Exploring virtual universes

The real universe is too big to explore with rocket ships— it would take 500,000 years just to get to the edge of our own galaxy at the speed of New Horizons, the probe we sent to Pluto (and the fastest man-made object)! We also can't just watch galaxies evolve because it takes so long for them to change— it takes almost 200 million years for the Milky Way to rotate once!

Instead, astronomers must create mathematical models of galaxies. These models are often so complex that they can't be solved by hand! As a result, they employ supercomputers to approximate the solutions with simulations. This technique has proven remarkably effective at answering many important questions about galaxies.

The importance of feedback

Feedback is important— and not just the kind from your boss. In galaxies, feedback can determine the size, shape, and color of a galaxy as well. But here, feedback means *the energy given back to the environment.* This energy can come from stars (in the form of supernovae, stellar winds, or pressure exerted by light) or when a supermassive black hole consumes matter (sometimes called an active galactic nucleus, or AGN).

If astronomers don't include feedback in their models, the resulting galaxies have great difficulty matching the ones seen in the real universe. Recent simulations that include realistic feedback models successfully produce realistic galaxies that astronomers can use to make predictions for the real universe. Take a look at the cover of this pamphlet to see for yourself!

What's going on at Northwestern?

The FIRE simulation project

At Northwestern, Claude-André Faucher-Giguère leads the galaxy formation group and uses the FIRE simulations to simulate how galaxies form and evolve over time. The galaxy formation group is engaged in a number of projects focused on

- Star formation — how feedback regulates the rate new stars are formed
- Supermassive black holes — how they grow and provide feedback by accreting gas
- Galactic environments — how galaxies are fed by and interact with the material around them

Learn more…

There are many great resources that one could use to learn more about galaxies, galaxy formation, and computer simulations.

- **FIRE simulation project website**
  fire.northwestern.edu
- **Ned Wright's cosmology tutorial**
  http://www.astro.ucla.edu/~wright/cosmo_01.htm
- **Gene Smith's astronomy tutorial**
  https://casswww.ucsd.edu/archive/public/tutorial/Galaxies.html
- **The Cosmic Web: Mysterious Architecture of the Universe**
  by J. Richard Gott
- **PBS library of videos and activities**
  https://illinois.pbslearningmedia.org/subjects/science/earth-and-space-science/the-universe-and-its-stars/galaxies/

Galaxy Formation and Evolution

A CIERA series pamphlet

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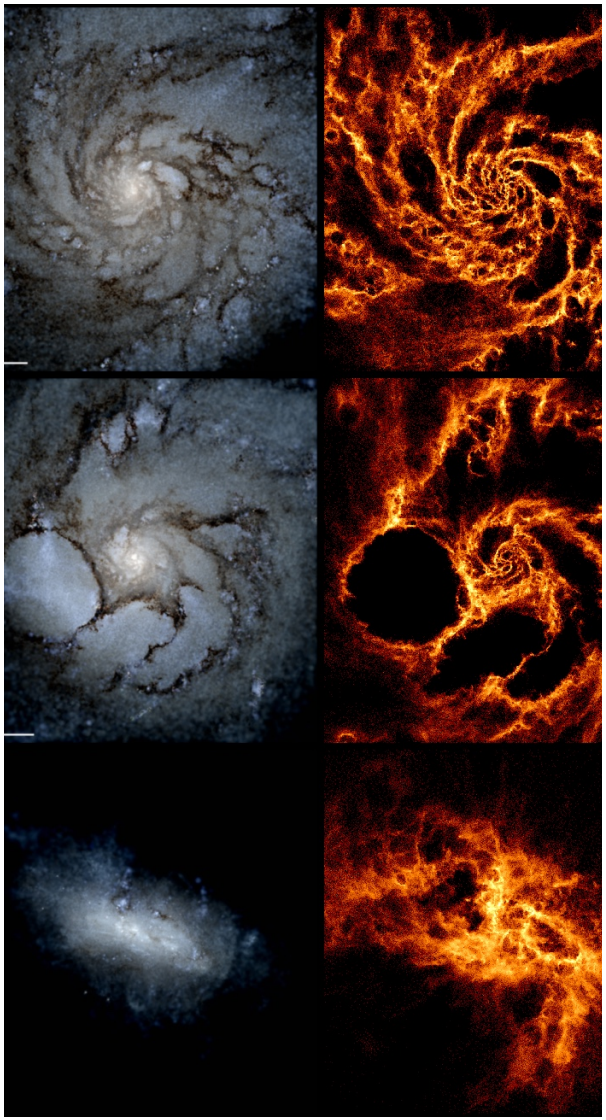
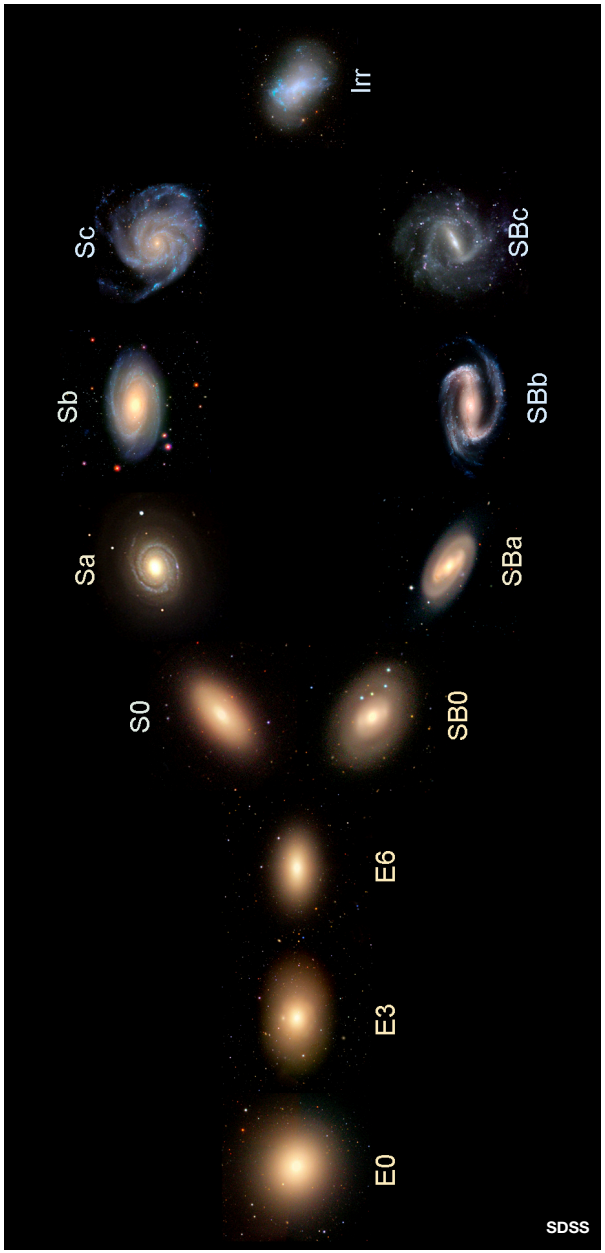
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS



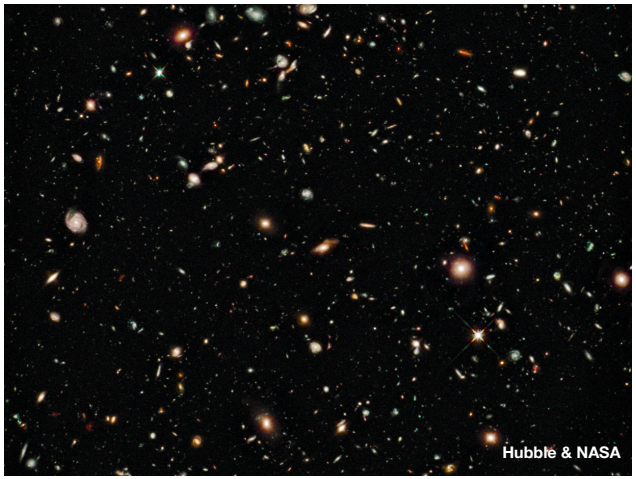
A universe full of galaxies with many different sizes, shapes, and colors.



A sky full of stars (and galaxies)

When Edwin Hubble first observed the night sky at the beginning of the 20th century he was intrigued by the "spiral nebulae" he couldn't explain. After studying them in more detail, he eventually showed that these "nebulae" were not only much further away than anyone had previously thought, but that they were actually galaxies just like our own!

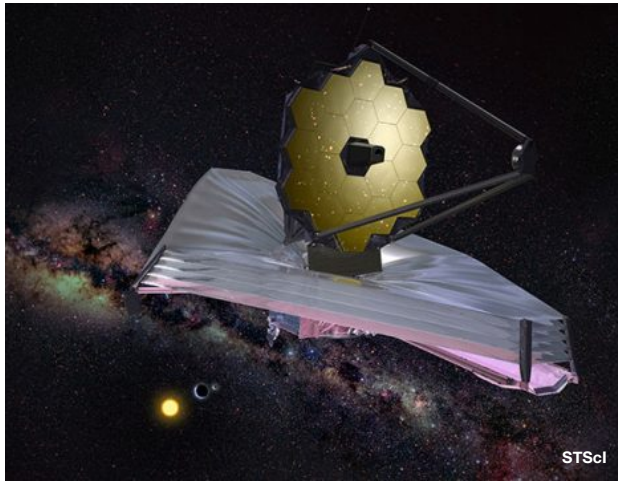
He classified these galaxies according to their shape in order of increasing spirality. When he first proposed this classification scheme some interpreted it as a chronological sequence. Astronomers no longer believe that galaxies progress through the classifications chronologically but the organization of the "**Hubble Tuning Fork**" (see left diagram) is still useful to categorize the many types of galaxies that we observe.



The impact of Hubble

The universe in the Hubble eXtreme Deep Field

To produce the eXtreme Deep Field (XDF) image above the Hubble Space Telescope (HST) stared at a seemingly empty patch of sky 1/10th the diameter a full moon and revealed the image above. In it, (almost) every object is a galaxy— there are over 8000 of them, some over 10 billion light-years away! Extrapolating this view to the rest of the sky predicts that there are over *100 billion* galaxies in the universe. HST is able to study the closest ones in exquisite detail, making many of the beautiful close-up images you may have seen.



Next generation with JWST

Exploring the universe in the near-infrared

The future of extragalactic astronomy is bright (but it's also dim)! To look deeper into the past, astronomers need more sensitive instruments that can see fainter galaxies. Enter the James Webb Space Telescope (JWST), NASA's next generation HST. JWST will observe in the near-infrared and with higher resolution than HST. It has a 8x larger mirror than HST (which is made up of gold hexagons that will unfold into their final positions) and it is slated to launch in 2021.