Dark Matter

12-1-20

Fact: Galaxy rotation curves can't be predicted by our current theories of gravity with the amount of visible matter and the discrepancy is large with much observational evidence from every corner of the universe (so it can't be ignored).

Possible solutions:

i) Come up with new theories of gravity, but we know that the predictions of current models are *extremely* accurate in the stellar size regime (from GPS to LIGO). Any new theory must account for all observations, and make new ones.

*IN ALL CASES, A COOL NAME IS REQUIRED

ii) Come up with new ideas for where mass that does not produce E&M radiation or the radiation is not detectable might be, and its origin. Your theory must be falsifiable, which means that it ~~mak~~ must make predictions that you can test.

iii) A combination of options above, but better to check one orthogonal direction at a time.

Let's look at the theories first

• Modified Newtonian Dynamics (MoND) Sounds like "monde" which is french for "world"

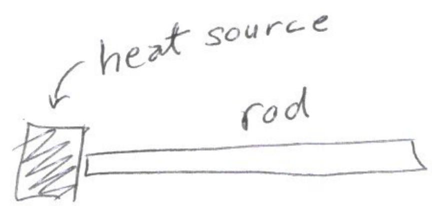
At very ~~low star~~ small F_{grav}, $F_{grav} = \frac{Gm_1m_2}{r}$

instead ~~at~~ of $F_{grav} = \frac{Gm_1m_2}{r^2}$

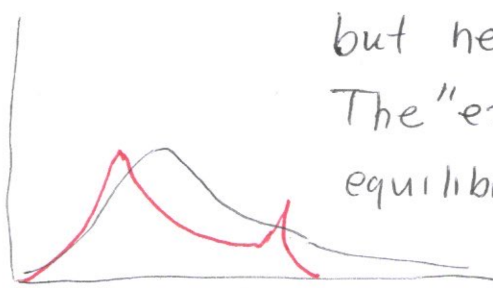
Possible origin: Gravity is an entropic force

Entropic forces are "effective" forces but have no force carriers. Remember that $F = -\nabla U$. What if we consider the free energy? $F = -\nabla U + \nabla TS$ "real" force minimizes energy

$F_{ent} = T\nabla S$ There is an effective force that moves the system in the direction that maximizes entropy

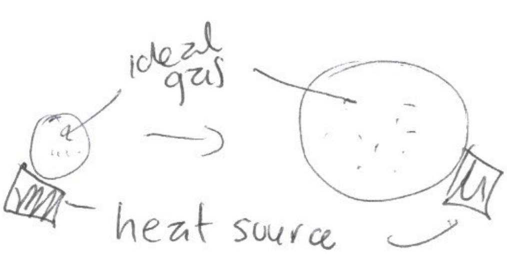


Entropy maximized if velocity distribution is Maxwell-Boltzmann, but heat sources modifies the distribution The "effort" of the system to reach equilibrium results in heat conductivity



~~Fe~~ $U - TS + PV$ Entropic effect

"real" energy



When you heat up a gas the expansion is in part entropy maximization

Ted Jacobson from UMD proved (1995) that you can derive the Einstein field equations by assuming that the entropy of an event horizon is proportional to the area of the event horizon and using $dQ = TdS$, that is, gravity is an entropic force, or closely related.

This is uncontroversial.

Erik Verlinde (Amsterdam) showed in 2009 that at low densities, following a treatment similar to Jacobson's, it is possible to recover the $1/r$ dependence needed to explain the flat rotation curves.

This is controversial, but makes predictions, is good science. Some observational evidence agrees, other disagrees, some theoretical works suggests that some predictions of the theory are non-physical, but currently a good amount of work

Pros: Theory is from first-principles, no fitting parameters
Not ruled out. No need for dark matter (non baryonic)

Cons: Difficult to test in the lab, still needs some dark matter (but can be baryonic) for stellar clusters.
Does not help with galaxy formation dynamics.

Matter, possible nature and forms.

- Baryonic matter
  - Gas
    - Atomic gas It would produce 21-cm radiation and we don't see ~~x~~this. Ruled out.
    - Ionized gas It would produce x-ray radiation and we don't see this. Ruled out.
    - Molecular gas Would need to contain essentially no metals since we could otherwise detect CO emission, and be very cold to avoid H_2 emission. THIS IS POSSIBLE.

      But such gas would absorb UV light, so we could see it against the background, and this has not been achieved. Still, not ruled out.
  - Dust Would radiate in the IR and this is not observed, would absorb visible light and thus could be seen against the background and it is not. It is made of metals and metals are only 2% of baryonic matter. Ruled out.

- Massive Compact Baryonic Halo Objects (MACHOs)

  came before WIMPs

  - Main sequence stars Are not dark. Ruled out.
  - Neutron stars Produce metals when they are formed in supernova explosions and ~~the~~ halos are not metal-rich (see previous point for gas). Ruled out.
  - Black holes In the numbers/mass needed, we would see their gravitational effects on visible members of the halo. Ruled out.
  - White dwarfs Similarly to neutron stars, they would have left (light) metals and this is not observed, but solar wind enriching is not as well understood as supernova enriching. We should be able to see their precursor stars in high red-shifted galaxies and we don't, but difficult to observe such galaxies. Unlikely but not completely ruled-out.
  - Brown dwarfs In the numbers required, $\sim 10^3 - 10^4$ week-long microlensing events would be detected when observing the Large Magellanic Cloud, but they are not. Ruled out.

Overall, the fact that we can account for the observed abundance of chemical elements with Big Bang nucleosynthesis makes baryonic origin of dark matter less likely.

- Non-baryonic matter
  - Electrons: This is equivalent to ionized hydrogen which has been ruled out.
  - Neutrinos: They do have mass, but not enough to account for all dark matter.
  - Primordial black holes: Microlensing observations have constrained their abudance to below what is needed to account for rotational velocity, but only in the case in which distribution is homogeneous. Unlikely but not completely ruled out.
  - Weakly interacting massive particles (WIMPs)

    In order for the haloes to be formed by unknown and undetected particles, the self-annihilation should be smaller than $\langle \sigma v \rangle \simeq 3 \times 10^{-32}\ m^3/s$, this is possible if the mass is $\sim 100\ GeV/c^2$ (the proton mass is $\sim 1\ GeV/c^2$) and the particle interacts only via gravity and the weak force (or its interactions via em or strong force are even smaller). If this is the case WIMP-antiWIMP would have stopped earlier after the Big Bang than for normal matter, so its abundance is greater

The annihilation of WIMPs would produce gamma rays, neutrinos that can be detected and Observations are underway, and it might be possible to create them at, e.g., CERN

If ~~kept~~ conservation of lepton number and baryon number is relaxed (so you can go ~~from~~ to ~~one~~ having more ~~to~~ of one than the other), then ~~you~~ supersymmetry predicts such a particle. This beyond the Standard Model of particle physics and it is called the WIMP miracle.