DARK MATTER AND PARTICLE PHYSICS

Three pedagogical lectures

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- ⋆ Some basics of dark matter
- ⋆ Bits of phenomenology
- ⋆ Connection with particle physics

TRUTH IN ADVERTISING

This is not meant to be a review of the entire field.

I am not an expert on dark matter, so this should be regarded as a view of an interested outsider.

The Planck data became public on last Thursday while I was travelling. This talk is a pre-Planck talk.

- ⋆ The success of the SM $\Longrightarrow$ Rampant theoretical speculation.
- ⋆ Grand unification, one unified gauge coupling in theory renormalized at the GUT scale (1974). Hutzpah to extrapolate over 13 orders of magnitude in energy
- ⋆ Measured gauge couplings did not “unify” in the SM (1989).
- ⋆ If the SM is embedded in a GUT, the scalar sector of the SM comes with its own theoretical issues.

ELABORATION OF THEORETICAL ISSUES

Usually stated as: “Radiative corrections to the Higgs scalar mass parameter are quadratically divergent”

$$m_H^2(\mathrm{phys}) = m_H^2 + Const \times \frac{g^2}{16\pi^2}\Lambda^2 + Const \times \frac{g^2}{16\pi^2} m^2 \ln\frac{\Lambda^2}{m^2} + \ldots$$

(One loop), $Const \sim \mathcal{O}(1)$,

Interpret Λ as the scale where the SM ceases to be valid because physics not contained in the weakly coupled SM becomes important.

In real calculations where SM is embedded in a bigger theory with new particles at the scale $M \gg M_{\mathrm{weak}}$, $\Lambda = M$.

In 1974 GUT models $\Lambda \sim 10^{15}$ GeV (a bit larger in SUSY GUTs.)

How large can Λ be?

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Logically, Λ could be anything since the SM is renormalizable.

However, perturbative unitarity requires $m_H(\mathrm{phys})^2 < (\mathrm{few\ hundred})$ GeV^2.
Indeed, today we know that $m_H^2(\mathrm{phys}) \simeq$ (125 GeV)^2.

$m_H^2(\mathrm{phys}) = m_H^2 + Const \times \frac{g^2}{16\pi^2}\Lambda^2$ (One loop), $Const \sim \mathcal{O}(1)$,

If $\Lambda \sim 10^{15}$ GeV, the balance between Λ^2 and the Lagrangian parameter m_H^2 that yields $m_H(\mathrm{phys})$ to be $\mathcal{O}$(100) GeV is extremely sensitive to high scale physics.

If we do not allow this exquisite sensitivity, $\Lambda \lesssim \mathcal{O}(\mathrm{TeV})$ – a SOFT LIMIT.

New degrees of freedom (or perhaps form factors or new strong interactions) must manifest themselves below the scale Λ, and we all hope this will happen soon at the LHC.

Many different possibilities for the new physics at the TeV scale accessible to experiment have been considered.

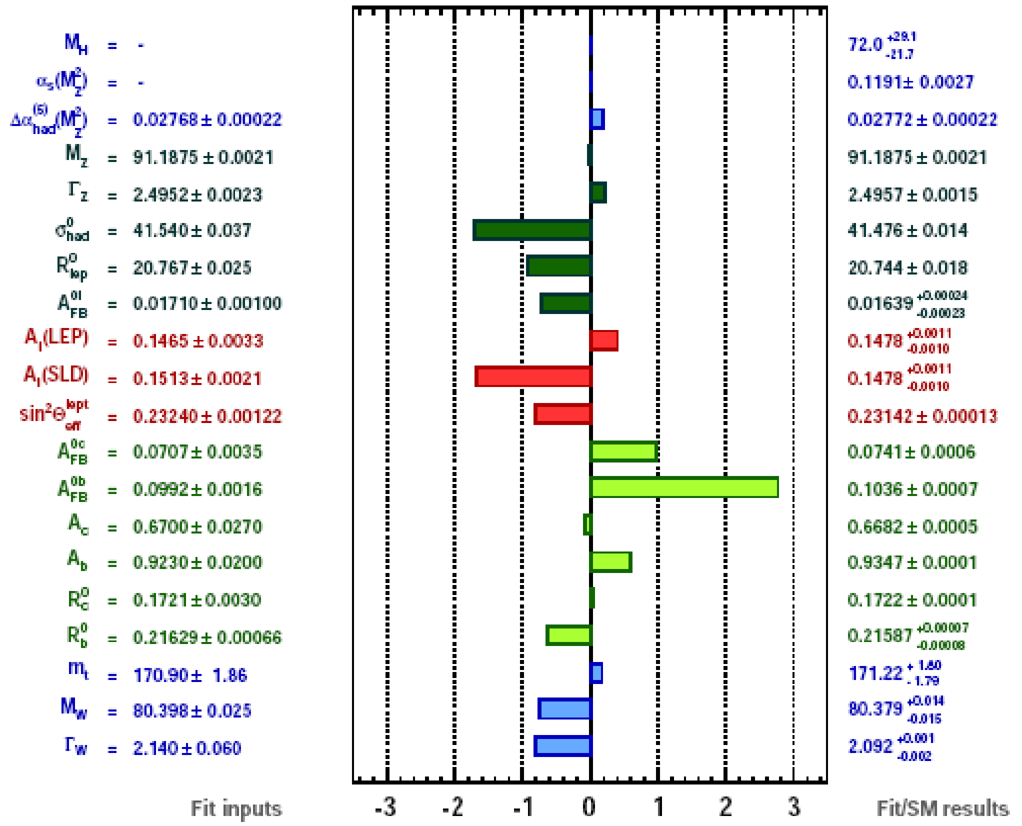
We will return to this later, noting only that many of these come with an entire sector of particles, characterized by a quantum number that distinguishes the new particles from Standard Model particles.

For now, we set aside theoretical issues and focus on experimental questions that cause us to look beyond the Standard Model.

Global fit of high Q^2 measurements gives a very reasonable fit to SM.

$\chi^2/dof = 17/13$

Loop corrections crucial ('t Hooft and Veltman → Stockholm)



M. Goebel, Hamburg Diploma Thesis (2008)

Everything also looks good with the LHC data. We've even found the missing piece in the Standard Model as Tao Han will describe.

What then are we talking about?

- Once upon a time, the instability of the Higgs sector was the only motivation for SUSY (or some other new physics) at the weak scale.
- LEP has measured the 3 gauge couplings; however these do not unify within the Standard Model. (just theoretical foo-faw?)
- Neutrinos have masses. (de Gouvea)
- Why are there more baryons than anti-baryons?
- There is good evidence for non-luminous matter on various scales in our universe.
- The expansion of our universe seems to be accelerating.

Examination of these questions has led to lot of activity in the last 30 years!!!!

We will return to the first item later.

Neutrino masses are the purview of de Gouvea’s lectures.

We do not yet have a good definitive answer for the origin of baryon asymmetry.

The last item is too difficult for me to say anything sensible about.

Hence we will focus on the non-luminous matter.

Why do we think dark matter exists?

The answer goes back to Fritz Zwicky (∼1933) who was observing orbits of galaxies in clusters. Their motion did not seem to obey Newtonian gravitation.

$$\frac{v^2}{r} = \frac{GM(r)}{r^2} \tag{1}$$

If matter is concentrated in the "centre" (away from galaxies whose motions are being observed),

$$M(r) = \text{constant}, \quad \Longrightarrow v \propto \frac{1}{\sqrt{r}}.$$

However Zwicky observed, $v = \text{constant}$, and concluded that $M(r) \propto r$, even though observations of visible matter seemed to suggest to the contrary. (This trick had worked once before for the discovery of Neptune at a location predicted by Le Verrier.)

In the 1970s, Vera Rubin and Kent Ford made detailed observations of stellar velocities for various spiral galaxies, and found these were also not in accord with Newtonian gravitation. These observations suggested that there must be non-luminous mass in a halo around the luminous stuff in these galaxies.

For the Milky way, $v \sim 220$ km/s, and $\rho(\mathrm{DM}) \sim 0.3$ GeV/cm^3.

Cosmological Evolution

- Our Universe is expanding, “literally creating space” between two points as time progresses. The expansion rate is characterized by

$$H \equiv \frac{\dot{a}(t)}{a(t)},$$

with $a(t)$ being the scale factor in the FRW metric.

- If we characterize the energy momentum tensor by the energy density and an (isotropic) pressure with the equation of state, $\rho = wp$, we get,

$$a(t) = a(t_0)\left(\frac{t}{t_0}\right)^N, \quad \text{with } N = \frac{2}{3(1+w)}.$$

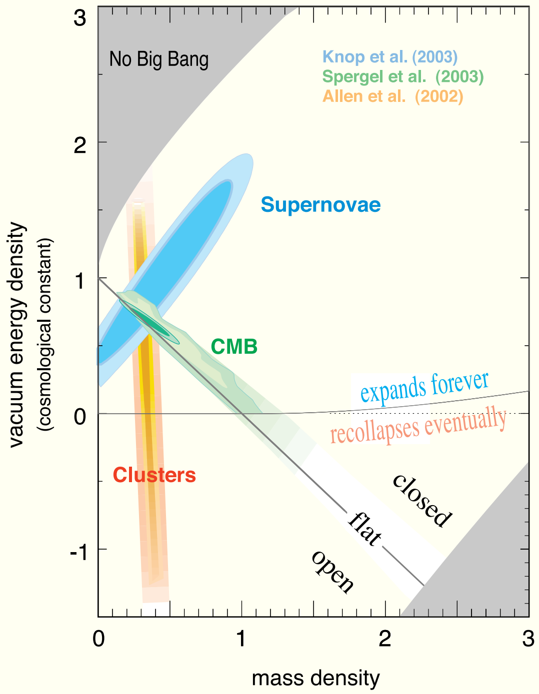
- As the Universe expands, radiation and relativistic matter $(w = 1)$ red shift as well as dilute, non-relativistic matter $(w = 0)$ dilutes.

$$\rho_{\text{rad}} \sim a^{-4}, \quad \rho_{\text{matter}} \sim a^{-3}.$$

- The energy density from a cosmological constant does not change with time.

Thus, radiation (relativistic matter) dominates in the early history of the Universe, non-relativistic matter dominates later, until the cosmological constant takes over. Of course, other types of things with differing value of w may be present.

During the last decade and a half, a remarkably consistent picture appears to have emerged where the energy content of the Universe is shared by something that looks like a cosmological constant and matter. The ΛCDM model



The energy budget of the Universe is dominated by some unknown substance that we parametrize as a cosmological constant.

WMAP power spectrum of tempertature fluctuations

We know that the photons left over from the Big Bang have left an exquisitely homogenous, isotropic radiation that forms the best blackbody spectrum ever.

This spectrum shows have tiny temperature fluctuations of $\mathcal{O}(10^{-5})$ imprinted on them.

These fluctuations are thought to have come from fluctuations in temperature in the era when the protons and electrons combined to make neutral atoms ($T \stackrel{<}{\sim} 1$ eV). These arose because of small inhomogeneties in the matter distribution that required photons to climb out of gravitational potential wells in overdense regions, and vice-versa. Hence, these fluctuations are an imprint of the matter density fluctuations in the era of recombination.

How big do we expect these over and underdense regions to be?

Clearly, the region could not be much larger than t_{rec} as there would have been no time for the matter to have collapsed under its own gravity.

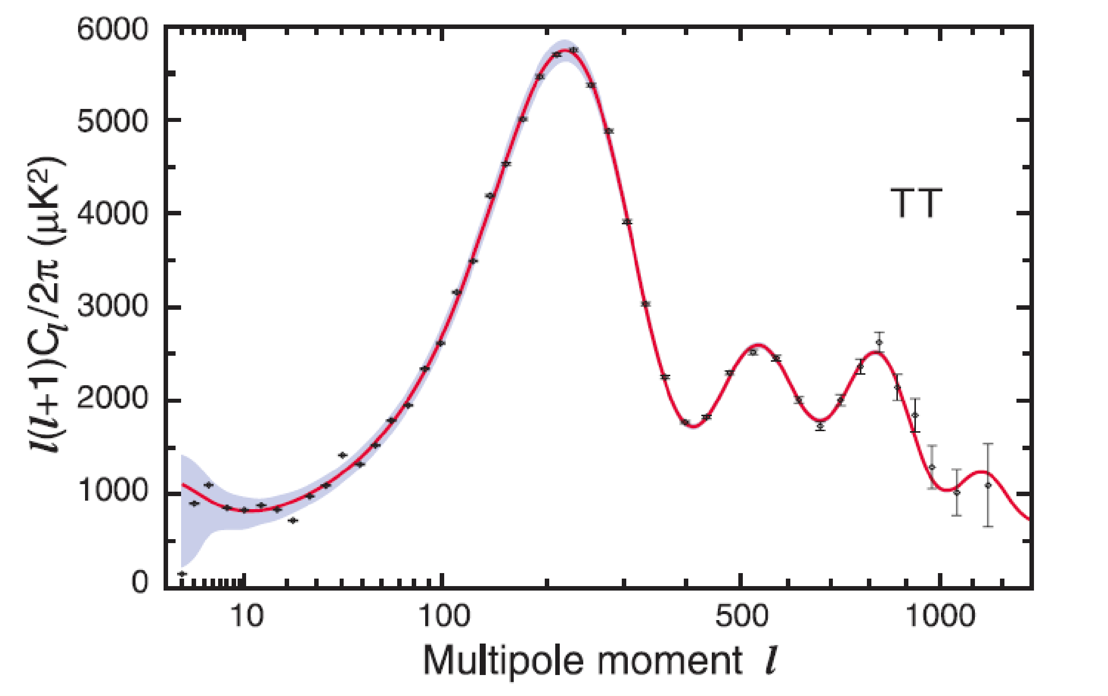
A region much smaller than t_{rec} would have collapsed, and gotten hot. The increased photon pressure would have disrupted the collapse. (I assume here that the photons couple to the collapsing matter.)

The Goldilocks size, therefore, is t_{rec}. The region collapses, becomes overdense, but because there has been no time to get heated, the collapse is not yet disrupted.

The size is determined by the geometry of the Universe. For a flat Universe, this size would correspond to an angular size of about 1 degree today. In the WMAP analysis, this would result in a big peak at $l \sim 200$, in agreement with the data!

★ The first peak determines the matter density in the Universe.

WMAP power spectrum of tempertature fluctuations



Baryon acoustic oscillations

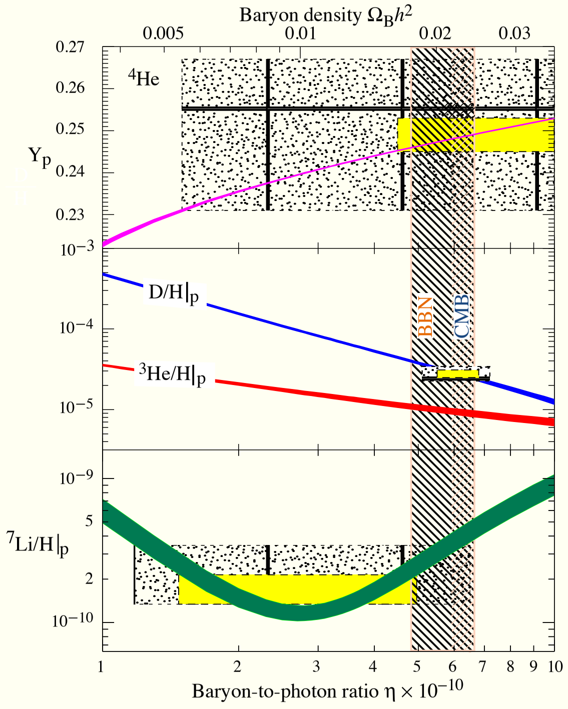
Remember that the baryonic component of the matter is what couples to photons.

The collapse of overdense regions smaller than t_{rec} is what is damped by the pressure of the radiation which resists the collapse, setting up a sound wave in the baryon-photon fluid. This causes the next peaks in the WMAP spectrum of temperature fluctuations.

These next peaks are used to infer the density of baryons. It is found that $\Omega_{baryon} \lesssim 0.2\Omega_{matter}$.

Thus, the matter that is inferred from the first peak is mostly stuff we do not know about. Most of it is <u>not the baryons that we know.</u>

Quite independently of WMAP, the calculations of light element abundances are compatible with the observed values of D, He^3, He^4 and Li abundances if the ratio $n_B/n_\gamma \sim 6 \times 10^{-10}$. Since the number of photons can be obtained from thermodynamics, we obtain the mass density in baryons in agreement with that obtained above.



More reasons to believe in non-baryonic matter

- ⋆ Gravitational lensing effects that have been seen interpreted as large amounts of non-luminous matter.
- ⋆ Hot gas seen in x-rays could not be gravitationally bound by the gravity of just the luminous matter in the galactic clusters.
- ⋆ Non-luminous appears to be necessary to seed the large scale structures that are seen. Remember radiation pressure resists clumping of just baryonic matter. The non-luminous matter needs to be cold.
- ⋆ The bullet cluster

The Bullet Cluster