National Aeronautics and Space Administration

Testing gravity with the motion of galaxies in and around galaxy clusters

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1 The Idea

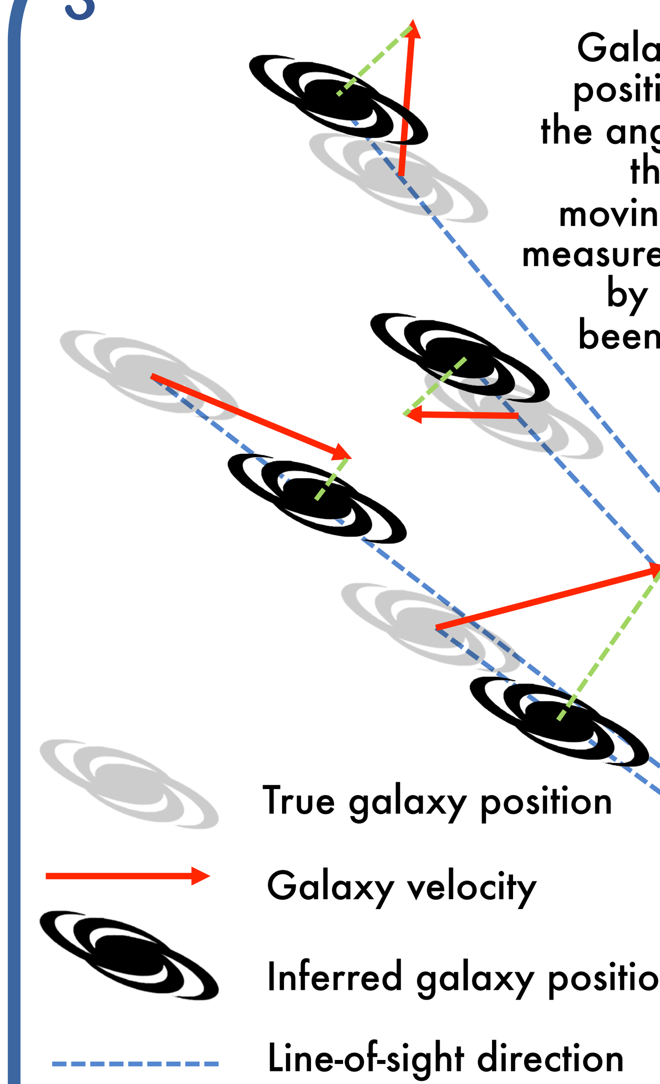
Galaxy clusters are the largest gravitationally bound objects in the Universe, meaning that their gravity has a profound influence on the motion of nearby objects. In particular, galaxies in and around galaxy clusters can have velocities of around 1000 km/s or greater. Our work uses the positions and velocities of galaxies around clusters (as encoded in the redshift-space cluster-galaxy correlation function) to test theories of gravity and constrain cosmological parameters.

Here we present our method, which we have so far tested on mock data generated from simulations. The main goal of our method is to be able to robustly predict the redshift-space clustering of galaxies and clusters down to scales of 1 Mpc, which is considerably smaller than the scales to which traditional models are trusted. We want to make this prediction as a function of cosmological parameters, as well as for different theories of gravity, and then compare these predictions with the observed Universe.

2 Correlation Functions

The observable that we aim to model here is the cluster-galaxy correlation function in redshift space, . The cluster-galaxy correlation function measures the excess probability of cluster-galaxy pairs having a particular separation, compared with a case of randomly distributed clusters and galaxies. Because the Universe has no preferred direction (it is statistically isotropic on large scales) the real-space cluster-galaxy correlation function, , depends only on the 3D distance between clusters and galaxies. An example of this real-space correlation function is shown in 5(a), where (for example), the value of implies that the average galaxy density 3 Mpc/h away from the centre of a galaxy cluster is 8 (=1+) times the average galaxy density in the Universe.

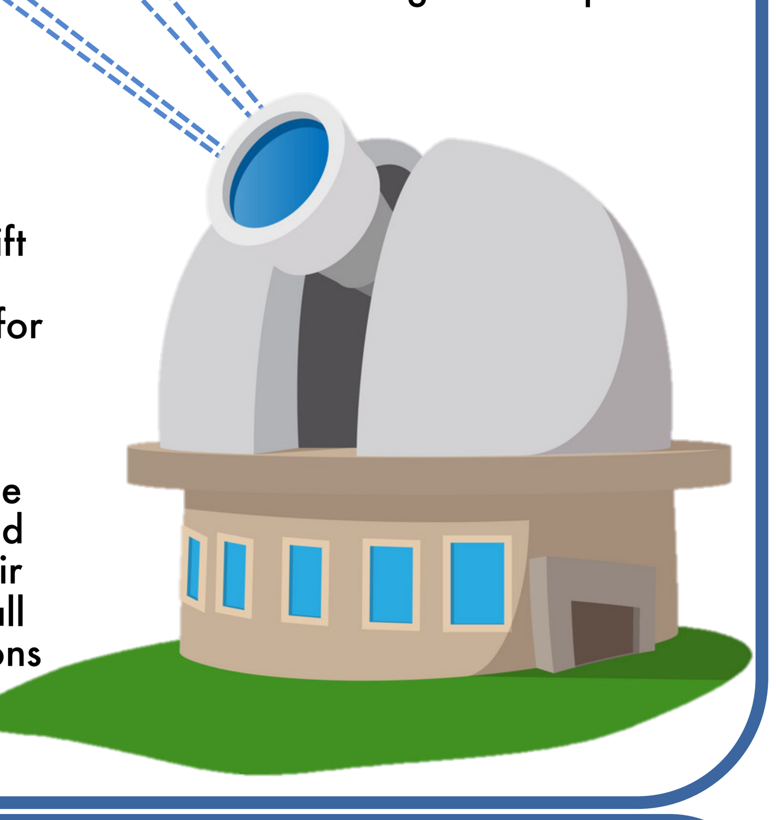
3 What is 'redshift space'?



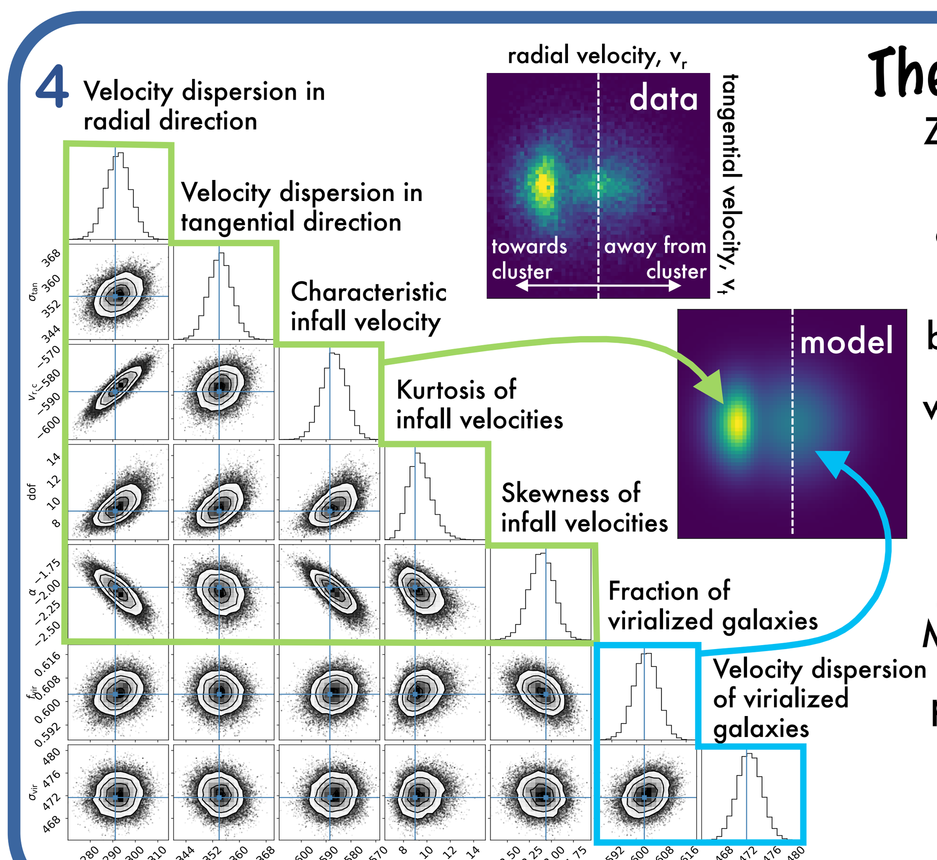
Galaxy redshift surveys measure 3 quantities related to the position and velocity of each galaxy. Two of these describe the angular position of the galaxy on the sky, and the third is the "line-of-sight" velocity, i.e. how quickly the galaxy is moving away from or towards us. This line-of-sight velocity is measured in terms of a "redshift", which describes the amount by which the wavelength of light emitted by a galaxy has been stretched between being emitted and us measuring it.

There are two primary factors that contribute to a galaxy's redshift. The first is the expansion of the Universe, and we call the redshift due to this "cosmological redshift". The cosmological redshift increases the further away a galaxy is, because light travels at a finite speed, and so the light from more distant galaxies was emitted longer ago, when the Universe was smaller. The second factor is the "peculiar velocity" of the galaxy, which is how fast the galaxy is moving relative to the average background expansion.

For galaxy redshift surveys, the cosmological redshift is typically much larger than the redshift due to peculiar velocities, so we can use the redshift of each galaxy as a reasonable proxy for the distance to that galaxy. Combined with information on the angular position of each galaxy, this allows us to make maps of the positions of galaxies in 3D space. However, the peculiar velocities of galaxies move the inferred position of galaxies in this map away from their true locations (see diagram above), and we call these shifts - from true to inferred galaxy positions - redshift-space distortions (RSD).



4 The velocities of galaxies around clusters



Zu & Weinberg (✷) analyzed the Millennium cosmological simulation and found that the velocity distributions of galaxies lying in spherical shells centered on galaxy clusters could be well described by a 7 parameter model. The velocity distribution describes the number density of galaxies with different velocities, where the velocities are broken up into a radial component (describing the velocity of the galaxy away-from / towards the cluster center), as well as a tangential component. The Zu & Weinberg model has two distinct components: an infalling component, represented by a skewed t-distribution, and a component for virialized galaxies.

To the left is an example, looking at the velocity distribution of galaxies that lie between 1 Mpc/h and 1.5 Mpc/h from the center of a cluster in a simulation ("data"). The best-fitting model is also plotted, as well as the posterior distribution on the model parameters. This radial shell is close to the virial radius of the clusters, so the galaxies within it are a mixture of virialized galaxies and those infalling for the first time.

✷ https://arxiv.org/abs/1211.1379

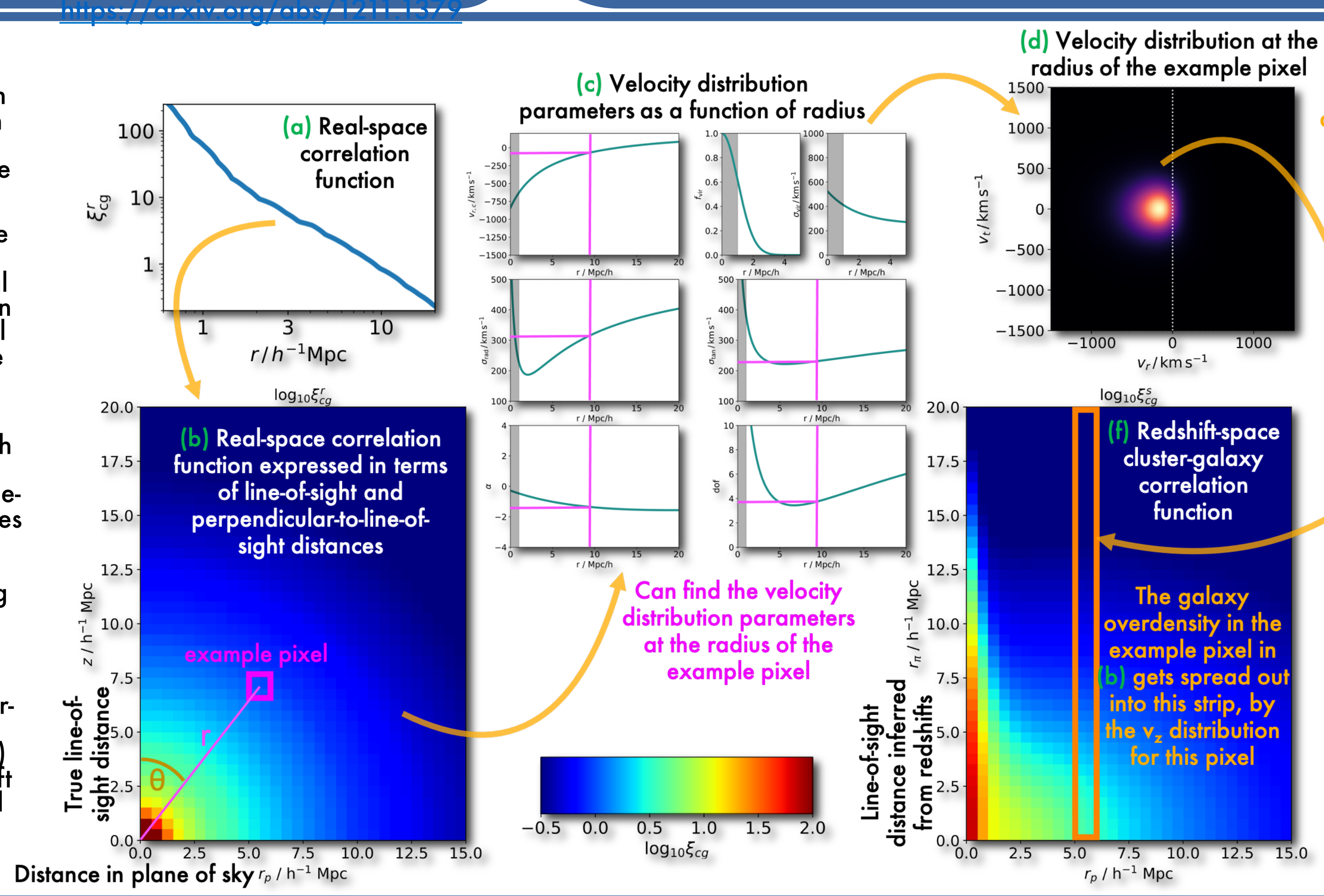
5 Calculating the observable, ξ_{cg}^s

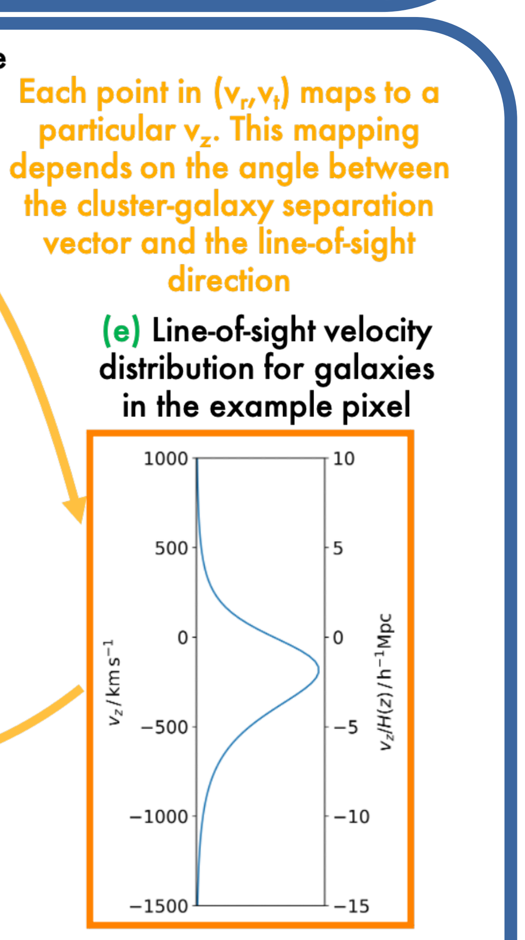
When fitting the 7 parameters of the velocity distribution (described in 4) to simulation data, we find that they vary in a smooth manner with radius, as shown in (c). These 7 functions of radius depend on the cosmological parameters, the mass of the galaxy clusters, and also the law of gravity.

The model observable is shown in map-(f), and our goal is to calculate this, taking as input the real-space clustering (a) and the 7 velocity-distribution functions (c). When analyzing observational data, the real space clustering will be inferred from the projected correlation function (which is unaffected by peculiar velocities) and the functions in (c) will be predicted by an emulator trained on cosmological simulations (see 7).

For each pixel in map-(b) we can find the velocity distribution of galaxies in that pixel using (c). This velocity distribution, combined with the angle between the cluster-galaxy separation and the line-of-sight direction (marked as θ in (b)) can be converted into a distribution of line-of-sight velocities (v_z, see (e)). These line-of-sight velocities move galaxies from their true (real space) positions, to their inferred positions in redshift space, so the v_z distribution can be used to redistribute the overdensity of galaxies in a pixel of map-(b) into a strip running along the line-of-sight in map-(f).

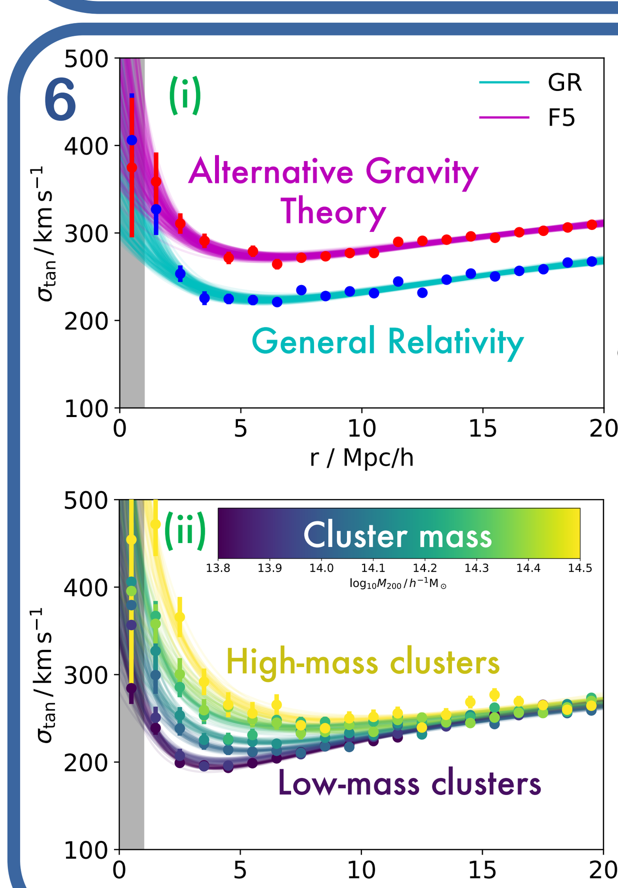
Doing this for every pixel in map-(b), and summing up the results, we get map-(f). This map expresses the excess density of galaxies as a function of position away from the centers of clusters, where the cluster-galaxy separation is split into a component in the plane of the sky (which depends on the observed angles between cluster-galaxy pairs) and a component along the line-of-sight (which depends on the redshift differences between cluster-galaxy pairs). This map can be calculated directly from a galaxy redshift survey combined with a catalog of galaxy clusters.





Repeating the procedure (here illustrated for one example pixel) for all pixels in the real-space correlation function map, we can generate the redshift-space correlation function map.

6 Cosmology dependence of galaxy kinematics



The galaxy velocity distribution parameters as a function of radius (shown in 5c) depend on various factors, including the mass of the galaxy clusters, the cosmological parameters, and the theory of gravity. This dependence can be studied using cosmological simulations run with different cosmologies and gravity theories. In (i) and (ii) we show just one of the 7 parameters, σ_{tan}, as an example.

In (i) we show that when changing from general relativity (GR) to a modified gravity theory known as F5 (✷), the tangential velocity dispersion increases, which is to be expected given the additional "fifth force" enhancement to gravity in F5.

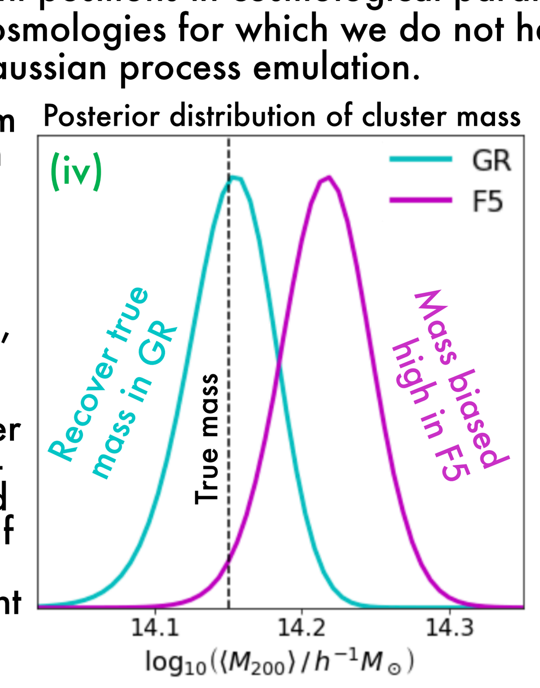
In (ii) we show that changing the cluster mass (while keeping the gravity model fixed to GR) also changes $\sigma_{tan}(r)$, with more massive clusters leading to larger velocity dispersions for infalling galaxies.

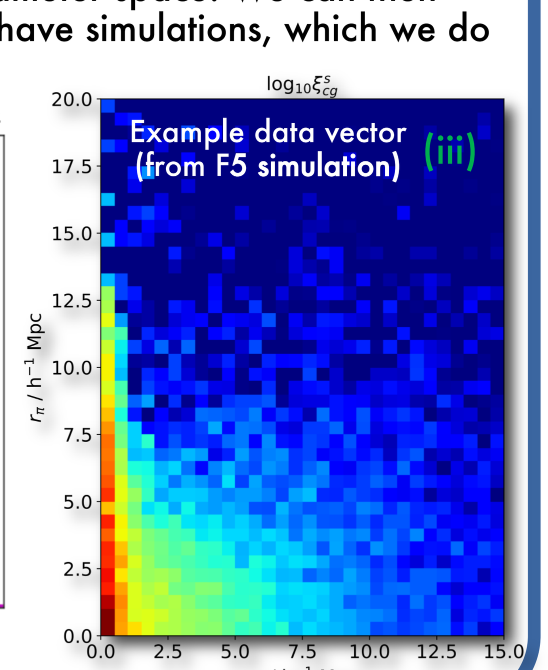
✷ F5 is a variant of f(R) gravity, where $|f_{R0}|=10^{-5}$

7 Emulation and testing gravity

We cannot predict the curves in 5c from first principles, because they depend on non-linear gravitational evolution. Instead, we can use cosmological simulations run with different cosmologies and/or gravity theories to find the curves in 5c at different positions in cosmological parameter space. We can then interpolate to find the expected curves for cosmologies for which we do not have simulations, which we do using Gaussian process emulation.

If we build our Gaussian process emulator from GR simulations, but then fit to mock data from an F5 simulation (shown in (iii)), we infer a cluster mass that is larger than the truth (iv), because gravity is enhanced in F5 (see 6i). Gravitational lensing on the other hand is insensitive to the enhancement to gravity in F5, and so should measure the true mass in both GR and F5. Comparing the cluster mass inferred from galaxy kinematics, with the cluster mass from lensing (as measured by future JPL-involved missions such as SuperBIT, Euclid and Roman) will therefore test theories of gravity. If general relativity is correct, the two measures should agree, but if they disagree it would point to some departure from GR.





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