From Galaxy Formation to Kinematics

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In collaboration with: Joel Primack, Aaron Romanowsky, Greg Novak and TJ Cox.
Fast rotators are above the isotropic, oblate rotator line

Slow rotators are \textbf{not} scaled-down fast rotators

- More massive
- Round, have $\epsilon \sim 0.0-0.2$

How do slow rotators form?

(Emsellem et al. 2011)
Simulated Binary Mergers

- Simulated binary mergers and remergers with varying mass ratios, initial conditions, and orbital parameters at high resolution
- Form galaxies with $\lambda < 0.1$, but are far too elongated $\epsilon = 0.0 - 0.4$

→ Do not form slow & round rotators in binary simulations

(Bois et al. 2011)
Simulated Multiple

- Bournaud et al. 2007 simulated 10 1:10 mergers, 5 1:5 mergers, etc.
- Multiple mergers decrease remnant $v/\sigma$, form rounder remnants
- Results are independent of mass ratio; only dependent on remnant mass

→ Did not reach slow or round rotators, but there is a trend towards slow/round with multiple mergers (Bournaud et al. 2007)
Simulations: Progenitors

- All late-type galaxy models
- Designed to model SDSS galaxies
- D, Y, Z series are bulgeless
- G3, G2, G1, G0 in order of descending mass
- G3 also a gas fraction series
- G3BL is a G3 without a bulge (not shown)
- Sbc series have small bulges

→ Progenitors cover a range of gas fractions (‘gf’) and mass ranges, and may be bulgeless (‘BL’).
Schematic: Assembly

**Binary mergers**
- Two progenitors
- Minor, major mergers
- $R_{peri}, \epsilon,$

**Sequential mergers**
- Either G2 or G1
- Either 4 or 8 overlapping major+ minor mergers

**Remergers**
- Either G2 or G1
- Also, 4 and 8 progenitors
- Every merger a is always a remerger

Cosmologically-motivated orbits. Not statistical.

Randomly chosen initial orientations, impact parameters. Idealized simulations.
With increasing gas fraction: faster rotators, higher ellipticity

rotation

 elongate

round

ellipticity

dispersio

supporte

Increasing gas fraction
Binary Mergers: Orbital Variations

- Varying orbital initial conditions:
  - Spin (pro/retrograde), varying pericenter, orbital ellipticities
- Only specially constructed initial zero angular momentum case is a slow rotator – but quite elongated
Multiple mergers: Major vs. minor

- Both sets of simulations have the same number of identical progenitors
- Multiple minor merger remnants are slower and rounder
Misalignments

- Fast rotators $\sim 5^\circ$
- Slow rotators $0^\circ - 90^\circ$

$\lambda_{SAURO}$

SAURON and simulations in good agreement

(Emsellem et al. 2007)
ATLAS$^3$D finds kinematically decoupled cores and other non-regular rotators with high frequency in their slow rotator sample. How do these features arise? 82% Fast Rotators, 17% Slow Rotators, many with either KDC or CRC features.

(Krajnović et al. 2011)
Polar orbits yield fast rotators but also KDCs

- Polar orbits impart significant momentum out of the plane of the progenitor galaxy.
Sequential Merger KDCs

- Small-scale KDCs present in many velocity maps for sequential series
- Major mergers result in a more disrupted remnant kinematic structure
• **Multiple** mergers have KT rates of 20%–90%
• **Binary** mergers have KT <30%, with exceptions
Conclusions

- Binary mergers generically form fast rotators
- **Slow rotators** are in general not formed in dissipational binary major mergers. The exceptions depend on unique initial conditions:
  - Bulgeless galaxies that are essentially dry mergers
  - Zero initial angular momentum
  - Sequential multiple mergers can form round slow rotators

- Kinematic twists much more prevalent in polar orbits and slow rotators
Overall Trends (averaged over all projections)
Multiple Mergers

- Spiral progenitors are at least 1:10 stellar mass ratio
- Effective number of progenitors is mass-weighted
- Semi-analytic models predict that the most massive systems form by multiple mergers
- Multiple, minor mergers are a relevant scenario

(Left: Bell et al. 2003, Right: de Lucia et al. 2006)
Title
Simulation parameters

Table 1. Properties of progenitor galaxy models. $M_{\text{tot}}$ is total mass, baryons plus dark matter; $c$ is concentration ($R_{\text{vir}}/r_s$); $M_{\text{stars}}$ is the initial stellar mass; $B/D$ is the bulge-to-disc ratio; $f_g$ is the initial gas mass divided by $M_{\text{tot}}$; $R_{1/2}$ is the initial three-dimensional stellar half-mass radius.

<table>
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<tr>
<th>Type</th>
<th>$M_{\text{tot}}$ ($10^{10} , M_{\odot}$)</th>
<th>$c$</th>
<th>$M_{\text{stars}}$ ($10^{10} , M_{\odot}$)</th>
<th>$B/D$</th>
<th>$f_g$</th>
<th>$R_{1/2}$ (kpc)</th>
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(Covington 2008, Cox 2004, Cox et al. 2006)
**Simulation parameters**

Table 1. Progenitor galaxy properties, grouped by series.

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