Beyond M_{BH}-σ

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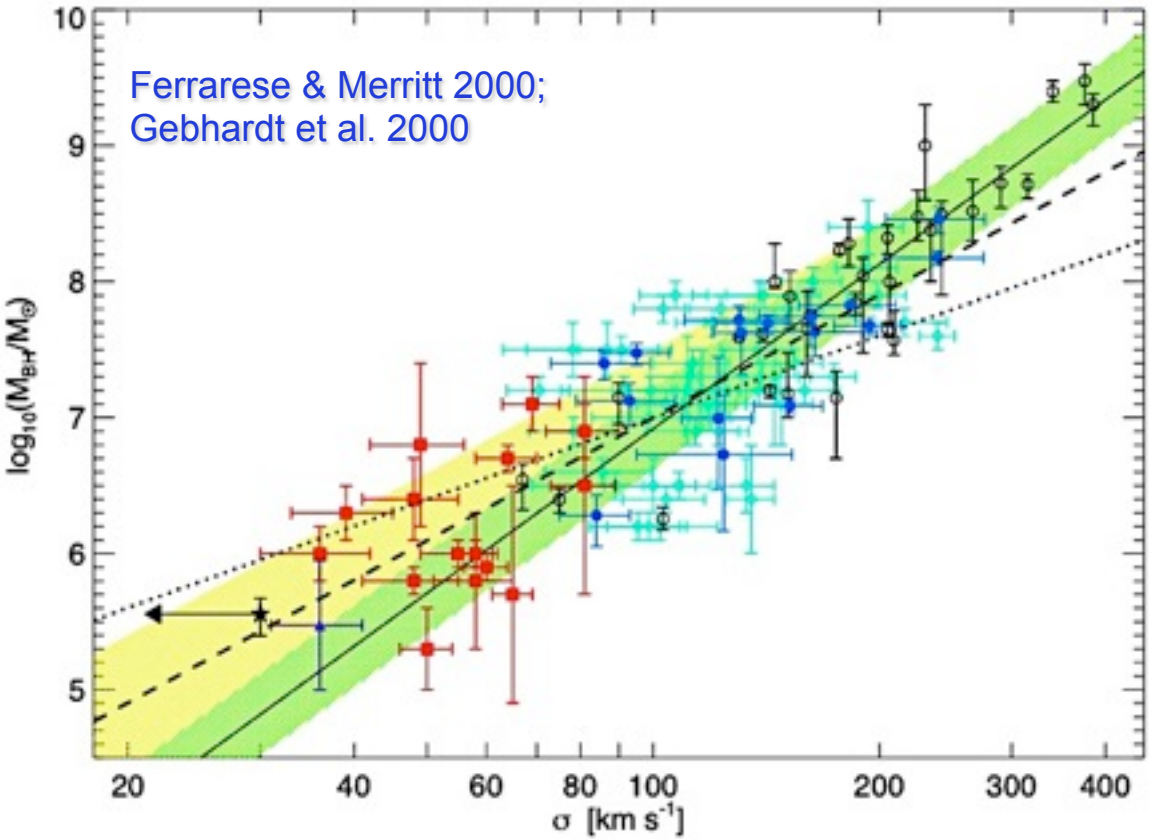
Lars Hernquist, T. J. Cox, Brant Robertson, Volker Springel,
Tiziana Di Matteo, Elisabeth Krause, & others

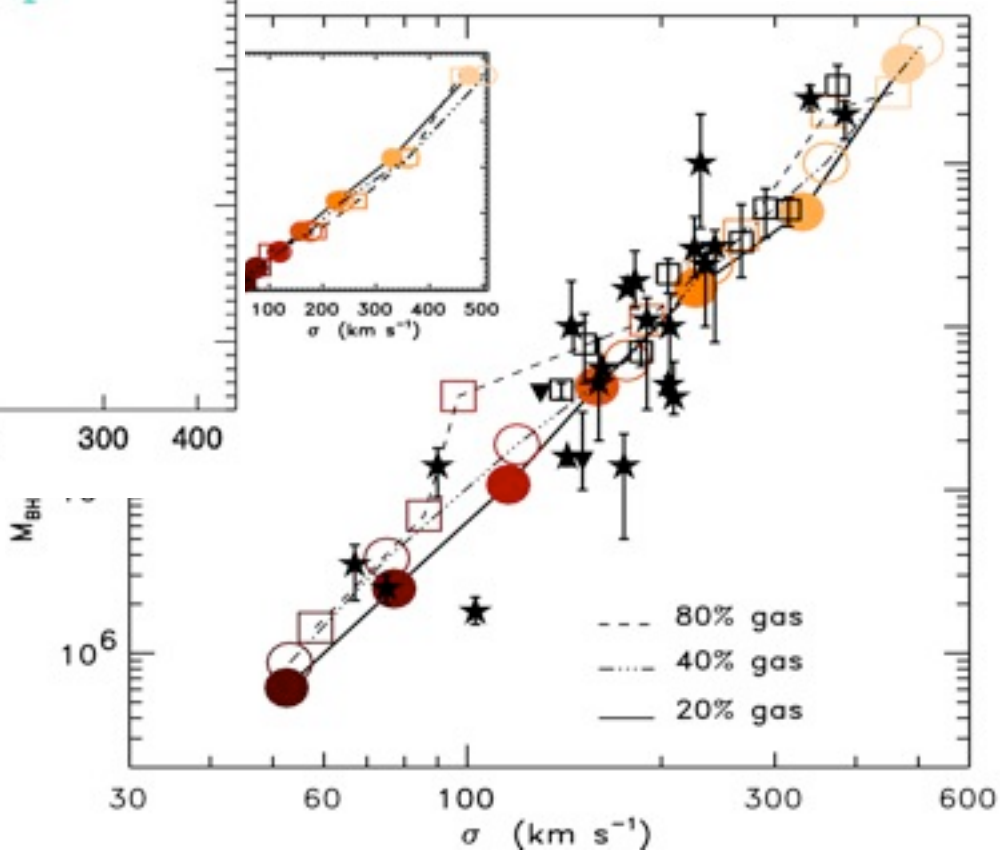
M-sigma Relation Is Now Canonical

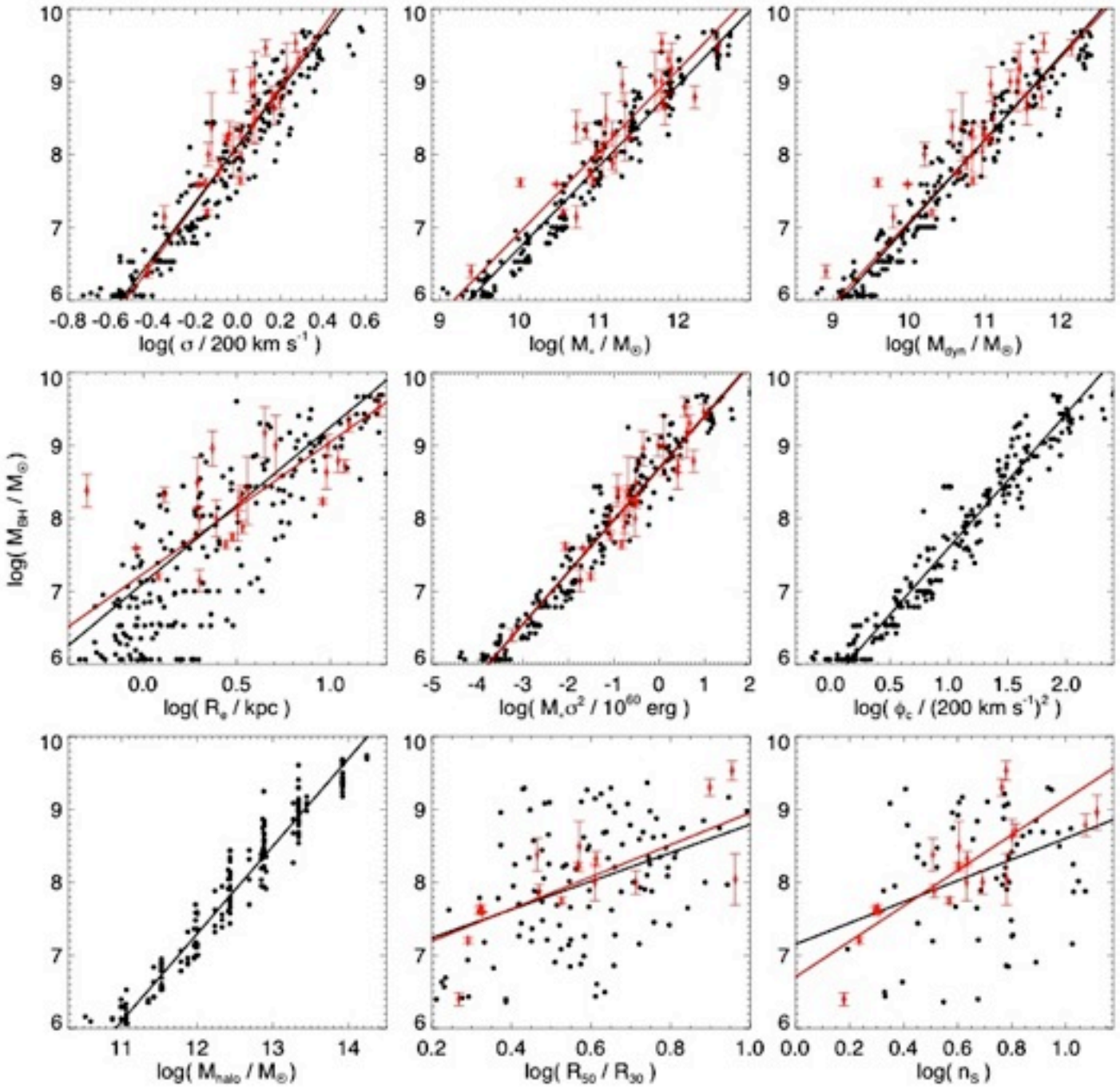
BHs & BULGEs CO-EVOLVE IN SOME SENSE



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

Di Matteo et al. 2005

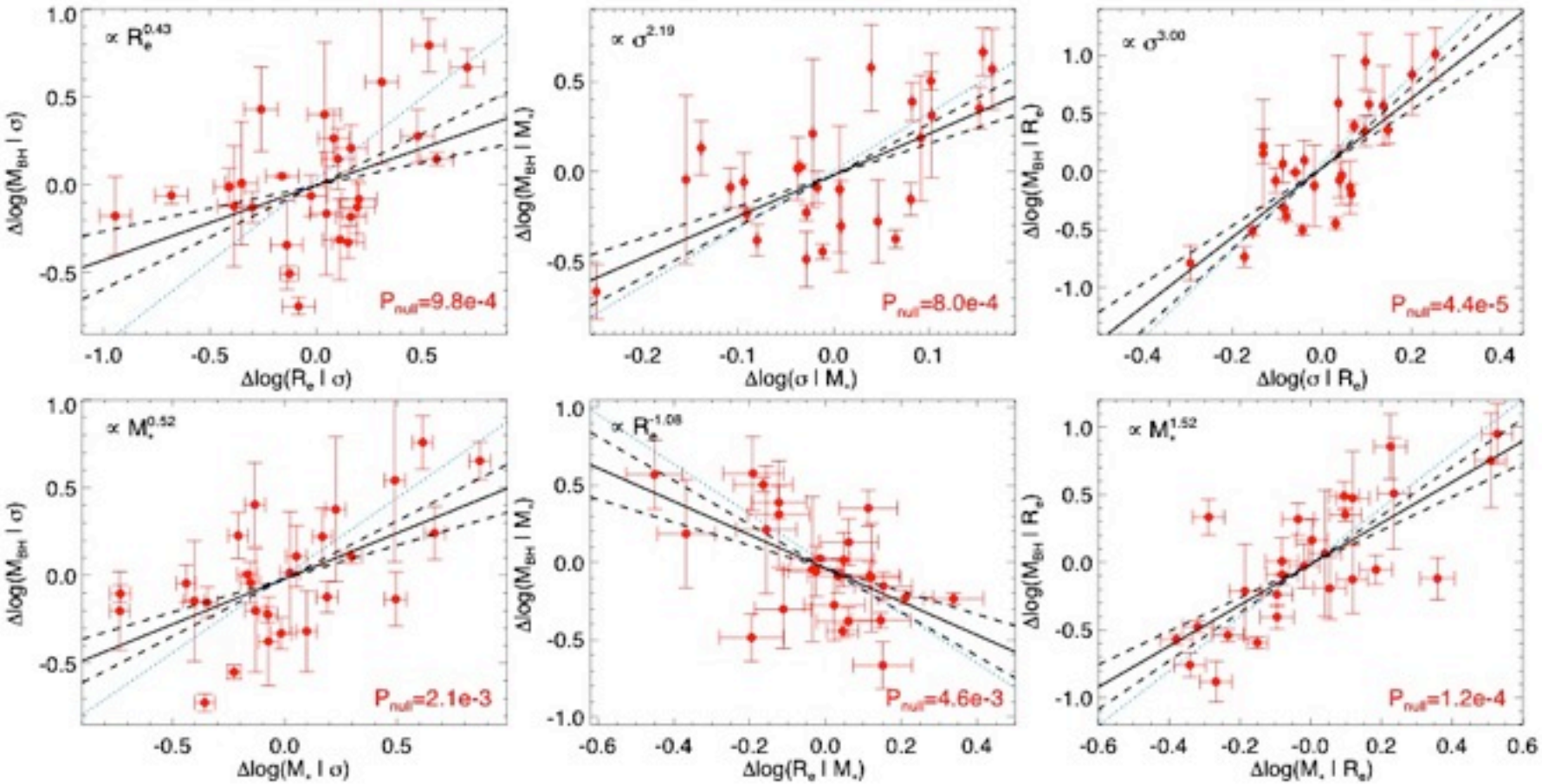



log(M_BH / M_⊙)
log(σ / 200 km s^-1)
log(M_* / M_⊙)
log(M_dyn / M_⊙)
log(R_e / kpc)
log(M_*σ^2 / 10^60 erg)
log(φ_c / (200 km s^-1)^2)
log(M_halo / M_⊙)
log(R_50 / R_90)
log(n_S)

Which Correlation Is “Most Fundamental”?

COMPARE RESIDUALS

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

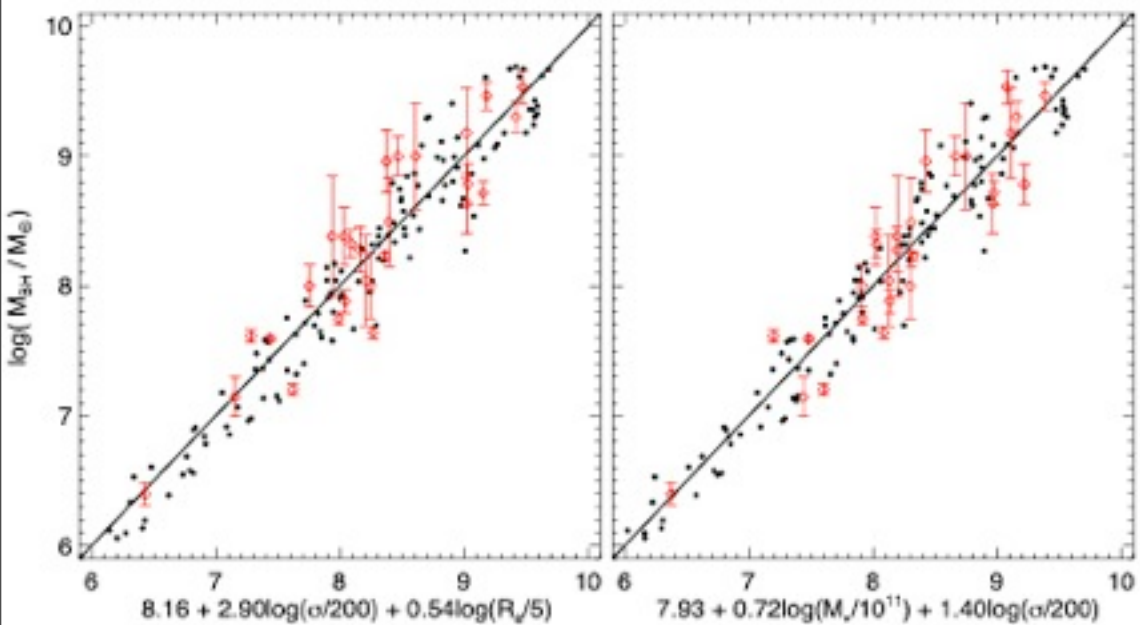


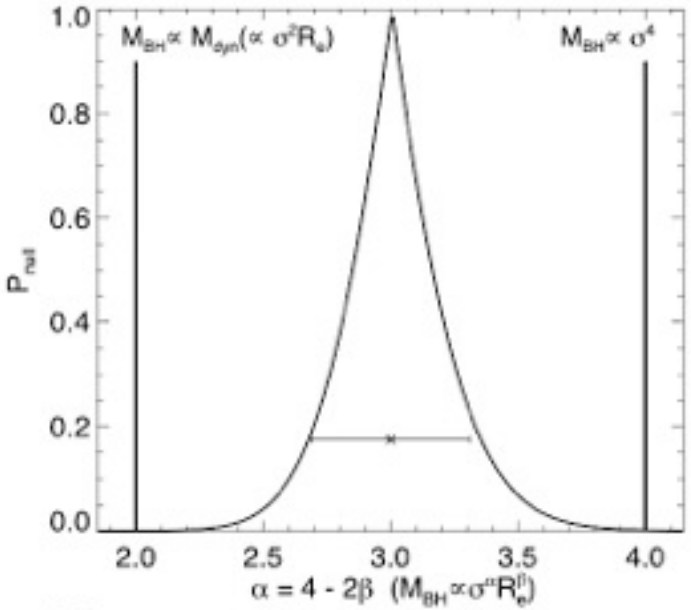
~3s significant residual trend with respect to ANY single variable correlation!

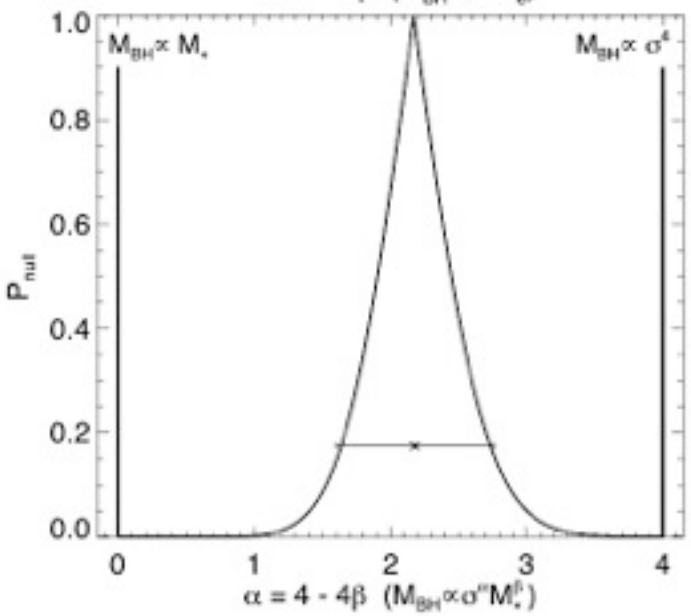
Which Correlation Is "Most Fundamental"?

WHAT ELIMINATES THE SECONDARY VARIABLES?

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







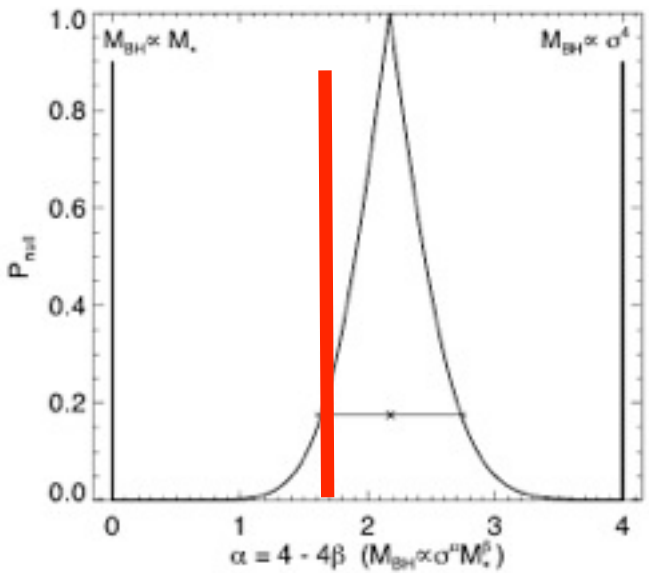
- Given the spheroid FP, these are the *same*

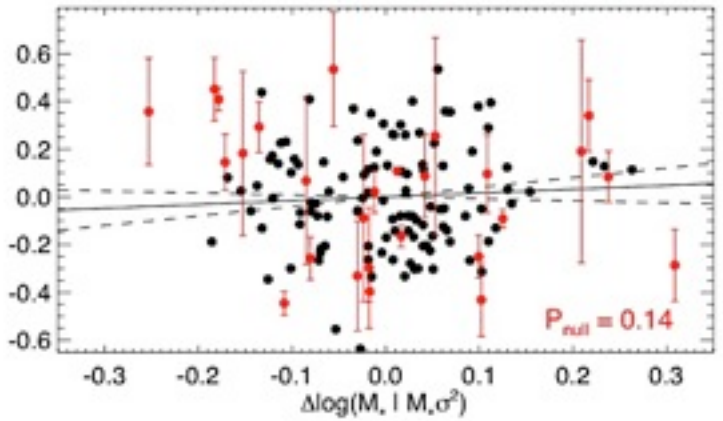
What Does this FP-Like Relation Imply?

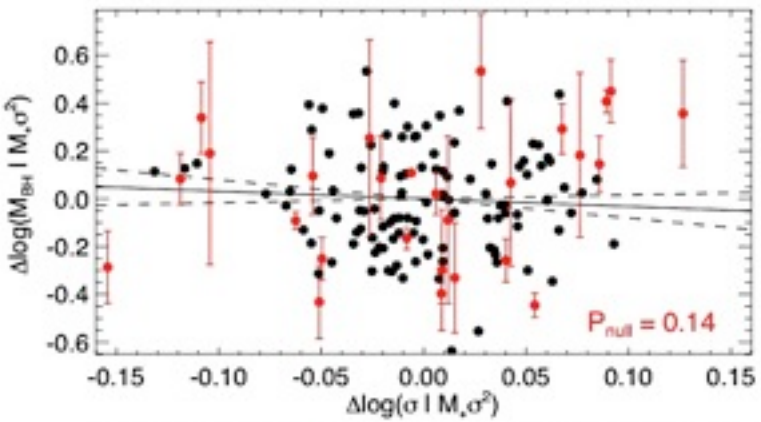
IS THERE ANY PHYSICAL MEANING?

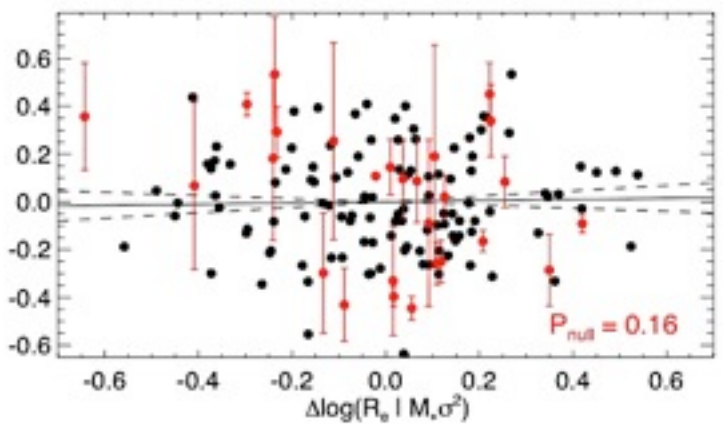
- Reasonably close to binding energy, but with "tilt":
  - $M_{bh} \sim E_{binding}^{2/3} \sim (M_{bul}\, s^2)^{2/3}$

- Pressure-driven outflow needs to unbind everything within R_{bh} in t_{dyn}:
  - $M_{bh} \sim M_{bul}^{1/2}\, s^2$



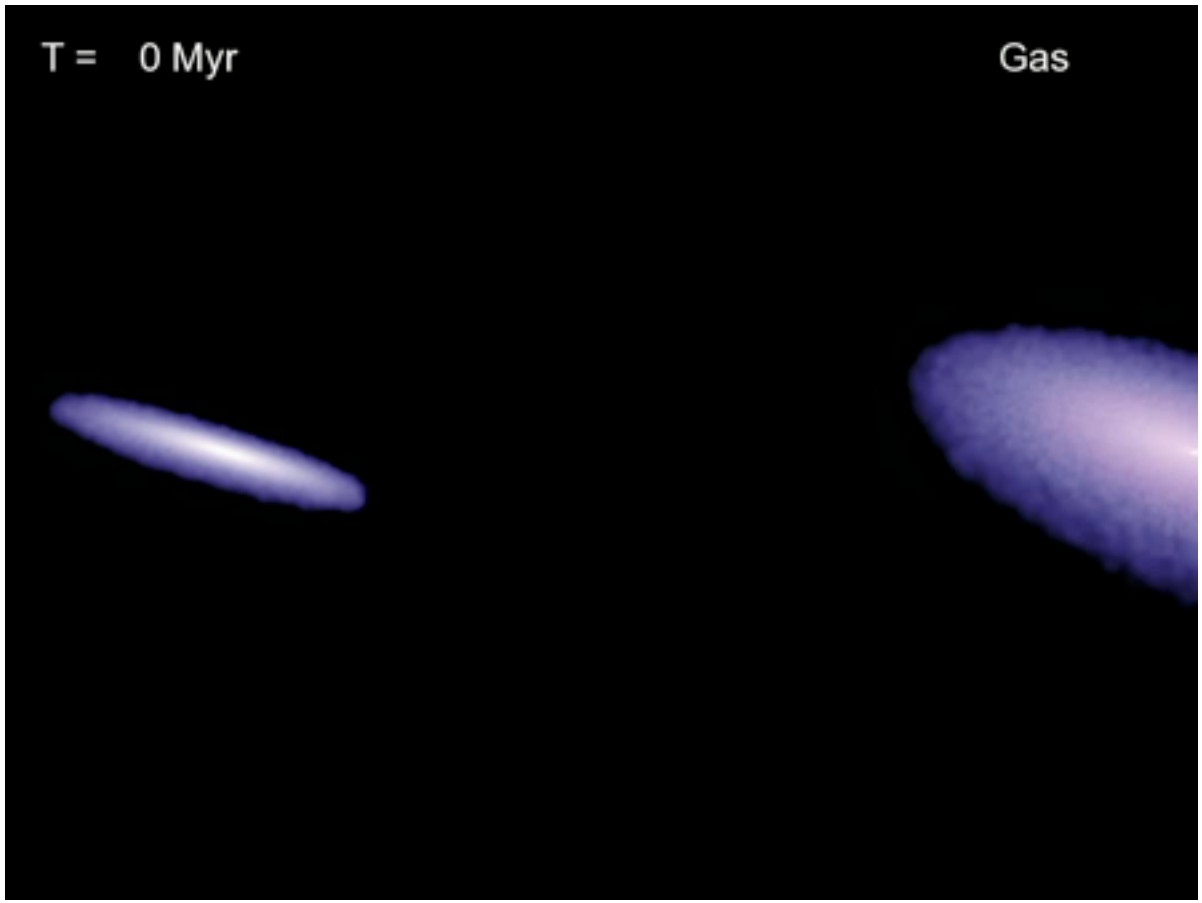


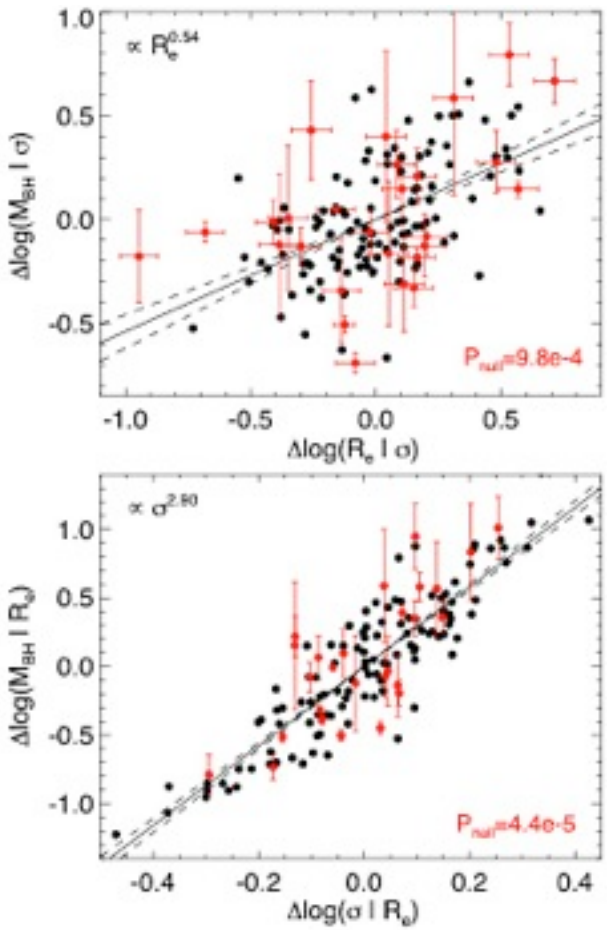




Do Feedback-Regulated Simulations Predict This?

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

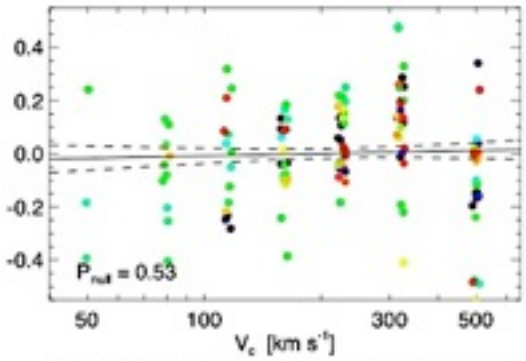


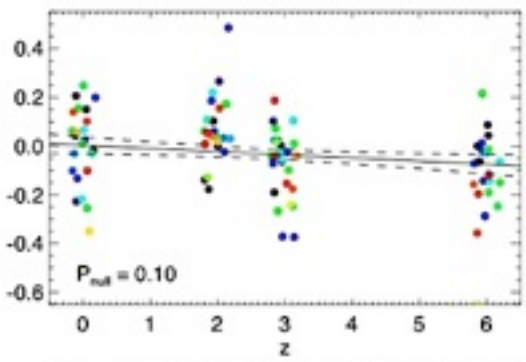


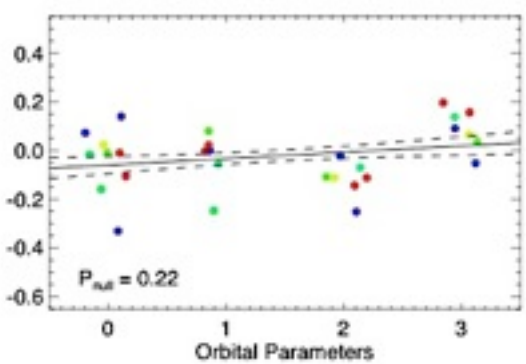
- Supports basic Silk & Reese ’98 argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential depth

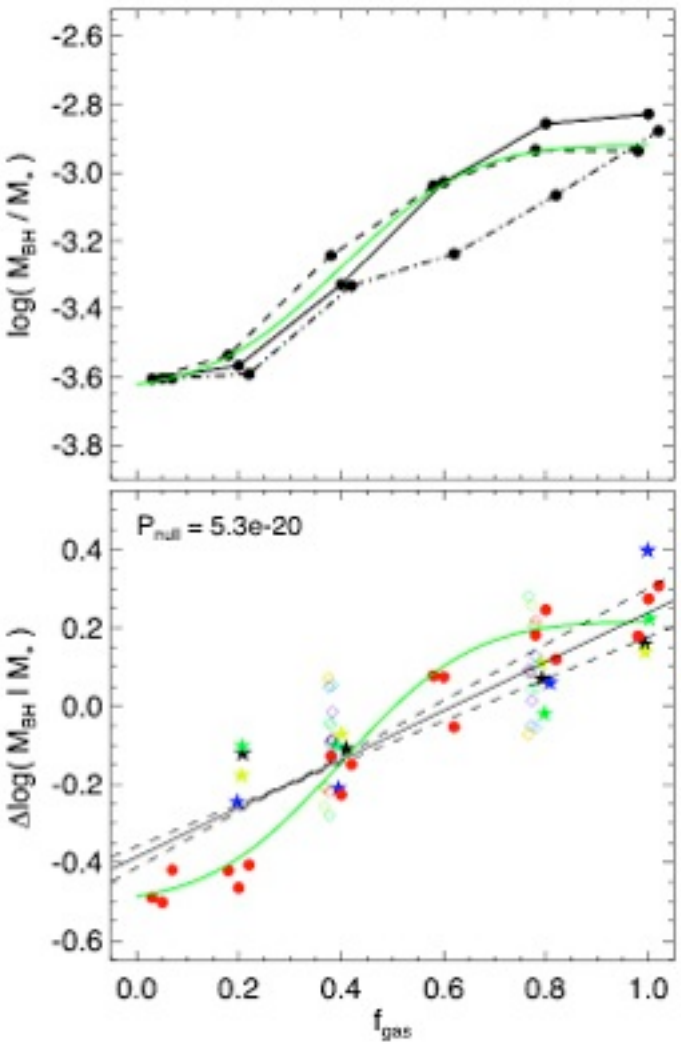
Can We Get Away From This?

HOW DOES THE RELATION DEPEND ON INITIAL CONDITIONS?





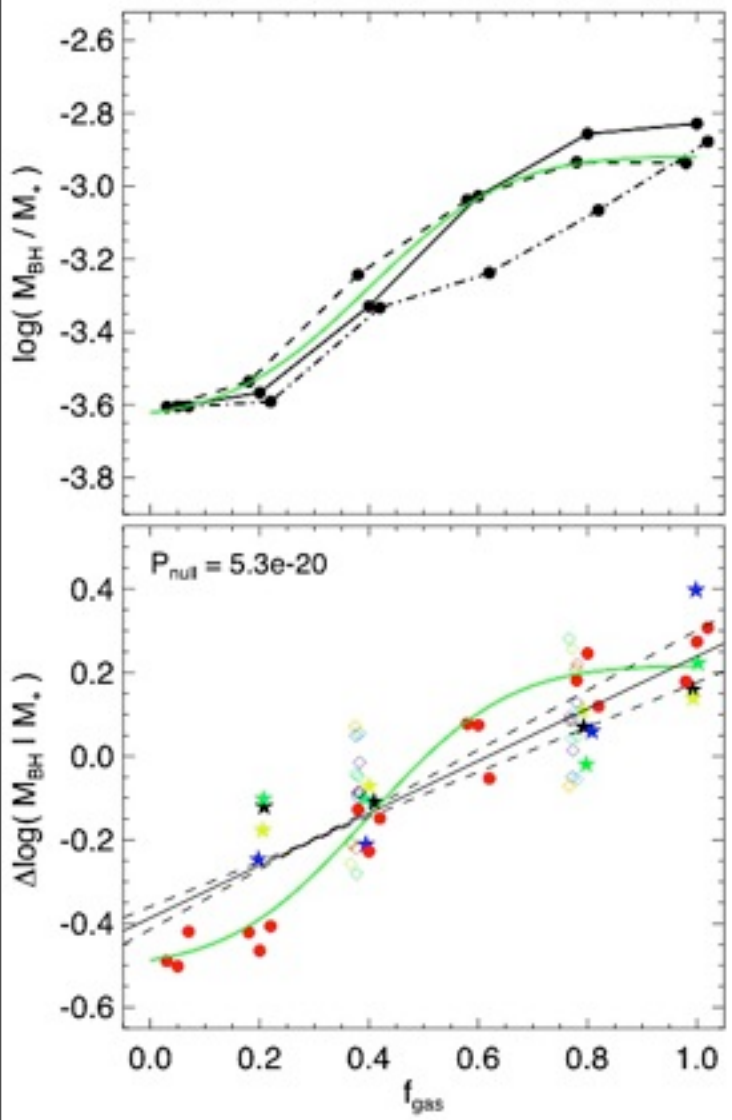




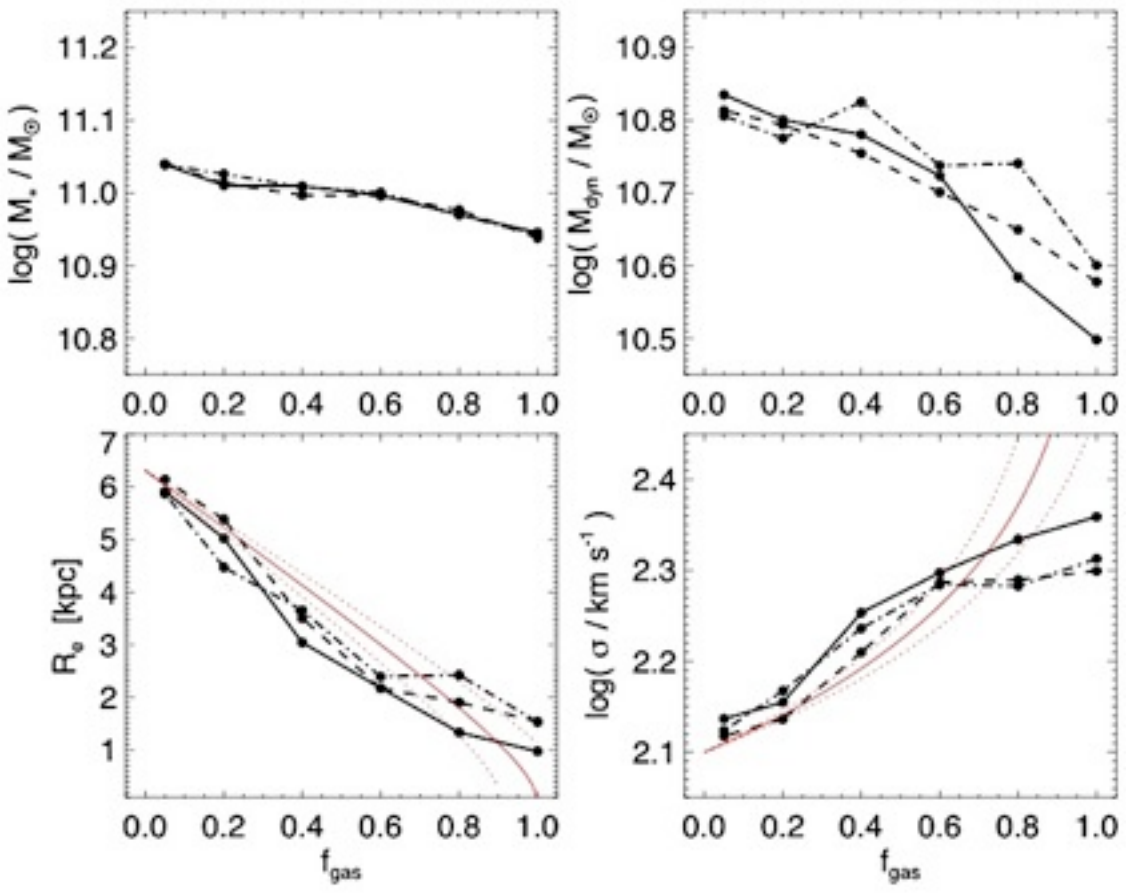
- Primarily a *local* correlation with *final* state:
  - Can't get "off" this correlation if feedback still self-regulates
- Can move *along* the correlation
  - Changes projections:
    - M_{bh} - M_{bul}
    - M_{bh} - s

Moving Along the BH FP-Like Correlation

GIVEN THIS CORRELATION, HOW DO YOU MOVE IN ITS PROJECTIONS



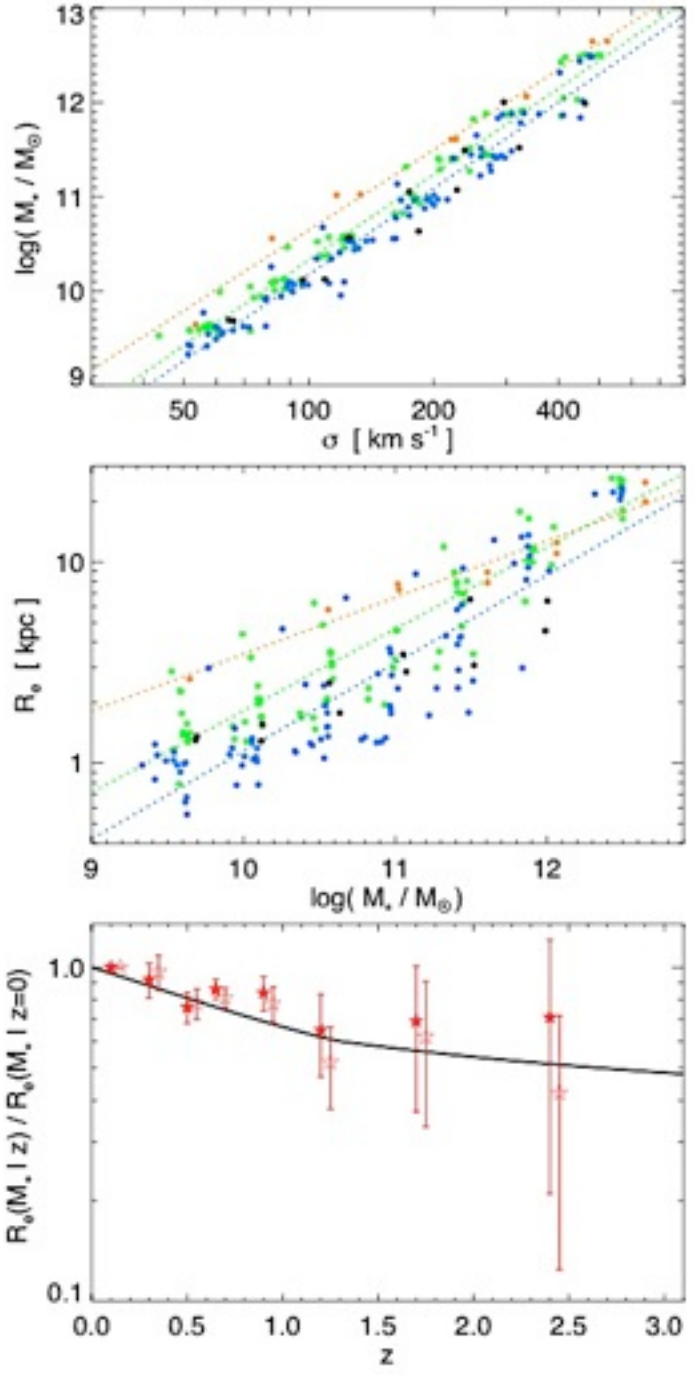
- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
- Deepens the central potential



Moving Along the BH FP-Like Correlation

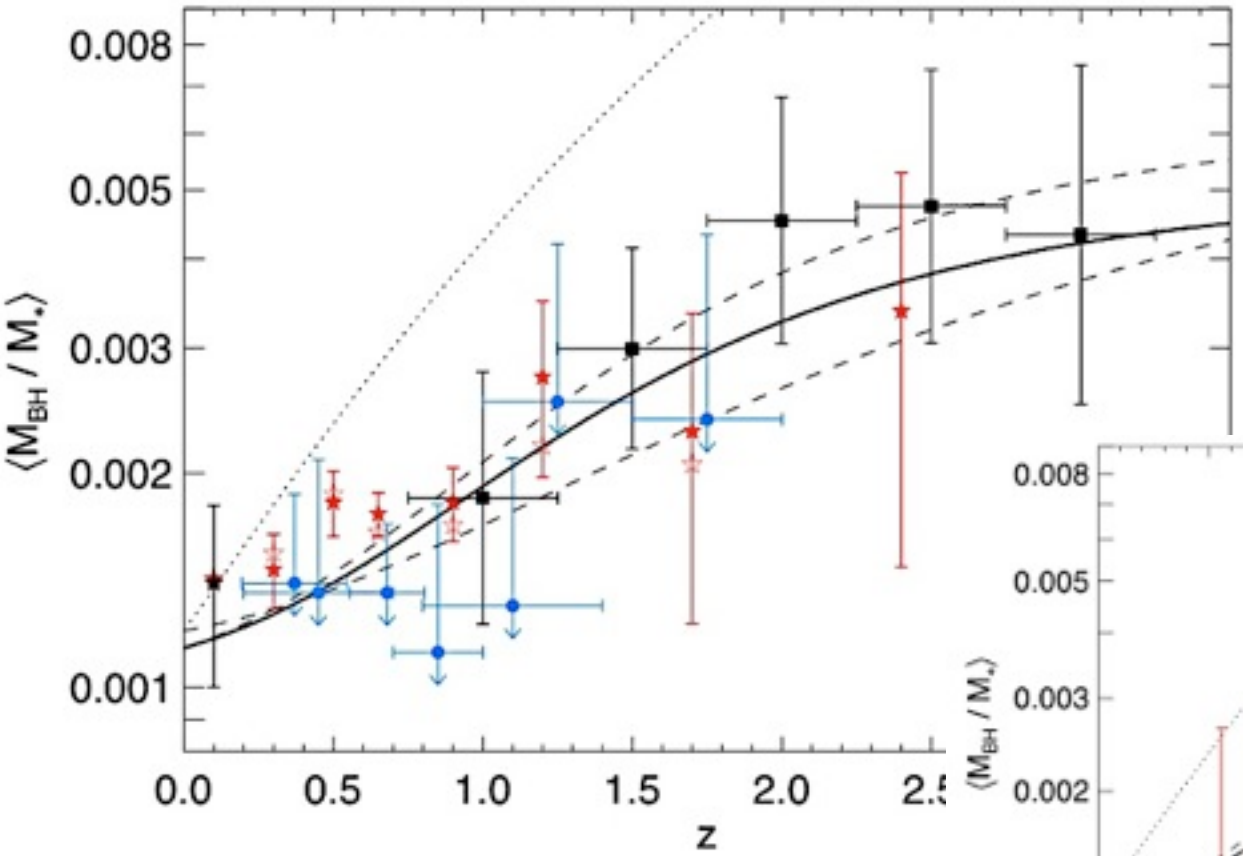
IMPLICATIONS FOR REDSHIFT EVOLUTION

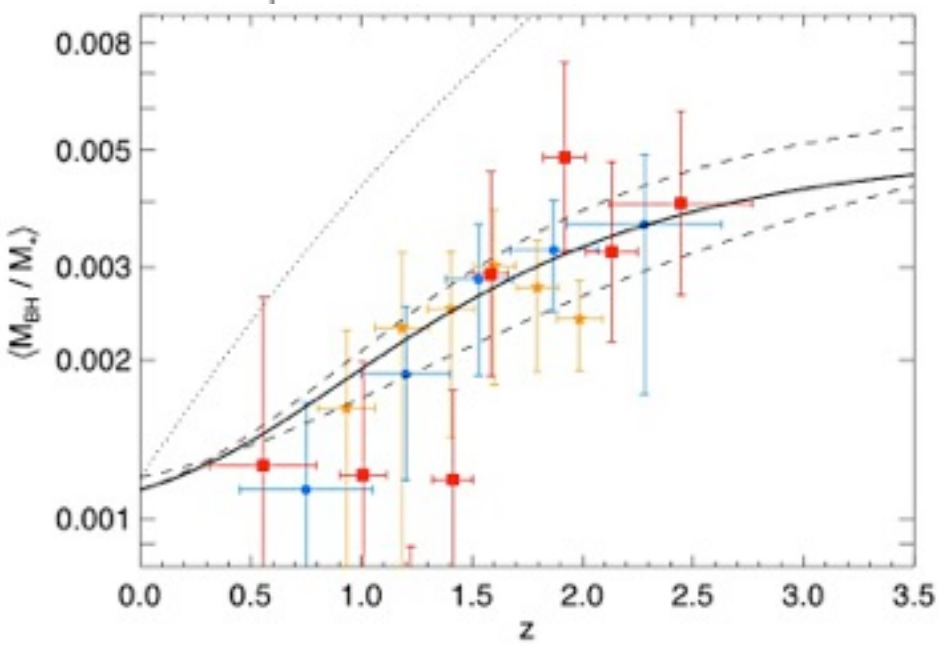
- High-z galaxies are more gas-rich:
  - Expect more compact remnants
    - Khochfar & Silk
  - See them: smaller R_e, larger s at fixed M_{bul}
    - Trujillo et al.; Zirm et al.



Moving Along the BH FP-Like Correlation

IMPLICATIONS FOR REDSHIFT EVOLUTION

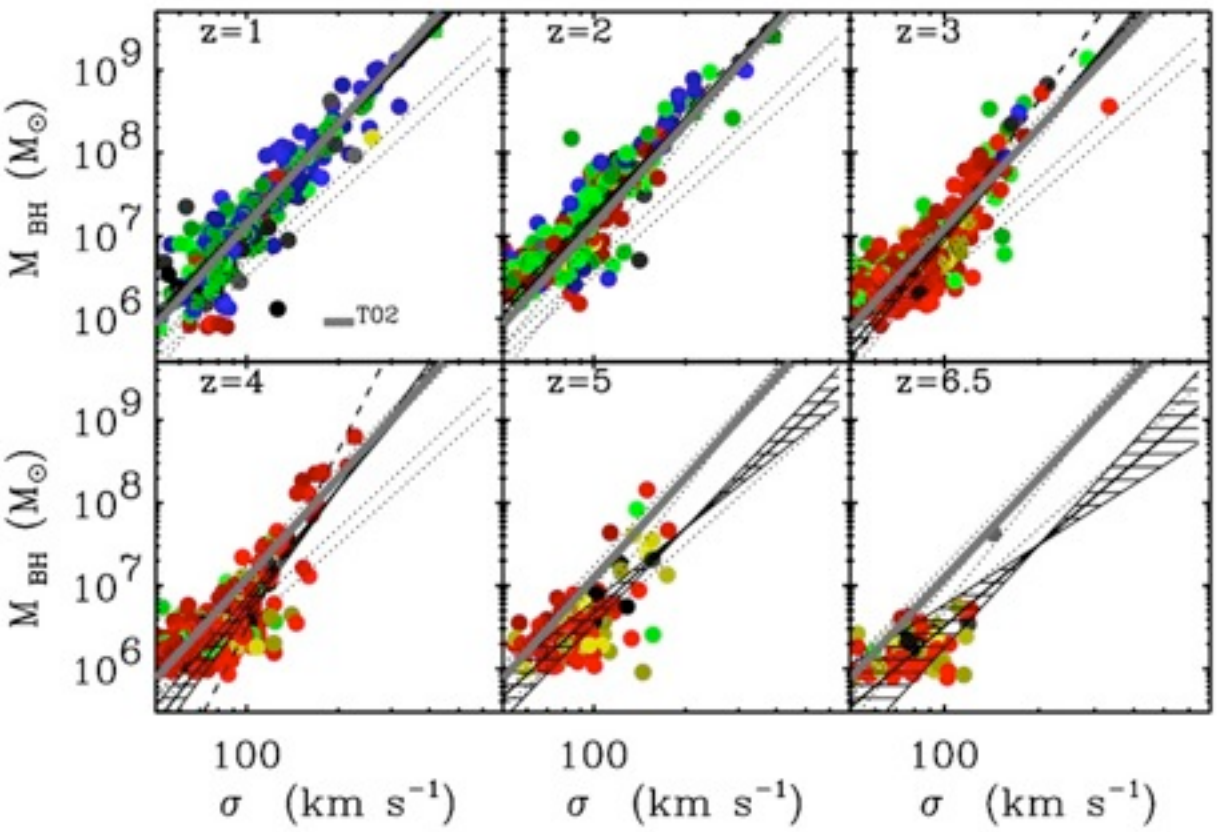




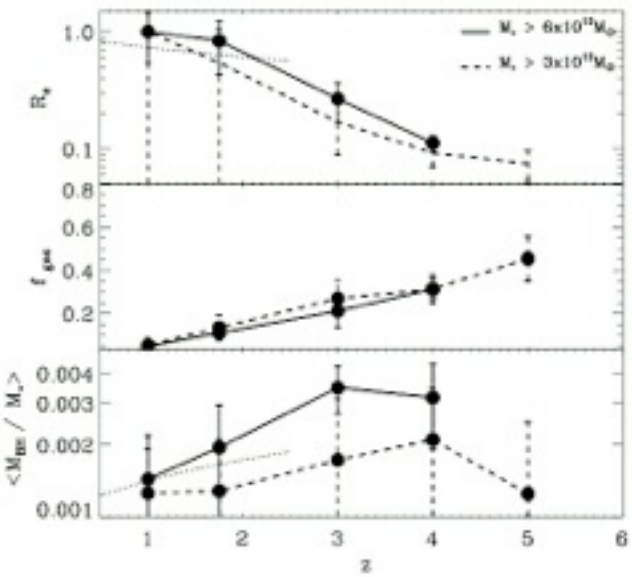
- $M_{bh} \sim M_{bul}^{1/2}\ s^2$
  - Larger M_{bh} at fixed M_{bul}
    - Peng et al.; Fine et al.; Shields et al.; Merloni et al.; Walter et al.
  - Different evolution in M_{bh}-M_{bul} & M_{bh}-s

Moving Along the BH FP-Like Correlation

IMPLICATIONS FOR REDSHIFT EVOLUTION



Di Matteo et al. 2007



- Recent cosmological simulations: same effect

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

Implications for BH Demographics

HOW MANY EXTREME BHs ARE THERE?