Massive Gravity

Lecture 8 - November 19th, 2011

Today we will talk about a subject that got its start in 1939, but which has had an explosion of progress in the past 18 months: massive gravity. Massive gravity is the name we have given to the attempt to understand what the gravitational force would be like if the graviton has a mass. General relativity, Einstein's theory of gravity, is special because it is the unique theory of a massless graviton. General relativity is both elegant and highly complex, so it is not a simple thing to figure out if it can be modified to allow the graviton to have a mass!

The idea of massive gravity has a crazy history:

- **Fierz-Pauli action**: Wolfgang Pauli and Markus Fierz were the first to figure out how one might add a mass to a graviton. Their theory was only an approximate theory, but intriguingly the theory they found was unique, like GR.
- **vDVZ discontinuity:** this is the name given to the discovery, by van Dam, Veltman, and Zakharov in 1970 that Fierz-Pauli approximate theory could never agree with observations in the Solar System because of a mismatch between the gravitational force and gravitational lensing.
- **Vainshtein mechanism:** in 1972, Arkady Vainshtein figured out a way around the vDVZ discontinuity by pointing out that theories that improve on the Fierz-Pauli approximation will avoid the discontinuity

Pauli and Fierz, who first considered how to add a mass to gravity in 1939

- **Boulware-Deser ghost:** Also in 1972, Boulware and Deser showed that unless something special happens, any theory that fixes the vDVZ discontinuity will possess a "ghost" instability, which is essentially evidence that the theory is internally inconsistent.
- **DGP braneworld model:** In the early 2000s, people studying the Dvali, Gabadadze, Porrati model discovered that it was very similar to a theory of gravity with a mass. And sure enough, part of the DGP model had a ghost, just as Boulware and Deser would predict. But the surprise was that there was a part of the theory that did not have a ghost, thanks to a special new "galilean" symmetry that was related to the 5th dimension in the theory. This raised the hope that this new symmetry was just the "something special" needed to evade the Boulware/Deser ghost.
- **de Rham and Gabadadze "fix" DGP:** in late 2009, Claudia de Rham and Gregory Gabadadze independently figured out a way of constructing a theory of massive gravity from a 5th dimension that seemed able to avoid ever having a ghost.

- **de Rham, Gabadadze, Tolley model:** by early 2010, de Rham and Gabadadze were working together and had found a way to write a purely 4 dimensional version of massive gravity beyond the Fierz-Pauli approximation that appeared to avoid the Boulware-Deser ghost. They were then joined by Andrew Tolley in making the theory fully general, and showing that improvements to the Fierz-Pauli approximation did not necessarily ever lead to ghosts.
- **Hassan / Rosen proof of no ghosts:** the last piece of the puzzle fell into place just this year (2011), when Rachel Rosen and Fawad Hassan proved that the de Rham, Gabadadze, Tolley model never has ghosts.

This great story will only be really exciting if the theory is true and we can prove that it's true using observations. We're still working on how to test the theory now, but some possibilities include:

- **Extra gravitational force:** the theory predicts that gravity can get stronger between galaxies than it is on Earth. This could be seen by comparing the way galaxies move to predictions coming from General Relativity
- **Different dark energy:** One of the most exciting facts about the massive gravity theories is that they can possibly explain today's accelerated expansion rate without a cosmological constant. If so, it's possible that observations will be able to detect the difference between a normal cosmological constant theory and a massive gravity theory
- **Altered gravitational lensing:** In 2011, I wrote a paper that pointed out that massive gravity theories cause a subtle change in the way that gravity bends light as compared with GR. This might be detectable by future observatories, and is the only prediction of massive gravity so far that can't be imitated by other theories.

Gregory Gabadadze, Claudia de Rham, and Andrew Tolley, who discovered the ghost-free version of massive gravity in 2010. Their theory was proven to be ghost-free by S. F Hassan and Rachel Rosen in 2011.