The Dark Side of the Universe

Are Dark Matter and Dark Energy “real” or Einstein gravity breaks down at astrophysical scales?

PART I: Dark Matter vs. New Gravity

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Understanding the Universe and its laws

Matter
Standard Model Particle Physics

Space and Time
General Relativity

Cosmologists cannot explain nor understand the observations!
Non-Standard (Dark) matter crucial to explain observations at many different scales!
All Observations indicate we need the same amount of Non-Standard (Dark) Matter!
Dark Stuff dominates the Universe: 95% !!

Not something you would sweep under the carpet…
New exotic particles were proposed as dark matter, but have never been observed (after decades searching)!

All the previous conclusions were assuming General Relativity as the theory of gravity

We infer Dark Matter and Dark Energy from the behaviour of ordinary matter in a gravitational field

So... Is it possible that there is no dark stuff, but Einstein’s General Relativity does not work at large scales?
1830s astronomers noticed Uranus did not follow the expected Kepler orbit. Could Newton’s law of gravity be wrong?!
Le Verrier and Adams predicted presence and position of Neptune from Uranus’s anomalous orbit. Neptune was found in 1846 exactly at the predicted position!!

There are no reason to expect all planets except Uranus to obey Newton’s gravity.

There must be another planet out there one has not seen yet...

Le Verrier and Adams predicted presence and position of Neptune from Uranus’s anomalous orbit.

Neptune was found in 1846 exactly at the predicted position!!

New (Dark) planet provided the explanation!
Observed Mercury's perihelion precession: 5600.73 arcseconds per century

Calculated Newtonian corrections: 5557.62 arcseconds per century

1855 Le Verrier and others tried to explain it with “dark matter”: new planet Vulcan, new asteroid belt, etc

New Law Gravity (General Relativity) provided the explanation!
Planet velocities in the Solar System

Rotation Curve in Solar System decreases, because most of the mass in the Sun, therefore the force is smaller at larger distances.

\[ F \propto \frac{m_1 m_2}{r^2} \]
Stars rotating in a galaxy (Vera Rubin 50 years ago)

- Stars in galaxy bulge should move fast
- Stars at the galaxy edge should move slower
Evidence for Dark Matter: Stars’ velocity does not decrease!

- Gravitational attraction is not decreasing with distance from galaxy centre
- Mass must increase with distance from galaxy centre!
- This Mass one cannot see is: Dark Matter!
Dark Matter Halo
Dark Matter represents 90% of the total mass, normal matter only contributes with 10%
Galaxy rotation curves: dark matter only explanation?

- Gravitational attraction not decreasing with distance from centre

- 1) Either mass increase with distance from galaxy centre!

- 2) …or the force does not decay as $1/r^2$
Modified Newtonian Dynamics: an alternative to dark matter

• Milgrom(1984) proposed a phenomenological force law: gravity falls off more slowly far away (MOND)

\[
\begin{align*}
F & \propto \frac{1}{r^2}, \quad a > a_0, \\
F & \propto \frac{1}{r}, \quad a < a_0.
\end{align*}
\]

\[a_0 = 10^{-8} \text{cm/s}^2 \sim cH_0\]

Explains galaxy rotation curves very well and many other galactic properties with standard matter only!
Cluster of Galaxies

Galaxies
(10%)

+ Intergalactic gas
(90%)

+ Dark Matter
(90% of total cluster mass)
How do we “see” in cosmology

10% Optical

90%
Gravitational Lensing: probe to “see” dark matter

Mass curves spacetime, and that makes light bend
The larger the mass (large spacetime curvature) the bigger is the image distortion!
Gravitational Lensing can be used to map spacetime curvature (mass concentrations)
Collision of Clusters: galaxies separated from intergalactic gas

90% mass in x-ray gas

10% mass in galaxies
x-ray gas, although 90% of standard matter, does not contribute to spacetime curvature!

Lensing contours: large spacetime curvatures

Strong spacetime curvature (Mass) with galaxies

There is something very massive (and dark!) around the galaxies!

Dark matter exists and cannot be explained by a new gravitational law
Most probably a new undiscovered particle beyond the Standard Model of Particle Physics

It must be very massive and does not interact electromagnetically!

Hopefully we will detect it in the Large Hadron Collider!