Substructure in the Coma Cluster

By Carola Ellinger

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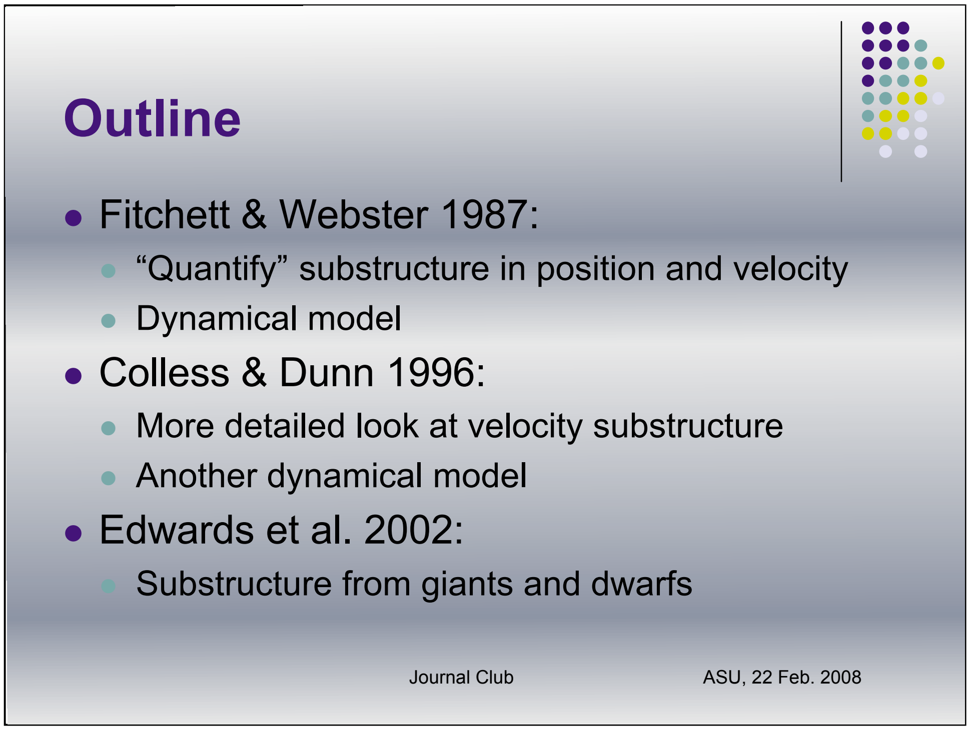


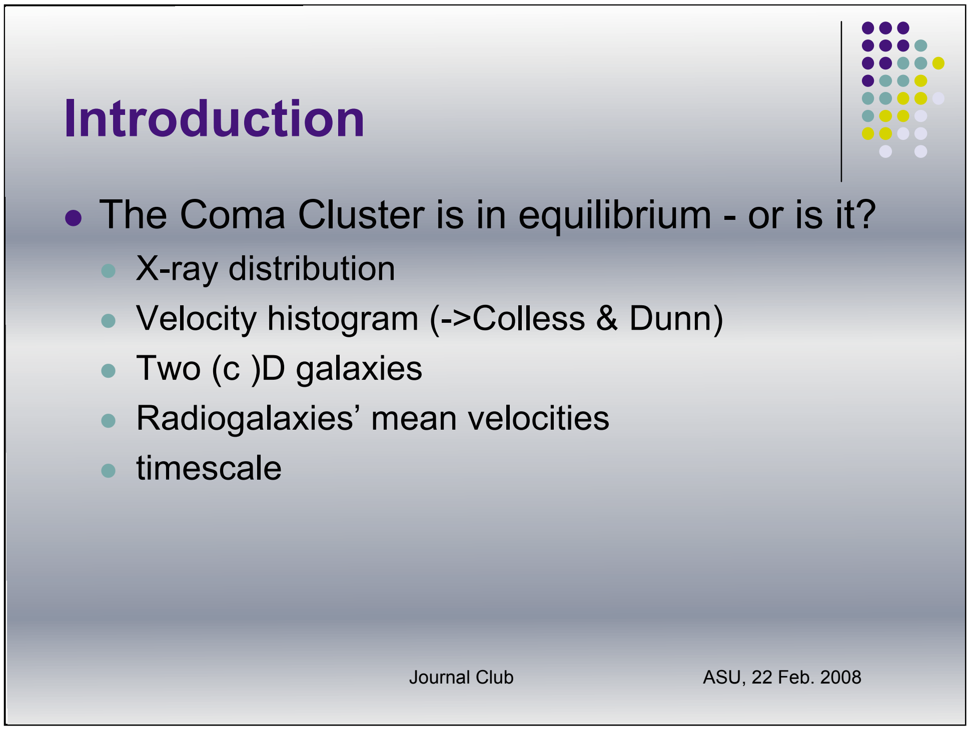
I will talk about these three papers, in chronological order

The first one, F&W, is the first one to quantify the significance of the substructure that is seen in the positions of galaxies, and applies that also to the line-of-sight velocities. They identify two subclumps in position, and possibly in velocity. They then proceed to making a dynamical model of how the coma cluster may have evolved to this.

The second paper, C&D, use a much larger sample than F&W and analyze it (specifically the non-gaussian vel. Distribution) for subclumps in velocity space. After find evidence for two velocity subclumps, they also make a dynamical model to figure out what is going on.

The third paper, Eea, looks at different galaxy types - giants and dwarfs - to gain insight into the dynamical history. They also find that Coma has not evolved to equil. Yet.

The main focus is on the first paper, and I use the other two just to supplement the conclusion of the first, so I will be skipping a lot of the last two papers, to stay in within the allotted time.



The coma cluster has always been assumed to be in equilibrium (because that is the easiest to do), but there are some facts that shows that it might not be. F&W list several arguments why the coma cluster cannot be in equilibrium:

X-ray distribution doesn't fit and equil. Distr. Well

Velocity histogram is skew at 3% sign. Level -> not gaussian (if not gaussian, not equil)?

D galaxies = massive giant elliptical galaxies thought to be at the bottom of potential wells; since there are two, cannot have equil?

D=dominant, cD= with halo, 10x more massive than giants

Mean vel. Of radio galaxies is higher than mean vel. Of cluster -> diff. components in cluster.

Timescale arguments (from E. et al): dyn. Fric.~ 22Gyr for typical galaxy (1e12Msol)

Fitchett & Webster 1987: Spatial velocity substructure

- Maximum likelihood: “Lee”- function
- Statistical significance: calibrated using Monte-Carlo simulations
  - Case a: $\sigma = \frac{\sigma_0}{r}$ Case b: $\sigma = \frac{\sigma_0}{\sqrt{r^2 + r_c^2}}$

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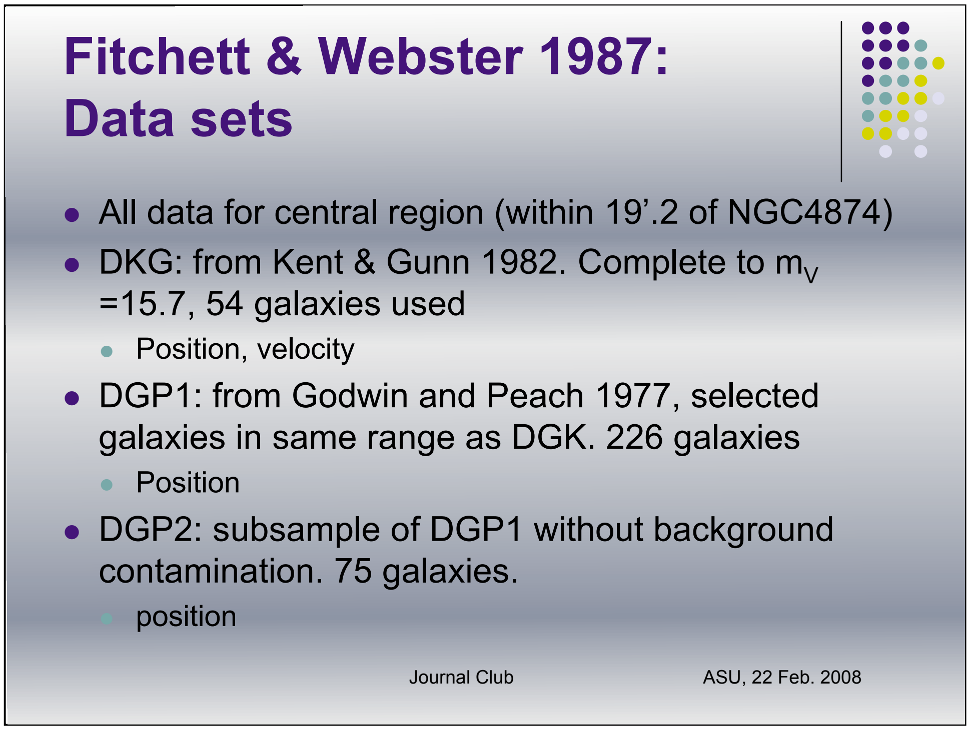
-to analyse the data, F&W use a ‘new’ statistical technique based on max likelihood to detect substructure: if you have e.g. 2-D positions (x,y) of the galaxies, plot them and then project the positions onto a line and then calculate the ‘clumpiness’, L, of projected points. Repeat for different orientation of the line -> get L(phi). First done by Lee(1979), therefore F&W call it Lee function. The advantages: works for elliptical cluster as well, assign statistical significance to determined substructure, most sensitive to 2 clumps.

-Since there is no expression for Lee-function, need to calibrate its significance - use Monte-Carlo simulations for that. This is done to determine if the clumping that is seen is real, and not an effect of a certain galaxy distribution. It was tested for these two different profiles, where sigma denotes surface density. The core radius was taken as the radius of the analyzed region, 9’.6.



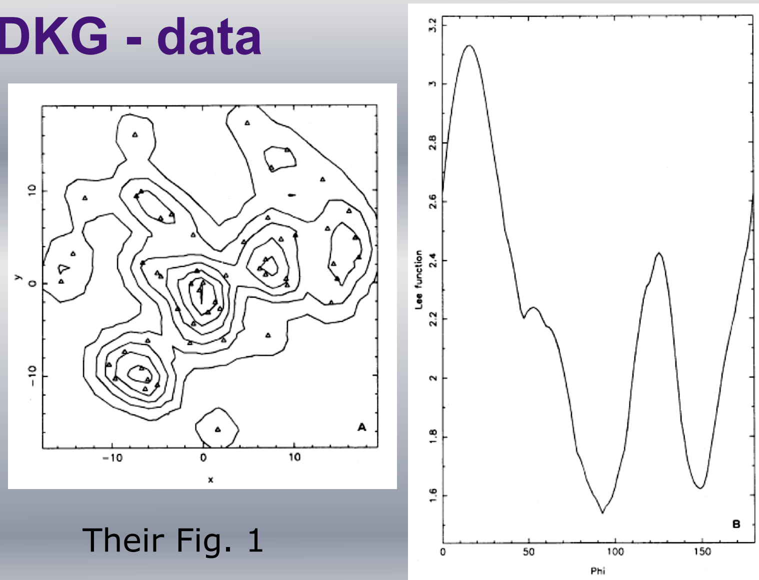
They wanted to investigate the central region, which they take as the region within 19'.2 of NGC4874

DKG: they selected galaxies brighter than 15.7 mag in V, They claim that all galaxies in this set belong to the cluster and that it is complete to that magnitude.

DGP1: covers 1.22 square degree field centered on coma cluster. They picked out galaxies in the same spatial region and magnitude as DGK.

DGP2: subsample to DGP1. They select galaxies brighter than V25=15.5 to remove some fo the background contamination from this data set. The 25 refers to the isophote of the 25th mag.

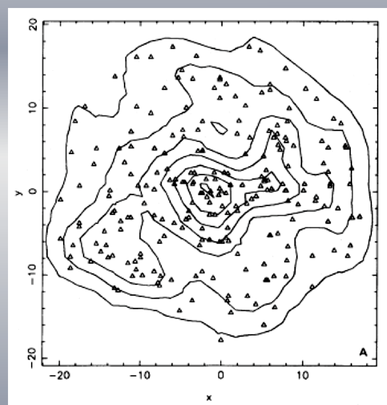
Fitchett & Webster 1987: DKG - data

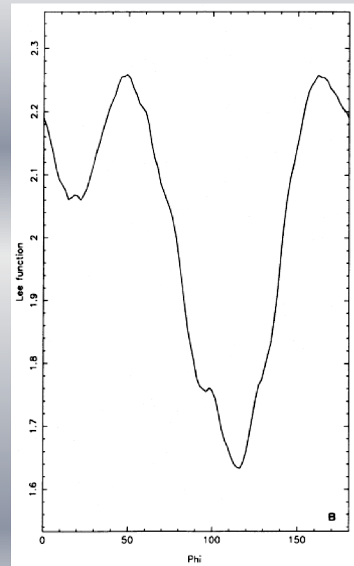


Their Fig. 1

The left panel shows the positions on the plane of the sky of the first data set (DKG). Contours = density contours, triangles - actual galaxies. Substructure is obvious. The right panel shows the Lee function. <explain axes>

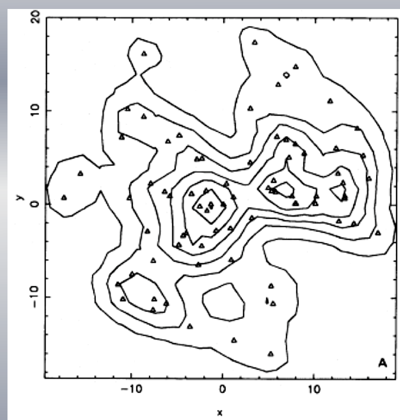
Fitchett & Webster 1987: DGP1 - data

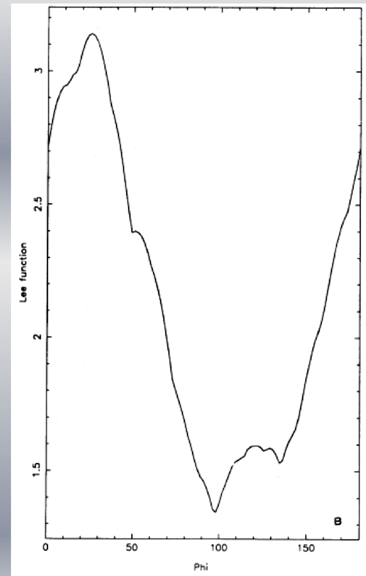




Their Fig. 2

Fitchett & Webster 1987: DGP2 - data





Their Fig. 3

Fitchett & Webster 1987: Results

	L_{rat}	Significance Case a	Significance Case b
DKG	2.03	6.5%	12.5%
DGP1	1.35	11.9%	27.6%
DGP2	2.34	0.12%	0.48%

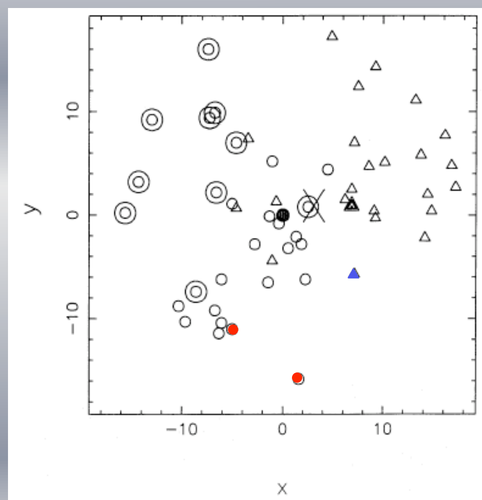
The measure of interest here is the ratio, Lrat, of the max and min value of L.

The significance levels are calibrated with the aforementioned Monte-Carlo simulations. Lower significance is better, it basically tells us what the chance is that the clumps we see is due to the distribution, and not real (?)

Case b: expected to have lower significance since a constant density core can more readily lead to chance clumping

Ergo: THERE IS SUBSTRUCTURE! (in positions)

Fitchett & Webster 1987: DKG - velocity data

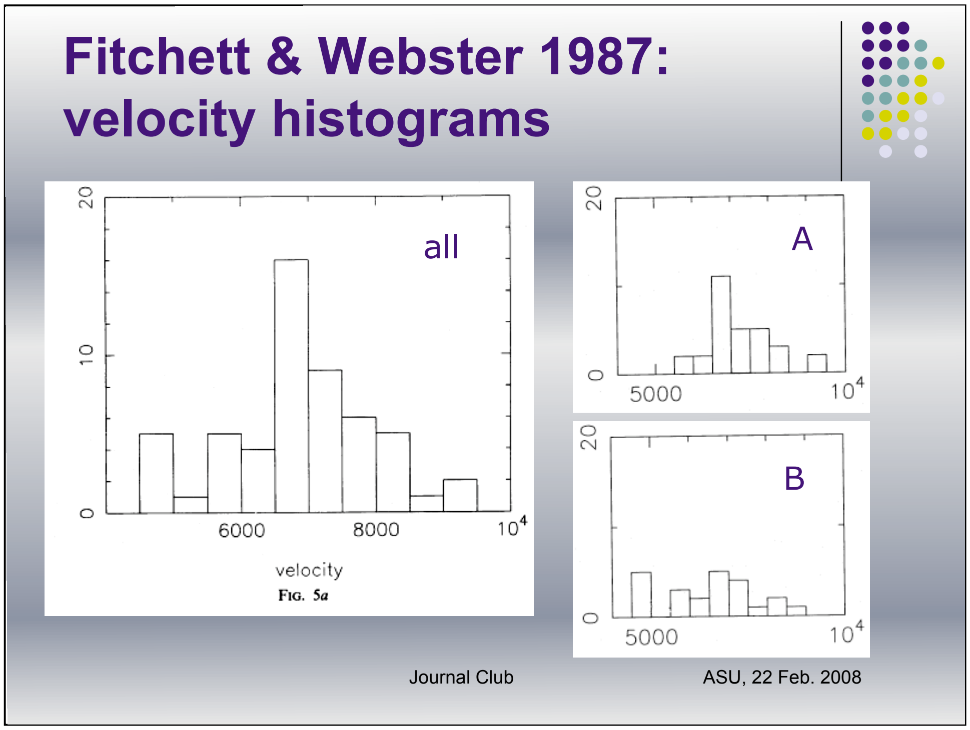


Their Fig. 4

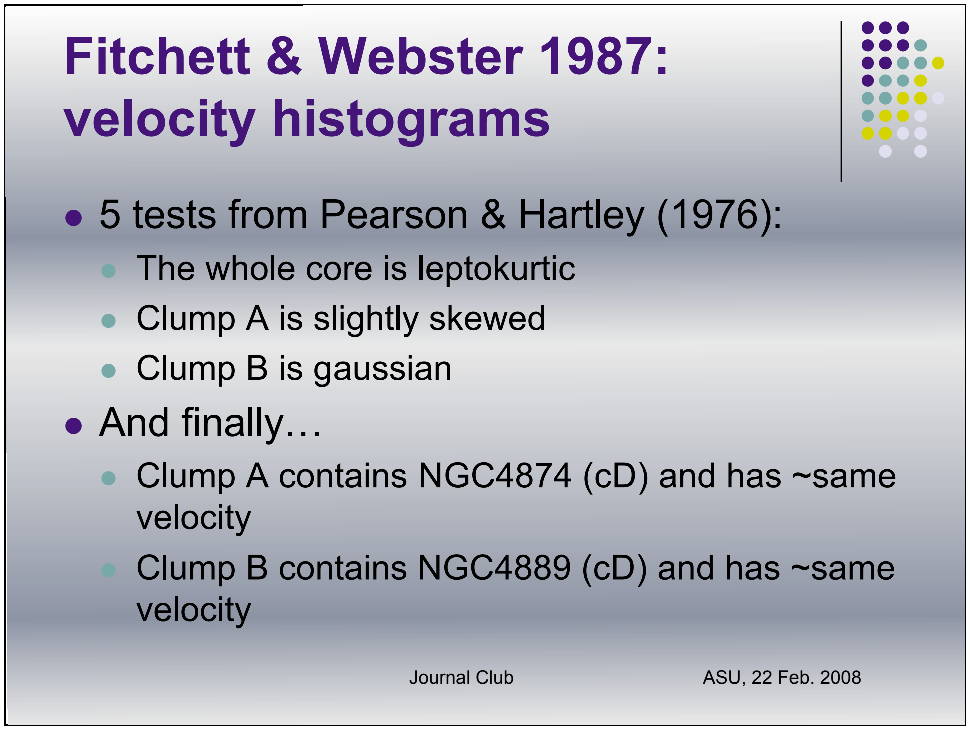
There were velocities available for the DKG data set, so F&W did the Lee statistics in 3-D (x,y,v) on that, and just show the results into the two most likely subclumps in space. Circles (red) are one subclump, triangles (blue) the other. So you actually not only have to spatial subclumps, but each also has a distinct clumping in velocity. The double circle means high velocity.

Filled circle = 4874

Filled triangle = 4889



After they established that there are subclumps, they take a look at the line-of-sight velocity histograms of the DKG data set. Graphed are the histograms for all galaxies, and separately for each clump. The x-axis on each is velocity in km/s (?). Then they perform a bunch of statistical tests to see to what degree these histograms are not gaussian.



The tests were taken from Pearson and Hartley, and not really further described. Basically, the tests were used to determine the level of leptokurtic, platykurtic behaviour and skewness.

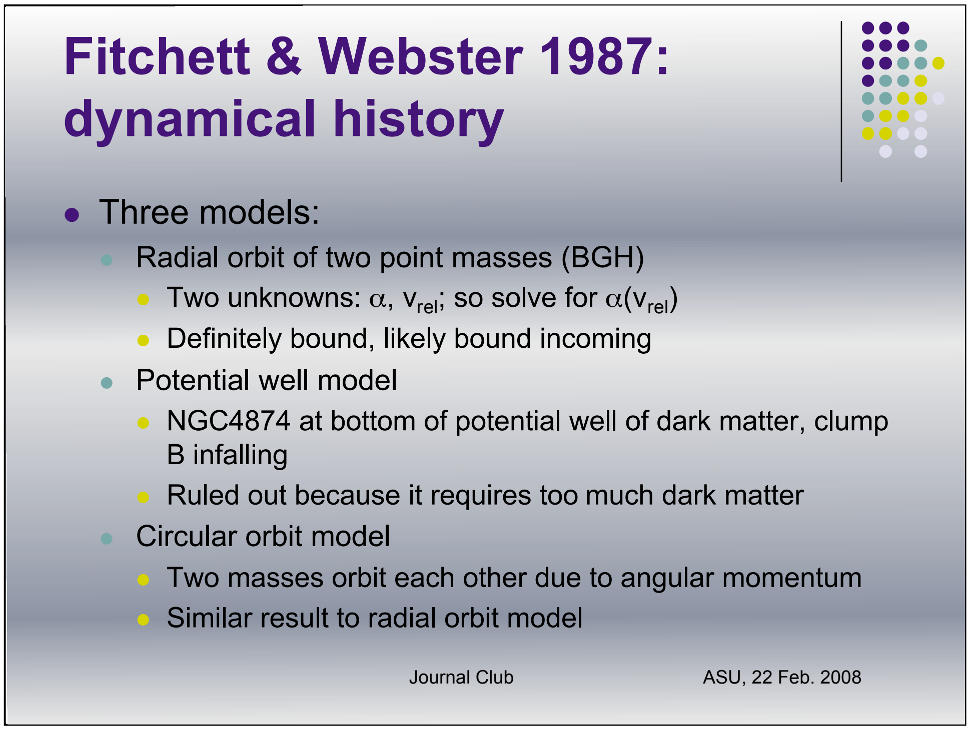
Leptokurtic:

Platykurtic:

Results are:…

Clump A: remember Figure 4 where the high velocity galaxies were marked, these are possibly the reason for the skewness. So, it is likely that there is substructure to clump A, but this is not really investigated.

Another thing that the authors remark is the following…



They use three models to figure out the dynamic properties of the cluster. The first one is taken from Beers, Geller & Huchra (1982). They assumed they know everything except for alpha and vrel, where alpha is the angle between the plane of the sky and the line joining the two masses, and vrel is the relative velocity between the two. Then they solved for alpha as a function of vrel for different regimes - unbound outgoing (just passing each other), bound outgoing (passing but going to turn around), bound incoming (going towards each other).

The result is that the two clumps are definitely gravitationally bound, and probably moving towards each other after passing each other once before, and quite aligned with the line of sight.

Potential well model: not really discussed, but is… . They do the same analysis, infering alpha of vrel, but they basically rule this model out because the dark matter potential well required to make it work is unreasonably large.

Next. Circular orbit model: if two masses are falling towards each other, they might start orbiting each other due to their ang. Mom. Again, solve the appropriate equ. Of motion for theta, vrel, and get a similar result for theta as in BGH, but not as good (definite).

Fitchett & Webster final remarks

- Curiosity: the radial model prefers alignment of clumps either with the plane of the sky or the line of sight -> masses overestimated?
- more data is needed!

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The radial model here and also applied to other clusters favor alignment close to the sky or line-of-sight. The probability of that occurring that often is small, so the authors propose the explanation that the masses of the clusters have been overestimated. If they do their radial orbit model with a total mass reduced by factor of five, they get a more likely distribution of projection angles. Or it could be some observational bias

Colless & Dunn (1996): Data

- Velocity distribution in cluster core
- Galaxies from Godwin, Metcalfe & Peach (1983)
- Positions from APM
- Redshifts from NED and own measurements
- =552 galaxies within 1.3deg of the center of the Coma Cluster
- 465 of those belong to the cluster (sigma clipping)

They look at the velocity distribution in a larger region centered on the cluster core.

The catalogue from GMP has over 6000 galaxies within 1.3 deg of the center of coma cluster, and is complete to mag b=20, which is 2510 galaxies. The positions were supplemented with the APM measuring machine at the Royal Greenwich obs.

Redshifts were taken from NED database, and from own observations at KPNO 4m telescope with Hydra. This leaves 552 galaxies. Using sigma clipping to determine cluster membership, they were left with 465 galaxies. Sigma clipping is…

Colless & Dunn (1996): velocity distribution

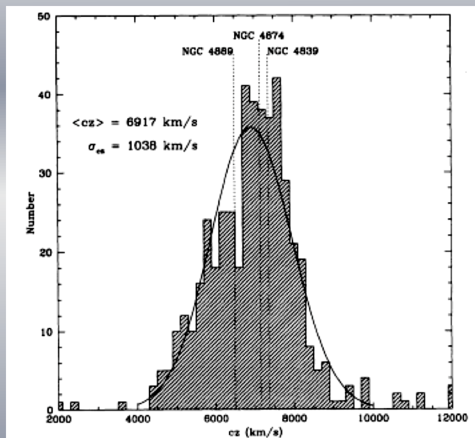

FIG. 5.—Distribution of radial velocities for galaxies in the Coma cluster. The curve is a Gaussian with mean 6917 km s^{-1} and standard deviation 1038 km s^{-1}. The velocities of the three dominant cluster galaxies are indicated.

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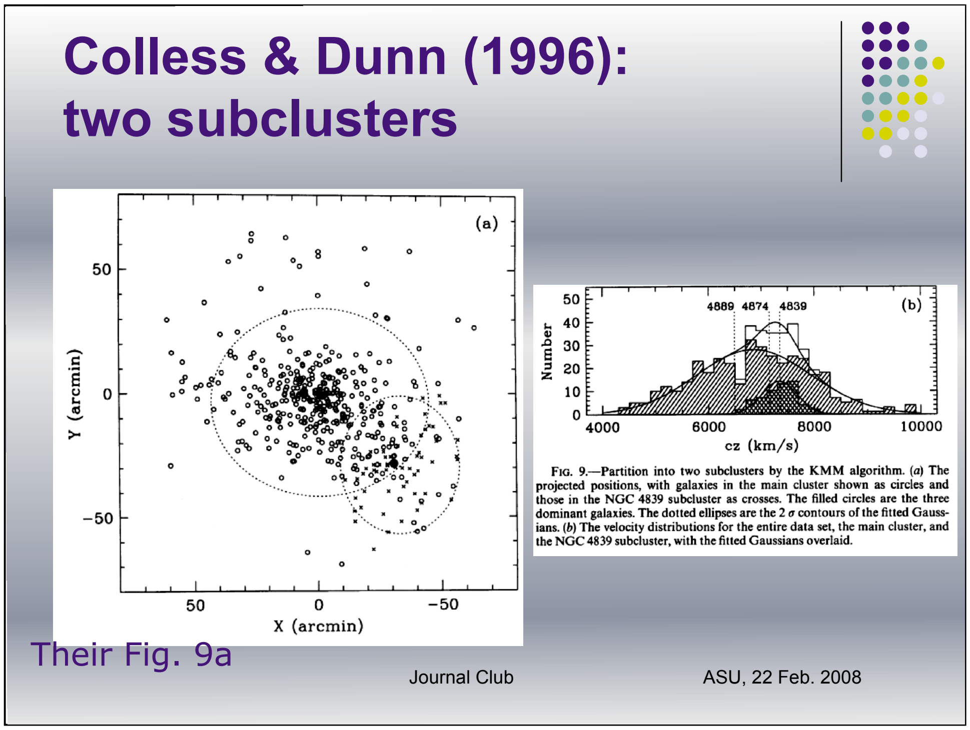
This graph, which is their fig.5, shows the velocity distribution, together with a gaussian curve. It is not overwhelming, but noticeable that the gaussian doesn't really fit. Various statistical tests confirm that.



They then do an improved Delta-test (compare small # of neighboring galaxies (their vel and sigma) to overall cluster via standard K-S two sample test) on the cluster, and are able (as F&W) to group the galaxies into two subclusters - one around NGC4839 and one around the main body. Again, the velocities and std.dev. Match up…

So then, if you take two gaussians - one for the main body and one for NGC4839 and neighbors, you get a good fit to the data, so the authors conclude from that, that those galaxies (4839) are responsible for the skewness.

Colless & Dunn (1996): dynamical model

- Two body model: two point masses following linear orbit
  - find $\alpha(M_{tot})$
  - Most likely solution: bound incoming at 74deg to line-of-sight with v_{rel} = 1700km/s
- Velocity distribution in early vs late type galaxies

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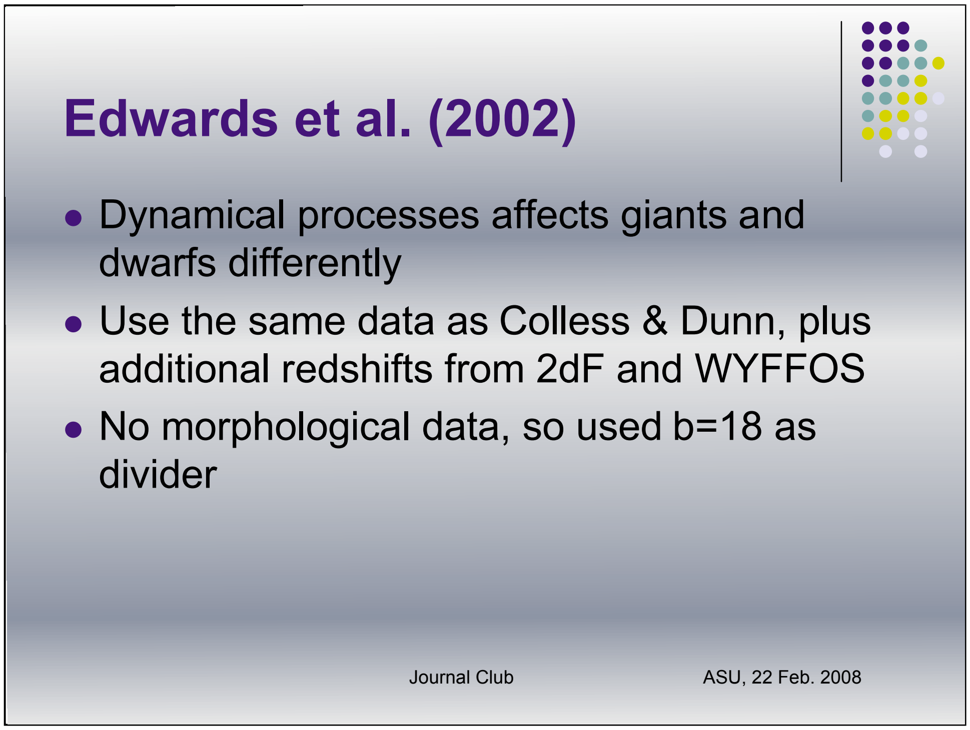
C&D also try to model the dynamical evolution of the cluster, and use a model very similar to the radial orbit model of F&W. So they have the subclusters as two point masses on a linear orbit (moving towards or away from each other), use the appropriate equ. Of motion, and solve for alpha as a function of total mass. They get various solution regimes, again find that the sol is definitely in the bound regime. After plugging in an assumption for the total mass, they get three possible solutions, and they say that the most likely one is a bound incoming one with clusters close together, at an angle of 74deg to the line of sight, and with a rel vel of 1700km/s. So basically the two subclusters passed each other once already, turned around, and are now about to smash into each other again.

C&D also note that in the main subcluster only the early types are consistent with the overall vel. Dist. (since most there are early types), but the late types' vel. Disp. Is sqrt(2) larger - which is consistent with late types infalling (virialized: K/P ~.5, infalling: K/P~1, sigma_infall~sqrt(2)*sigma_virial). But in ngc4839 subcluster, both vel. Dist. are consistent with each other.

With all this in mind they propose that NGC4874 could be the original dominant galaxy of the Coma cluster, 4889 belonged to a subcluster that is in the process of merging with the main cluster, and is now ejected from it (resembles what F&W found), and 4839 belongs to another subcluster that is about



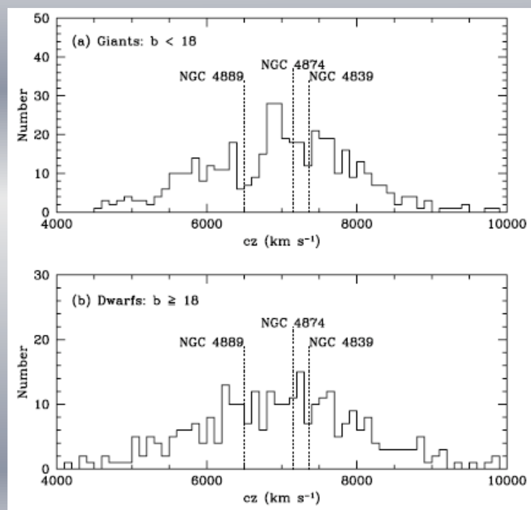
Velocities and vel distr. Of giant vs dwarf galaxies can give clues about the dynamical state and history of a cluster, since there are affected differently. For example, a cluster first goes through violent relaxation (see binney and tremaine book), the result is that all galaxies have the same vel. Dist. Then a cluster relaxes through dynamical friction, which takes longer, and the result is equipartition of energy, or all have the same kinetic energy (which means that smaller masses, like dwarfs, have a much higher velocity, and velocity dispersion, than giants). Virial equil. Means that sigma_dwarfs=2^.5*sigma_giants.

For their study they used the same set as C&D supplemented with additional redshifts that were more recently acquired with 2dF and wyffos.

Since there is no morphology data availabe, they used a b-mag of 18 as the dividing line between giants and dwarfs.

What they end up with is 452 giants and 293 dwarfs within 20′ of the cluster center.

Edwards et al. (2002): velocity distribution



Giants

Dwarfs

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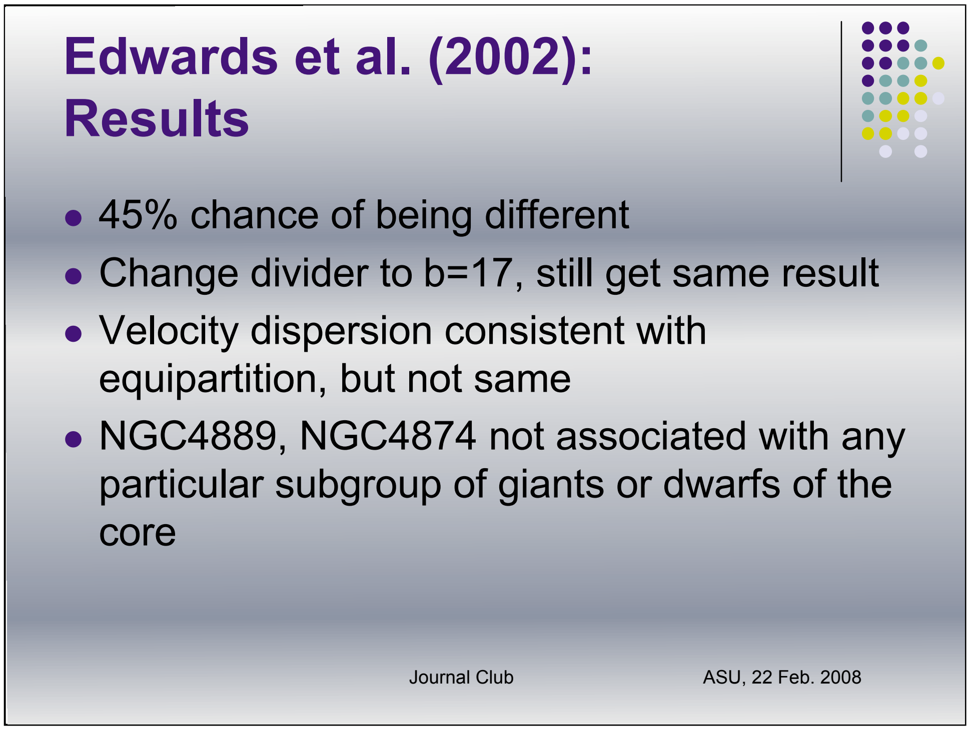
C&D found a non-gaussian distribution, but their galaxies are essentially all giants (as classified by Eea), so the authors are interested whether dwarfs will show the same. So they plot it, perform statistical test (lilliefors), and viola, dwarfs actually do have a gaussian distribution (or rather, are much more likely to do). So are they different from giants?

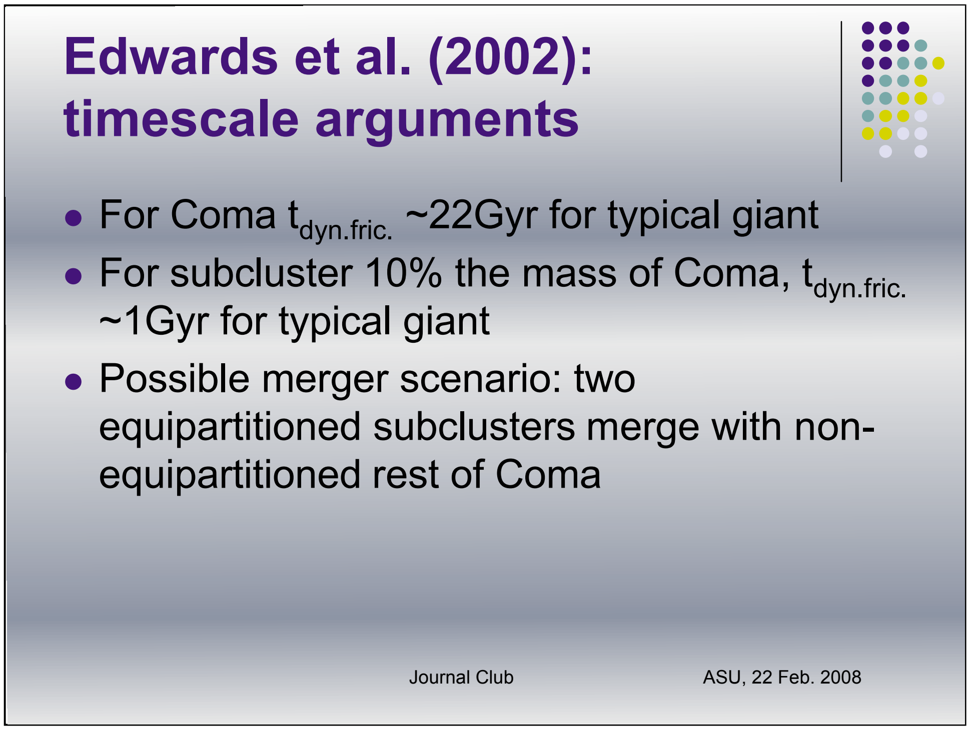


A two-sample K-S test to compare the two distributions says that there is only a 45% chance of them being different. They think about it (they take 293 random giants and tested for gausianity; 3% of the times it was gaussian), and come to the conclusion that it is also possible that both are from the same distributions, but not enough dwarfs are in the sample to detect that. Need at least 330 dwarfs to be able to tell.

They then changed the dividing b-mag to 17 to see if that has any effect on that. That means they have now 439 dwarfs and 306 giants (so more dwarfs), but their tests still give the same result as before. So now they are pretty sure that the dwarfs are a different distribution than the giants.

They then look at the vel. Disp. Of giants (979km/s) and dwarfs (1096km/s) , and find that the dwarfs are slightly higher. This is consistent with equipt. In the sence that dwarfs have a higher disp. But the expected disp. For complete equipartition is 482 for giants and 1523 for dwarfs. The dwarfs could not come from recenty infallen ellipticals, because those would be not gaussian. So it’s probably a subcluster merging with coma, and has just started to proceed to equipartition.

Eea also investigate whether one of those two galaxies are associated with a particular subgroup in space or velocity of either the giants or the dwarfs. (they plot a velocity in density vs position plots for giants and dwarfs, perform 3 stat. tests to see how different the plots are; the make the same plots for



Lastly, Eea list some time scale arguments to support their conclusions.

The time scale for dynamical friction to move the cluster to equipartition is about 22Gyr for a typical giant galaxy in coma (1e12 Msun). Since the time scale is inversely proportional to galaxy mass, more massive galaxies relax quicker. But even the dominant galaxies (4889, etc), which are 10x more massive than the giants, have a time scale of 2.2gyr, not enough to have settled to the bottom of the potential well.

But a subcluster that is 10% the mass of coma could have at least significantly progressed towards equipartition,

Merger model: assuming two equipartitioned subclusters 10% each of the mass of Coma, merge with a non-equpartitioned Coma, simulate this and see what you get. Results: get a similar overall vel disp. As observed. And about a third of the simulations give a non-gaussian vel. distribution of giants, but almost all dwarfs were gaussian.

The statistical tests from the real data applied to these generated data also gave similar results, namely, that differences between the giants and dwarfs were not certainly detected.

The end - thank you!