Today's colloquium:

Jeff Kimble (Caltech)

The Quantum Optics Circus - Flying Photons, Acrobatic Atoms, and Entangled Ensembles



Physics 311 General Relativity

Lecture 20: Dark matter and dark energy

Today's lecture:

- Einstein's field equation predicts unstable universe. Einstein's solution: "cosmological constant".
- •The "Big Bang" idea.
- The present day view of the universe's expansion.
- Universe's dark side: dark matter and dark energy
- Dark matter candidates and searches for them
- Dark matter and dark energy balance determine the fate of the universe...

Our small universe

- At the time Einstein wrote his General Relativity theory, our universe was small the size of the Milky Way galaxy! "Spiral nebulae" were considered a part of it.
- Einstein's original field equation does not allow the universe to be stable: the pull of gravity will collapse all the mass to one point.

 $R_{\mu\nu} + \frac{1}{2}Rg_{\mu\nu} = 8\pi T_{\mu\nu}$



Cosmological constant: the vacuum energy

• To resolve this problem, Einstein introduced term proportional to a constant Λ , which he called the "*cosmological constant*":

 $\mathbf{G}_{\mu\nu}$ + $\Lambda \mathbf{g}_{\mu\nu}$ = 8 $\pi \mathbf{T}_{\mu\nu}$

• He added the term to keep the Universe from falling apart, to keep it *static* – a proper way, Einstein believed, for a Universe to be. The meaning of the cosmological constant is the density and pressure of empty space, the *vacuum energy*. Numerically, cosmological constant is:

 $\Lambda = (8\pi G/3c^2)\rho$

where ρ is the energy density of vacuum.

Our expanding universe

 In 1922 Alexander Friedmann came up with differential equations describing the expanding universe. The first of the two equations, usually called the Friedmann equation, is

 $H^2 = 8/3\pi\rho - K/a^2$

Here, H is the *Hubble parameter* describing the expansion rate of the universe, ρ is the energy density of the universe, and K/a^2 is the curvature, with a being the "scale factor" – a = 1 is "today".

• A few years later, in 1924, Edwin Hubble discovered (after looking hard at the night sky!) that the Universe is a lot bigger, that the "spiral nebulae" are indeed galaxies, much like our Milky Way, millions of light years away. He also estimated the rate of the *expansion* of the universe and the age of the universe. This led Einstein to abandoning this "cosmological constant" term, calling the cosmological constant his "biggest blunder".



Is Λ really zero?

- Even though the Universe is indeed expanding, the rate of expansion has probably been different and different times.
- For example, there apparently was a period of *inflation* in the early Universe, a very rapid expansion.
- At present, the rate of expansion is apparently *increasing* (this is called the *accelerating Universe*).
- Neither of the two phenomena can be described by a vanishing cosmological constant.
- There also is a lack of matter in the universe. If we add up masses of all galaxies and all the intergalactic dust, we get the universe that is too "thin" and too light...

Present view of the composition of the Universe



Luminous matter: what we can see – galaxies, quasars, stars...

Nonluminous matter: what we cannot see – intergalactic dust, neutrinos...

Dark matter: unknown, very weakly interacting particles.

Dark energy: the energy of the vacuum

Evidence for dark matter

• Galactic rotation curves: stars in galaxies move at the same velocity, regardless of their distance from the galactic center. This implies that either the theory of gravity is (very!) wrong, or there is a lot of stuff in the galaxies we do not see. Galaxy VIRGOHI21 in Virgo Cluster appears to be made of 99.9% dark matter!





Galaxy Cluster Abell 1689 Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STSc) G. Hariig (STScI), G. Illingworth (UCO)Lick Observatory), the ACS Science Team and ESA STScI-PRCO3 Ofa Gravitational lensing: the amount of light bending my massive objects is an independent measurement of the mass. Masses of galaxies and galaxy clusters measured that way are much grater than the estimates from the observed luminous matter in galaxies.

More evidence for dark matter: the Bullet Cluster



Simulation of what happened there



Dark matter candidates: axions and WIMPs

- So, what IS this dark matter? It has to be made of something some particles.
- These particles should very weakly interact with the "ordinary matter", yet have non-zero mass to be attracted by galactic nuclei and other massive objects.
- Two leading candidates today: the "axions" and the "WIMPs" ("Weakly-Interacting Massive Particles").

Axion: an extension to standard model

• Axions were postulated by Peccei and Quinn in 1977 to explain the very small (if any) charge-parity non-conservation in quantum chromodynamics (CQD). The name was coined by Frank Wilczek after a popular brand of detergent, because the particle was supposed to clean up the mess in QCD.

• Searches of axions have yielded no result so far. Axions are predicted to interact with, and even convert to (and back), photons. Thus, axion searches either look for their effects on light polarization (PVLAS experiment) or a direct production of photons from axions.



Dark matter axion searches



LLNL axion detector – moving to UW! (Prof. Leslie Rosenberg) • It is predicted that axions can convert to photons. The energy of resulting photons is proportional to the mass of the original axions.

• Recall that photon energy E = hfthus the frequency of the photons is

 $f = E/h = m_a c^2/h$

• The mass of the axion is predicted to be very small, so the photon frequency is expected to be in only a few hundreds of MHz range (RF).

• To detect these photons, a very large and very cold high-Q RF cavity can be used, together with very sensitive single-photon detectors.

WIMP: the lightest supersymmetric particle

- Supersymmetry is a theory that predicts another form of symmetry in the world of elementary particles: for every boson there is a fermion, and for every fermion a boson.
- These supersymmetric "partner" particles, if they exist, are unstable and all decay into the lightest of them all, the *lightest neutralino*.
- "Light" is not very light the mass is predicted anywhere between 10 and 10000 GeV up to 10000 times the mass of a proton!
- They only interact via weak interaction and gravity, thus detecting them is very difficult.

(Curiously, another, less likely, dark matter candidate is MACHO – Massive Astrophysical Compact Halo Object. Brown dwarfs or small chunks of heavy elements)

Searches for WIMPs

• Searches for WIMPs concentrate on their interaction with atomic nuclei. A WIMP is so heavy, it would deposit a significant amount of energy upon scattering off a nucleus.

• Since the interaction is so weak, the events are expected to be extremely rare, once a day to once a year.

• To reduce the background, the detectors are kept at cryogenic temperatures (as low as 50 mK), and deep underground.





EXPANSION OF THE UNIVERSE



Size of Λ tells us how old the Universe is



courtesy of NASA