Gravity controls the Geometry of Spacetime, this is the foundation of Cosmology.

- Since gravity curves Spacetime, if it is strong enough, the rules of Euclidean geometry do not apply.
- Parallel lines eventually meet.
- Sum of angles of large triangles exceeds 180.
- Overall gravity of all the matter in the Universe can cause curvature, Einstein realized.
- Another non-Euclidean geometry is possible.

All I know is no one who goes in there ever comes out.
“Milky Way”
Band of starlight not aligned with our Equator, nor our Solar System was revealed by Galileo’s telescope to be a GALAXY of billions of Suns. That mind-boggling increase in human perspective was only the start...!
Things to know about galaxies

1. They are HUGE and numerous “Island Universes”

2. They are vast gas re-cycling machines to make stars (which are not made anywhere else)

3. They are mostly DARK MATTER

...4. They make giant black holes in their centers [next lecture...]
But a serious problem is evident: Blue light cannot travel through the disk of our Galaxy.

→ Only at long wavelengths--Infrared and Radio can we see all the way across our own Milky Way galaxy.

Closer view of the plane of the Milky Way towards Sagitarius, Which systematically absorbs the blue light, But Passes the redder light.

This infrared picture (tilted to horizontal) gives much better view of Our Milky Way galaxy than any visible photograph.
Interstellar matter has lots of dust grains, which absorb visible light.
close-up view of the Interstellar dust absorption in the "Horsehead Nebula"
Hubble Close-up of dense regions of interstellar dust and gas
Dusty gas clouds obscure our view because they absorb visible light. This is the interstellar medium that makes new star systems. Visible versus Infrared views of our Milky Way. Younger stars and interstellar matter are in a very flat disk.
From earth, we see our galaxy edge-on, making full circle around the sky\textsuperscript{\(\rightarrow\)}
So we are not at the edge of the Milky Way.
But we are also NOT at the center:

\textbf{Globular star clusters} all centered around direction of Sagitarius\textsuperscript{\(\rightarrow\)}
that must be the direction towards the center of our Milky Way

\textbf{Primary features: disk (youngest), bulge, halo/globular star clusters (oldest)}
If we could view the Milky Way from above the disk, we would see its spiral arms.
How did our Milky Way spiral galaxy form?

It has a flat disk of gas and dust for the same reason as in the formation of our Solar System: spin (angular momentum) is conserved during gravitational collapse.

Our galaxy probably formed from a giant gas cloud when it got dense enough to collapse.

Halo stars formed first as gravity caused cloud to contract. Now they're very old.

Remaining gas settled into a flat rapidly spinning disk.

Stars continuously form in disk as the galaxy recycles gas.
Birth of a Star

Densest clouds of gas in a galaxy cool off (by radiating visible and IR photons)

When they become cold, gravity wins over gas pressure –

> runaway gravitational collapse Instability:

• Positive Feedback: when gravity contracts a lump of mass, the results is that all pieces become closer together -->

• amplifying the gravitational force causing the contraction -->

• further accelerating the gravitational collapse -->

unstable runaway process, until a new non-gravitational force builds up enough strength to balance the inward gravity
This dense cloud of interstellar gas is collapsing to form new stars

(Astronomy’s prettiest pictures are of stars being born or dying)
Young stars born from interstellar gas in Orion’s sword, usually with a surrounding flat disk of dust and gas.
Energy from the new young stars will disrupt the gas clouds out of which they formed, ending this episode of star formation.
Pleiades: slightly older cluster of young stars, almost clear of interstellar matter. [all the faint white dots are real, but in the background]
Young (massive) stars are hot enough to emit UV photons. Which ionize interstellar gas:
Glowing Hydrogen gas gives characteristic pinkish glow of (Balmer) emission lines

The youngest galaxies are filled with interstellar gas clouds. Like this, forming hundreds of stars per year.
The disks of galaxies have all the interstellar gas (and dust, which absorbs visible light): This is the dense, cold raw material for forming new stars.

Much of star formation happens in spiral arms: The young massive blue stars produce UV photons ionize hydrogen gas and make it glow pink.

These spirals are a density wave pattern:

Whirlpool Galaxy
Gravitational collapse is often ‘triggered’ by an external compression.

Stars tend to be born together in time and space.

They are born with a wide variety of masses.

The biggest ones are always the rarest.

Currently our entire Milky Way galaxy forms about 1 new star per year, mostly in its gas-rich spiral arms.
Skip this pretty picture:'Barred' Spiral Galaxy, shows another common wave pattern
Pulsar Distribution over the Sky

- Pulsars are in our galaxy and come from massive star collapse.
- In contrast to the distribution of Gamma-Ray Bursts, the pulsars are closely related to position within the galaxy: their space distribution shows a clear connection to the Milky Way.
After a large number of GRB’s were found uniformly over entire sky, it became evident that they are not associated with our galaxy. Therefore, they must be (at large distances) outside of Milky Way.
Why doesn’t Sun fall into center of Milky Way?  
Same reason Earth doesn’t fall into Sun!
Sun’s orbital motion (radius and velocity) tells us mass within Sun’s orbit from Kepler’s Third Law

\[ V_{\text{orbit}} = (G M_{\text{in}} / R)^{1/2} \]

\[ \Rightarrow M_{\text{in}} = R^3 / P^2 = 1.0 \times 10^{11} M_{\text{Sun}} \]

Since Sun is an average star, this implies about \( 10^{11} \) stars inside our Milky Way orbit (far more than all the grains of sand on Earth!)
“Rotation curve” of our solar system is very simple: Orbital velocities decrease with distance from Sun.

Kepler/Newton:
Orbital period decreases, because most of the mass is contained in the sun.

\[ V_{\text{orbit}} = \left(\frac{GM_{\text{in}}}{R}\right)^{1/2} \]
Where \( M_{\text{in}} = M_{\text{Sun}} \)
The (totally typical) rotation curve for our Milky Way Galaxy

The Sun’s orbit encompasses about 100 billion solar masses; A circle twice as large => surrounds twice as much mass A 4 times larger circle surrounds 4 times more mass

Most of our galaxy’s mass lies well beyond our Sun, tens of thousands of light-years from the galactic center.

Most of the mass is located in the spherical halo; the total amount of the mass is \(~ 10x\) the total mass of all the stars in the disk. --> this mass emits very little radiation if any --> **90% of total mass is “dark matter”**
Rotation Curves of other spiral galaxies (are actually easier to measure than our Milky Way):

Measure the Doppler shifts:

Only issue is how much is galactic disk tilted with respect to the line-of-sight to Earth? We guess that by assuming these galaxies look ROUND when viewed perfectly face-on.
Spiral galaxies **ALWAYS** have flat rotation curves, as far out as it is possible to measure them (completely different from our Solar System!)

The “visible” part of our galaxy extends only out to ~50,000 light years, BUT constant orbital velocity means:

\[ M_{\text{in}} = \text{Constant} \times R \]
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

→ The visible matter (Stars) is only the central “tip of the iceberg”, with the great majority of the mass being in the much larger dark matter) halo.

→ So 90% of gravitational mass in rotating spiral galaxies is “Dark”. We find same result in non-rotating (“elliptical”) galaxies, where random velocities of stars are “too high”.

Before speculating on nature of this dark matter, let’s examine more data on it, where we measure gravity on larger scales...
We’ve seen that the spatial distribution of stars is highly non-random: they are ALL clustered together inside galaxies.

Are galaxies distributed randomly in the Universe, or do they also show some clustering patterns?
Dusty gas clouds obscure our view because they absorb visible light. This is the interstellar medium that makes new star systems. Large and Small "Clouds Of Magellan" are companion Dwarf galaxies orbiting our Milky Way.
Irregular Galaxy (Large Magellanic “Cloud”)  Faint Cepheid Variable Stars proved that this Cloud is outside our own Galaxy—a separate “Island Universe”!
Spiral galaxies are often found in groups of galaxies (up to a few dozen galaxies, like our “Local Group”, with Andromeda).

We’re on the edge of the (typical) “Virgo cluster”, with a thousand members.
Big Elliptical galaxies are much more common in huge clusters of galaxies (they are merger products of “galactic cannibalism”)

(hundreds to thousands of galaxies: almost every “dot” in this picture is a galaxy)
How much dark matter in clusters of galaxies?
Orbits of Galaxies in Clusters

Galaxies clumped together --> all should be orbiting around their common center-of-mass (like stars in star clusters).

Observe galaxy motions in a cluster and find out how much mass there is in a cluster (by applying Newton's laws of motion and gravitation).

Compare this mass estimated from the galaxy's orbital motions with how much light there is in a cluster.

--> a lot of mass "missing" in clusters of galaxies (it is about 95% of all the mass!)
Clusters contain large amounts of X-ray emitting hot (millions of degrees) gas.

Temperature of hot gas (particle motions) tells us cluster mass, since gravity = gas pressure:

85% dark matter
10% hot gas
5% stars
Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster’s mass; more mass --> more “bending”
Einstein worked out possibility of gravitational lensing for his astronomer friend Mandl: “It is of little value, but it makes the poor guy happy… There is no great chance of observing this phenomenon.” [in grad school, MM agreed… until his first night on the 200-inch…]
All three methods indicate similar amounts of dark matter.
What have we learned?

• Describe three independent ways to measure the total mass of a cluster of galaxies.
  • (1) We can use the orbital speeds and positions of the galaxies to estimate the cluster’s mass. (2) We can estimate the cluster’s mass from the temperature and distribution of its hot, intra-cluster medium, which we can measure with X-ray observations. (3) We can measure a cluster’s mass, and sometimes the distribution of its mass, by observing how it affects the appearance of more distant galaxies distorted by the gravitational lensing of the cluster.

• What have we learned about dark matter in galaxy clusters?
  • All three methods of measuring cluster masses agree and imply large amounts of dark matter in clusters.
Why is it called “dark matter”?

How dark is it?

10 to 100 times darker than solar-type stars

In itself, this allows many possibilities ...

(such as Astro 4 students? but they would have been detected by their infrared radiation)
What is the (Dark) Matter?
Two Basic Options

• Ordinary Dark Matter (MACHOS)
  - Massive Compact Halo Objects:
    dead or failed stars in halos of galaxies (brown dwarfs, black holes ...), or you

• Extraordinary Dark Matter (WIMPS)
  - Weakly Interacting Massive Particles:
    mysterious neutrino-like particles
MACHOs occasionally make other stars appear brighter through lensing... but not enough lensing events to explain dark matter.

These lensing events very rare: one star in a million each year.

Some dim star-like objects (MACHOS) are indeed found in our galaxy’s halo, but not in large enough numbers to account for most of the Milky Way’s dark matter.