Dark Matter and Dark Energy

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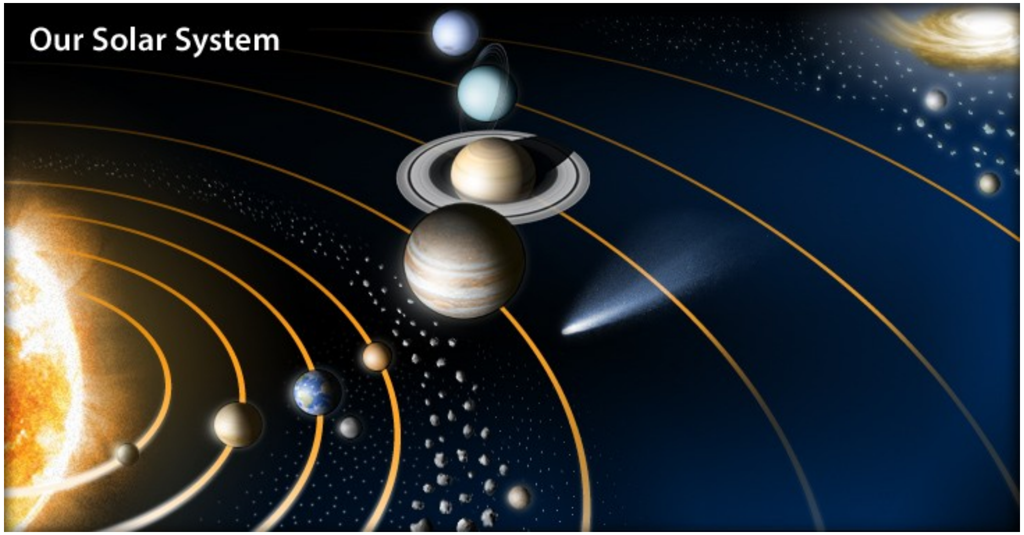
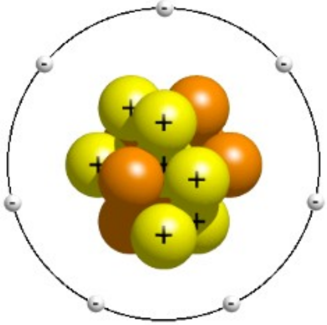
also from **Shamit Kachru (Stanford and SLAC)**

Introduction

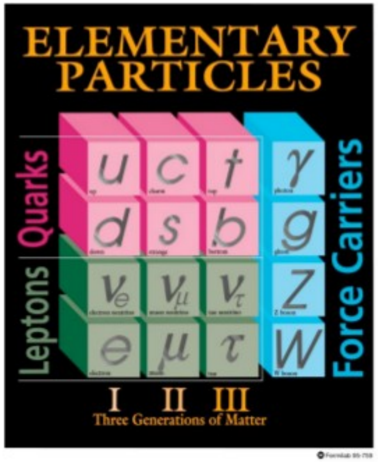
Newton first understood that the same laws that we can infer from terrestrial experiments, also apply in the heavens:



... 250+ years later ...

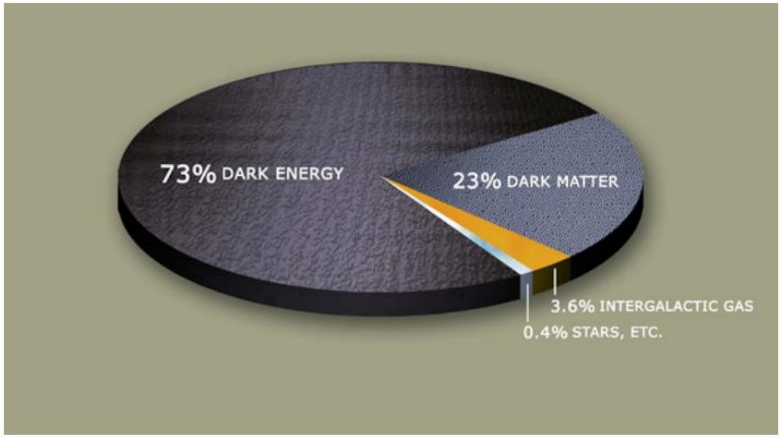


We have learned a lot about the constitution and interactions of ``terrestrial'' matter !



We know we don't know…

But, starting with Newton's observation, we can infer that what we know about constitutes only a small fraction of what exists:



In fact, Newtonian logic suffices to understand 1/4 of this. The other 3/4 requires Einstein.

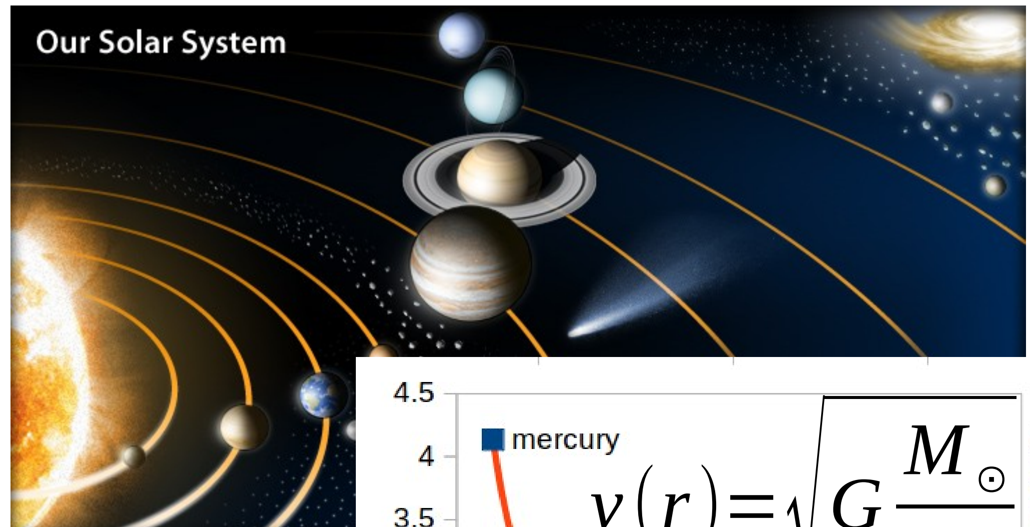
Galaxies are massive, gravitationally bound systems that consist of stars and stellar remnants, gas and dust, and, as it happens, a bit more.

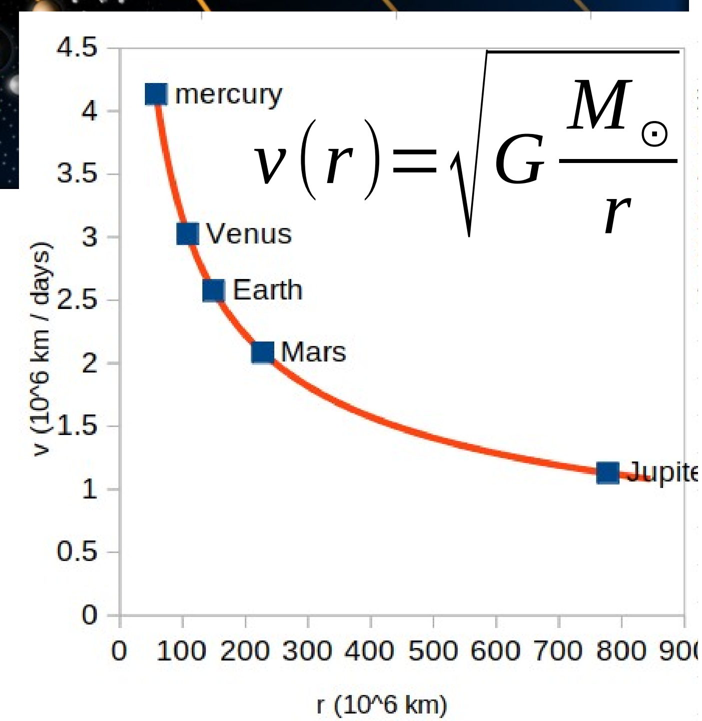
There are in excess of 170 billion galaxies in the observable Universe. Telescopes capable of imaging distant galaxies came online in the first quarter of the 20th century.

Orbits speed law

$$m\frac{v^2(r)}{r}=G\frac{m\,M(r)}{r^2}$$

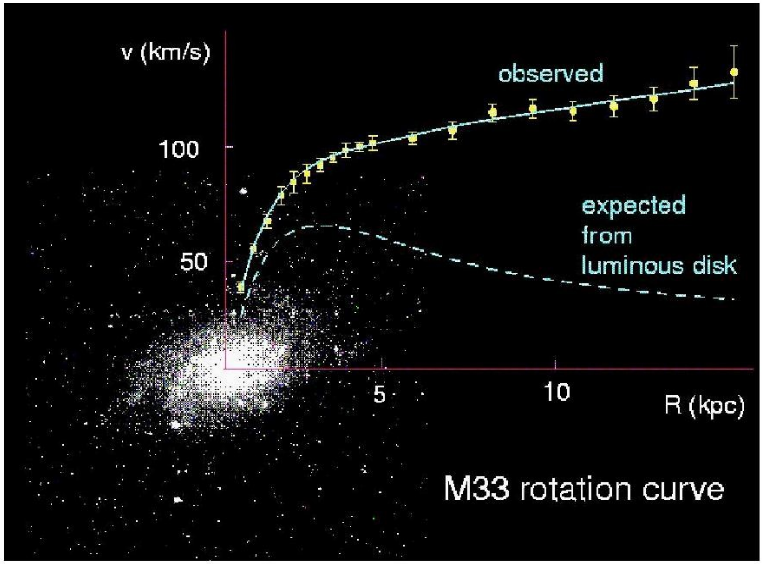
$$v(r)=\sqrt{G\frac{M(r)}{r}}$$





Must be something more

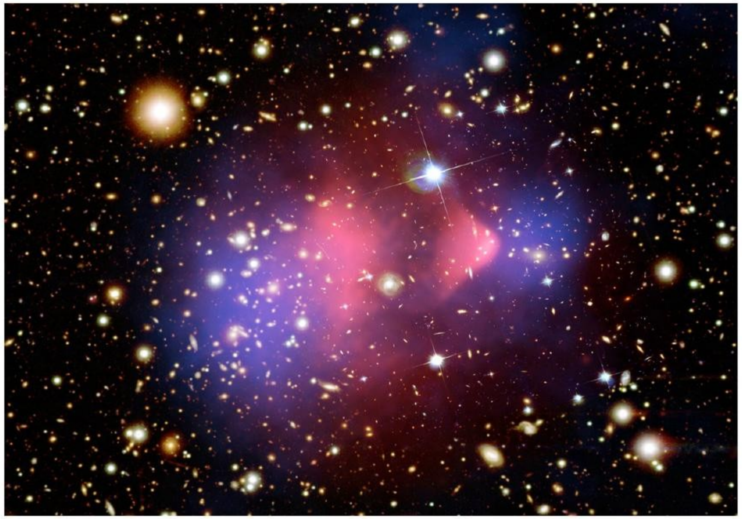
Fritz Zwicky and Vera Rubin were the first two to argue that there is more to typical galaxies than meets the eye:



Must be something more

The flatness of the curve indicates that there is more matter present outside the luminous core of the galaxy.

Quantitative estimates, based by now on a bewildering variety of independent probes, indicate that there is five times more of this “dark matter” than there is stuff we know about!



From indirect tests, as well as e.g. the Bullet Cluster event,

The bullet cluster

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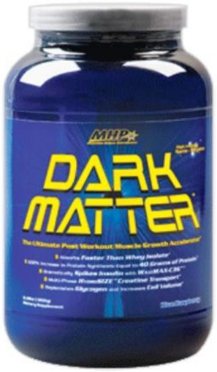
Dark matter candidates

we know the dark matter interacts with "our" stuff very weakly. (Its self-interactions are also bounded).

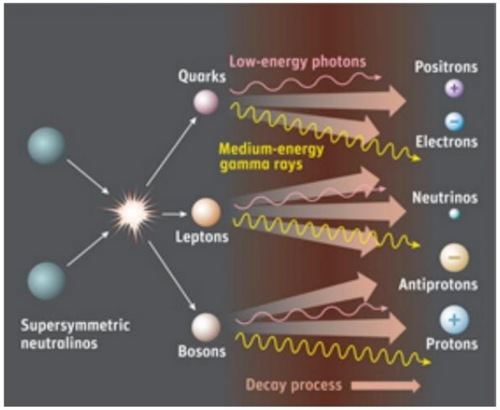
Many candidates have been proposed for the composition of this stuff (and maybe more than contributes some fraction):

- Thermal Relics – equilibrium at early times
  - SUSY – neutralino
  - SUSY – gravitino
  - Neutrino
    - standard model + "sterile"
    - right-handed
- Non-thermal Relics – everything else
  - Axion
  - Primordial Black Holes
    - Planck mass and larger
  - ???

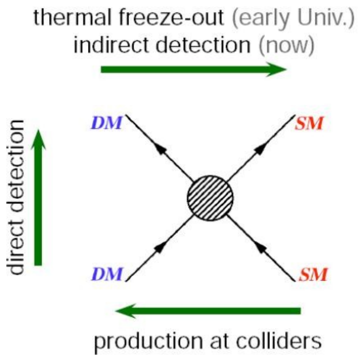


Discovering DM

We aim to learn about it using either astrophysical "dark matter annihilation" events (e.g. in the center of the galaxy):



or via production or direct detection here on Earth:



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Dark Energy

Given that "our" 4% of the stuff gives rise to such diverse structures and consequences, it is perhaps reasonable to think that many things could be afoot in the dark sector.

Dark Energy

This still leaves us with a missing 75%. First of all, how do we know that? It is already perhaps surprising that we could infer the existence of the dark matter, which interacts so very weakly with us.

The key to the discovery of dark energy lies back in the original observations of Einstein and Hubble.

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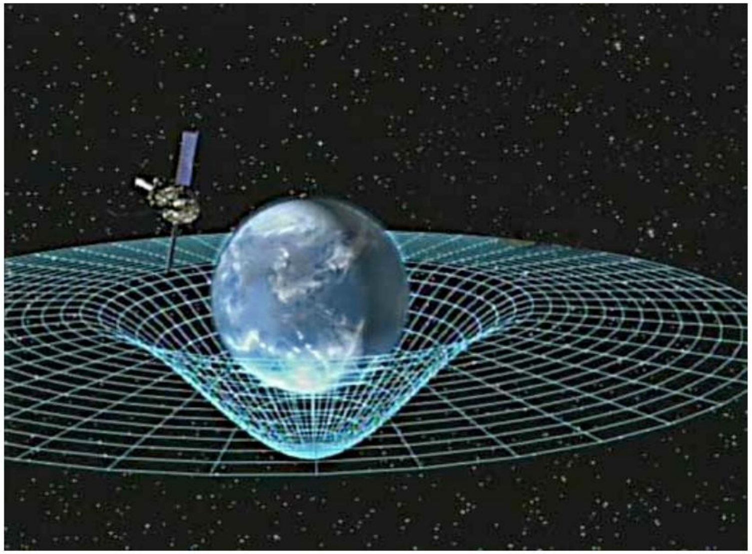
Einstein’s geometry

Einstein:

Gravitation is geometry. The geometry of space is fixed by the matter within it.



Hubble:

Space-time at the largest scales illustrates this!

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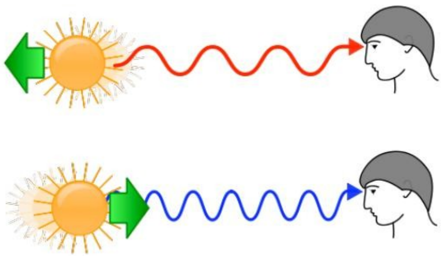
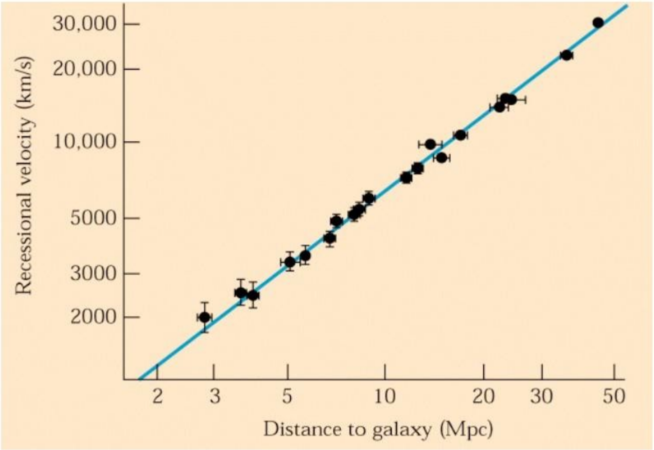
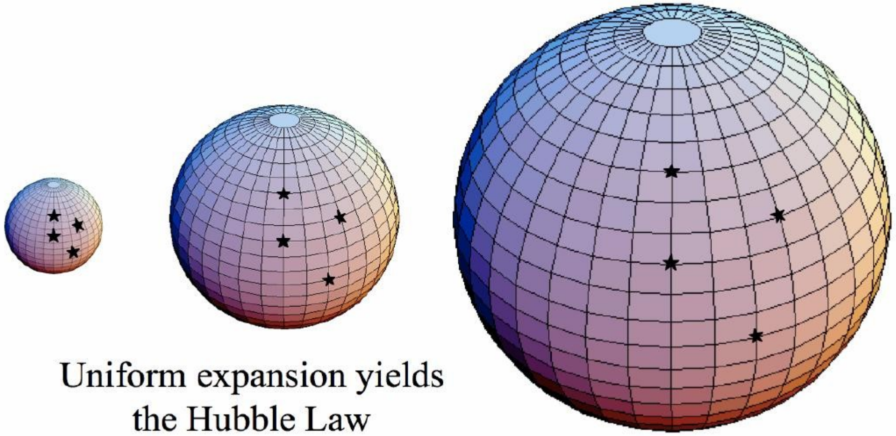
Expanding universe

Expanding Universe encoded in “redshifts”:







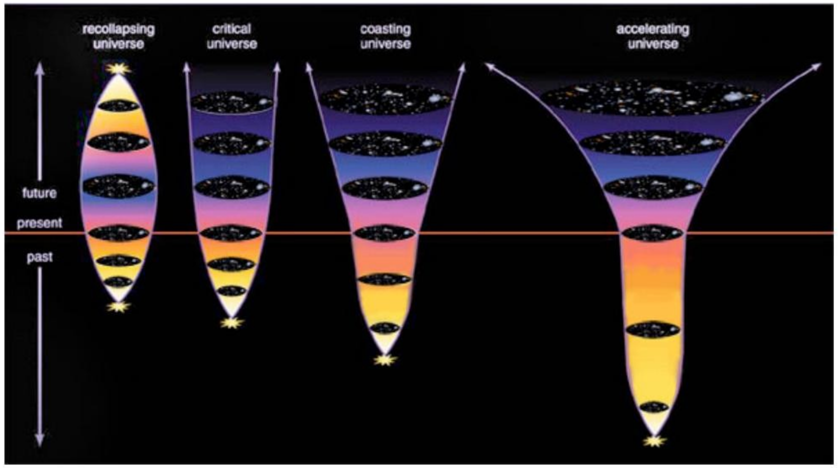
Uniform expansion yields
the Hubble Law

Expansion mathematics

In a simple equation, the spatial slices are expanding in time in a way governed by a(t), the "scale factor":

$$ds^2 = -dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

The dynamics of the Universe at large scales is then determined by how the various matter sources "tell" a(t) to behave:



Accelerating universe

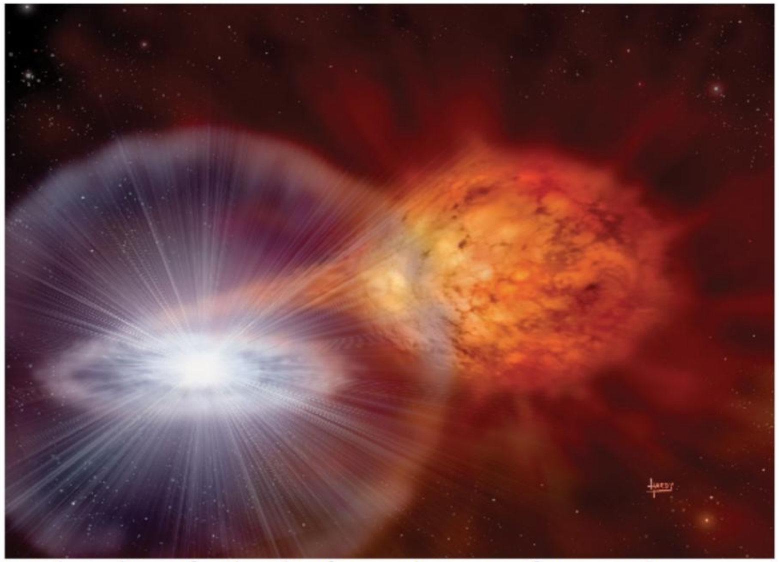
*Very little mass leads to a Universe which expands forever, with the expansion slowed slightly by the gravitational pull of matter.

* In contrast, above a critical amount, there is enough matter that its gravitational pull causes recollapse of the spatial slices -- a “big crunch”.

What was completely unexpected in 1998, when the verdict came in, was the third possibility: a Universe that not only continues to expand, but whose expansion accelerates!

Supernovae

But this is what was found by a detailed study of the properties of distant Type IA supernovae.



Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

Because of the way they arise, such supernovae are thought to be ~ "standard candles".

Accelerating universe

Old supernovae are brighter than they should be - because the expansion is accelerating!