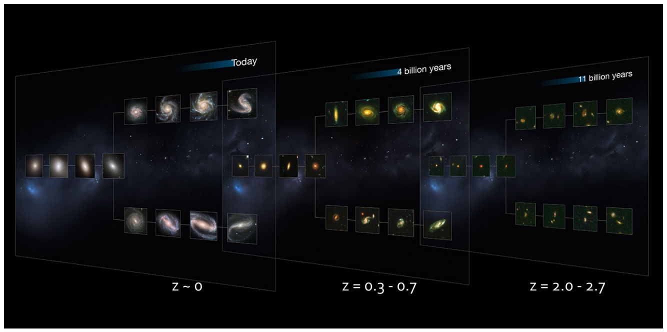
When did the Hubble Sequence Form?
What is the galaxy merger rate?
How do galaxy disks settle into spirals?
How are bulges and spheroids created?
How are bulge formation and SMBH growth correlated?



ESA Press Release on Lee et al. 2013

Quantitative Morphology

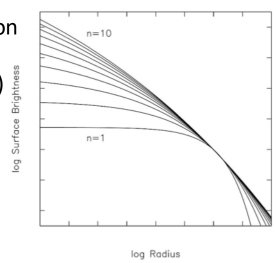
- With large surveys, want to quickly build a catalog of objects (e.g. Source Extractor; Bertin+1996)
- Need to define statistics that describe shape, size, irregularity of galaxy light profiles
- **Parametric Morphology** (fit a model to light profile)
  - 1 component fit : Sersic n, r_{eff}
  - 2 Component (Bulge + disk) → GALFIT, GIM2D
- **Non-parametric Morphology** (irregular features)
  - Concentration-Asymmetry
  - Gini-M_{20}
  - M-I-D

  Alternatively … Galaxy zoo hubble project (Willett+2017)

GALFIT (Peng+ 2002)

http://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html

- GALFIT is a data analysis algorithm that fits 2-D analytic functions to galaxies and point sources directly to digital images -→ Bulge – Disk RATIOS
- Functions: Sersic/de Vaucouleurs, King, etc
- Sersic → **$I(R)\ \alpha\ e[-k\ R^{1/n}]$**
  - n = index → tells you the concentration of light (so often get correlations between Sersic index and galaxy type)
  - n = 1 gives exponential disk
  - n = 4 typical of ellipticals (de Vaucouleurs)
  - Most 0.5 < n < 10



Surface Brightness Profile of Spiral Galaxy NGC 7331

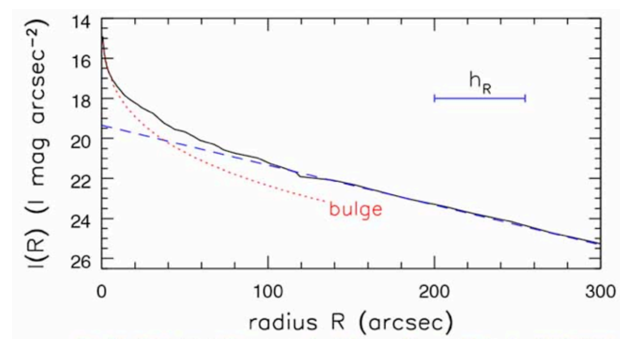
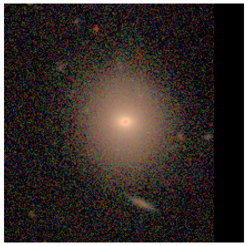
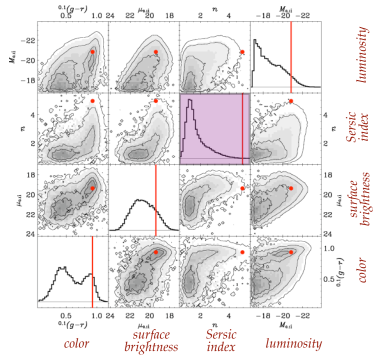


Fig 5.4 (R. Peletier) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The solid line shows surface brightness in the I band., near 8000 Angstrom. The dashed line is an exponential with scale length h_r = 55" (3.6 kpc); the dotted line represents additional light, attributed to a bulge.

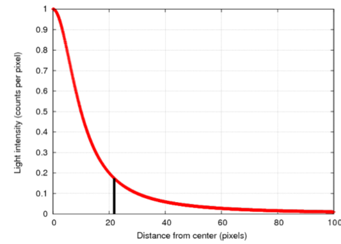
Concentration tends to track the stage (spiral → elliptical)
since it correlates with bulge/disk ratio



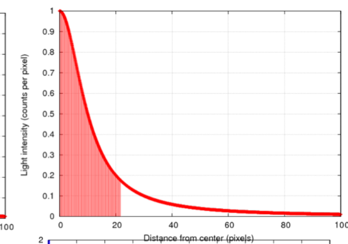


Courtesy: Mark Whittle (UVa)

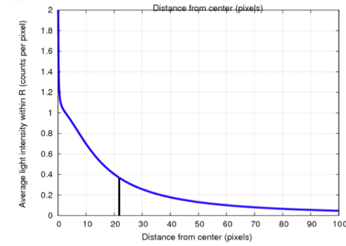
Petrosian 1976: A Distance Independent Measure of Galaxy Size



Local intensity at R ~ 22 pixels
~ 0.18 counts/pixel



Integrated Intensity
~ 0.38 counts/pixel



Petrosian Radius (rp) (adopted by SDSS)

Galaxies do not all have the same radial surface brightness profile, and have no sharp edges. In order to avoid biases - measure a **constant fraction of the total light, independent of the position and distance of the object --** Want a metric that would yield the same value if a galaxy were suddenly to move to twice its current distance.

Semi-major axis of an ellipse where the surface brightness = 0.2 x mean surface brightness within that ellipse. Where I(r) is the azimuthally averaged surface brightness profile. Blanton+2001; Yasuda+2001

$$\mathcal{R}_P(r) \equiv \frac{\int_{0.8r}^{1.25r} dr'\, 2\pi r' I(r') / [\pi(1.25^2 - 0.8^2) r^2]}{\int_0^r dr'\, 2\pi r' I(r') / (\pi r^2)} = 0.2$$

Petrosian Ratio

Galaxy Flux is then

$$F_P \equiv \int_0^{N_P r_P} 2\pi r'\, dr'\, I(r') .$$

Where Np = 2 to capture nearly all the flux from most galaxies

Isn't perfect – affected by substructure, really bright nuclei (Seyferts)
So could have multiple rp or none..

Once we have the Petrosian Radius, we can use it to measure other quantities which will similarly be independent of a galaxy's distance. Useful to come up with methods of classifying galaxies that can be automated. CAS method:

- **Concentration (C)**

  $C = 5 \log_{10}(r_{80} / r_{20})$ (Bershady+2000)

  e.g. r_{80} circular aperture containing 80% of the Petrosion flux (total flux within the ellipse with semi-major axis 1.5 x rp)

  If light is very concentrated r_{20} and r_{80} are both small, C→0

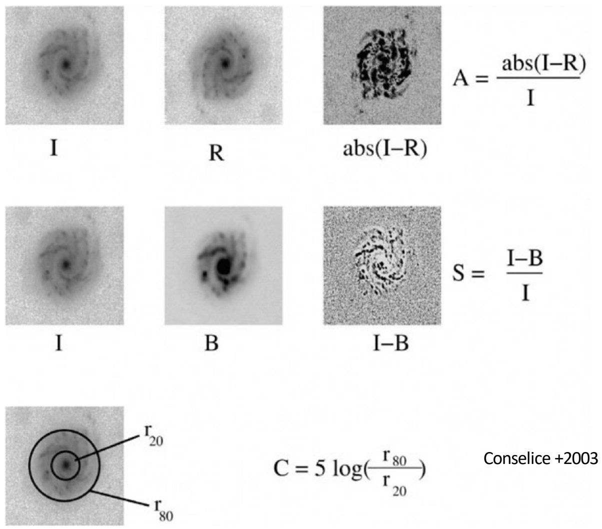
- **Asymmetry (A)** (Abraham+ 1996, Conselice 2003, 2000)

  $$A = \sum_{i,j} \frac{|I(i,j) - I_{180}(i,j)|}{|I(i,j)|} - \sum_{k,l} \frac{|B(k,l) - B_{180}(k,l)|}{|B(k,l)|}.$$

  Subtract a reflected or rotated version of the image from the original and look at the normalized residual (requires knowing the center – x, y_{center} are variables used to minimize A) .

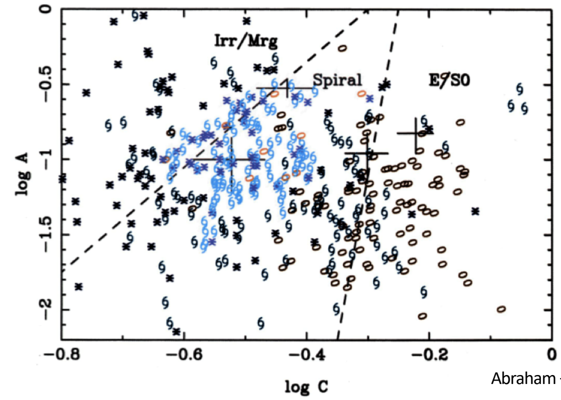
  If circular A = 0

- **Clumpiness (S)** subtract version of image blurred/smoothed by factor of 0.3x rp – yields degree of clumpiness (Conselice 2003)



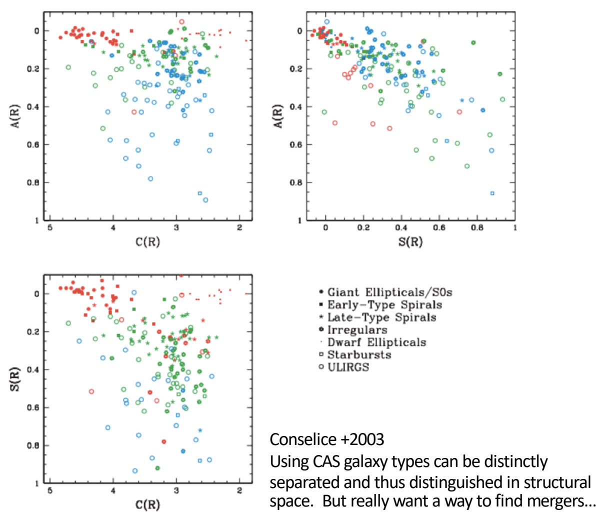
Conselice +2003

Concentration & Asymmetry



Abraham + 1996

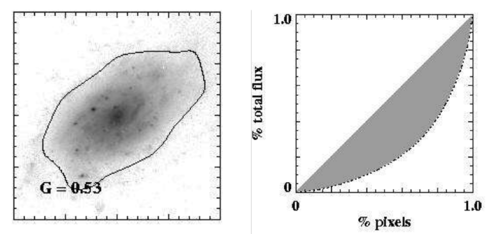
Concentration tells you more than asymmetry …
Asymmetry → doesn't reliably tell you mergers (could just be irregular galaxy)



Conselice +2003
Using CAS galaxy types can be distinctly separated and thus distinguished in structural space. But really want a way to find mergers…

Gini Coefficient

- Used in economics to measure distribution of wealth in population
- G= relative distribution of flux in galaxy's pixels (Abraham + 2003)
- G = 0 uniform surf. brightness (egalitarian)
- G=1 all flux in single pixel (absolute monarchy)
- Don't need to define the "center"



Courtesy J. Lotz

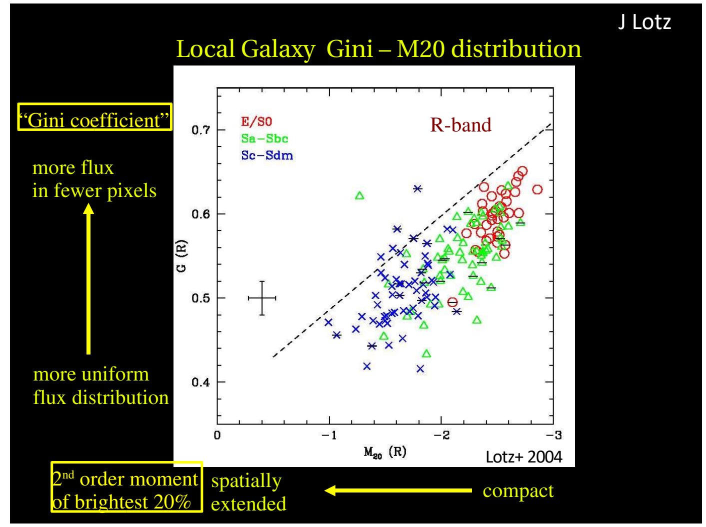
M_{20} (Lotz +2004)

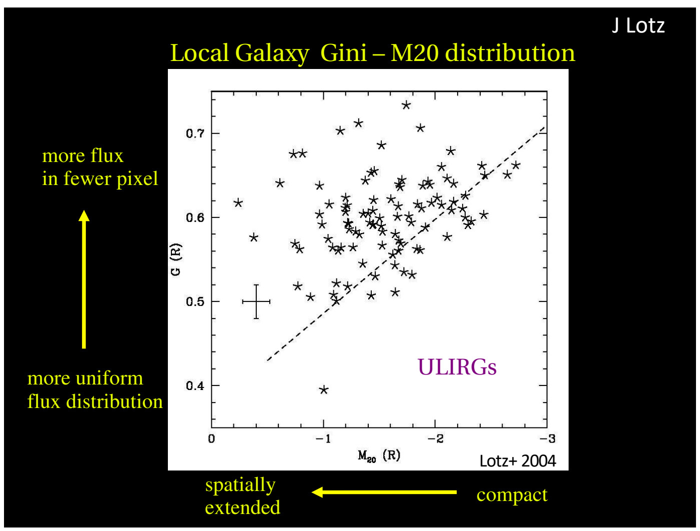
- 2nd order moment of the brightest 20% of the galaxy's flux – traces the spatial distribution of any bright nuclei, bars, spiral arms
- Total 2nd order Moment = Flux in each pixel multiplied by the squared distance to the center of the galaxy, summed over all the galaxy pixels
- Similar to concentration, but does not assume a particular geometry

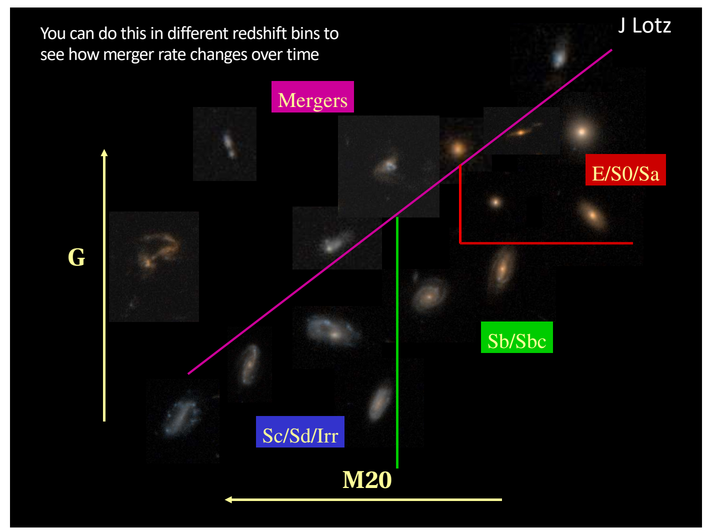
$$M_{total} = \Sigma_i M_i = \Sigma_i f_i r_i^2$$

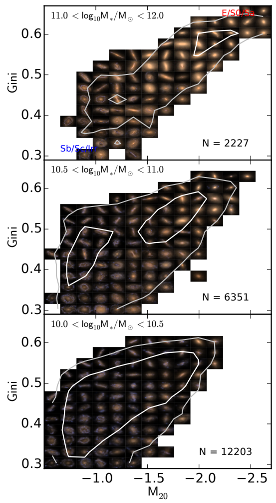
$$M_{20} = \log 10 \frac{\Sigma_i^n M_i}{M_{total}} \quad \text{where } \Sigma_i^n f_i \le 0.2\, \Sigma_i f_i$$

If spatially extended, n is large and
Sum(Mi) → Mtot
So M20 → 0









Snyder + 2015

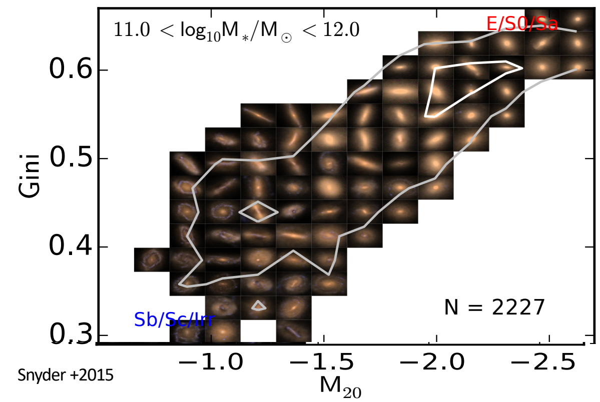
Illustris Simulation

Rest-frame g-band morphology distributions and color-composite images as a function of mass

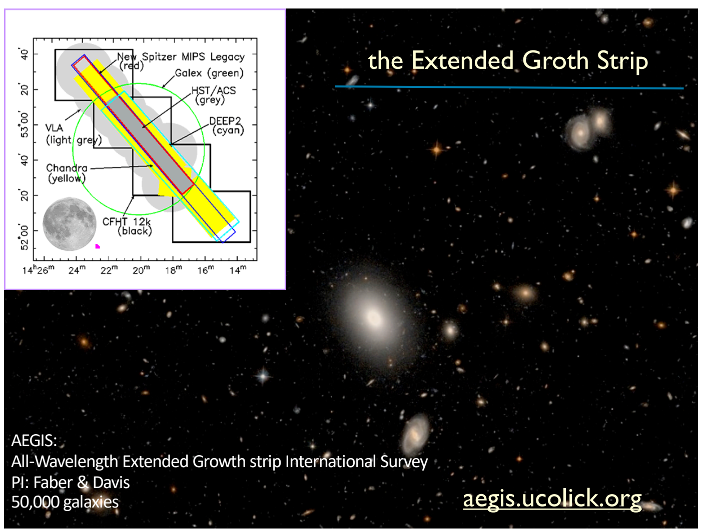
White – bins containing > 10 galaxies
Grey – bins containing > 100 galaxies

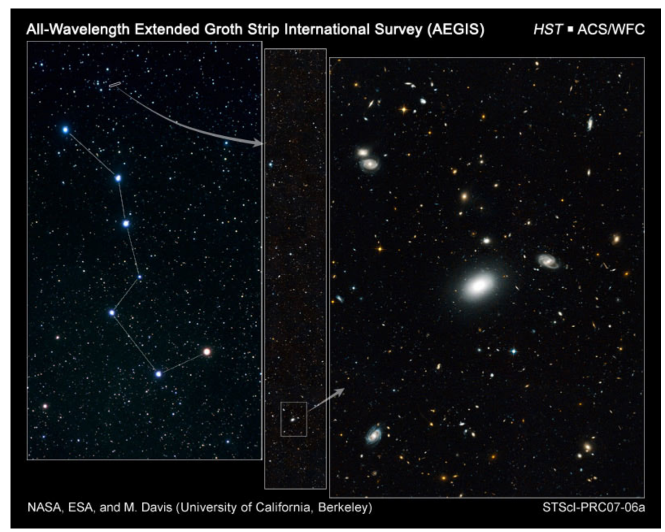
Lower mass – reside in late type regions
G < 0.6, M20 > -2

Can use this to test simulations, or for selecting mergers, could use sims as a training set

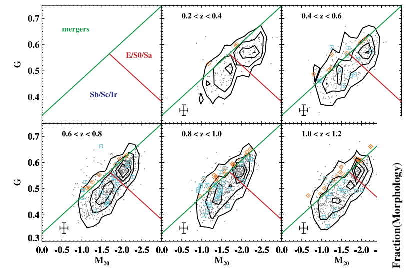


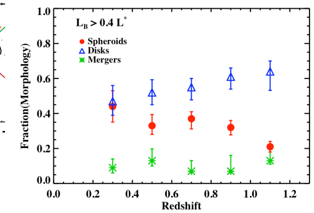
Snyder +2015





G-M_{20} finds galaxy mergers out to z~1





Lotz et al. 2008a, AEGIS team
HST ACS V(z<0.6) and I (0.6 < z < 1.2)

weak evolution in "merger fraction"?

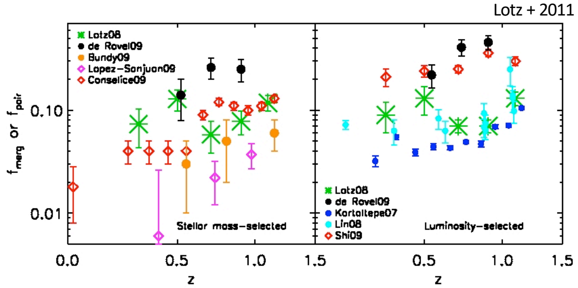
Slide from J. Lotz

Major Merger Fractions over time

'merger fractions' don't agree…

DIFFERENT METHODS !!!
Green stars: G-M20 mergers
Filled circles : close pairs
Diamonds: asymmetric galaxies

Lotz + 2011

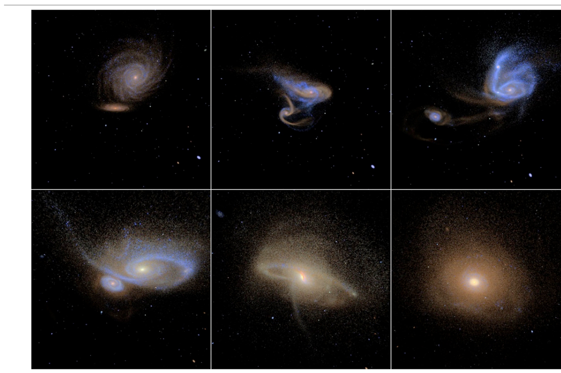


2009: major disagreement in literature over merger fraction and it's evolution

(see also Brinchman et al. 2000, Bundy et al. 2005, Jogee et al. 2008, Bridge et al. 2009, Robaina et al. 2010, Xu et al. 2011...)

Slide from J. Lotz

Calibrating Morphology with Simulations



T.J. Cox, P. Jonsson

Slide from J. Lotz

Volume Avgd Merger Rate

$$\Gamma_{\rm merg} = \frac{\phi_{\rm merg}}{T_{\rm merg}}$$

Number of ongoing merger events per unit comoving volume, above some mass/Luminosity limit

Amount of time for merger to occur (initial encounter -> merger)

$$\phi'_{\rm merg} = \phi_{\rm merg} \frac{\langle T_{\rm obs} \rangle}{T_{\rm merg}} = f_{\rm merg} n_{\rm gal}$$

Problem, number density of mergers *observed* depends on the average timescale during which the merger can be observed (depends on the method used to define a merger!)

$$\Gamma_{\rm merg} = \frac{\phi'_{\rm merg}}{T_{\rm merg}} \frac{T_{\rm merg}}{\langle T_{\rm obs} \rangle} = \frac{\phi'_{\rm merg}}{\langle T_{\rm obs} \rangle}$$

Fractional Merger Rate

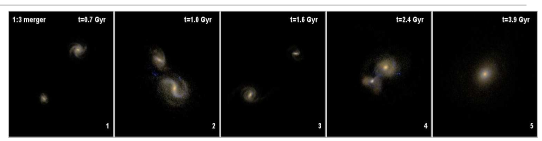
merger events per (bright/massive) galaxy

$$\Re_{\rm merg} = \frac{f_{\rm merg}}{\langle T_{\rm obs} \rangle} = \frac{C_{\rm merg} f_{\rm pair}}{\langle T_{\rm obs} \rangle}$$

G-M20
Asymmetry

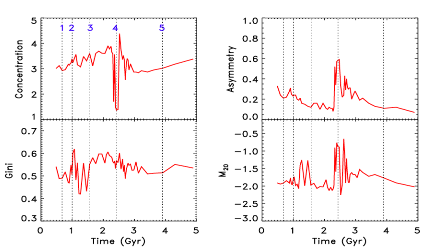
$C_{merg} = 0.6$
Correction factor
(projection effects)

Timescale for Observing a "Merger"



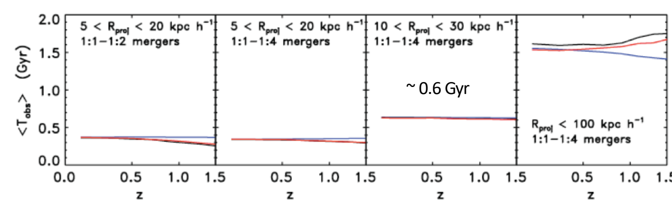
timescales for finding mergers depends on method to find merger and type of merger (major/minor, gas-rich, gas-poor)

Lotz et al. 2008b,
Lotz et al. 2010a, b

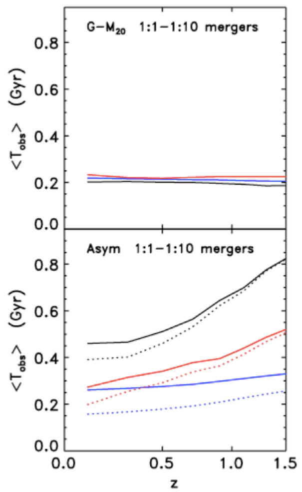


Slide from J. Lotz

Tobs for Pair fractions depends sensitively on pair separation assumed



Lotz+2010



G-M20 and Asymmetry are
Both affected by major AND
minor mergers

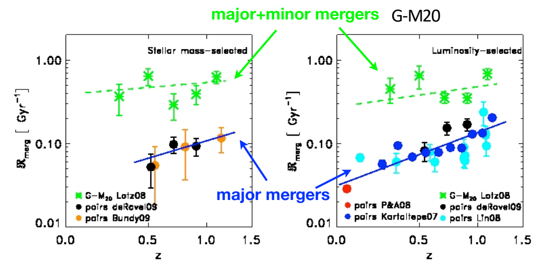
G-M20 doesn't care about gas fraction
But only captures merger when double
nuclei are present – short lived

Black: many gas rich mergers
Blue: very few

Asymmetry lasts longer than G-M20
Strongly increasing gas fractions with z,
means stronger asymmetry.

Lotz+2010

Merger Rates per 10^{10} M⊙ galaxy at z<1.5



normalize by consistent T(z) and use same parent sample selection:

$\Re_{pairs} \sim (1+z)^{\alpha}$ α = 1.7 ± 3.0 (stellar mass); 2.1± 0.2 (luminosity)

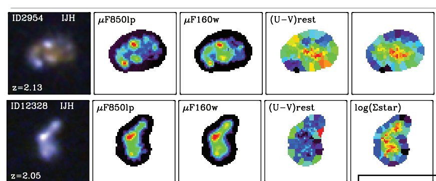
$\Re_{G\text{-}M20\ (major+minor)}$ α = 0.5 ± 1.6 (stellar mass); 0.8 ± 1.4 (luminosity)

Lotz et al. 2011

Slide from J. Lotz

Low-Resolution/ low-S/N regime … Problems …

Clumps v. Mergers

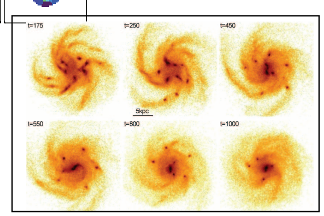


Wuyts et al. 2013

bright-off center "clumps" can look like interactions;

much more common at z>1
(Förster-Schreiber et al. 2006)

can migrate to center to form a bulge



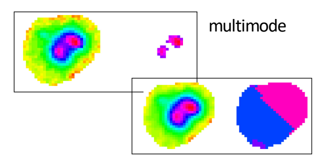
Elmegreen et al. 2009

Slide from J. Lotz

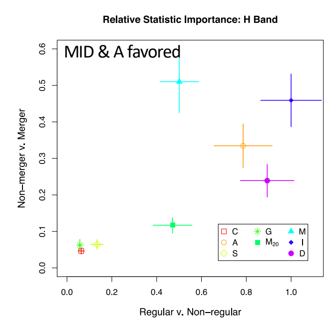
Multimode, Intensity and Deviation (MID)

New (better) way to find z~2 Mergers

(Designed to find double nuclei)



Freeman et al. 2013



M: Ratio of areas of brightest pixels
I: Pixel Grouping based on intensity gradients, taking ratio of top two groups
D: Distance between brightest pixel group and galaxy intensity center

beats G-M_{20}, CAS at finding CANDELS visually classified mergers for WFC3/H < 24 galaxies

Slide from J. Lotz

See also Conselice+2014 Review
Peth+2016