

# Structural Evolution of Early-Type Galaxies

Modelling Deprojected Morphology

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# Chang et. al (2013)

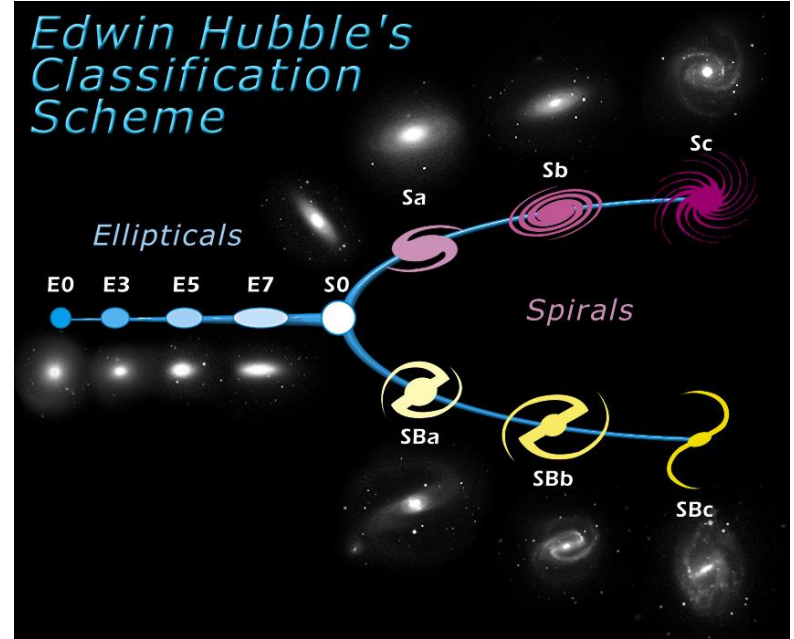
“Projected axis ratio measurements of 880 early-type galaxies at redshifts  $1 < z < 2.5$  selected from CANDELS are used to reconstruct and model their intrinsic shapes.”

“[...] even at a fixed mass, the projected axis ratio distributions cannot be explained by the random projection of a set of galaxies with very similar intrinsic shapes. However, a two-population model for the intrinsic shapes, consisting of a triaxial, fairly round population, combined with a flat ( $c/a \sim 0.3$ ) oblate population, adequately describes the projected axis ratio distributions of both present-day and  $z > 1$  early-type galaxies.”

- CANDELS (Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey) is a HST survey designed to study the first third of galactic evolution

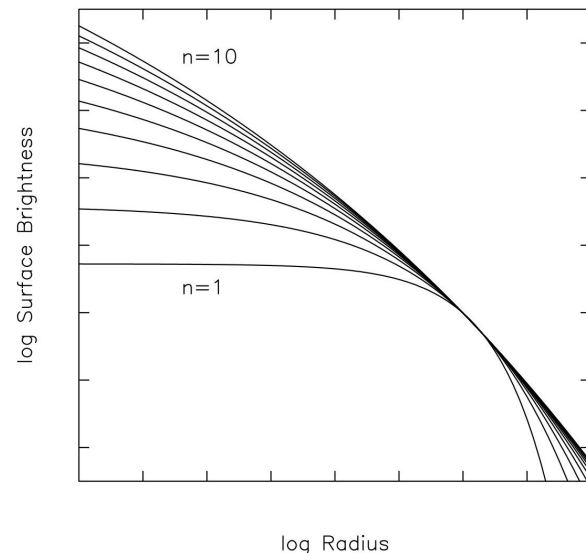
# Hubble's Classification

- We can broadly classify galaxies into early and late types
- For our modelling purposes, ellipticals are generalized to be ellipsoids of varying axial ratios



# Selecting Data

- The data is selected from HST CANDELS catalogs
- Early type galaxies up to  $z$  of 2.5 selected
- The structural parameters (radii, Sersic indices, and projected axial ratios) are taken from Van der Wel et al. (2012), who fit Sersic profiles algorithmically to individual galaxies



$$\ln I(R) = \ln I_0 - kR^{1/n}$$

# Binning the Data

- Data is binned by stellar mass and redshift
- Only data with “good” flags from the GALFIT routine are accepted
- Produce a mass-selected sample with “reliable structure measurements”

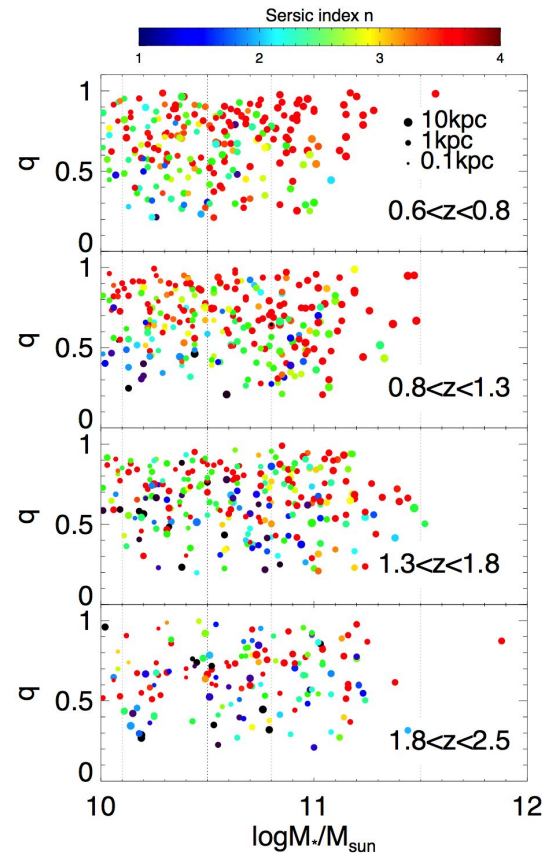
TABLE 1  
SAMPLE SIZES

$\log(M_*/M_\odot)$	10.1 – 11.5	10.8 – 11.5	10.5 – 10.8	10.1 – 10.5
Redshift	Numbers			
SDSS	32842	13640	13991	5211
H12	1321	384	475	462
$1 < z < 2.5$	569	197	168	204
$0.6 < z < 0.8$	220	47	67	106
$0.8 < z < 1.3$	256	78	66	112
$1.3 < z < 1.8$	244	88	71	85
$1.8 < z < 2.5$	147	55	47	45

Chang et al. (2013)  
Table 1

# Evolution of Projected Axis Ratios

- High mass early type galaxies are generally rounder with higher Sersic indices than low mass ones, but this trend weakens around  $z = 2$
- At all redshifts, flatter galaxies have lower Sersic indices.
- This indicates that the observed axial ratios are not only the result of different viewing angles.



Chang et al. (2013)  
Figure 3

# Defining a Model

- Assume early type ellipticals can be classified as ellipsoids with differing axial ratios
- We can also define ellipticity and triaxiality parameters:

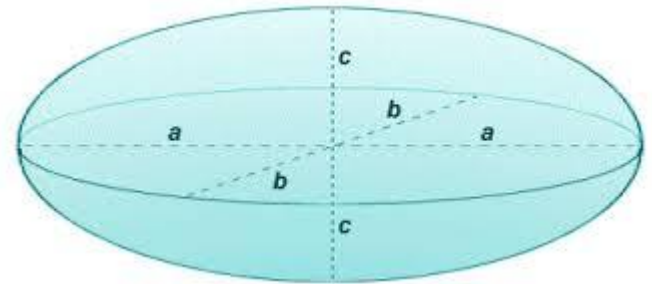
$$E = (1 - \gamma) \quad (1)$$

$$T = \frac{(1 - \beta^2)}{(1 - \gamma^2)} \quad (2)$$

$$m^2 = x^2/a^2 + y^2/b^2 + z^2/c^2$$

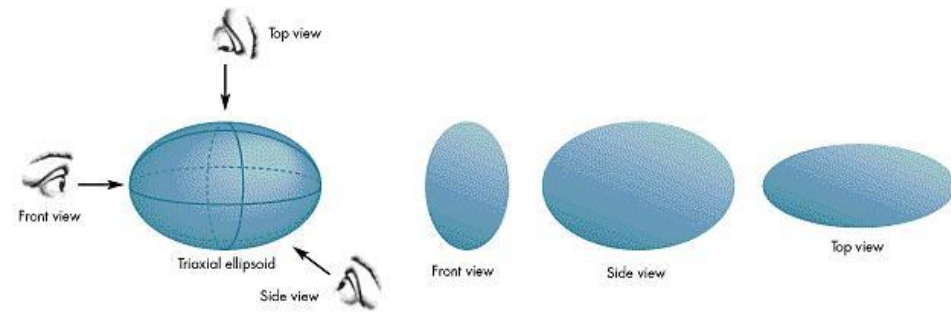
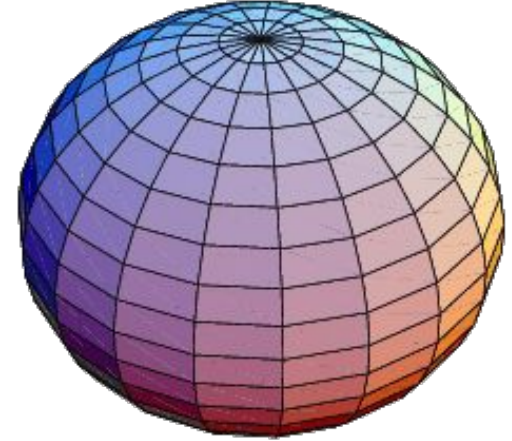
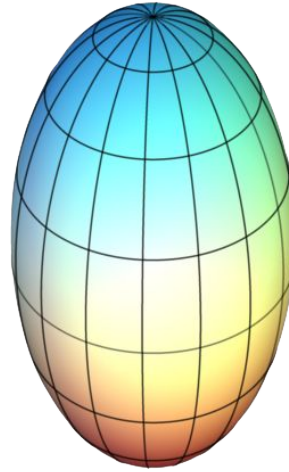
$$\beta = b/a$$

$$\gamma = c/a$$



# Prolate and Oblate Spheroids

- Spherical ( $A \sim B \sim C$ )
- Prolate - ( $A > B \sim C$ )
- Oblate - ( $A \sim B > C$ )





# Analytically Approximate the Intrinsic Axis Ratio Distribution

- According to Fall & Frenk (1983):

$$\psi_O(\gamma) = \frac{2\sqrt{1-\gamma^2}}{\pi} \frac{d}{d\gamma} \int_0^q \frac{\phi_O(q) dq}{\sqrt{\gamma^2 - q^2}} \quad (1)$$

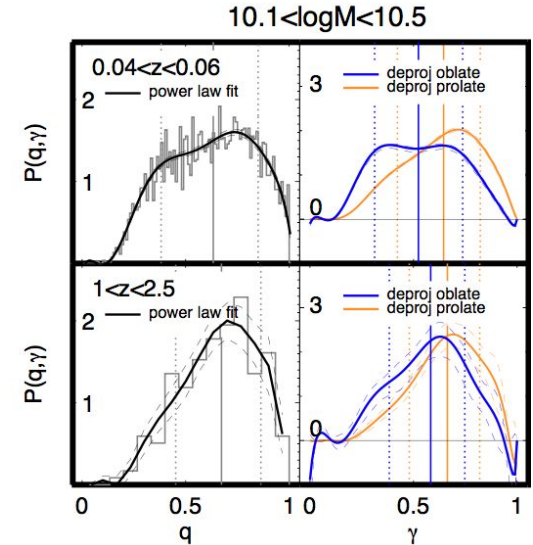
$$\psi_P(\gamma) = \frac{2\sqrt{1-\gamma^2}}{\pi \gamma^2} \frac{d}{d\gamma} \int_0^q \frac{\phi_P(q) q^3 dq}{\sqrt{\gamma^2 - q^2}} \quad (2)$$

- Where  $\phi$  is the distribution of projected axis ratios
- These equations can be rewritten analytically as:

$$\psi_O(\gamma) = \frac{2\gamma^{m-1}\sqrt{1-\lambda^2}}{B(0.5m, 1.5)} \quad (1)$$

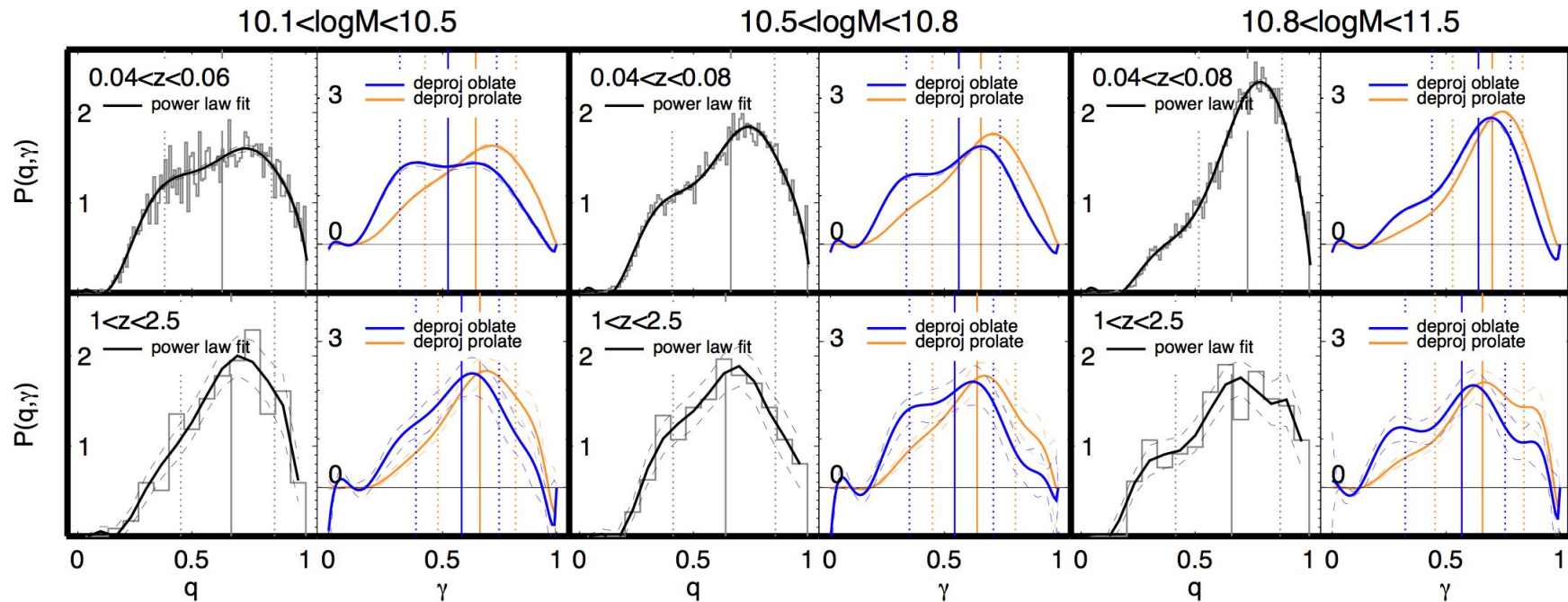
$$\psi_P(\gamma) = \frac{2\gamma^m\sqrt{1-\lambda^2}}{B(0.5m + 0.5, 1.5)} \quad (2)$$

- Where  $B(x,y)$  is the beta function



Chang et al. (2013)  
Figure 6

# “Deprojecting” the Projected Distribution



# Projected Axial Ratios

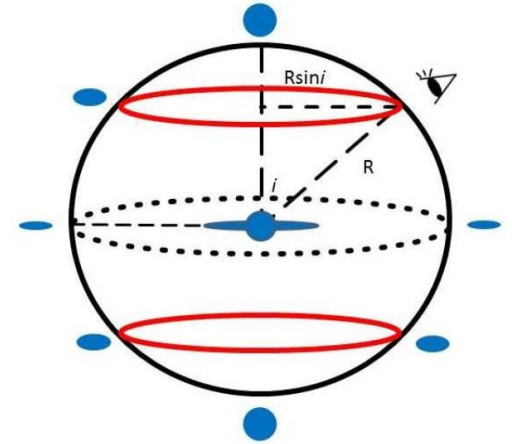
- The projected axial ratio,  $q$ , we observe depends on the viewing angles ( $\theta, \phi$ ) and also the unknown 3D axial ratio.
- If we know the axis lengths we can calculate  $q$  as follows:

$$A = \frac{\cos^2 \theta}{\gamma^2} \left( \sin^2 \theta + \frac{\cos^2 \phi}{\beta^2} \right) + \frac{\sin^2 \theta}{\beta^2} \quad (1)$$

$$B = \cos \theta \sin 2\theta \left( 1 - \frac{1}{\beta^2} \right) \frac{1}{\gamma^2} \quad (2)$$

$$C = \left( \frac{\sin^2 \phi}{\beta^2} + \cos^2 \phi \right) \frac{1}{\gamma^2} \quad (3)$$

$$q(\theta, \phi; \beta, \gamma) = \sqrt{\frac{A + C - \sqrt{(A - C)^2 + B^2}}{A + C + \sqrt{(A - C)^2 + B^2}}} \quad (4)$$



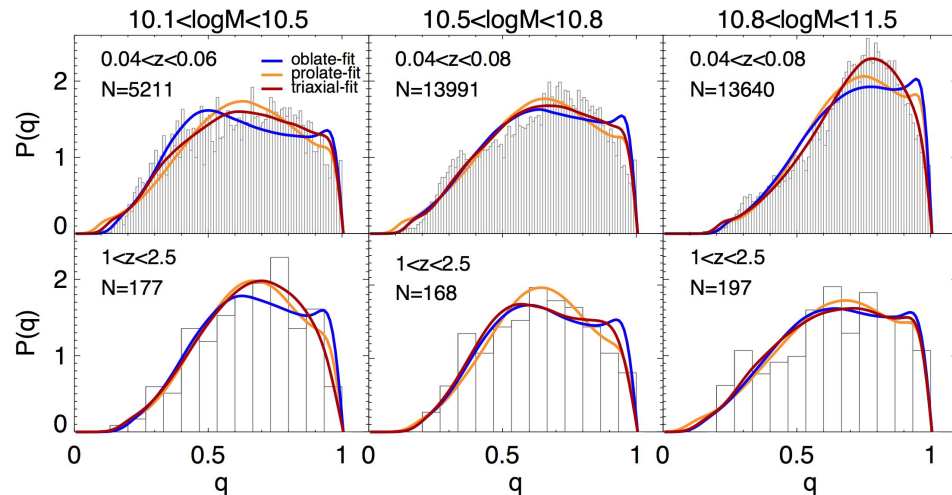
$$\beta = b/a$$

$$\gamma = c/a$$

Katrina C. Litke  
(2011) Figure 2

# Numerical Reconstruction of Projected Distribution

- Chang et al. assume Gaussian distributions in  $T$  and  $E$  with dispersions  $\sigma_T$  and  $\sigma_E$
1. Numerically generate  $\beta$  and  $\gamma$  distributions
  2. Assign random viewing angles ( $\theta$ ) to each element of distribution
  3. Using the equation for  $q$ , generate the probability distribution for projected axial ratios



Chang et al. (2013)  
Figure 7

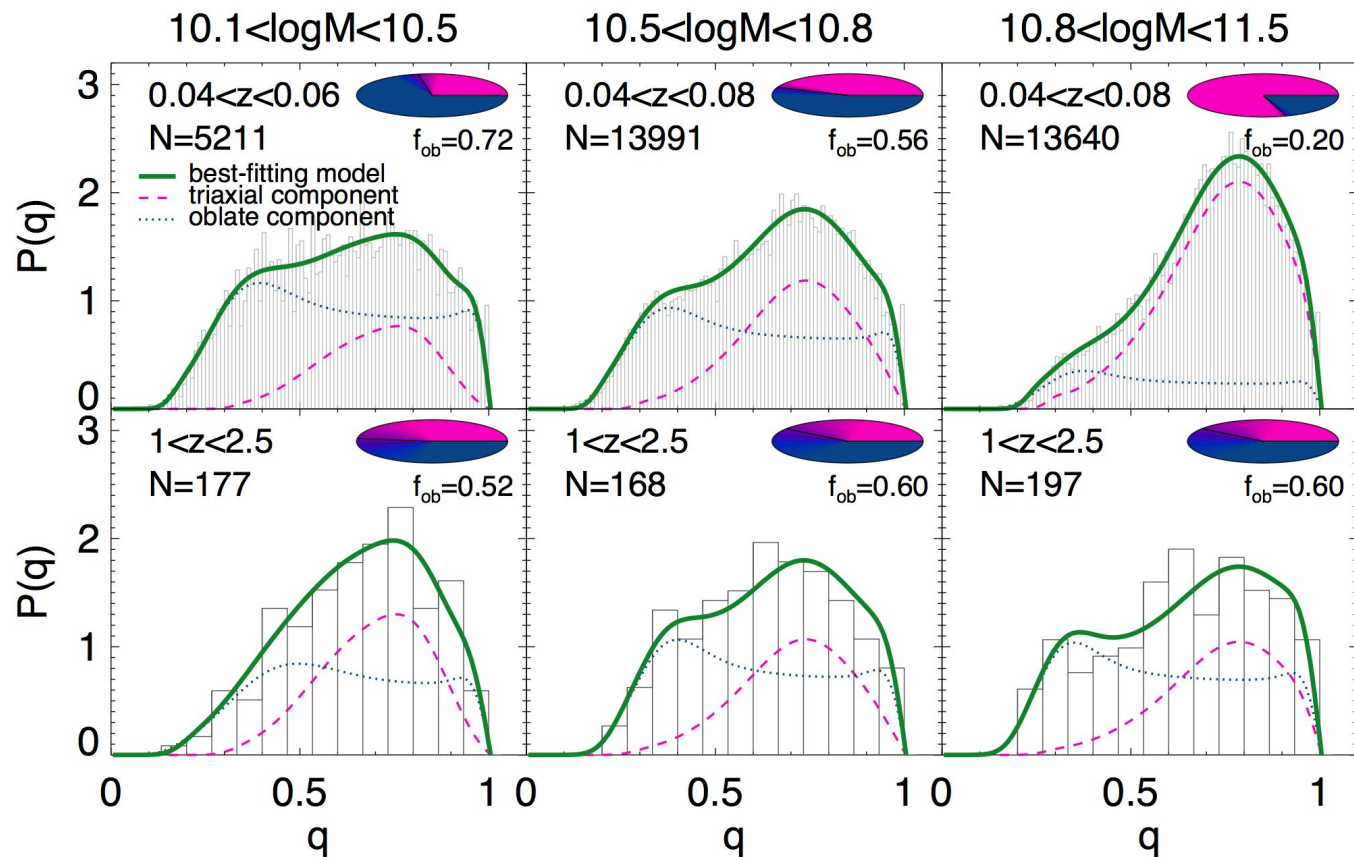
# Finding the Best-fitting Model

- Total likelihood is given by  $L = \sum_{q_{data}} \log p(q_{data}|q_{model})$
- Create a grid spaced as  $(\Delta T, \Delta \sigma_T, \Delta E, \Delta \sigma_E)$
- For low-redshift sample create a grid as  $(\Delta f_{obs}, \Delta T, \Delta \sigma_T, \Delta E, \Delta \sigma_E, \Delta b, \Delta \sigma_b)$ 
  - The extra parameters are fraction of the oblate component, the mean intrinsic axis ratio of the oblate component and its standard deviation
- Test the goodness of fit with K-S and M-W tests




“Histograms show observed distributions of projected axis ratios for present-day early-type galaxies from SDSS (upper row) and at  $1 < z < 2.5$  from CANDELS (bottom row), each in three mass bins.”

Chang et al. (2013)  
Figure 8



# Conclusions

- There is no single shape that can account for the observed axial ratio distribution
  - A two-population model for intrinsic shapes is adequate to describe present-day and  $z > 1$  early types.
  - In the present-day, the oblate fraction strongly depends on the galaxy mass; this trend disappears at  $z > 1$ .
  - Chang et al. attribute the lower incidences of disk structures at early cosmic time to the lack of settled star-forming progenitors, and the stripping of gas from disks in dense cosmic environments.
  - Classical elliptical galaxies “[...] emerge over time through merging and accretion of satellites, at the expense [...] of pre-existing disks.”
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# References

1. Chang et al. (2013)
2. Fall and Frenk (1983)
3. Van der Wel (2014)

