Galaxy scaling laws under the "gravitational microscope"

<table>
<thead>
<tr>
<th>Einstein Ring Gravitational Lenses</th>
<th>Hubble Space Telescope - ACS</th>
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<td>J073728.45+321618.5</td>
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NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

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Collaborators

Leon Koopmans (LSD+SLACS)
Adam Bolton (SLACS)
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Raphael Gavazzi (SLACS+)
Jason Rhodes (special guest)
Outline

1. The Fundamental Plane as a diagnostic of the internal structure of early-type galaxies
2. The bulge-halo “conspiracy”.
   1. Scaling relations between dynamical, weak and strong lensing properties
The internal structure of spheroids: clues to the formation process

- Dark matter halos detected (sometimes…)
- Most stars are old
- Tight scaling relations between various properties, velocity dispersion, size, luminosity, black hole mass… (e.g. Ma’s talk)
The formation of spheroids: questions

• How come the scaling relations, the FP in particular, are so tight?

• Many possible sources of scatter, including:
  – Stellar population effects
  – Distribution function differences
  – Dark matter content

• Yet somehow, baryons and dark matter “conspire” to produce small scatter
The Fundamental Plane as a diagnostic of galaxy structure

- Empirical correlation between size, luminosity and velocity dispersion
- Gives “effective M/L” at “effective mass”

Dressler et al. 1987; Djorgovski & Davis 1987; Bender Burstein & Faber 1992; Jorgensen et al. 1996
The “tilt” of the FP

- In terms of effective mass \((M_* = 5\sigma^2 R_e / G)\), the FP reads \(M_*/L \sim M_*^{0.25}\)

- Possible Explanations:
  - Stellar population trends (c.f. ‘downsizing’ measurements, e.g. Treu et al. 2005)
  - Dynamical Trends. More dark matter, change in distribution function, i.e. virial coefficient (5->K_v)
Tilt and tightness. Implications for the formation process

• Formation history, including environmental effects, is not “scale free”: star formation history, halo buildup, depend on final mass

• Yet, at any given mass, star formation history, mass profile, etc are remarkably homogeneous (another “conspiracy”)
What can lensing do for us?

- Most studies of high-z E/S0 measure their star formation history or demographics.
- What about the internal properties?
  - Do high-z E/S0 have dark halos? What do they look like?
  - What is the evolution of the mass structure of E/S0 over cosmic time?
- LENSING ALLOWS US TO “DISSECT” HIGH-Z E/S0s
\(Z > 0: \) lensing + dynamics
Example of data: 0047 at $z=0.485$

- 5.75 hrs integration; velocity dispersion profile to $\sim 5\%$

Koopmans & Treu 2003
Samples:

- **Lens structure and dynamics survey (LSD):** all (10) suitable gravitational lenses known <2002
  - (TT + Koopmans)

- **Sloan Lens ACS Survey:** ongoing survey. Largest sample of lenses so far (~50! Bolton’s talk).
  - (TT + Koopmans, Bolton, Burles & Moustakas)
Results: lenses are “normal” spheroids

Lenses live in the same FP as normal spheroids, once selection in $\sigma$ is taken into account (Treu et al. 2006)
Results: a scaling law measuring mass profiles!

"Lensing" velocity dispersion
Or in terms of ratio...

- The ratio of the stellar velocity dispersion to that of the best fitting lens model is very close to unity
- The mass profile is close to isothermal: $\rho \sim r^{-2}$. [Koopmans’s talk]
- How do the stars and dark matter know “where to go”?
- Dark-luminous mass “conspiracy”
Are E/S0 exactly isothermal? 1. Velocity dispersion trends

Do more massive galaxies have more dark matter? Wait for the next SLACS papers....
Are E/S0 exactly isothermal? 2. Enter weak lensing...

- Deeper ACS data (1 orbit F814W) available for 18 SLACS lenses (85 expected by the end of cycle 15).
- Background galaxy density \( \sim 80/ \) square arcmin
- Stacked weak-lensing analysis yields a significant detection of the shear (>8 sigma)
- Analysis exploits the most advanced corrections for ACS-PSF systematics (breathing, CTE…) developed for cosmic shear analysis (Rhodes et al. 2006)

Gavazzi, TT et al. 2006
Are E/S0 exactly isothermal? 2. Voila’!

Gavazzi, TT et al. 2006
Are E/S0 exactly isothermal? 2. Behavior at large radii

Constant M/L ratio doesn’t work

Isothermal works well

Gavazzi, TT et al. 2006
Are E/S0 exactly isothermal? 2. Behavior at large radii

Two component fit. Best slope with M/L=0 is $2.08 \pm 0.08$

Gavazzi, TT et al. 2006
Are E/S0 exactly isothermal? 3. “Velocity dispersion” profile

Gavazzi, TT et al. 2006
Conclusions

• The mass density profile of E/S0s can be measured to $z \sim 1$ by combining lensing and stellar dynamics

• Massive E/S0 lens galaxies are well reproduced by singular isothermal ellipsoids out to $z=1$:
  – Bulge/Halo conspiracy
  – Jury still out whether the trend extends to smaller masses

• Dark halos can be detected out to $\sim 100$ effective radii combining weak-lensing.
  – The total mass profile appears to be close to isothermal all the way out. The plot thickens…
The end