DJORGOVSKI: So finally let's turn to the formation of structures. How does all this happen? And this kind of encapsulates what we need to explain. When we look at cosmic microwave background we are looking at the universe that was 380,000 years old. And the density fluctuations of that time were a part in a million, less in smaller scales. Somehow today you have large-scale structure with contrast of on the order of 100. Typically large-scale structure stuff you see it's about 100 times denser than mean. And within galaxies themselves the mean density of inside galaxy is a million times higher than the mean density of the universe. So somehow we have to go from 10 to the minus 6 to 10 to the plus 6 in given number of billions of years.

So we think that all of these started through some quantum fluctuations in the very early universe particles, and Poisson distribution anywhere. And then the universe goes through a period of extremely rapid large expansion, that's called inflationary era, for which now there may be actual observational evidence. And so what used to be microscopic quantum fluctuations in energy density, just due to the pair production and annihilation, is now inflated to the scales of clusters of galaxies.

So that's where the fluctuations come from. And then the question is how are they going to evolve. And at first they evolve just due to the subgravity. Denser spots will create more material absorb smaller pieces. And this is what people who model structure formation do. You start with slightly non-uniform density field early on. You just let it go, simple Newtonian gravity nothing else, and it makes structures just like those that we see. So as far as gravitational formation of structure goes we got that.

Now turning gas into the stars is a different business all together. So the first question to ask is how long does it take for it to do that. And the concept here is free-fall time. If you have a density blob and you have test particle and such, the blob's going to collapse under its own gravity. And the outermost shells are always outermost shells. And so how long does it take for this particle to fall to the middle? And that's called a free-fall time and is given by the simple formula. So for galaxies, typically like Milky Way, that's kind of few hundred million years, which is comparable to their internal rotation periods and so on.

For a cluster that's more like several billions of years. So that tells you that galaxies have formed early on and clusters are still forming today. And that's exactly what the simulations are telling us. And we see continuum from very slight density fluctuations on large-scales to very dense clusters. So clusters of galaxies are still forming. Galaxies are more or less done.

And so the simulations then you can follow this in great detail, whether or not they have [? dissipation. ?] But also remember there are all these filamentary structures. There is a sponge-like typology in large-scales. Where did that come from? Now that's actually fairly easy to understand.

So consider a blob in the early universe that's over-dense. It's not going to be spherically symmetric, except by extreme random chance. Generally speaking it would be better described as a triaxial ellipsoid. There will be different flattening in each of the three orthogonal axis. So first this thing is expanding with the expanding universe. Then because it's got high enough cell gravity it turns around, it will first turn around on the shortest axis because that's the smallest r in [? m1 m2 ?] over r squared. And so it will start falling down upon itself along the short axis first while still expanding in the other two.

So from slightly flattened quasi-spherical blob you get into the pancake, something that will look like a sheet. Now the intermediate axis turns around and starts collapsing. And so your pancake turns into a cigar, something like a filament. And eventually the third axis collapses and you get quasi-spherical blob, which would be like a cluster of galaxies. So the origin of the typology is easy to understand. It's due to the expansion of the universe. And that initial fluctuations are not spherically symmetric. And so we can see that and both observe it in the sky and model it. But we still don't have a good way of describing it with numbers.

Now it turns out the dark matter plays a crucial role in the way the fluctuations evolve. And different kinds of dark matter will work differently. So, generally speaking, the smaller fluctuations will get erased. And they can get erased by different mechanisms particles flowing from one spot to another and so on. How much depends on the kind of particles. If particles are very low mass and move at near relativistic speeds then the density fluctuations can get very easily erased out to the scales that correspond to the speed of light times the time given to them.

If on the other hand dark matter is composed of heavy particles they don't move very fast, they cannot travel very far, so they only erase the smaller fluctuations not the big ones. In any case, it always eliminate smaller ones. The question is just how much and how efficient it is. And so we distinguish between simple hot dark matter, which is composed of very light particle, say like neutrinos, and the cold dark matter composed of some [? metal ?] particles like WIMPs. And the hot dark matter is much more efficient in erasing small scale fluctuations because they're streaming at relativistic speeds. And cold dark matter does the same thing, but kind of slowly.

Now this is why there is a bend in the power spectrum that they're showing you. This is why there is a turnover at high special frequencies, which means small masses. And the shape of this is directly related to the type of the dark matter that's out there. And it turns out that cold dark matter wins. Hot dark matter would completely erase structures and scales of galaxies. All we would see would be gigantic blobs of stuff. That's not what's observed.

So in cold dark matter scenario, or CDM that's what everybody calls it, you start making small things first. You keep merging them together, building up even larger and larger structures. And that's called hierarchical structure formation. You start from smaller go to bigger. And this keeps going on and on, you just move to an even larger scales. And all observations that we have pretty much follows by now.

Well that's all about gravity. Now what about dissipation? If you just look at gravity, look at those blobs in the earlier universe, they are over-dense, they turn around, fall upon themselves. But while they're doing that the universe keeps expanding. And so if the universe wasn't expanding they start with kinetic energy exactly equal to the potential energy. And then they end up with virilized state where it's one half. And because potential energy is inversely proportional to radius it means they had to shrink by a factor of two. And density would increase by two cubed, so eight, roughly a factor of 10.

So if it was just gravitational collapse in stationary universe we would have large-scale over-densities as a factor of 10. But because the background's been expanding by the time this is over the density contrast ratio is more like 200. And lo and behold that's exactly what we see. Remember I told you the over-density of large-scale structures is roughly a factor of 100 relative to the mean. It's more in dense clusters. It's a little less in filaments. But that's about it. So this tells you gravity is all you need to explain large-scale structure.

What about galaxies? They are a million times denser than the background, not a hundred times. So that means they had to dissipate extra energy in order to be able to shrink to small sizes to get this extra few orders of magnitude of density. So galaxies had to collapse by at least another factor of 10, maybe a little more, in order to achieve these densities. The only way they can do this is to get rid of this binding energy so that they have to radiate it away. And that process is called cooling. You can think of say electrons Compton scattering, of photons of micro background, or shock waves and collapsing galaxies releasing emission lines and so on. There are any number of processes can be used to accomplish this.

So dissipation is what makes galaxies distinct from large-scale structures. That's why galaxies are not just blobs of dark matter with baryons mixed in. But light is concentrated inside the dark halos. And nowadays people do numerical simulations of this that incorporate feedback from stars, dissipation, the whole kit and caboodle, and those simulations work a little better than just pure gravity ones. But this is a messy process. Because all these dissipative processes are essentially atomic scale, atomic physics. And we're modeling things on scales of megaparsecs and so on. So in these simulations even the best and the biggest ones, one particle that are following up, may be a million solar masses. That's some particle, right. So it's a lot bigger than a proton. And so there is a lot of approximations going on in how that's modeled. But by and large the basic physics I think we understand. It's just fairly messy process altogether.