The Universe in my pocket

The birth and life of galaxies

No. 23

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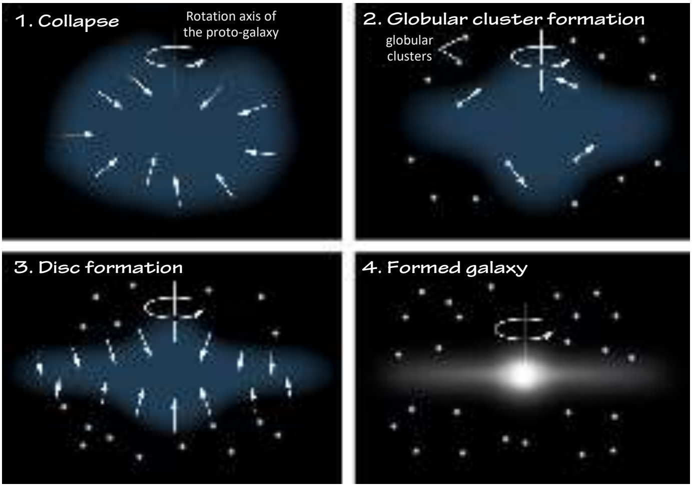
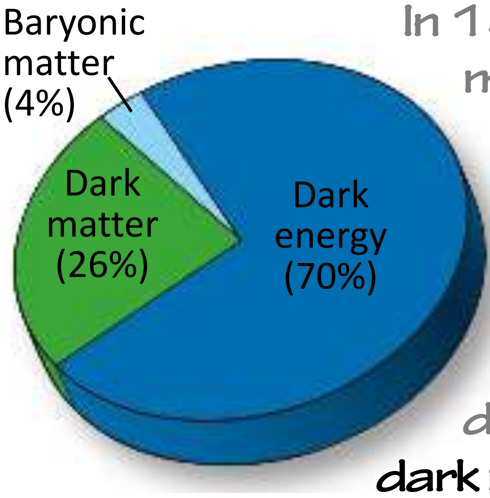


In the model proposed by Olin Eggen, Donald Lynden-Bell and Allan Sandage in 1962, galaxies formed from the **collapse of a giant gas cloud** around 10 billion years ago. The arrows in the figure indicate the direction of the gas movement. Today, we know that the galaxy formation process also is much more complex than suggested by this model.



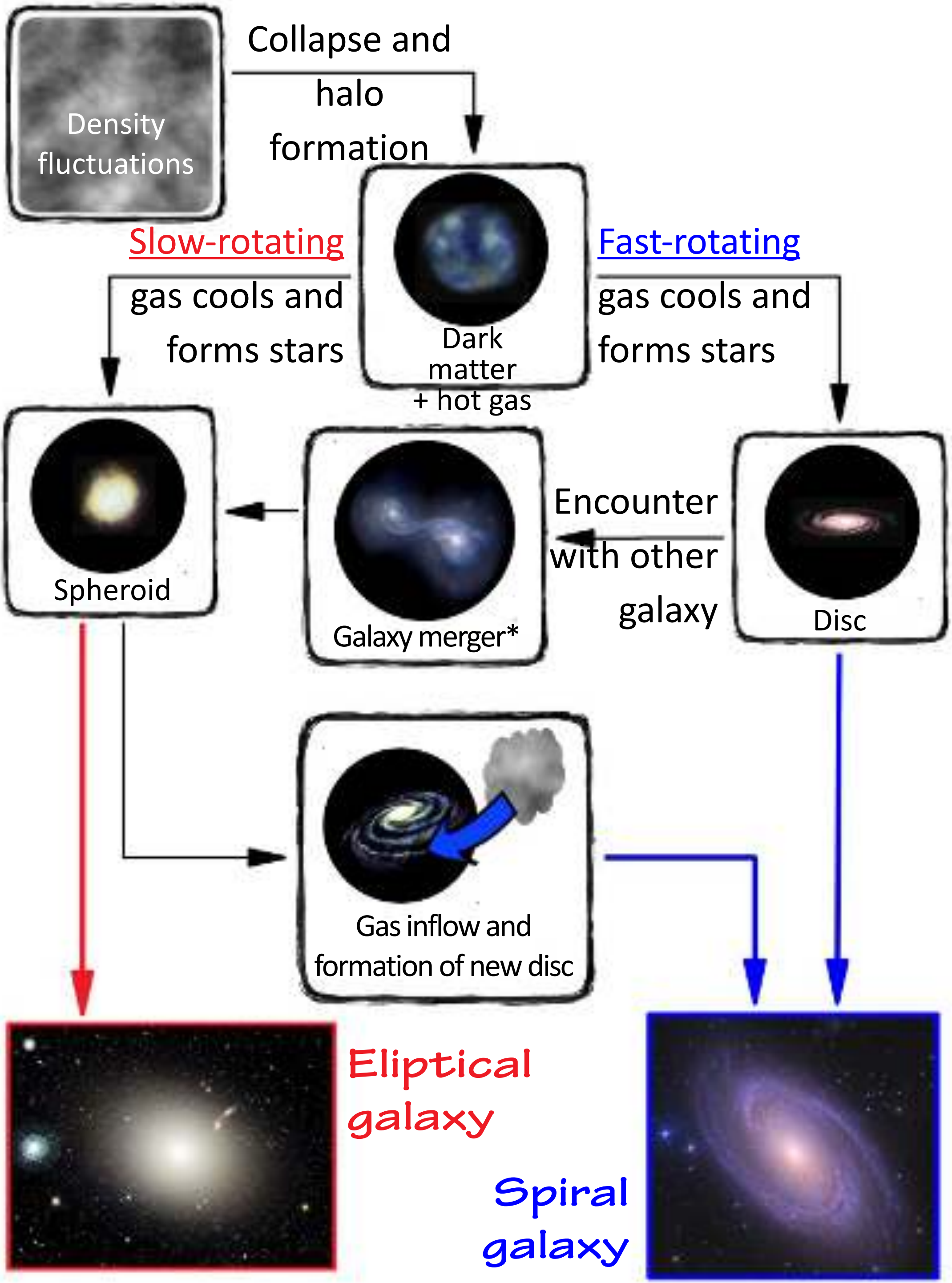
In 1933, Fritz Zwicky measured the velocities of galaxies in a massive cluster, and the high scatter in the velocities led him to deduce that the cluster mass is dominated by invisible **dark matter**. In 1998, two teams of researchers discovered that the Universe is expanding at an accelerated pace. Since we do not know the nature of the energy that causes this acceleration, we named it **dark energy**.

An Universe of galaxies

In 1924, Edwin Hubble showed that observed spiral nebulae were, in fact, other galaxies similar to our Milky Way*. About 30 years passed before the first models to explain the formation of these objects appeared. Therefore, our knowledge on this subject is very recent.

The current theory for the formation and evolution of galaxies is built in the cosmological framework of Lambda Cold Dark Matter. In this context, the Universe contains three main components: about 26% is cold dark matter, 70% is dark energy, and only 4% is normal matter we know (referred to as baryonic matter). The proportion between these components determines how structures in the Universe form and evolve. However, until now, we do not know what these dark components are.

* See TUIMP 3



Density fluctuations

Collapse and halo formation

Dark matter + hot gas

Slow-rotating gas cools and forms stars

Fast-rotating gas cools and forms stars

Spheroid

Galaxy merger*

Encounter with other galaxy

Disc

Gas inflow and formation of new disc

Eliptical galaxy

Spiral galaxy

*most common and violent way to destroy galaxy disks and turn them into spheroids.

From tiny density fluctuations

Any theory of galaxy formation and evolution has the difficult task of explaining what, when and how several physical processes occur to form all different types of galaxies that we observe today. We know that the Hubble* sequence is not an evolutionary sequence. The diagram on the opposite page illustrates the pathways that can lead to the formation of elliptical and spiral galaxies. It all starts with tiny density fluctuations in the very, very young Universe. As the Universe expands**, the amplitude of these fluctuations gets larger and larger. Finally, gravity wins and the dark matter halo collapses. Hot gas is attracted to these halos and cools, forming stars. Whether the outcome is an elliptical or a spiral galaxy will depend on how much rotation and gas the halo has and whether or not mergers with other galaxies occur.

* See TUIMP 3

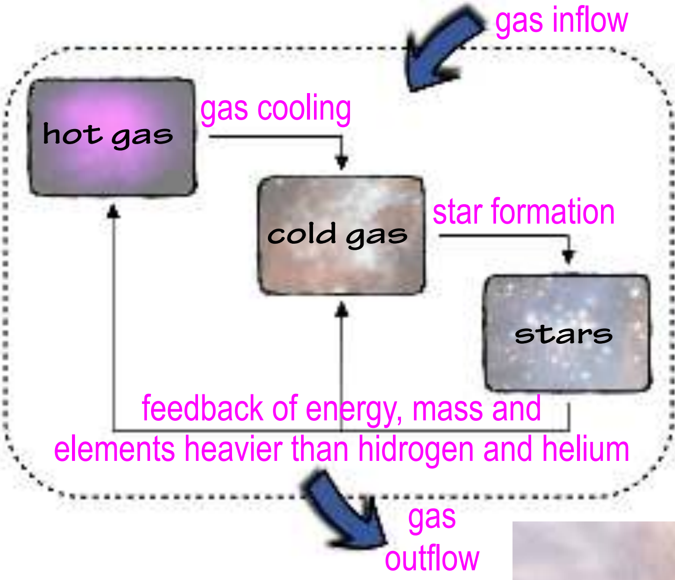
** See TUIMP 12

Credits: ESO/L. Calçada

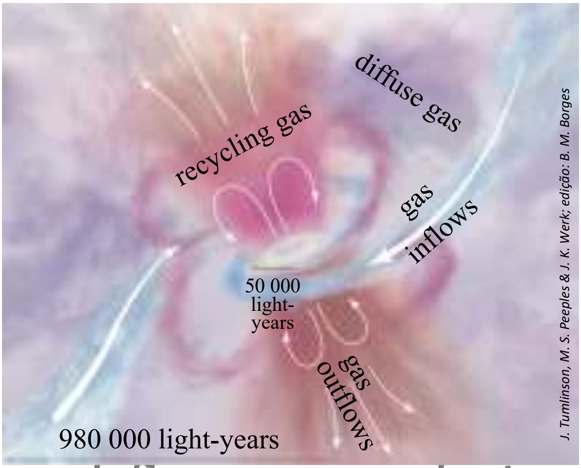
In the hierarchical model of galaxy formation, smaller galaxies form first and merge to form larger and larger galaxies. The **merger tree** shown in the figure above illustrates this process. Models indicate that the larger the galaxy, the greater the fraction of stars acquired through mergers with smaller systems.

The hierarquical Universe

In the cosmological model that describes our Universe, initial density fluctuations have larger amplitudes on smaller scales. It means that smaller dark matter halos form first and merge, forming larger and larger halos. The formation history of a dark matter halo can be described by a merger tree. Because smaller galaxies are in smaller dark matter halos, galaxy formation occurs in a hierarchically. However, observations show that smaller galaxies formed their stars at later times compared to massive galaxies. This ‘downsizing’ effect occurs because massive galaxies reached a critical total mass earlier, which prevented further star formation. On the other hand, small galaxies can form stars for a longer period, leading to extended star formation histories and younger stellar populations.

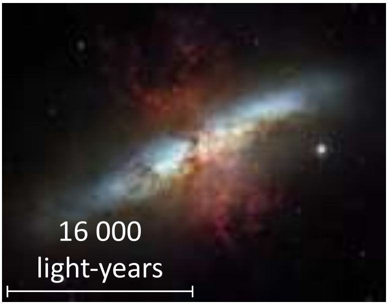


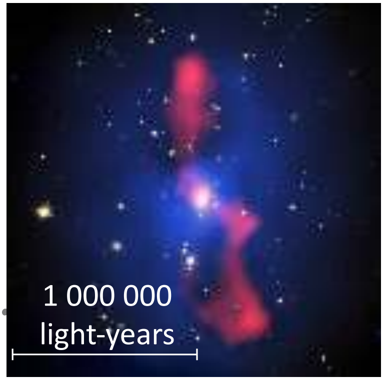
Left: Diagram illustrating the **cycle of gas and star formation** in a galaxy. As long as the galaxy has cold gas, stars can be formed.



J. Tumlinson, M. S. Peeples & J. K. Werk; edição: B. M. Borges

Right: Galaxies can acquire gas from their surroundings, as the figure illustrates. However, **feedback mechanisms** can heat the gas around the galaxy, preventing the gas inflow, or even eject its internal gas. **Below:** these mechanisms in action: supernova explosions causing gas outflows (left); and the energy released by the AGN* ejecting and heating the gas around the galaxy (right).



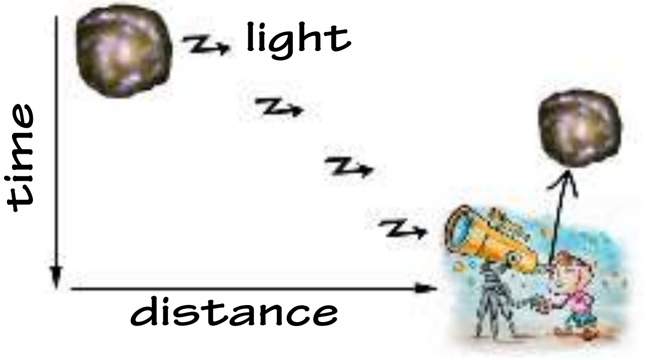


* See TUIMP 6

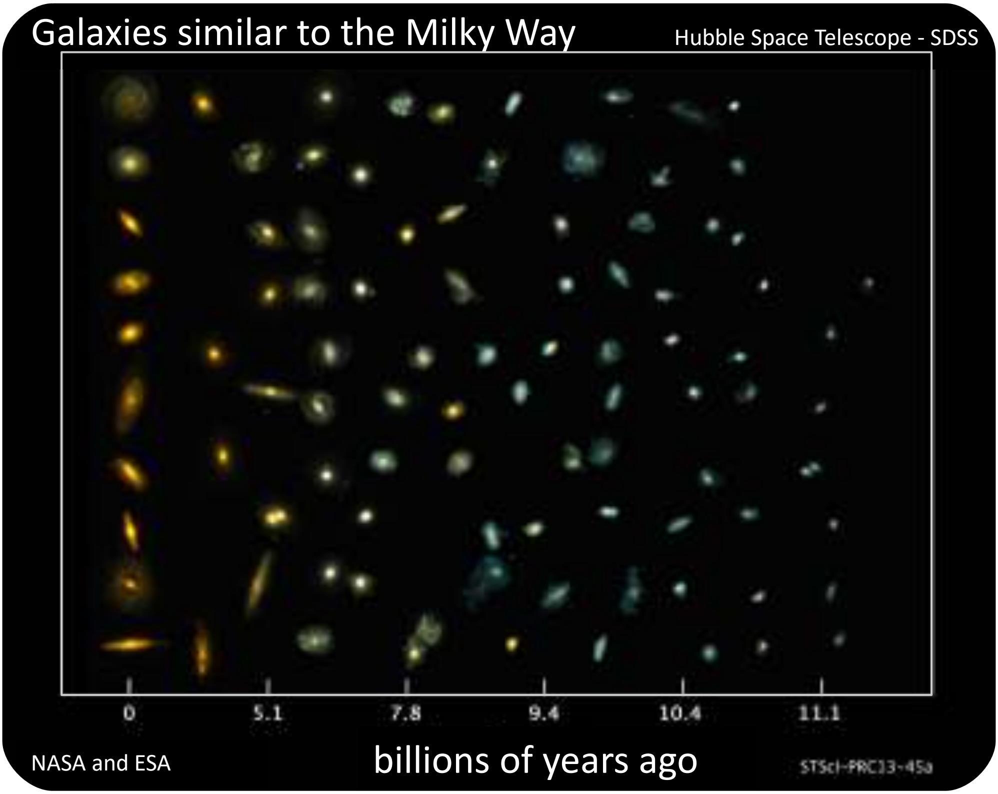
Converting gas into stars

As long as the galaxy has gas and the gas is able to cool, stars can form. However, supernova explosions release energy that can heat and eject gas from a galaxy. If the galaxy is small, gravity is too weak to prevent the gas from escaping, and this supernova feedback process will suppress star formation. In larger galaxies, the active galactic nuclei* (AGN) feedback has a greater impact on its star formation cycle. In an AGN, the galaxy central supermassive black hole, millions to billions times more massive than the Sun, is engulfing matter and releasing a huge amount of energy that heats the surrounding gas. Studies show that the properties of galaxies depend on the mass of their central black hole, indicating that feedback from these monsters plays a fundamental role in the evolution of galaxies.

* See TUIMP 6



On the right: Light has a finite velocity. Thus, the further away the galaxy is, the longer it takes for the light emitted by it to reach us - that is, the more in the past we see it. **Figure below:** observations of very distant galaxies showing what they were like a long time ago.



Galaxies similar to the Milky Way

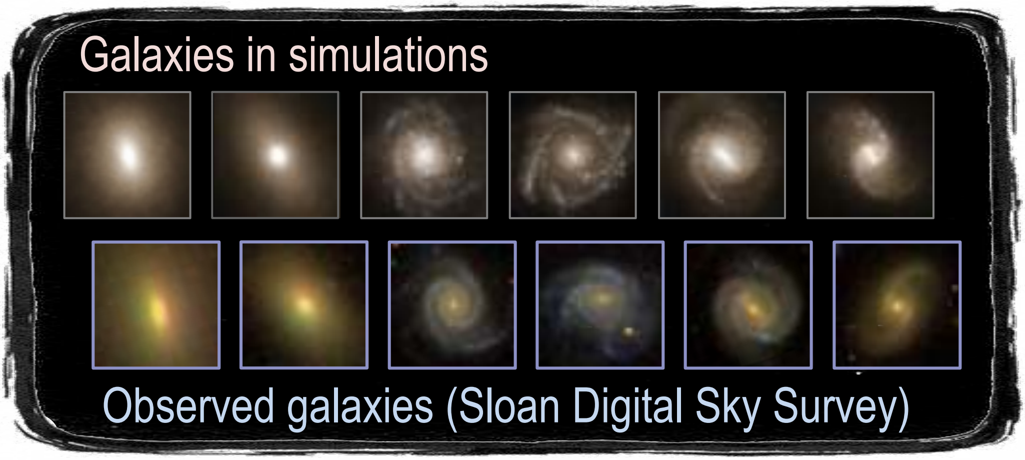
Hubble Space Telescope - SDSS

NASA and ESA

STScI-PRC13-45a

Observing the past

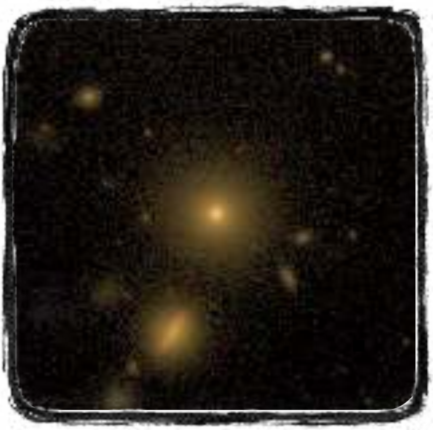
Light travels at a speed of 300,000 kilometres per second, which is high, but a finite value. The consequence is that deep observations of the sky open us a window to the past. With space telescopes, we can observe galaxies so far away that the light emitted by them travelled through space for about 13 billion years before reaching us. We, therefore, see these galaxies as they were 13 billion years ago! In the past, they were more irregular, had more gas, and formed stars at a much higher rate than galaxies today. The Hubble Space telescope brought out amazingly sharp pictures of galaxies, allowing us to discover many aspects of early galaxy evolution. The forthcoming James Webb space telescope will be able to obtain such fine pictures of galaxies at much greater distances, allowing us to observe the first galaxies!



Comparison between real observations and images of galaxies created from simulations run on supercomputers of the Illustris-TNG project. **Figure above:** different morphological types. **Figure below:** evolution of a simulated galaxy compared with observed galaxies of similar ages.

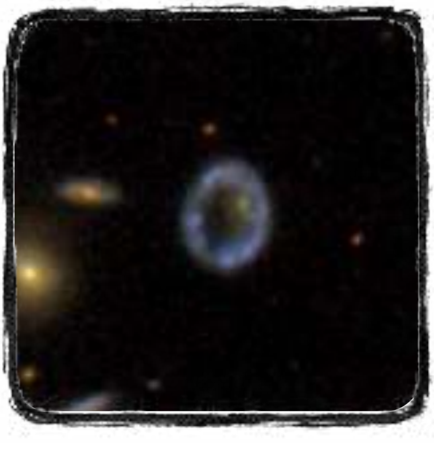
Creating galaxies

In recent decades, cosmological simulations performed on supercomputers have helped us understand how galaxies formed and evolved. The images on the other page show the results of one of the largest simulations ever made to date. These simulations describe more than 13 billion years of the cosmic evolution of a volume containing tens of thousands of galaxies. They include gas, stars, dark matter, dark energy, and several physical processes such as stellar evolution, chemical enrichment, and feedback mechanisms. Despite the immense complexity, we can see that the simulations reproduce incredibly well the properties of real galaxies! These simulations are so complex that, if it were possible to run them on an ordinary computer, they would take hundreds to thousands of years to be completed!



Quiz

Can you identify which of these images were created from simulations and which are real observations?



Answers on overleaf

Answers

The simulated images are from the Illustris project; the observations are from the Sloan Digital Sky Survey. It's hard to tell one from another, isn't it?

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This booklet was written in 2021 by Marina Trevisan from Universidade Federal do Rio Grande do Sul (UFRGS, Brazil) and revised by Allan Schnorr Müller (UFRGS, Brasil) and by Gary Mamon (Institut d'Astrophysique de Paris, France).

Cover image: spiral galaxy today, 4 billion and 11 billion years ago.
Credit: NASA, ESA.

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