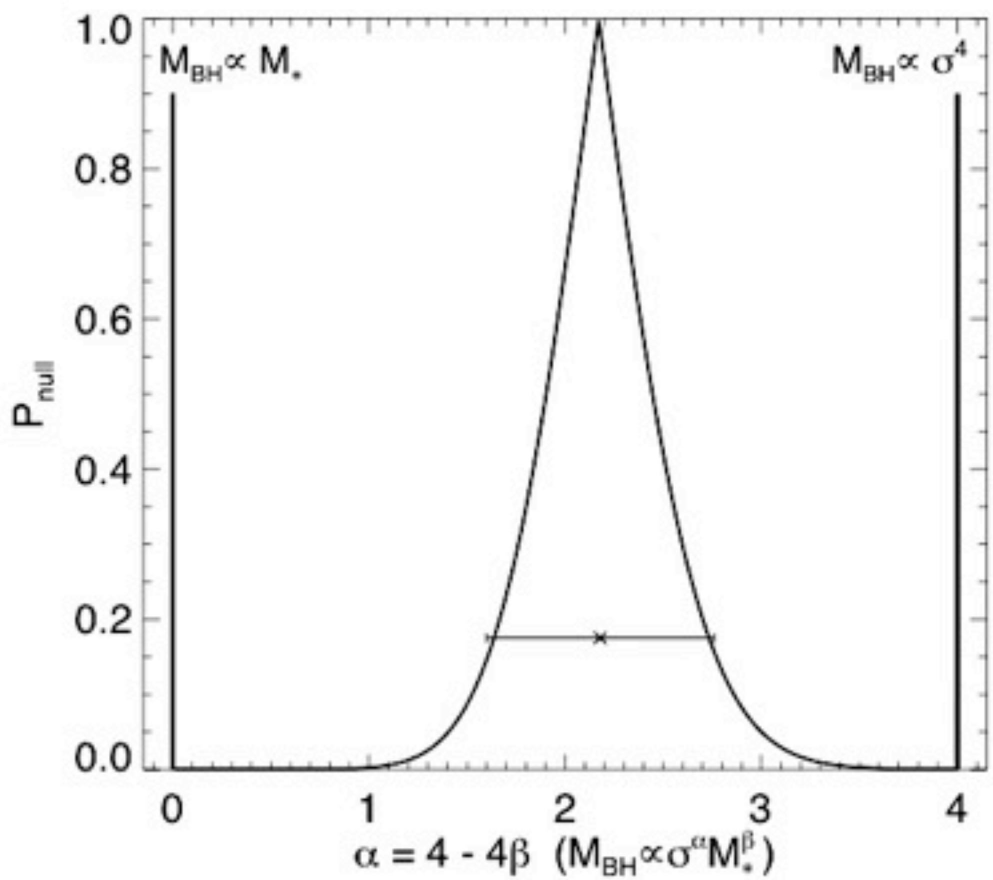


- Given the spheroid FP, these are the *same*

Which Correlation Is "Most Fundamental"?

WHAT ELIMINATES THE SECONDARY VARIABLES?

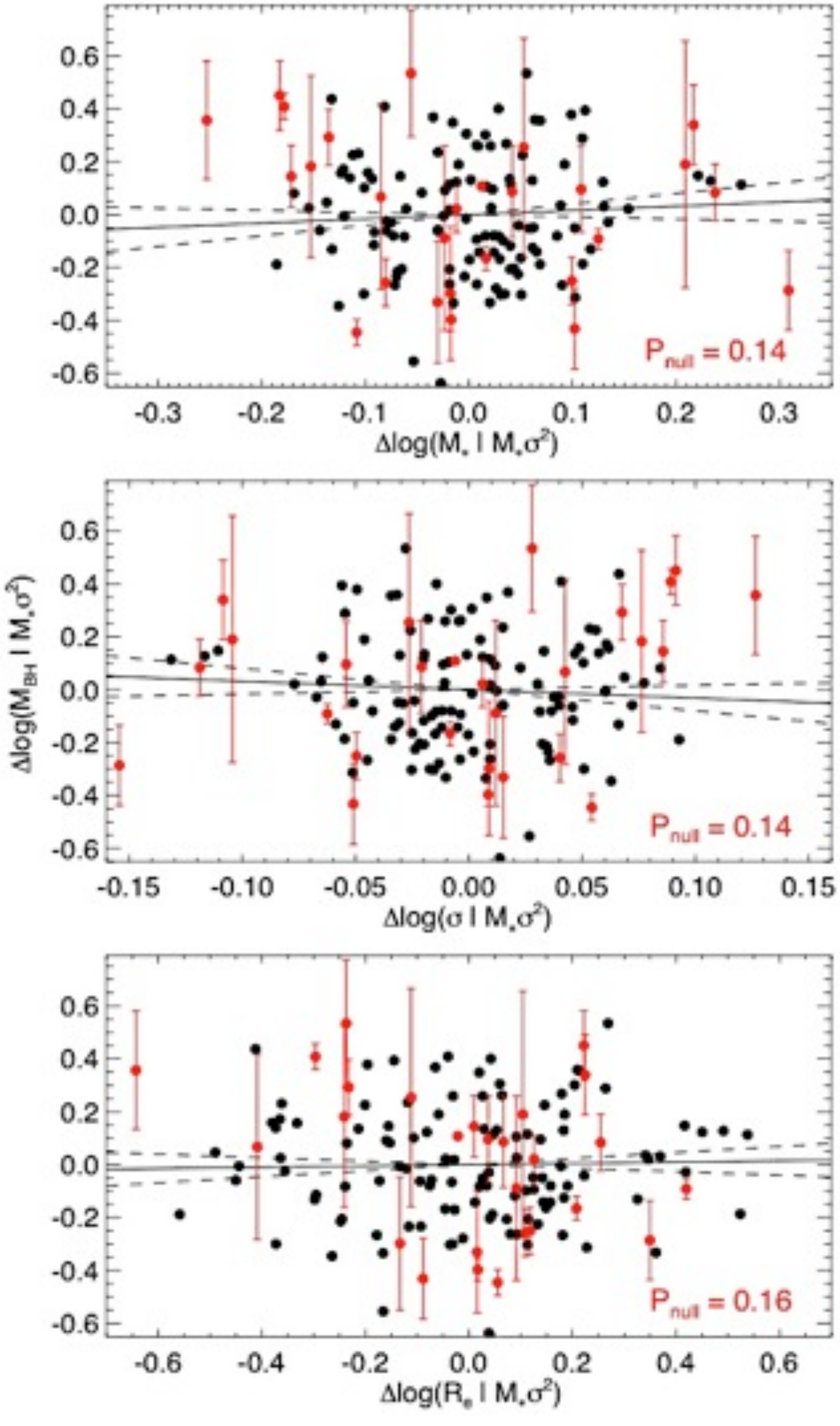


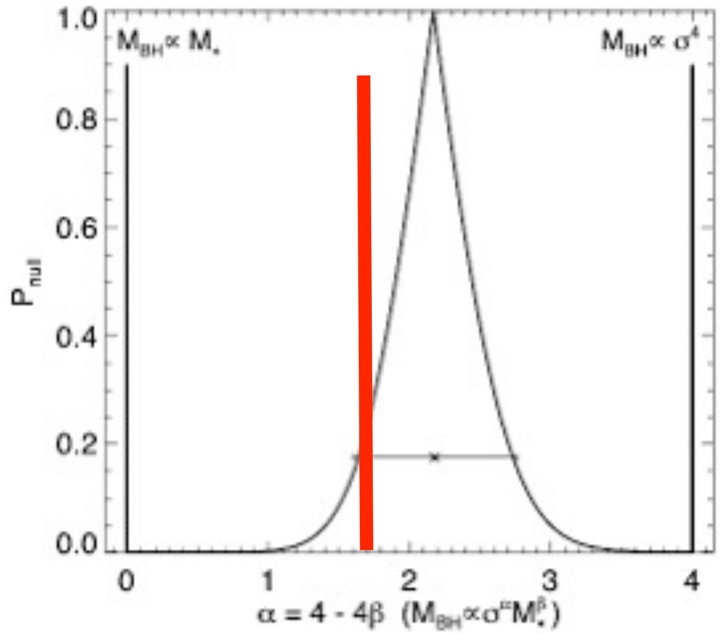


What Does this FP-Like Relation Imply?

IS THERE ANY PHYSICAL MEANING?

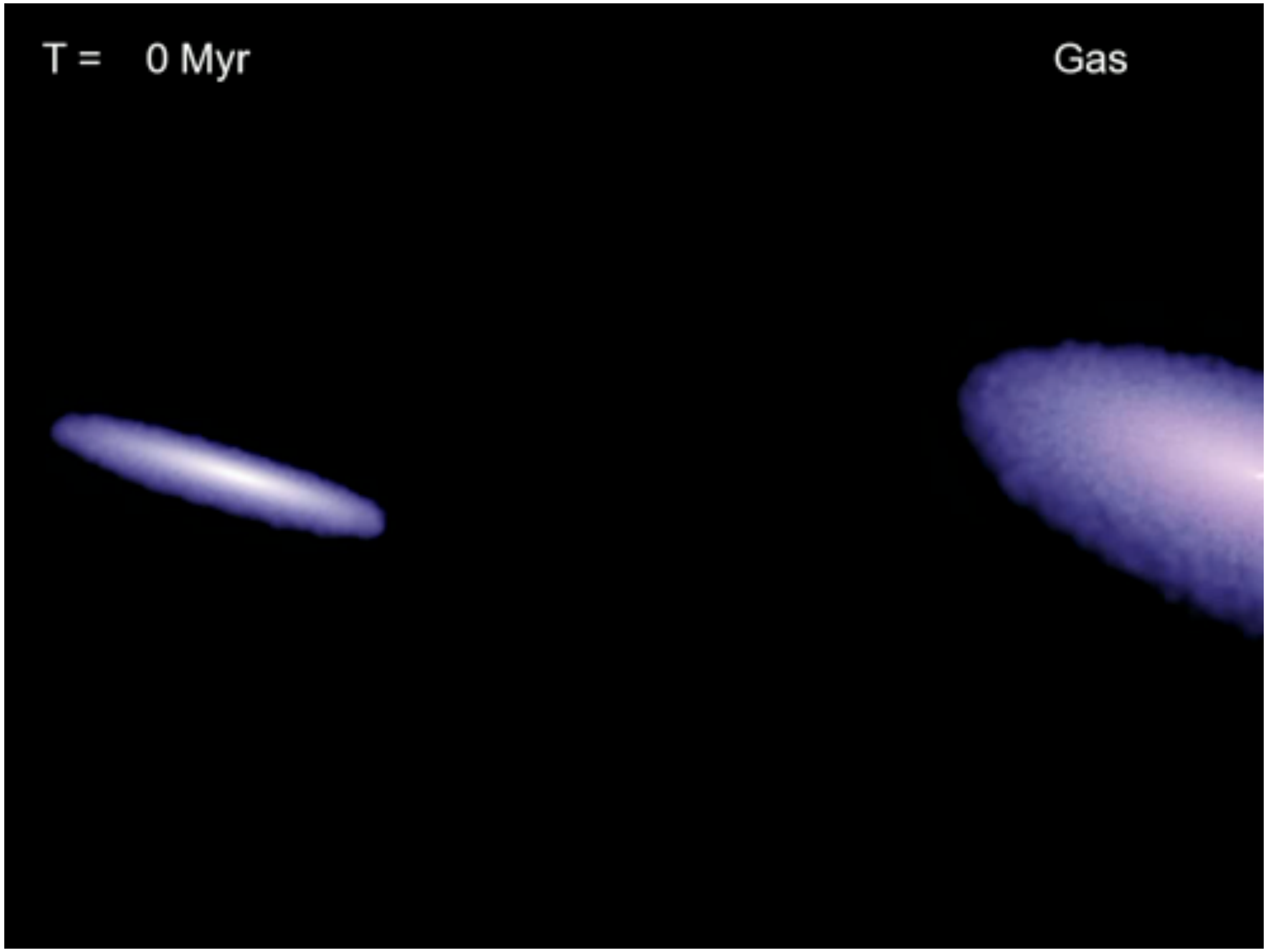
- Reasonably close to binding energy, but with "tilt":
  - $M_{bh} \sim E_{binding}^{2/3} \sim (M_{bul}\ s^2)^{2/3}$
- Pressure-driven outflow needs to unbind everything within R_{bh} in t_{dyn}:
  - $M_{bh} \sim M_{bul}^{1/2}\ s^2$

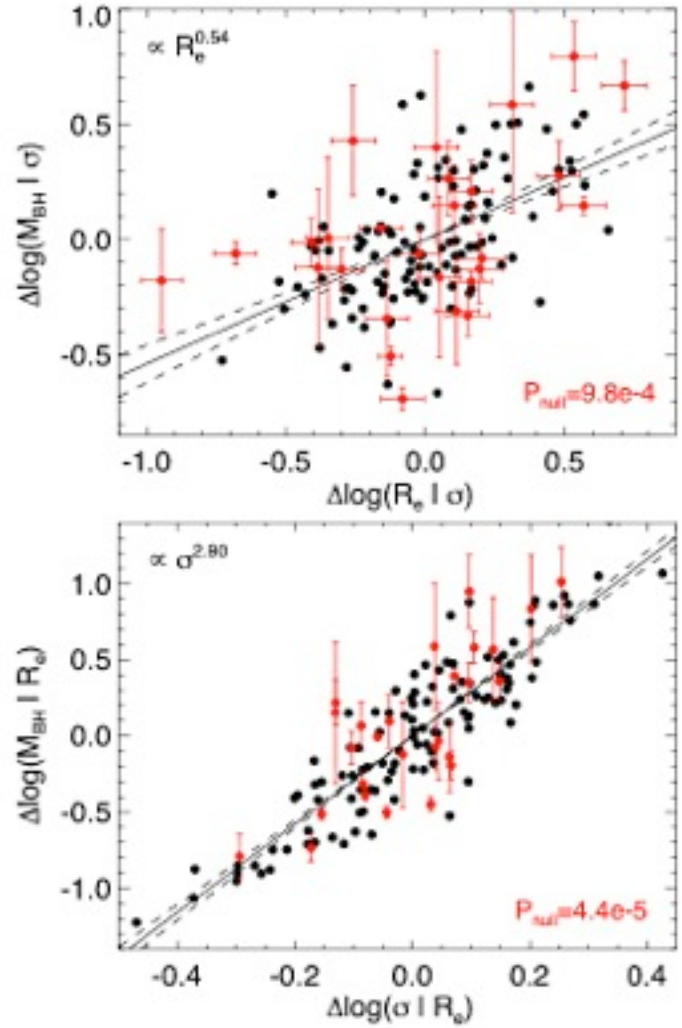




Do Feedback-Regulated Simulations Predict This?

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

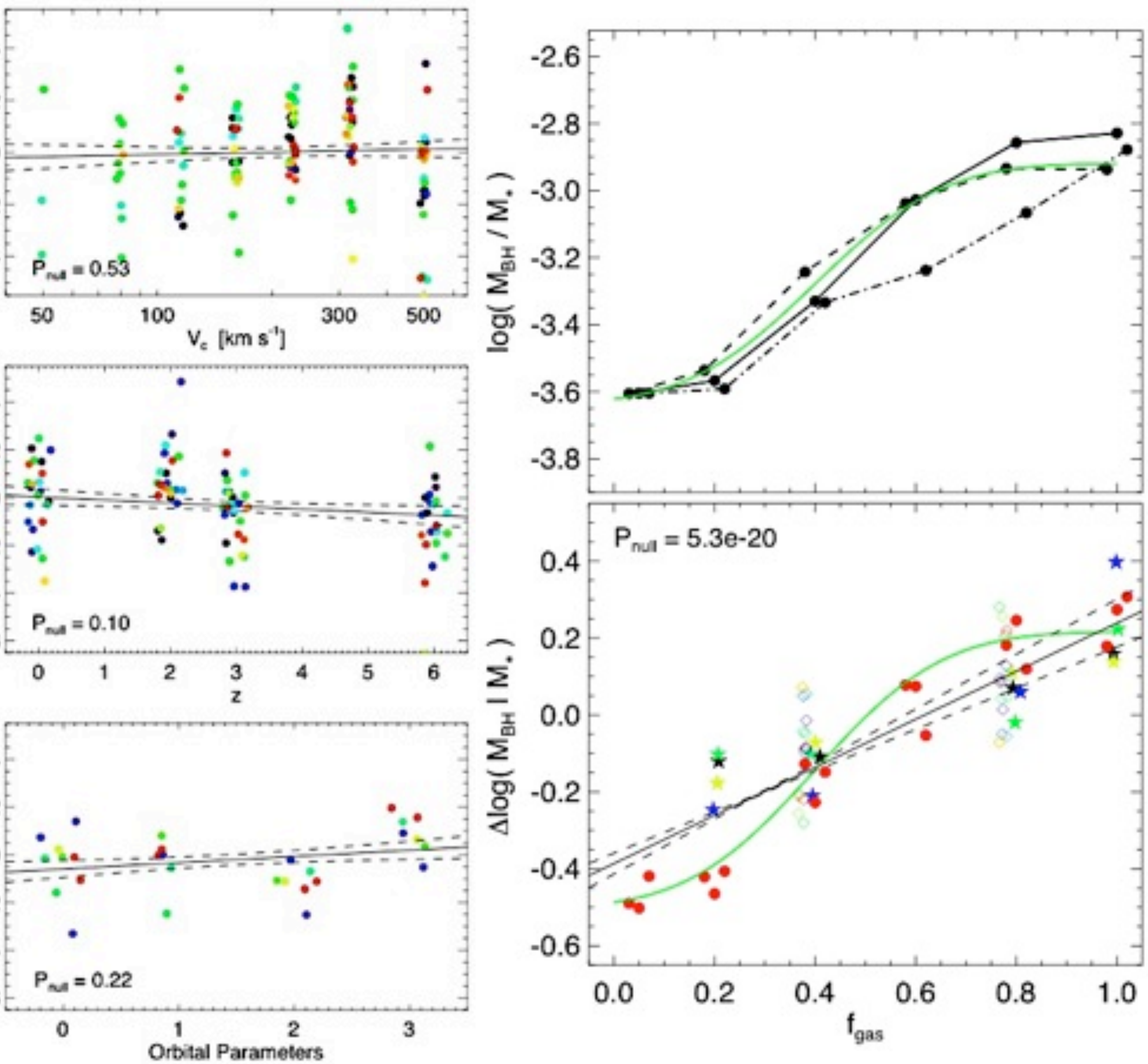




- Supports basic Silk & Reese ’98 argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential depth

Can We Get Away From This?

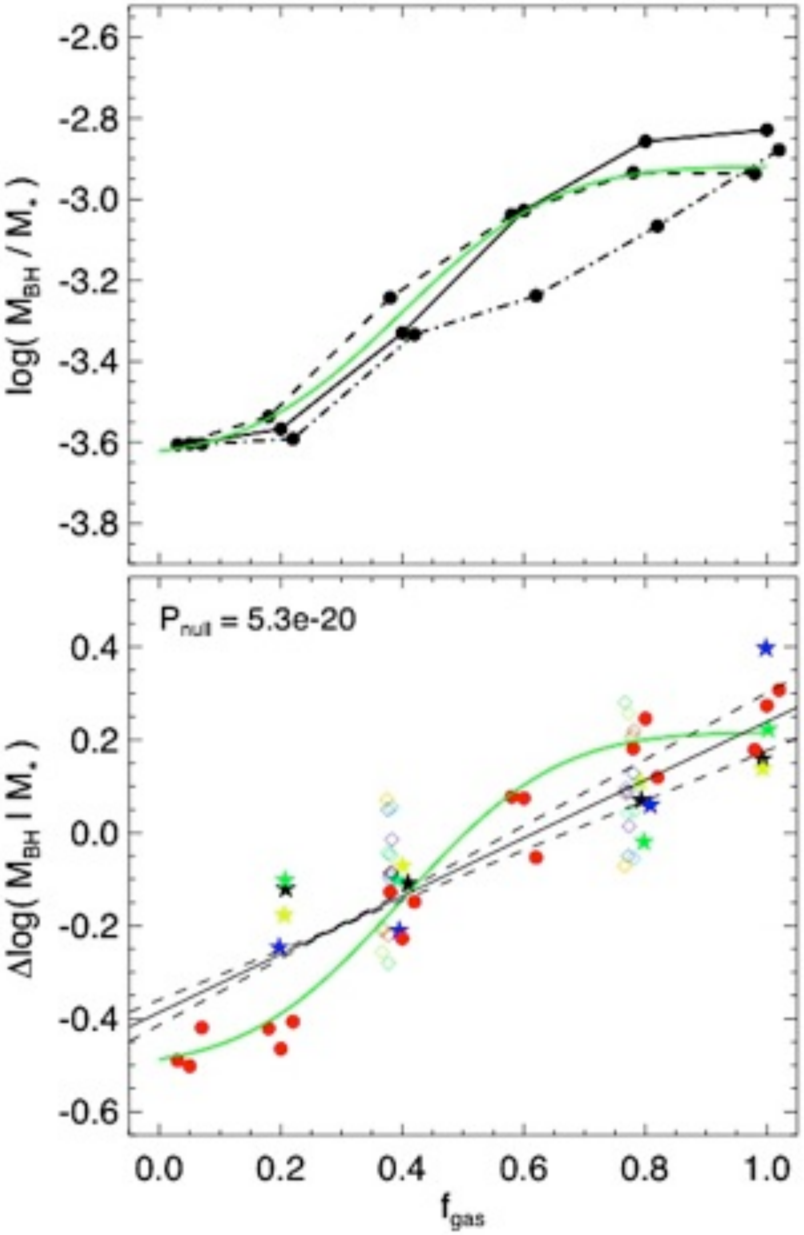
HOW DOES THE RELATION DEPEND ON INITIAL CONDITIONS?



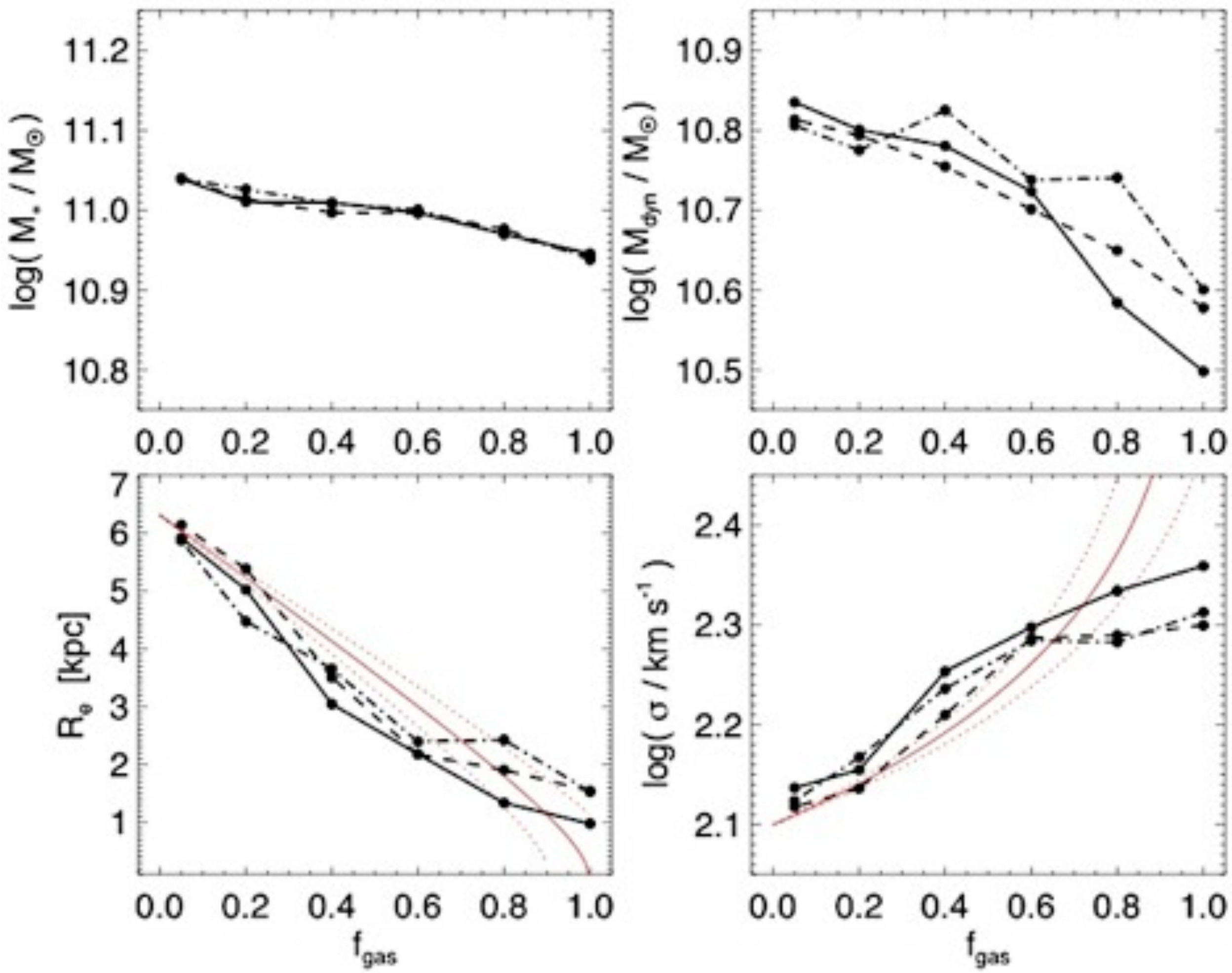
- Primarily a *local* correlation with *final* state:
  - Can't get "off" this correlation if feedback still self-regulates
- Can move *along* the correlation
  - Changes projections:
    - M_{bh} - M_{bul}
    - M_{bh} - s

Moving Along the BH FP-Like Correlation

GIVEN THIS CORRELATION, HOW DO YOU MOVE IN ITS PROJECTIONS



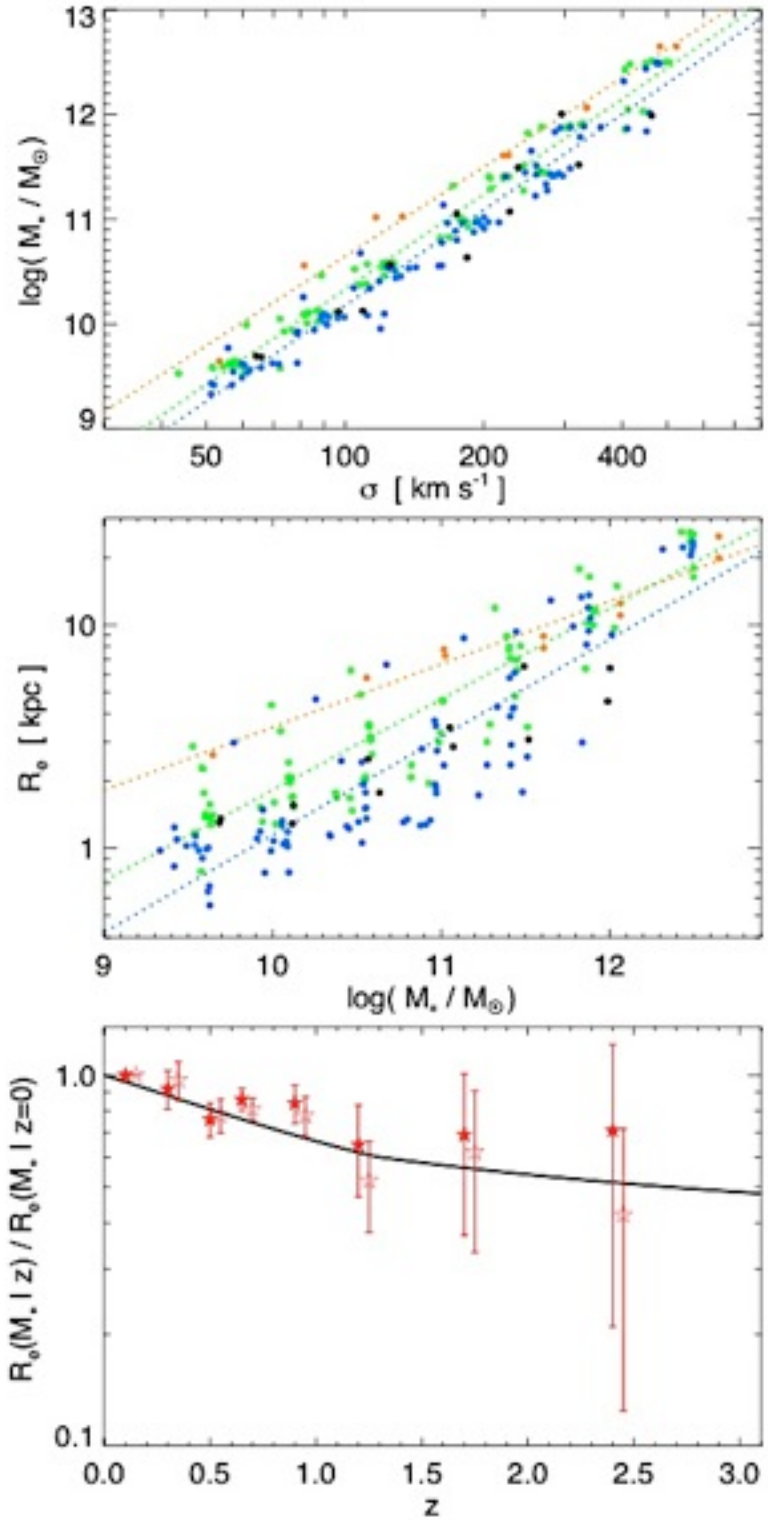
- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
- Deepens the central potential



Moving Along the BH FP-Like Correlation

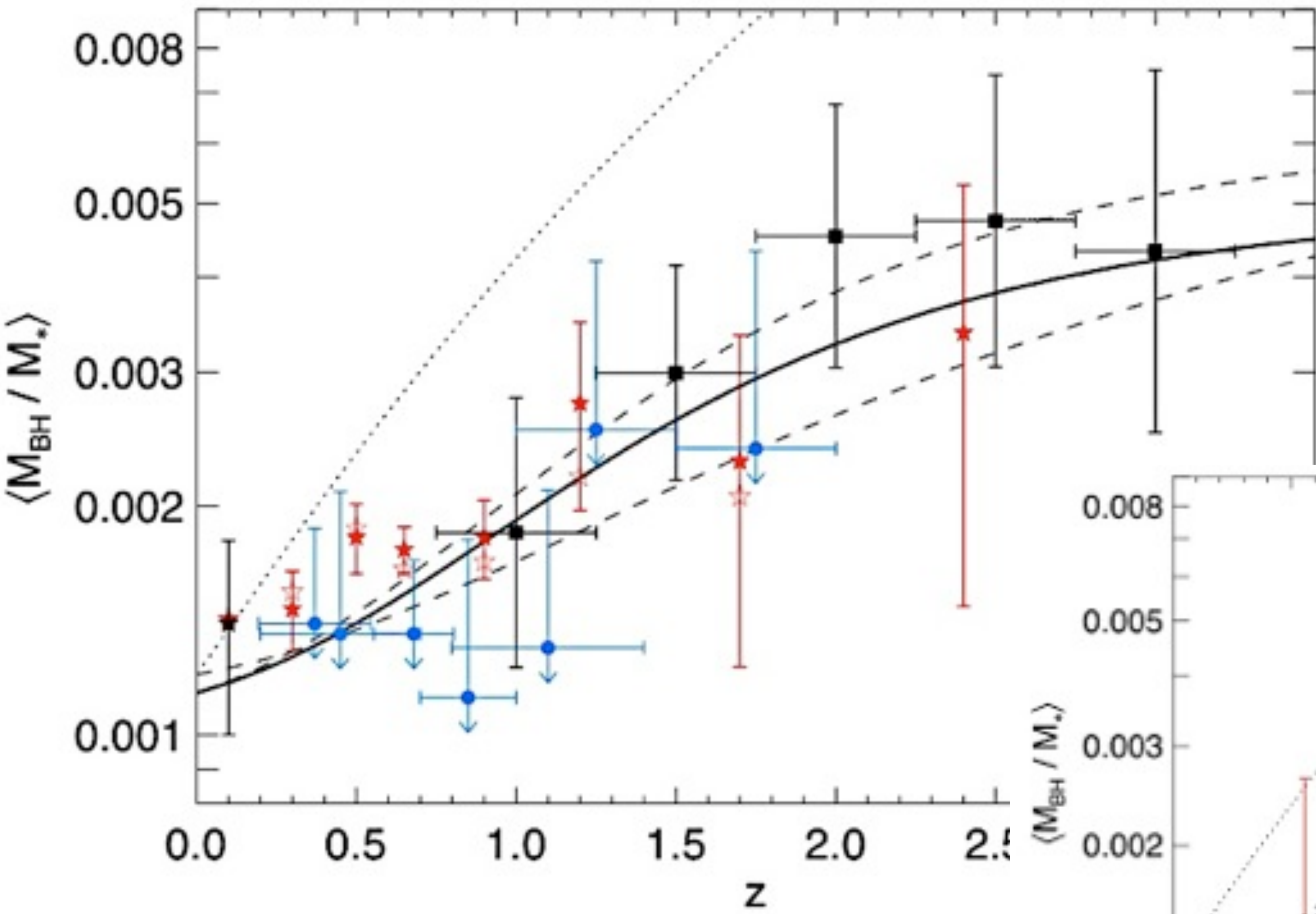
IMPLICATIONS FOR REDSHIFT EVOLUTION

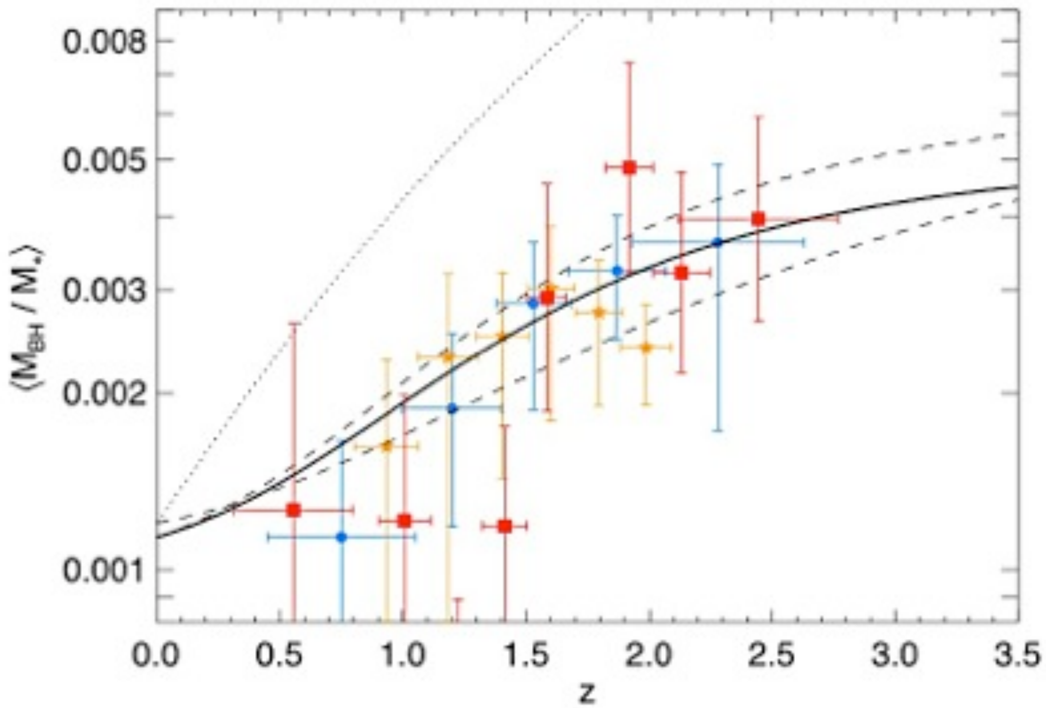
- High-z galaxies are more gas-rich:
  - Expect more compact remnants
    - Khochfar & Silk
  - See them: smaller R_e, larger s at fixed M_{bul}
    - Trujillo et al.; Zirm et al.



Moving Along the BH FP-Like Correlation

IMPLICATIONS FOR REDSHIFT EVOLUTION

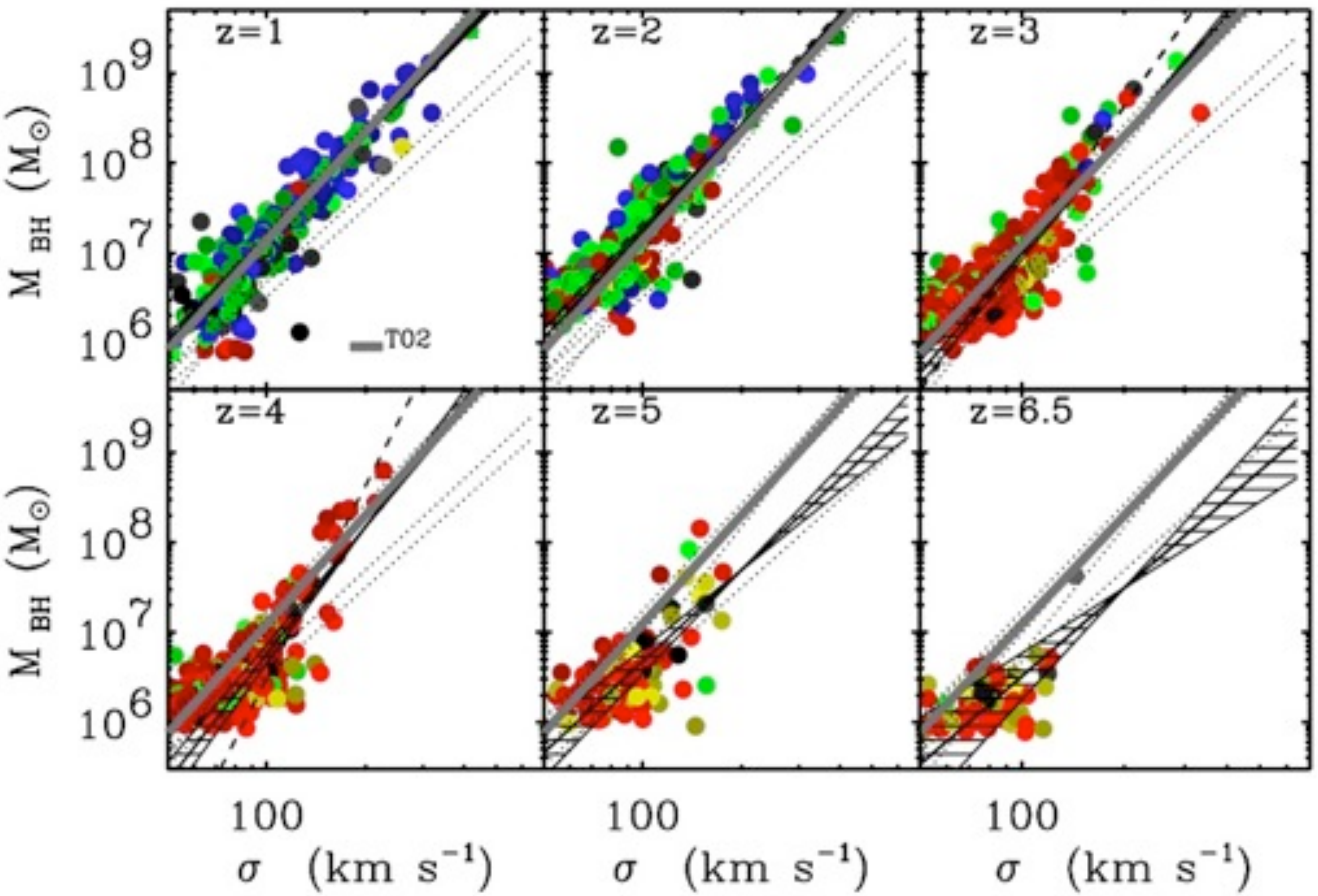




- $M_{bh} \sim (M_{bul}\, s^2)^{2/3}$
  - Larger M_{bh} at fixed M_{bul}
    - Peng et al.; Fine et al.; Shields et al.; Merloni et al.; Walter et al.
  - Different evolution in M_{bh}-M_{bul} & M_{bh}-s

Moving Along the BH FP-Like Correlation

IMPLICATIONS FOR REDSHIFT EVOLUTION

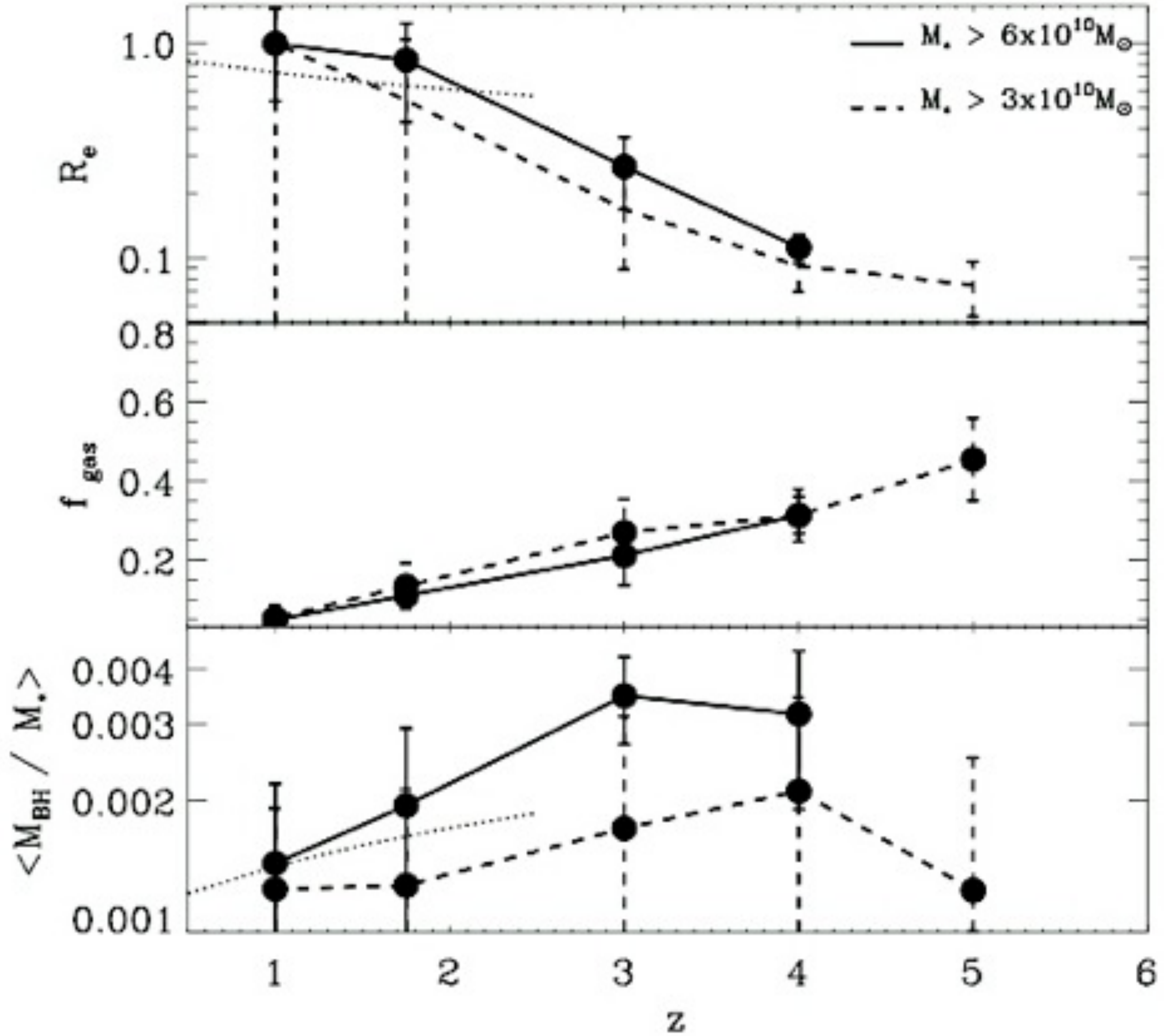


Di Matteo et al. 2007

- Recent cosmological simulations: same effect

Moving Along the BH FP-Like Correlation

IMPLICATIONS FOR REDSHIFT EVOLUTION

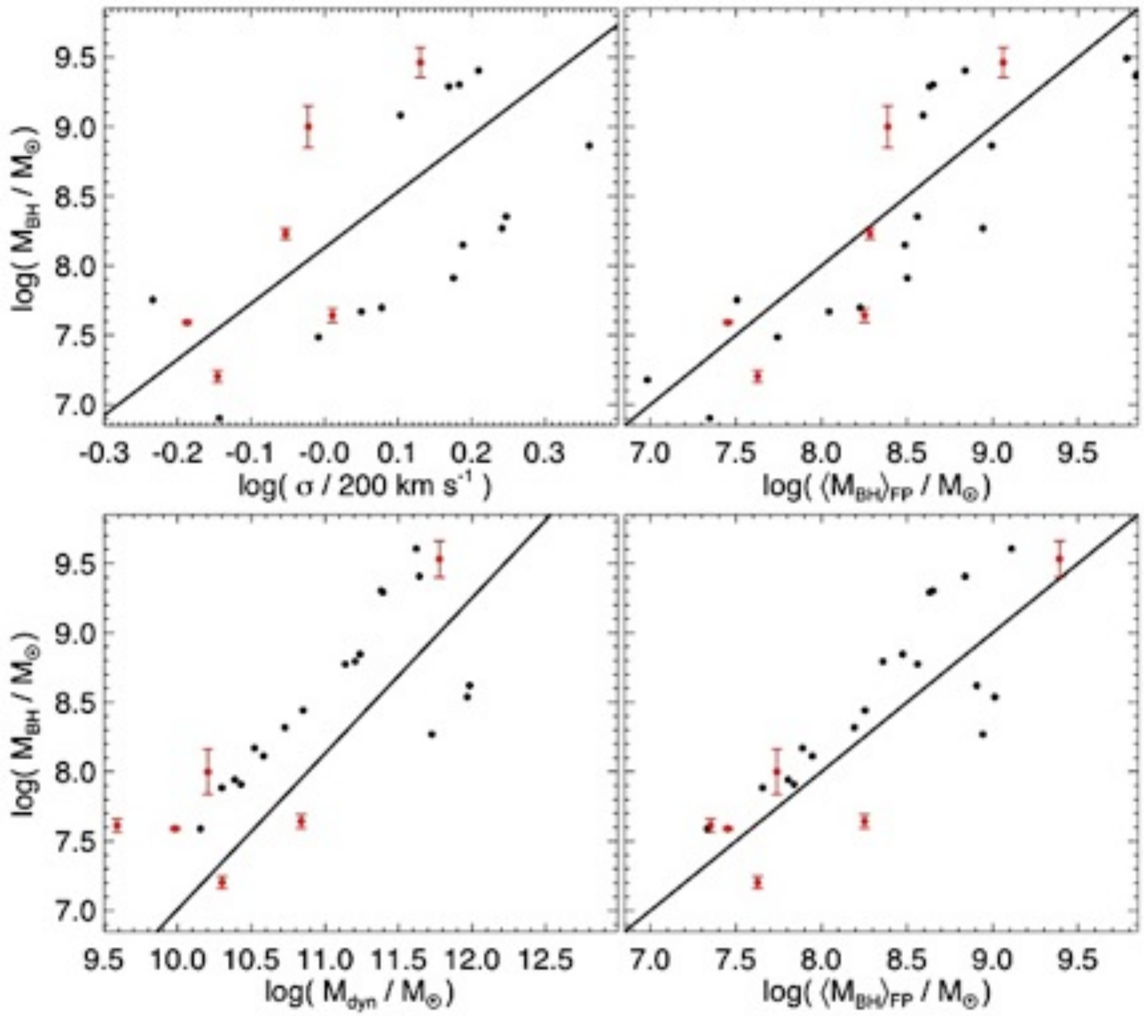


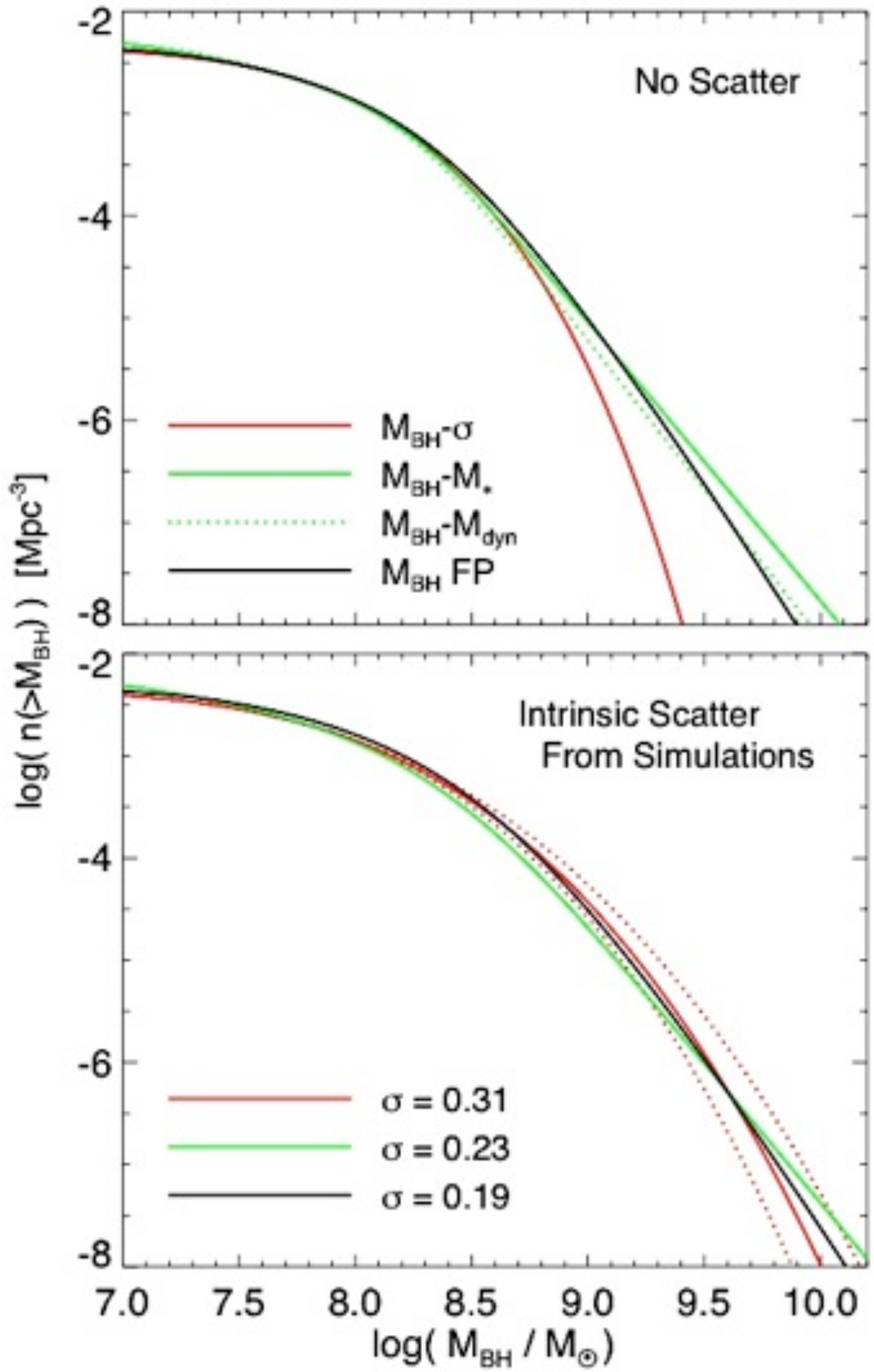
Di Matteo et al. 2007

- Recent cosmological simulations: same effect

Implications for BH Demographics

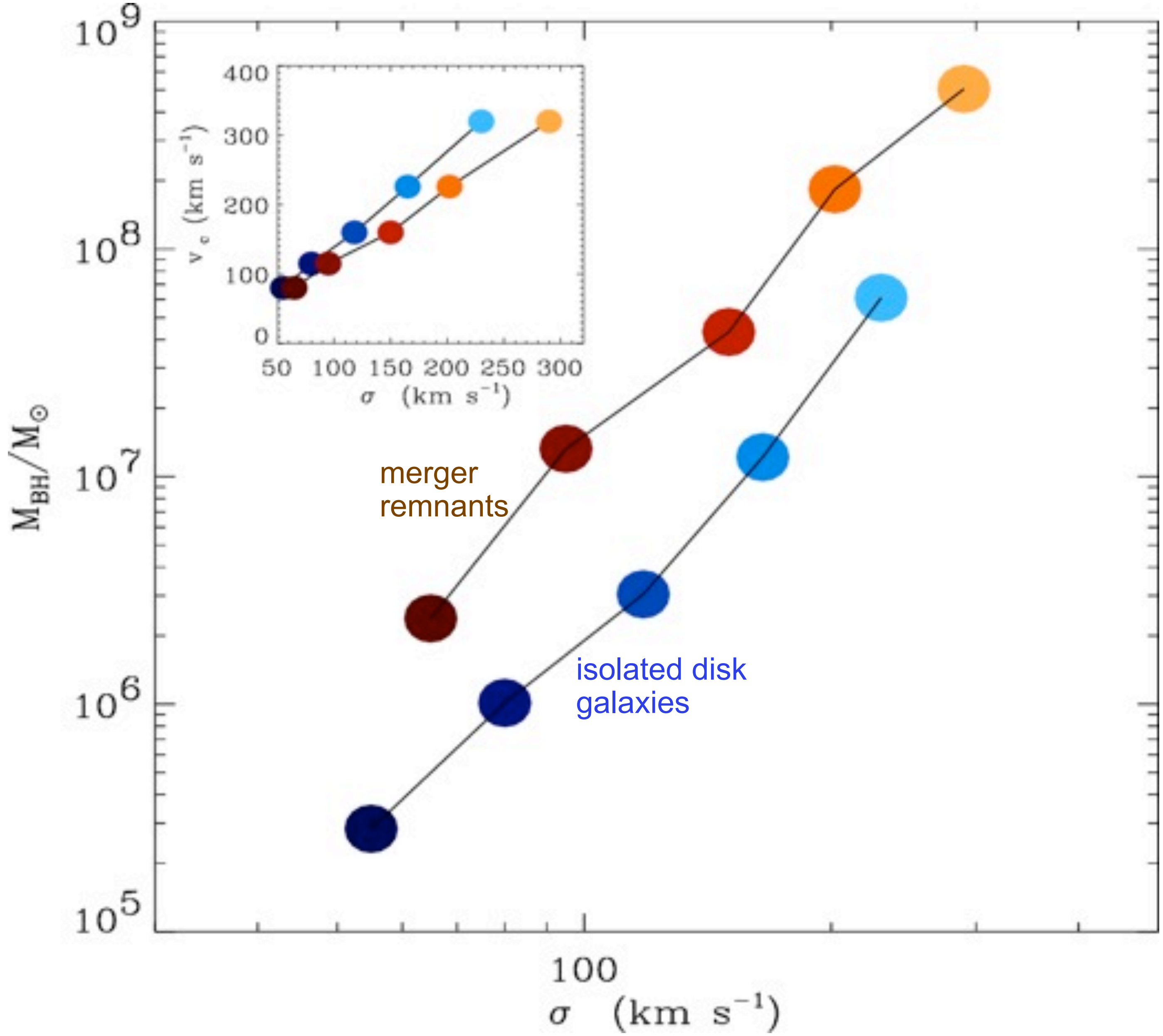
HOW MANY EXTREME BHs ARE THERE?





What about other fueling mechanisms?

BLACK HOLE MASSES IN ISOLATED GALAXIES AND MERGER REMNANTS



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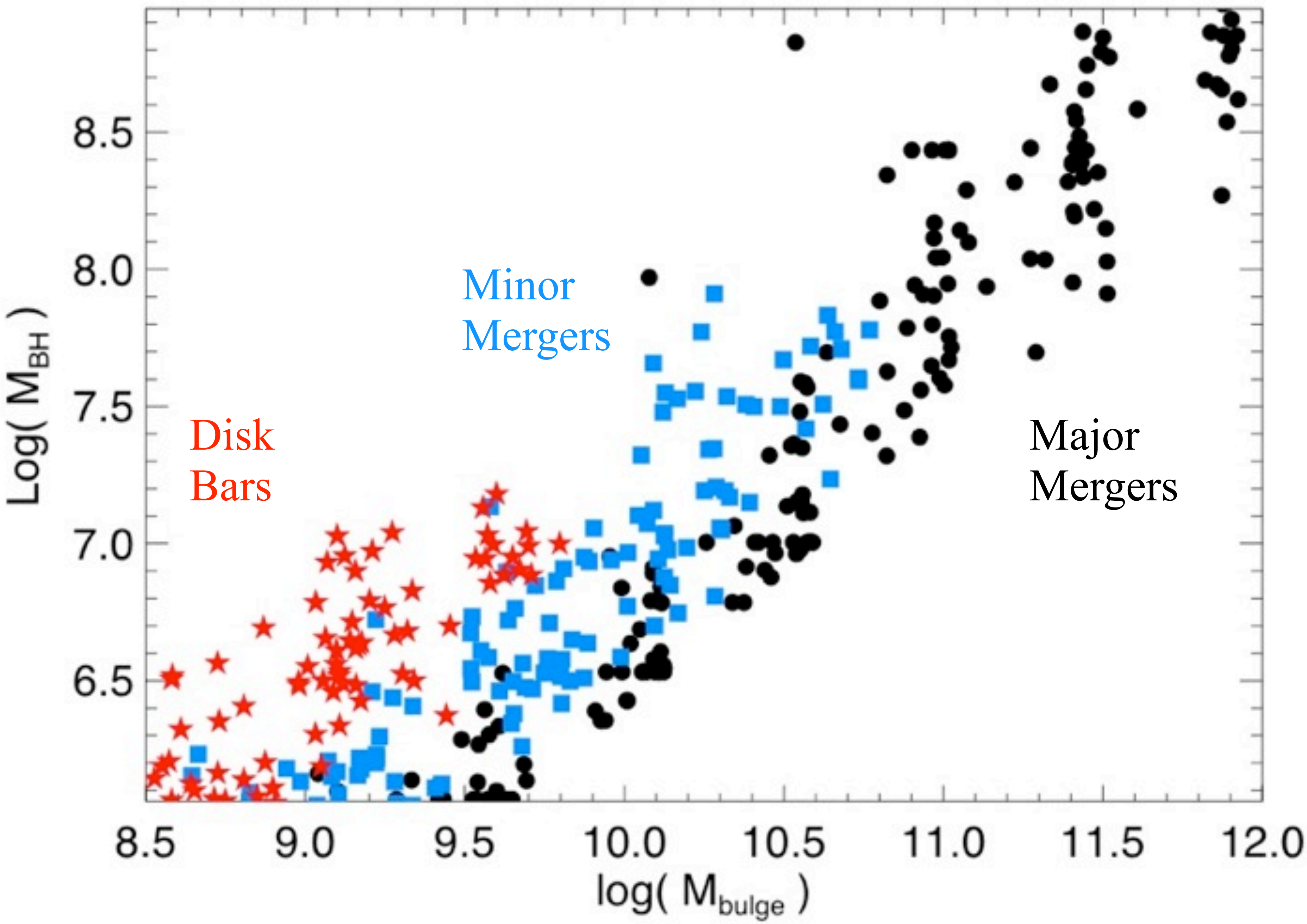

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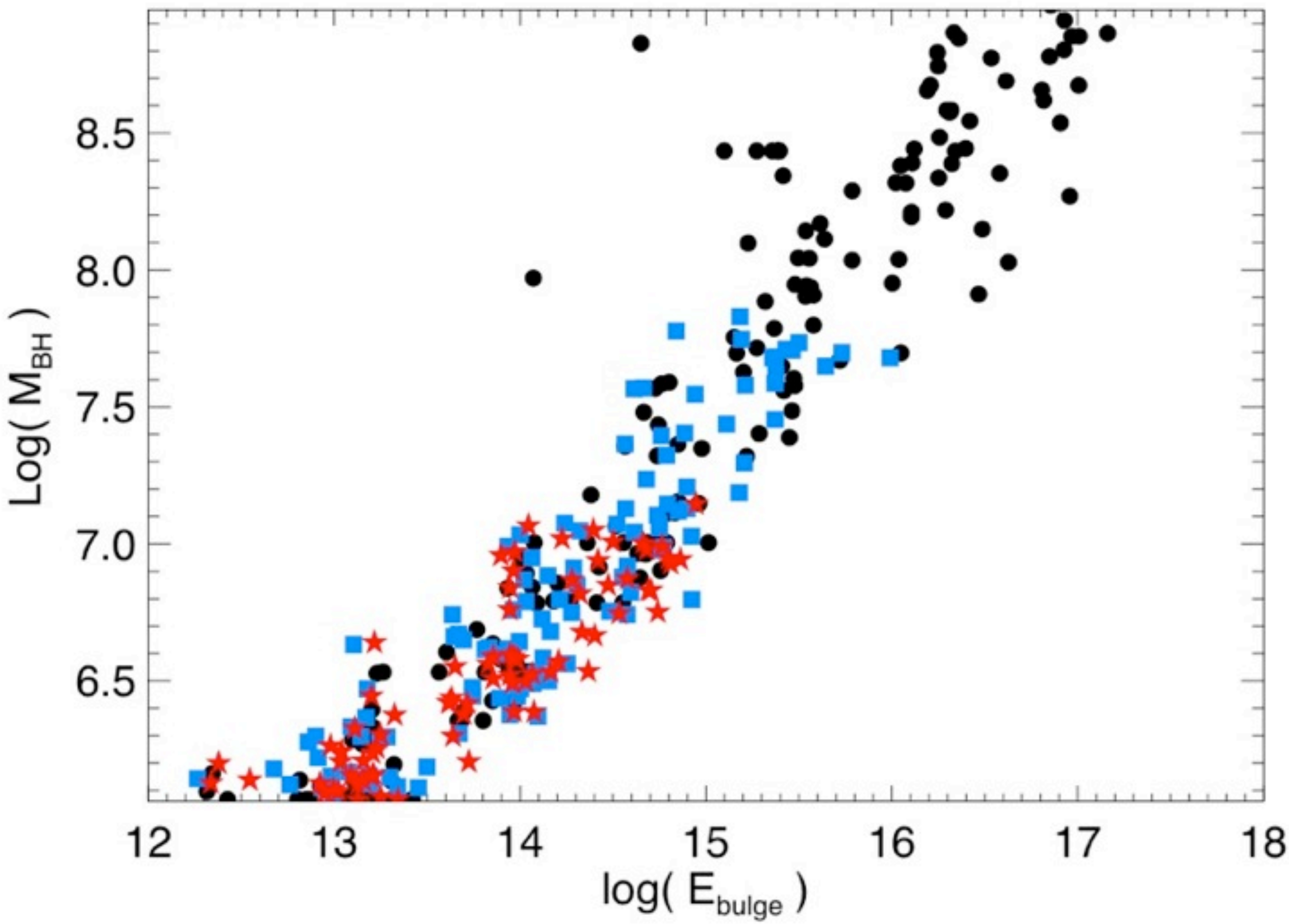
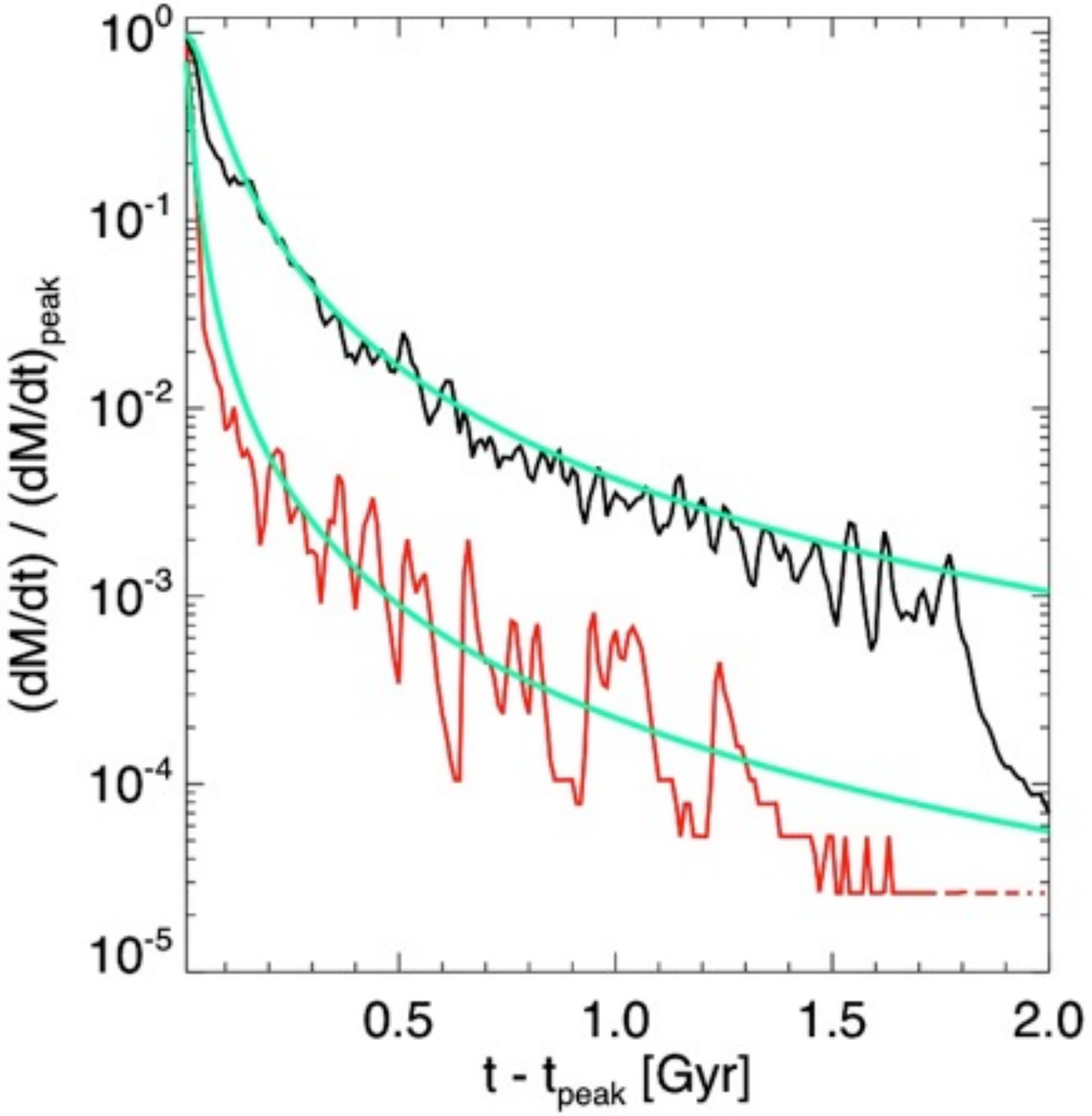


Generalizing the Model

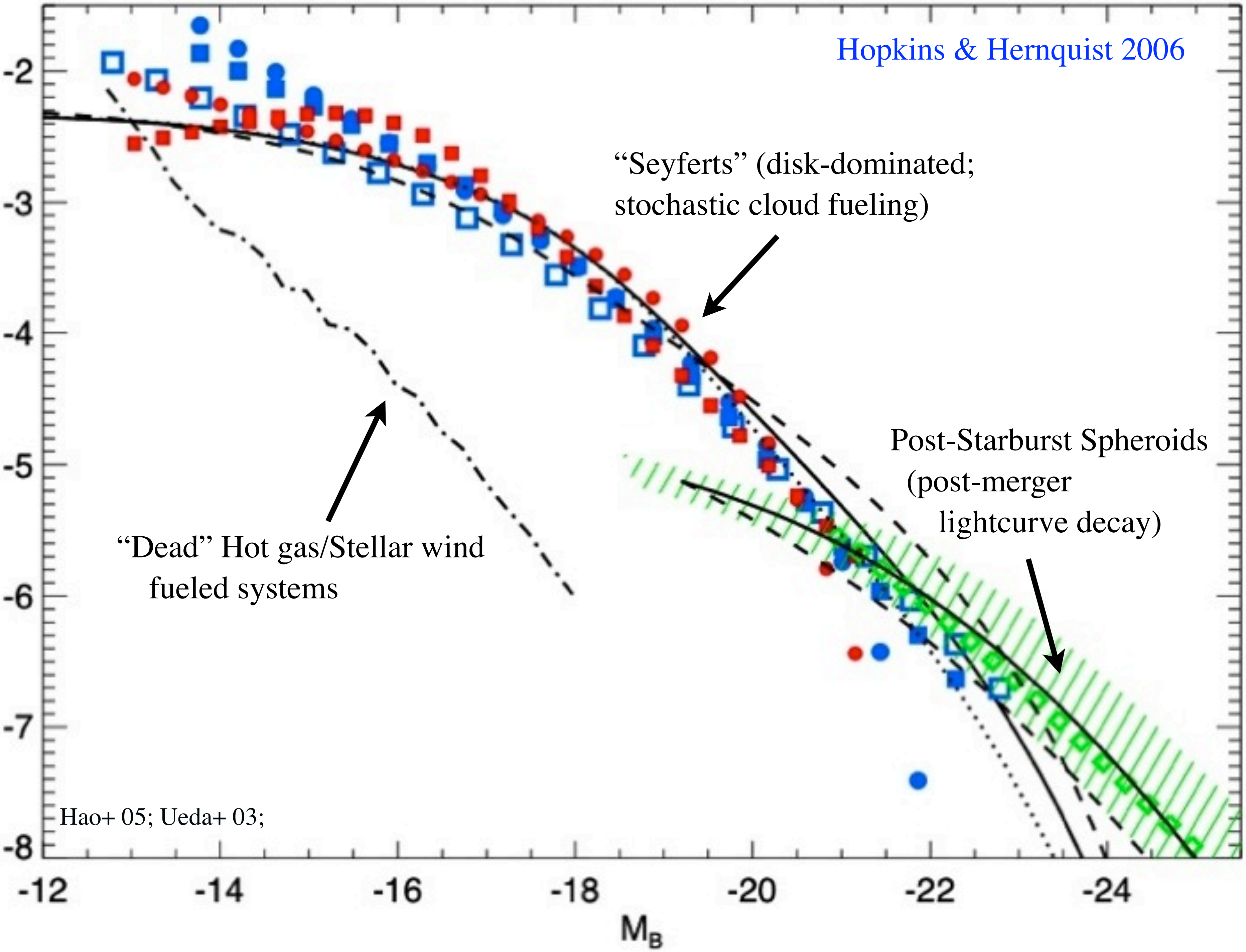
NOT ALL AGN ARE MERGER-DRIVEN

- 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



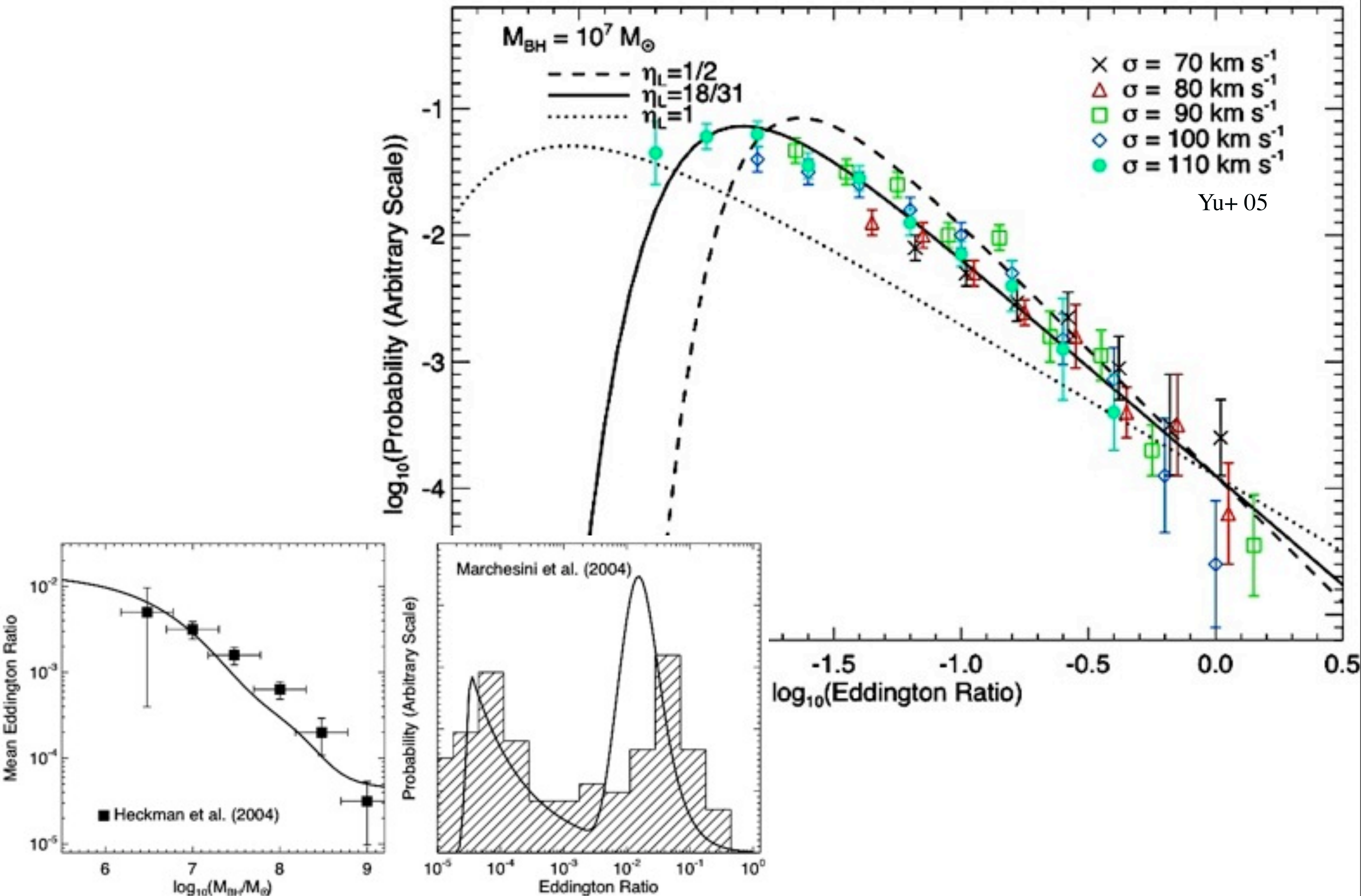
The Seyfert Luminosity Function

A STOCHASTIC BUT FEEDBACK-REGULATED MODEL



The Seyfert Luminosity Function

PREDICT THE EDDINGTON RATIO DISTRIBUTIONS FROM THIS FUELING MODE, AS BEFORE



Summary

- BH Mass is not determined by either M_{bul} or s alone:
  - $M_{bh} \sim E_{binding}^{2/3} \sim (M_{bul}\ s^2)^{2/3}$
  - $M_{bh} \sim M_{bul}^{1/2}\ s^2$
- Constrains feedback physics:
  - Some sensitivity to local potential depth
  - *Not* just some fixed fraction of bulge star formation or gas inflow
- Predicts redshift evolution in the "projected" correlations
  - Potentials get deeper, BHs get bigger
  - Tells us something fundamental about BH-bulge co-evolution
  - Important for feedback scenarios