Gravity Without the Equivalence Principle

by Andrew Downing[1]

Abstract

A simple method is presented to account for the macroscopic effects of potential unknown attractive and repulsive forces that obey the inverse square law. This method is implemented in an n-body simulation. Graphs and screenshots from the simulation are then used to show that practically any quantum mechanical big bang theory with many arbitrary types of particles and fundamental forces would necessitate cosmic inflation, structure formation in the early universe, Hubble's law, the cosmological principle, slightly accelerated expansion of the universe, and, in specific cases (such as protoplanetary disks), the equivalence principle, regardless of what the particles and forces in the theory are.

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A Speculation About Particle Physics

In general, discoveries in particle physics have tended to involve new and seemingly arbitrary types of particles and fundamental forces. Therefore, as we continue increasing the energy levels of particle colliders, wouldn't one expect to keep finding new and seemingly arbitrary particles and forces?

What would a quantum mechanical theory with many different particles and forces look like, anyway?

Accounting for Unknown Forces

In standard Newtonian mechanics, the strength of the electrostatic force can be calculated using the charges of the 2 objects and the distance between them, as shown below:

$$F=\frac{kq_1q_2}{r^2}$$

If we also wanted to include the effects of, say, gravity, we could add a second term containing the masses of the objects, as in the following:

$$F=\frac{kq_1q_2}{r^2}+\frac{Gm_1m_2}{r^2}=\frac{kq_1q_2+Gm_1m_2}{r^2}$$

However, if there were many such forces, the terms in the numerator would become difficult to keep track of. In that case, it would be far easier to use a single constant whose value depends on both interacting objects, like this:

$$F=\frac{g}{r^2}$$

Since the variable g represents the *sum* of the interactions between 2 objects, another advantage of doing this is that one no longer needs to know what the individual interactions (such as electricity and gravity) are to be able to model their total effects. In other words, this is a way to account for the macroscopic effects of all attractive and repulsive forces (including unknown ones) that obey the inverse square law.

What might this be useful for?

Modeling Considerations

If there were ever a time when the universe was influenced by many different fundamental forces, one of those times would be the big bang. (Let's keep track of the assumptions we are making and make this assumption #1.) If the big bang involved many types of particles and forces that we do not know about, making it extremely difficult to model in detail, it might be possible to crudely and approximately model it by using the formula described above. Since the variable g would represent the sum of many seemingly arbitrary (as always is in quantum mechanics) interactions between a specific pair of objects, it could be given random values that are normally distributed and centered at 0.

The high density initial state of the big bang (if there was such an initial state) can be approximated by putting many particles close together, essentially at a point (assumption #2). However, if 2 particles are at the same point, the inverse square law predicts infinitely powerful forces between them. In reality, we know that these forces are mediated by a finite number of fundamental particles (assumption #3). Two effects of this are that forces are applied at discrete times, as opposed to continuously over time, and that forces do not approach infinite strengths as the distance between particles approaches 0. An easy and very crude way to account for this is to update the model in fixed time increments and to slightly modify the previous formula to be the following:

$$F = \frac{g}{r^2 + n}$$

where n is a small positive constant. Other variations of this formula will be explored later.

Putting It All Together

Thus, it seems that if the big bang was governed by many different fundamental forces, then it may be possible to approximately model it at large scales by making only 3 nontrivial assumptions:

1. There are many different types of particles and forces.
2. Everything in the universe began very close together.
3. Forces act as if they are mediated by fundamental particles.

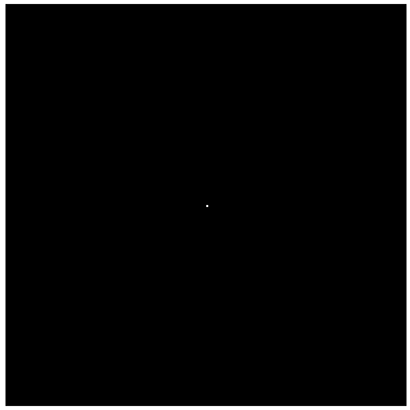
Since this should be fairly simple to implement using the method described above, why not test this idea by making a simulation that meets these conditions?

To do this, I made such an n-body simulator by modifying a previous program I made. If you want to follow along, study the code, or try variations on my examples, you can download the simulation at http://ad510.users.sf.net/gwep/download.php. Note that it requires the .NET Framework version 2 and the DirectX End-User Runtime to run. (The readme file contains links to download these.) Also, I'm not particularly good at designing user interfaces, so I recommend reading the readme file before running the program.

Now let's end the theory talk and make some predictions!

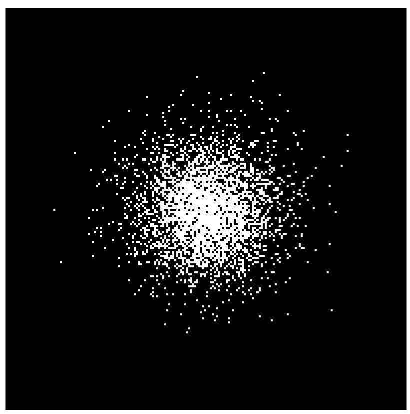
Cosmic Inflation

Conventional wisdom states that large amounts of negative vacuum energy caused the early universe to expand very quickly, but is it really necessary for this energy to come from nothing?



The first frame of the simulation. The parameters used in params.txt were `4000, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 15`, which from now on I'll put in parentheses.

Suppose that all particles at the moment of our simulated big bang have a velocity of 0. Since the particles are all close to each other, they exert strong forces on each other, some of repulsion and some of attraction. However, since all particles essentially are at a point, any acceleration would cause a particle to move outwards. (Again, starting everything approximately at a point is done for our convenience and this may not have applied to the real big bang.)



The second frame of the simulation. No matter which direction each particle is accelerated, they all move outwards.

Once the particles gain this initial acceleration, it is unlikely that any future acceleration will cause the particles to move back towards the starting point. This is true because there is an approximate balance of attractions and repulsions on each particle and because as the particles spread out, the forces exerted become weaker.

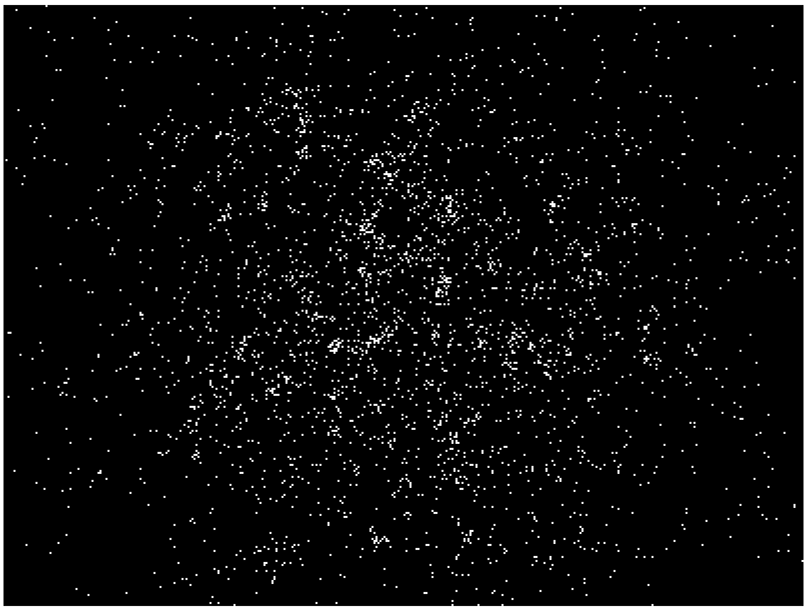
Interestingly, the inflation in this model is not exponential, unlike usual theories of inflation. As we continue studying the simulation, let's find out if this causes any problems.

First Signs of Structures

Simulating anything after the first moments of the big bang would require knowledge of the specific fundamental forces in the universe, and is going beyond the initial scope of the simulation. However, since having many particles and forces beyond those of the Standard Model would likely have an effect on cosmology, let's see what the simulation predicts anyway.

Stuff that attract each other tend to move closer together, and stuff that repel each other tend to move further apart. Thus, after some time, wouldn't you expect the stuff that are close together to be more likely to attract each other than the stuff that are far apart (at least for nonrotating structures)?

This is at least the case in this simulation, as each particle quickly moves toward a group of particles that it tends to attract more than repel. Since the total attractions/repulsions between pairs of particles are randomly generated, clumps of particles begin to form. Note that the size of these clumps can be tuned by changing the "inverse square law dampener" parameter. Curiously, increasing the "maximum initial velocity" parameter makes these clumps smaller because it artificially causes particles to move more quickly away from each other, making it more difficult to move towards particles they are attracted with.



Frame 50 of the simulation, using the same parameters as above[2].

So far so good, right?

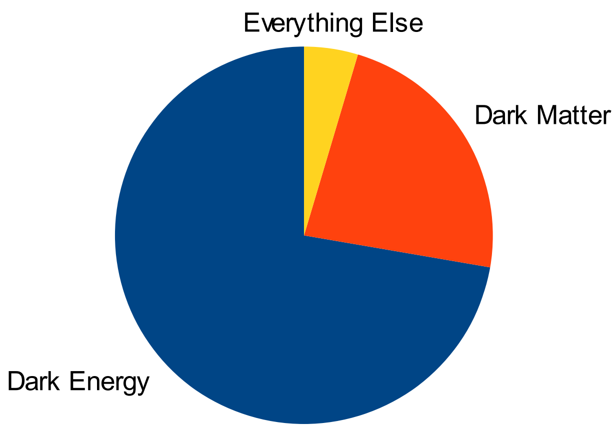
Discarding the Equivalence Principle

There's just one problem with this. While particles are attracted to the clumps they are in, they are not necessarily attracted to other clumps. That means the total forces on the particles don't follow the equivalence principle, which basically says that all objects experience the same acceleration in a given gravitational field.

This isn't necessarily a bad thing. It is a well known fact that the net forces on objects do not follow the equivalence principle. (Try picking up something with a magnet.) What is more troubling is that having many types of fundamental forces seems to imply rather spectacular violations of the equivalence principle after the big bang at scales where gravity is considered dominant.

2 I suggest watching the video of this at http://www.youtube.com/watch?v=fXyeBPDd6Mk to get a three-dimensional sense of where the clumps are.

This may not be such a bad thing either. Most structures much larger than the solar system cannot be successfully modeled with a naive application of general relativity. A well-studied and quite successful explanation for this is that there are vast quantities of invisible matter and energy in the universe, but the ad hoc assumptions required by this explanation (including the equivalence principle) have been notoriously difficult to reproduce in theories of quantum gravity. Since dropping the equivalence principle (and thus gravity) as a *fundamental* property of nature that applies everywhere is actually removing an assumption, rather than adding more, why not give it a try and see if it also works? Already, I find it interesting that we've found modern galaxies [1] and galaxy clusters [2] earlier in the universe than anyone expected, and that this model allows structure formation to occur early in the universe.



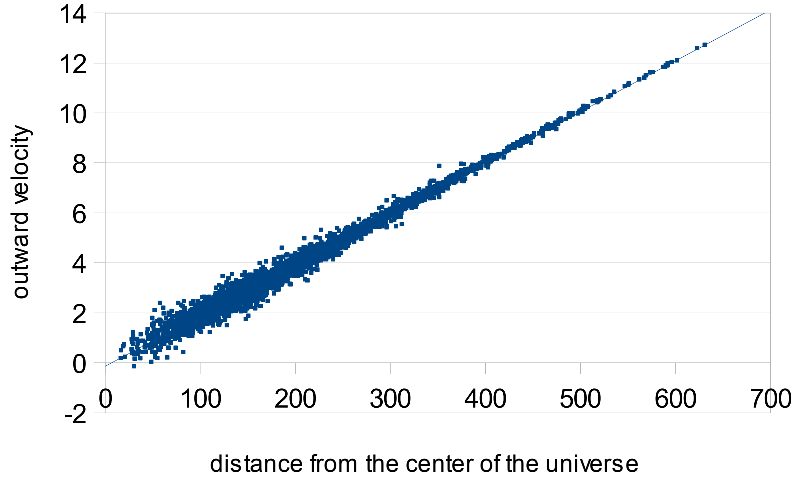
Either there must be a lot of dark matter and dark energy, or we have no clue what's happening at cosmological scales.

Also, while this appears to be making a clean break from the equivalence principle, systems that closely follow the equivalence principle can still emerge naturally and surprisingly often in certain types of situations. This will be discussed in more detail later on.

First, though, let's look at some of the other properties of this model.

Hubble Expansion

Hubble's law states that cosmological bodies tend to move away from each other at a speed proportional to the distance between them. This Hubble expansion is an almost inevitable result of the universe expanding from a point, and this model is no exception.

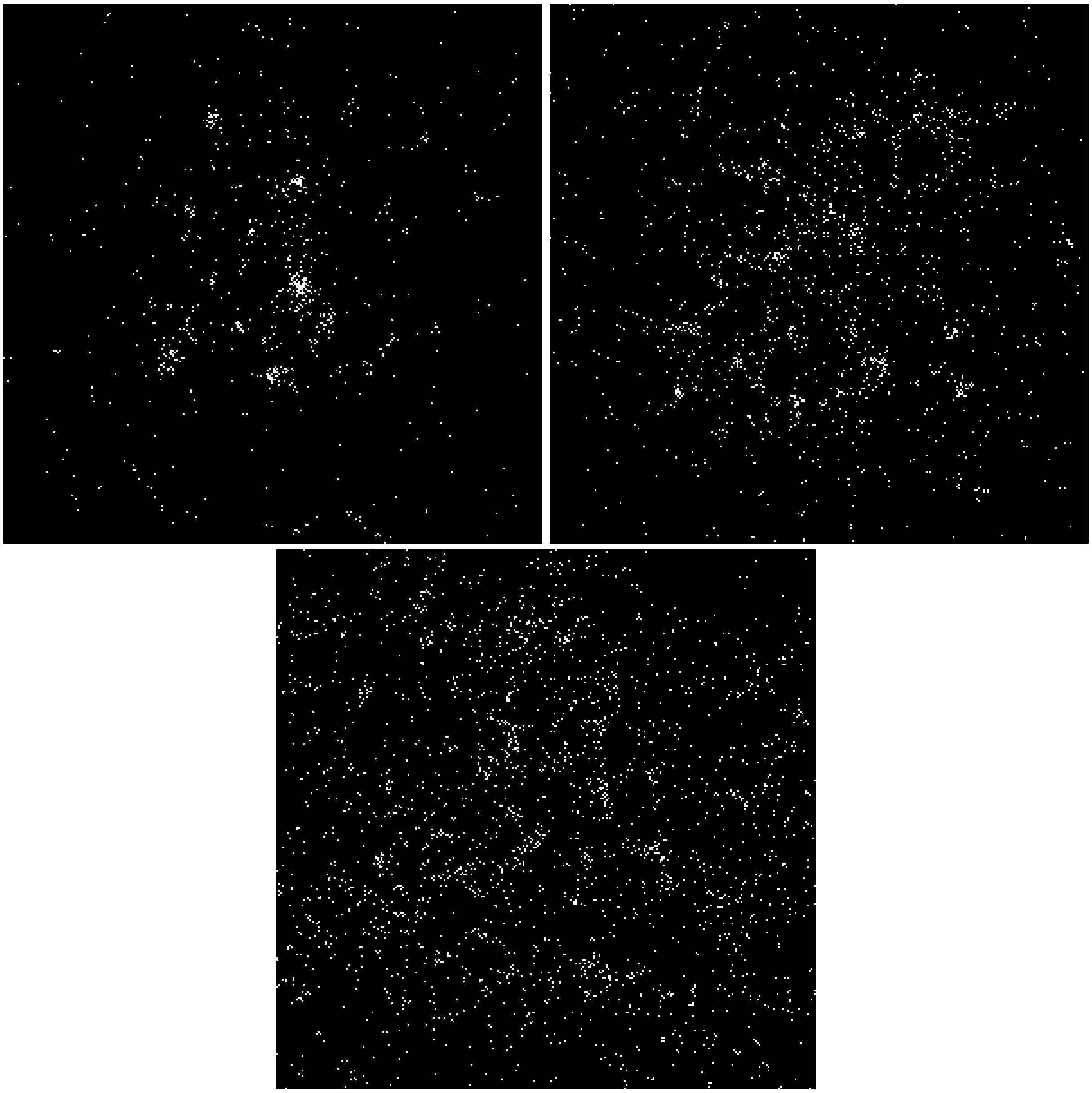


This graph was generated at frame 50, using the same parameters as above.

(Actually, the graph above isn't perfectly straight due to a subtle effect described in the section "The Accelerating Universe," but this is smoothed out over large distances by the property of the model discussed in the next section.)

The Cosmological Principle

The cosmological principle states that the universe at its biggest scales is just a big fog of uniform density, having no "special" places or directions. This is a bit more interesting. At first glance, it looks like the size and density of the clumps is much greater near the center of the simulated universe than at the edges, which appears inconsistent with the cosmological principle. However, as the simulation is run with more and more particles, the individual clumps do not get bigger or more dense. Instead, the large-scale visual inconsistencies get pushed further away from each other, making any given finite region look increasingly uniform. Thus, with infinitely many particles and perhaps a cosmological horizon to top it off, there wouldn't appear to be any special locations in the entire observable universe.



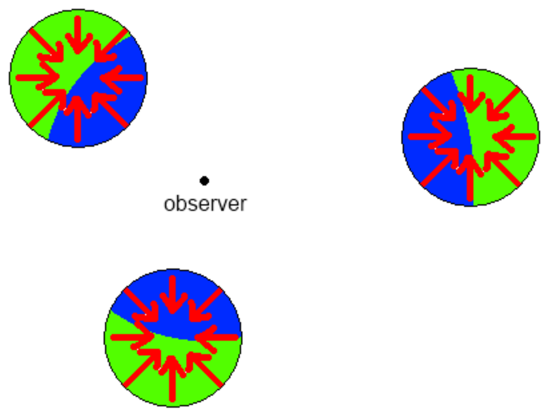
Full depth cross sections of frame 50 with 1000 (`1000, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 15`), 2000 (`2000, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 15`), and 4000 particles (`4000, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 15`), respectively, all other parameters held constant. As the simulation is run with more particles, more clumps are made, but their sizes and shapes remain consistent.

The Accelerating Universe

This one's a bit more complicated to explain, but I personally find it quite interesting.

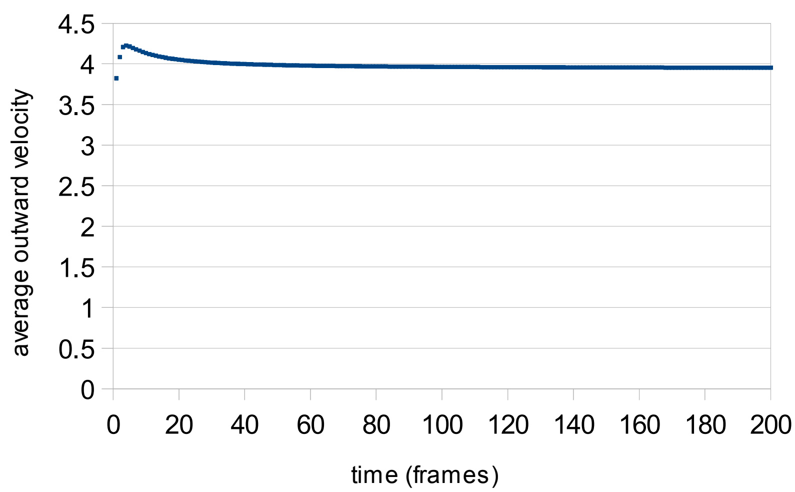
If the only stuff that are particularly likely to attract each other are the stuff that are close together, then at the largest scales there would be no significant attractions or repulsions (see "Discarding the Equivalence Principle"). (In fact, this would result in effects similar to those of a cosmological constant, such as the apparent slowness of galaxy cluster growth [3].) Therefore, if this simulated universe doesn't expand at exactly a constant rate, it must be the result of smaller-scale effects.

When the "clumps" are forming, attracting particles are moving closer together and repulsing particles are moving further apart. During this time, each clump can be thought of as a bunch of particles moving towards a common center. To keep things simple, let's assume that the clumps move away from each other at a constant rate and take the perspective of an observer in the middle of it all.



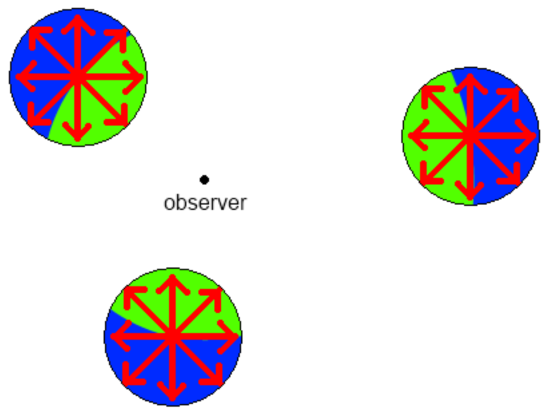
In the image above, you'll see that I divided each clump into 2 sections. The green sections represent particles moving away from the observer slower than the clump, and the blue sections represent particles moving away faster than the clump. Notice that the areas of the green sections are greater than the areas of the blue sections. This means that as the clumps are forming, the particles on average move closer to any given observer in the cosmic rest frame than anticipated by a constant rate of expansion. (This is easiest to understand by looking at the image above.)

The overall effect in the simulation is that the average outward velocity of the particles decreases over time.



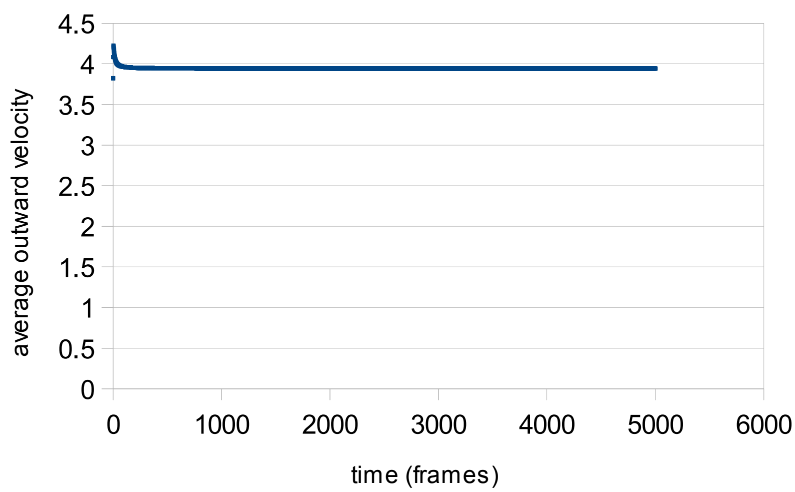
As the clumps form, the particles experience a net inward acceleration. (`4000, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 15`)

However, this process cannot continue forever. While there is no limit to how far apart things can be, things can only move closer together until the distance between them is 0 (or until they orbit each other). After that time, they can only stay together or move away from each other. The chaotic processes of the universe make it almost inevitable that they will eventually move apart at escape velocity. This happens all the time in the real universe as stars explode, black holes shoot out relativistic jets, galaxies interact and lose their outer regions [4], stars emit photons and charged particles, etc.

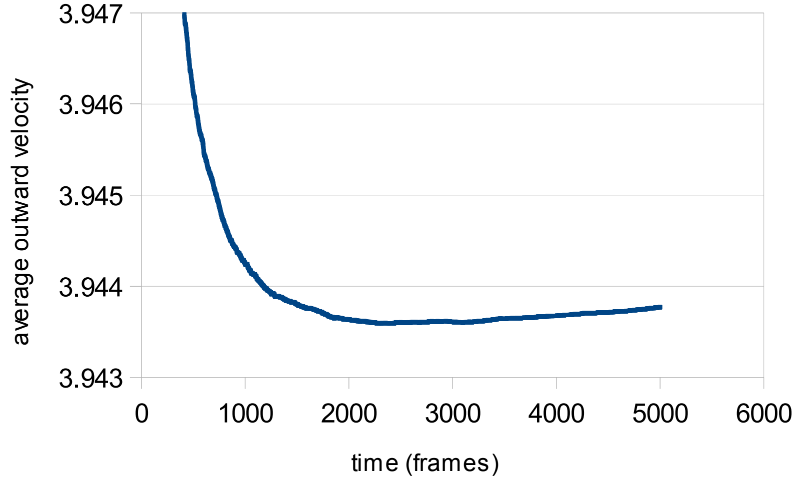


The overall effect is the opposite of that when the clumps were forming. As the particles move away from the individual clumps, the average distance of the particles from any observer in the cosmic rest frame increases by more than accounted for by a constant expansion rate.

Can this tiny, gradual effect influence the simulated universe at the largest scales? As you can see, after the clumps form, the average outward velocity of the particles flattens out and appears to approach a constant value.



Or does it? Here's a zoomed in view of the same graph (look at the Y axis):



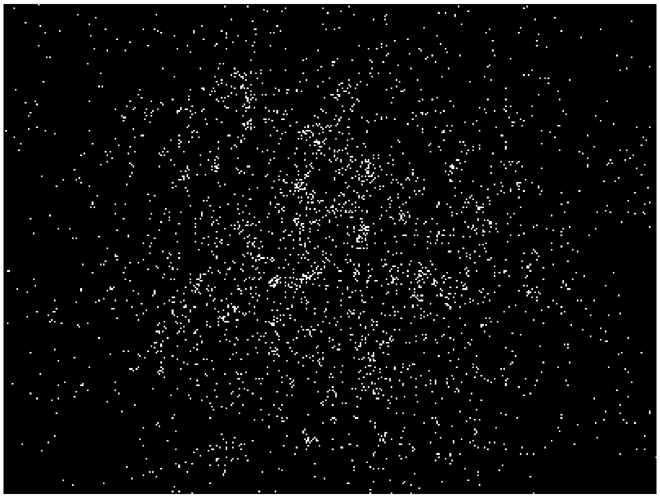
In this simulation, an inevitable result of the universe's gradual heat death is a tiny outward cosmic acceleration. (Note that most variations of this model I tried didn't have nearly as small of a outward cosmic acceleration, but every variation I tried, including this one, had it nonetheless. This will be discussed in the following section.)

Abuse Potential

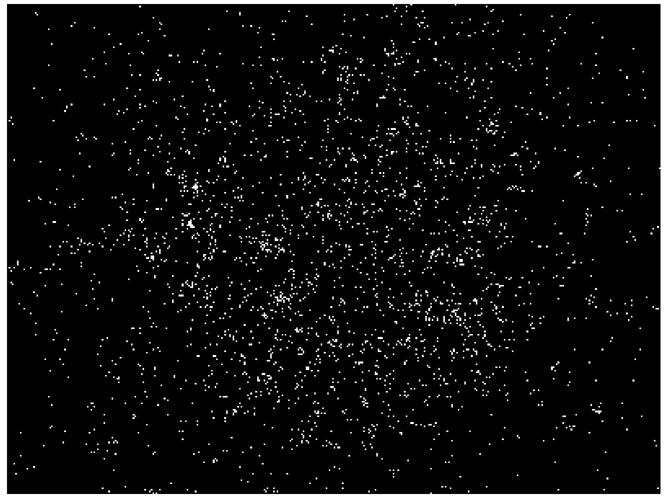
One of my favorite aspects of this model is that it is possible to change seemingly fundamental parts of the formula and still get very similar results. For reference, here's the formula I've been using to calculate the forces between pairs of particles in the examples above:

$$F = \frac{g}{r^2 + n}$$

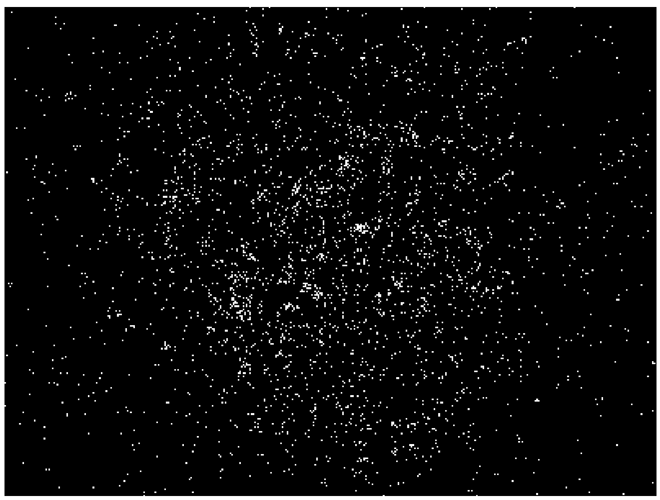
The variable g is different for each pair of particles, and tells how strongly they attract or repel each other. The values of g are randomly generated at the beginning of the simulation, and in the examples above, these values have a normal distribution and are centered at 0. Let's try some other probability distributions.



Frame 50 when giving the variable g a normal distribution, as I've done in previous examples. `(4000, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 15)`



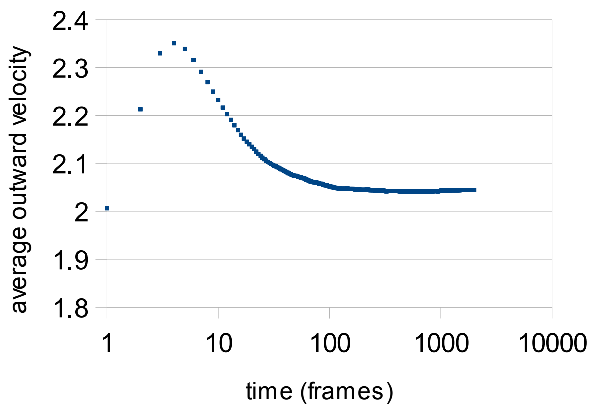
Frame 50 when distributing g values uniformly between -2 and 2. `(4000, 0, 0.01, 0, 0, 1, 0, 2, 0, 0, 15)`



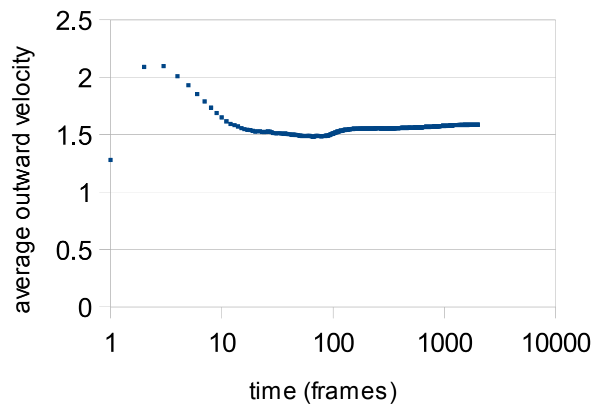
Frame 50 when randomly setting each value of g to either -1 or 1, and nothing else! `(4000, 0, 0.01, 0, 0, 2, 0, 1, 0, 0, 15)`

As long as the values of g average around 0, the model gives consistent results, regardless of how those values are distributed.

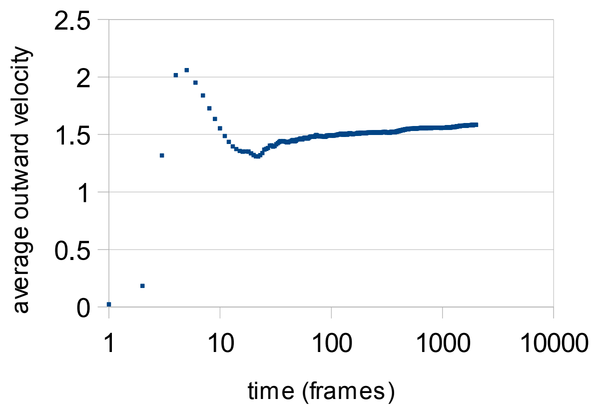
Now let's play around with the bottom part of the formula. This part is based on the inverse square law, but slightly modified to account for the fact that forces are mediated by fundamental particles (see "Modeling Considerations"). Different variations of this modification also give similar visual results (I've checked), so instead of looking at more screenshots let's look at graphs of something this might affect, say, the expansion of the simulated universe. For the following graphs, the simulation was run with 500 (rather than 4000) particles and time is shown on a logarithmic scale.



The result when adding a fixed value to the squared distance, as I've been doing in the examples above. The Y axis doesn't begin at 0 to show the slightly accelerated expansion beginning at about frame 500. (`500, 0, 0.01, 0, 0, 0, 0, 1, 0, 0, 10`)



The result when giving the distance calculation a fixed value at short distances while preserving the actual distance at larger distances. (`500, 0, 1.5, 0, 0, 0, 0, 1, 0, 1, 9`)



The result when modifying the strength of the inverse square law to approach 0 as the distance approaches 0! (`500, 0, 0.01, 0, 0, 0, 0, 1, 0, 2, 3.7`)

While the graphs have slightly different shapes, they all feature a rapid increase in average outward velocity corresponding to cosmic inflation, a decrease as clumps form, then a small, gradual increase as the clumps slowly break apart.

Given how much abuse potential this model has, doesn't it seem to suggest that the principles behind it are very general and would cause the same effects in a true quantum mechanical environment?

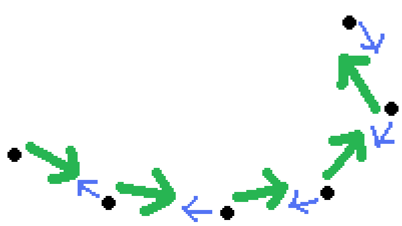
Galaxies

While this hasn't been my main area of study, a paper that discusses allowing violations of the equivalence principle as an alternative to dark matter simply wouldn't be complete without a mention of galaxies.

When working with a model that allows blatent violations of the equivalence principle, one might expect to have trouble reproducing the equivalence principle in a system that does not have to obey it. Actually, I've had the opposite problem. Despite my best efforts to make spinning disks that obviously violate the equivalence principle (to simulate various types of galaxies), they have all looked roughly like standard Newtonian gravity-obeying disks after several rotations! (If you're really interested, I put videos of my best attempts to make elliptical galaxies, spiral galaxies, and irregular galaxies on YouTube[3].)

Does that mean that it is impossible to reproduce the wide variety of galaxies simply by making the equivalence principle an exception rather than the rule? Of course not! Allowing each pair of particles to attract each other by a different amount opens up such a wide array of possibilities that I've probably only barely scratched the surface.

Here is one reason I think allowing violations of the equivalence principle might be a good candidate for making quickly rotating spiral disks with flat rotation rates. Recall that after some time, one would expect the stuff that are close together to be more likely to attract each other than the stuff that are far apart (see "First Signs of Structures"). In a spinning structure, wouldn't you also expect objects to arrange themselves so that they tend to attract stuff closer to the center more than stuff closer to the edges? While this would cause a sort of rubber band effect making stuff towards the edges orbit faster than expected, I've only tried a few variations of this idea and it is not clear how the structure would maintain this property over time.



I consider galaxy formation and evolution when gravity doesn't follow the equivalence principle to be a promising topic for future study, assuming I have the time and computing resources to do it. (I have other things I have to do, you know!)

Solar Systems and Obeying the Equivalence Principle

A major question throughout the history of gravity has been why it follows the equivalence principle. However, given how much recent cosmological observations seem to differ from general relativity's naive (no dark matter or dark energy) predictions, perhaps a better question would be why the sum of all influences other than electromagnetism, the strong force, and the weak force seems to follow the

3 The videos are at http://www.youtube.com/watch?v=wy-XhilpV9I, http://www.youtube.com/watch?v=333bB-bVQ98, and http://www.youtube.com/watch?v=PPCphi160xc, respectively.

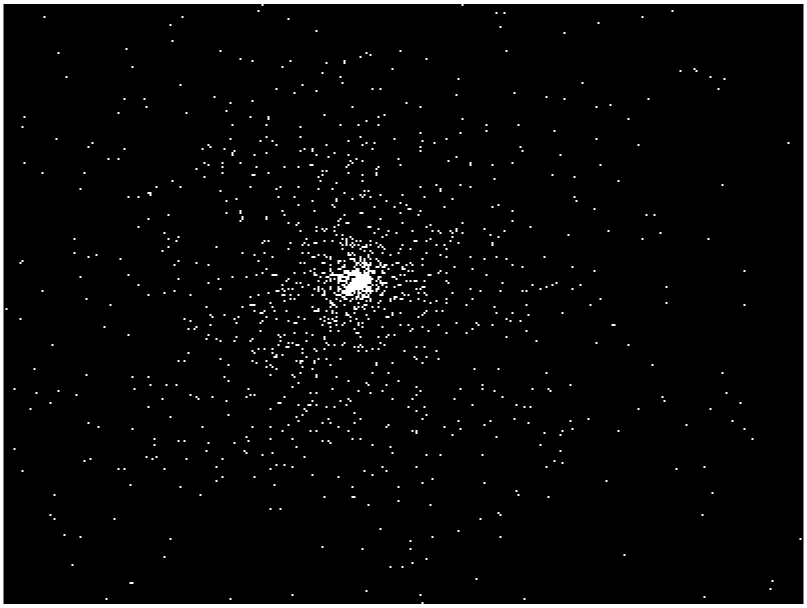
equivalence principle *inside the solar system*.

Gravity without the equivalence principle is a superset of gravity with the equivalence principle. That means that the easiest way to reproduce the familiar law of universal gravitation is to simply create a setup that does follow the equivalence principle, perhaps within a much larger universe that doesn't. However, even when one does not do this, the equivalence principle-violating effects still cancel out at appropriate scales surprisingly often.

The equivalence principle is a statement about all objects behaving the same way. Obviously, the huge variety of objects in the universe do not behave the same way. However, if one takes a wide variety of objects and puts them together in a blender, they will become nearly indistinguishable from each other [5], and for practical purposes appear to behave the same way. (Young solar systems seem to be analogous to blenders, as comets from as far away as Pluto apparently delivered an appreciable amount of ocean water to Earth [6].) Thus, how closely a system follows the equivalence principle could be a measure of how well "blended" it is.

However, since matter is made out of indivisible particles, it cannot be perfectly blended. This could explain why particles can still combine to form a wide variety of macroscopic objects despite the individual particles (and their varying quantum properties, if there are many types of particles and forces) being so well blended.

To demonstrate these concepts, the run below involves setting the particle attractions to random values centered at a positive constant (rather than 0), then starting the particles in a spinning disk. After the system takes a few moments to settle down, it appears to obey the equivalence principle despite the standard deviation of the attractions being 4 times greater than the average attraction.



Frame 1500 of a run that involves blatent violations of the equivalence principle, even though it doesn't look that way. `(2000, 1, 100, 0.025, 50, 0, 0.25, 1, 0, 0, 5)`[4]

4 I recommend watching the video of this at http://www.youtube.com/watch?v=QJ27UHra-14.

Conclusion and Testable Predictions

In summary, a model that makes the following nontrivial assumptions:

1. There are many different types of particles and forces.
2. Everything in the universe began very close together.
3. Forces act as if they are mediated by fundamental particles.

will naturally produce the following phenomena:

- cosmic inflation
- structure formation in the early universe
- Hubble's law
- the cosmological principle
- decelerated followed by slightly accelerated expansion of the universe
- the equivalence principle (in specific cases such as spinning disks)

regardless of what the particles and forces in the model are and how they behave at short distances!

Of course, this is nowhere near close to reproducing every cosmological observation from the big bang, and it would take expert research to determine whether any model based on the idea of many different particles and forces (or something with a similar effect) could apply to the real universe. However, even in this early stage of research, such models would make a few predictions that can be used to distinguish them from other theories such as dark matter/energy.

Perhaps the most obvious one is that no matter how hard we try, we won't find dark matter particles. It is quite possible that we will find new heavy particles, but they simply won't exist in enough quantities to be able to act as dark matter.

A common trend in the last decade or so is the discovery of mature galaxies [1] and galaxy clusters [2] surprisingly early in the universe's evolution. These have raised challenges for dark matter models, but so far have not ruled them out. If we find enough of these galaxy clusters that there simply couldn't have been enough dark matter to make them that early, then one possible explanation could be that gravity (or some unknown forces) didn't follow the equivalence principle. On a related note, models like the one in this paper would require that the expansion of the universe slowed down during that time.

The way the universe accelerates in this model has some unusual characteristics that can be used to make distinct predictions. Since the appearance of a vacuum energy in this model is actually the release of stored energy, objects in the early universe would appear too energetic to be consistent with conservation of energy if dark energy is not considered as part of the total energy. (If dark energy is considered part of the total energy, energy still probably wouldn't appear conserved in conventional models, but those models already predict that.) This extra energy might be interpreted as additional dark matter that mysteriously disappeared over time.

While failure to confirm the above predictions would probably rule out this paper's proposal, confirmation of them would still not be direct evidence of violations of the equivalence principle. If gravity doesn't follow the equivalence principle, then the equivalence principle-violating effects must appear at galactic scales to be able to serve as an alternative to dark matter. In particular, one effect would be that if something travels far enough relative to its surroundings without mixing with other substances, it will behave as if the gravitational constant is different (probably lower). Depending on the behavior of forces beyond the Standard Model, the change in the gravitational constant might spread out to nearby objects rather than being localized to the ones that moved far, potentially making this effect difficult to distinguish from dark matter.

Physicists seem to fear allowing violations of the equivalence principle, as if the mere thought of doing so would be permitting all sorts of strange phenomena prohibited by nature. Now that nature appears to allow such phenomena, perhaps it's time to say that dropping the equivalence principle isn't taking away the essence of gravity. It's enhancing it.

References

[1] http://www.sciencedaily.com/releases/2011/04/110412101330.htm
[2] http://www.science.tamu.edu/articles/753
[3] http://www.jpl.nasa.gov/news/news.cfm?release=2011-149
[4] http://www.spacetelescope.org/images/heic0810am/
[5] http://willitblend.com/
[6] http://www.jpl.nasa.gov/news/news.cfm?release=2011-312

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