The M-Sigma Relation and Black Hole Feedback
M-sigma
Sigma vs. mass

- Kinetic energy:
  - $E_k \sim Mv^2/2$

- Potential energy:
  - $E_p \sim -GM^2/R$

- Angular momentum:
  - $L \sim MRv$
Sigma vs. mass

- Start out with large cloud
  - No $E_k$, just $E_p$
- Contraction: $v \sim 1/R$
  - $E_k$ increases more rapidly than $E_p$
- Equilibrium:
  - “Virial theorem”: $E_k = -E_p/2$
  - $v \sim \sqrt{GM/R}$
M-sigma

$M_{gal} \sim 1000 \, M_{BH}$
Why is this surprising?

- \( R_{\text{gal}} \sim 30,000 \) light years
- \( R_{\text{BH}} \sim 10 \) light minutes (horizon)
  - ★ “Sphere of influence:” Where are stars bound to black hole
  - ★ Like horizon, but use speed of stars (200 km/s) instead of speed of light (300,000 km/s)

\[ \Rightarrow R_{\text{BH}} \sim 30 \) light years

\[ \Rightarrow 1000 \times \) smaller!
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Where could M-σ relation come from?

- Where do galaxies come from?
- Where do SMBH come from?
How do Galaxies Grow?

- Gas accretion - forming stars
- Mergers - forming & inheriting stars
Galaxy distribution

Theoretical Prediction

Space Density (log(\(\phi(M)\)))

\(M^*,\phi^*\)

\(\alpha\) - faint-end slope

Absolute B Magnitude (mag, h=1)
Galaxy colors
Stellar Evolution

- Galaxies are made from stars...

Brighter

Young

Bluer

Old
Why are big galaxies red?

• What makes blue galaxies blue?
  ★ Young stars (and old stars, but those are fainter)

• What makes red galaxies red?
  ★ Old stars, i.e., lack of young stars
Why are big galaxies red?

- So: if big galaxies are red...
  - ...they must have stopped forming stars
  - ...hold that thought
How do SMBH grow?

- SMBH *can* grow through accretion
  - That makes them bright
- Quasars are the brightest SMBH
  - Black holes grew as quasars
- X-ray background:
  - Universe filled with X-rays from quasars
Chandra Deep field North:
The X-ray sky is full of black holes
How do SMBH grow?

• Lots of gas
• Must drive that gas to the center
• This is best done in galaxy mergers: ★ Angular momentum of gas is lost in collision
• This also brings gas to galaxies ★ Makes them blue
Aha!

- Galaxies and SMBH should have grown at the same time!
Mergers and growth

- Quasars release enormous amounts of energy:
  - 10% of the rest mass energy of accretion can be released
  - For a black hole 0.1% the mass of a galaxy, that is 10x the binding energy of the galaxy!

- That’s gonna leave a mark...
• Computer simulation of “Feedback” by growing quasar in galaxy merger

Spring, DiMatteo, Cox, et al.
What happens to the black holes?

- The two initial black holes merge
- They grow through accretion
What happens to the stars?

- The stars merge to form a new galaxy
- The black hole turns blows away the gas
  - No more new (blue) stars
  - Galaxy is now red
  - Also: Galaxy is no longer a disk
• Same simulation, now showing the stars
Stage 1:

• Summary of theory for stage 1:
  ★ Star formation is regulated by black hole growth
  ★ Stars and black hole both grow until black hole blows away the gas

• Then:
  ★ no more gas, no more new stars,
  ★ no more black hole growth
$M \sim 1000 \, M_{\text{BH}}$
Is this necessary?

• Remember: Galaxies grow through mergers
• Black holes also grow through mergers
  ★ Suppose you start with a random distribution of black hole masses in small galaxies
  ★ Smash them together
  ★ Galaxies grow and black holes grow
Mergers

$M_{\text{BH}}$ vs $M_{\text{galaxy}}$
Mergers

M_{BH} vs M_{galaxy}
Mergers

$M_{\text{BH}}$ vs $M_{\text{galaxy}}$
Mergers
Mergers

\[ M_{BH} \]

\[ M_{\text{galaxy}} \]
Mergers

But: Some Black Holes get kicked out of galaxies in mergers
Mergers

But: Some Black Holes get kicked out of galaxies in mergers
M-sigma wrap-up

• The Jury is still out:
  ★ Mergers? *Must* play a role
  ★ Black hole feedback? *May* play a role

• Probably both