Particle Physics and the Universe

This is a rather active research area right now and we have to change numbers rather often. An example here is that the Hubble constant which was only know to within a factor of two is now quite well known. So keeping these notes up to date is always a bit of a problem, espescially since the new developments often involve a large technical background.

There are many areas of contact, there exists in fact a whole field called astroparticle physics for which by now many books and reviews have appeared.

The most exciting recent developments have been in the contact with cosmology but even this relation goes back quite some time.

1 Astrophysics constraints on Particle Physics

These consists of knowing the physics between a variety of astronomical objects and then using these to obtain limits on extra effects not included normally.

These typically appear in the radiation of particles in stellar (or their successors) which can have sizable effects. Here are some

- In stars the thermonuclear process is rather well understood. If there were more weakly interacting particles that would get radiated at a reasonable rate they would carry of heat from the thermonuclear fusion engine running in the core of the star. This provides limits on axions and all light weakly interacting particles. They have to be weakly interacting to get out the core. The best limits tend to come from red giants since these have the highest temperatures in the core.

- A celebrated example is the fact that neutrino oscillations were really first discovered from the solar neutrinos.

- When a star finally collapses and produces a neutron star, very many neutrinos are radiated. Detection of these and their arrival times have allowed many limits on neutrino properties.

2 Nuclear Formation in the Big Bang

In the early universe the neutrons were caught into (mainly) ^{4}He nuclei. The precise amount of neutrons that get caught in various light nuclei versus the total number of protons and neutrons available is very sensitive to many conditions around. This has allowed to put some limits on the numbers of light neutrinos before limits from LEP appeared. It also allows limits on the numbers of relativistically moving particles (usually called radiation) in general at the time of nuclear synthesis.

3 The dark matter problem

It is known that there exists a lot more matter in the universe than there is in stars and other normal objects. This was first discovered in the velocity curves of distant galaxies. Particle physics has many candidates for this in beyond the standard model scenarios.

- Massive neutrinos
- Axions
- Various supersymmetric particles, these come in a class known as WIMPs (Weakly Interacting Massive Particles)

There are basicallythree types, hot dark matter (neutrinos), cold dark matter (WIMPs) and the ones where various fields get expectation values (which may vary with time) and as such produce the dark matter content.

4 Baryon Number Generation

One of the mysteries is why is there any baryon number left at all. In the beginning, pick your favourite energy, there are very many quarks and antiquarks around, as well as leptons. When the temperature drops below that required to have creation reactions running the annihilation of quarks and leptons starts. But they do not annihilate fully, some of them are left and the universe now exists mainly of quarks and leptons, not of anti-quarks and anti-leptons.

This tiny left over is rather puzzling and in order to solve it many conditions need to be satisfied (CPT conservation assumed here):

1. There have to be baryon number violating processes
2. Some things need to go out of thermal equilibrium, otherwise the equal balance principle would have baryon and anti-baryon number equal.
3. CP violation needs to be present.

In fact the standard model has all these three properties but not in a way sufficient to create the observed asymmetry (but it makes it worse for other higher energy mechanisms to produce the asymmetry). Grand Unified Theories provide one option for producing this imbalance.

5 Inflation

There are many problems associated with the fact that the universe is very big and looks rather homogenuous and isostropic on very large scales, as well as being very flat. These problems are:

- Flatness problem: this arises because the universe now is rather flat but the evolution from general relativity is such that the universe moves away from flatness with time. So in order to be as flat as observed now it had to be extraordinarily flat at early times.

- Horizon problem: Many of the areas of the universe can not have exchanged signals with each other because of the expansion of the universe. But still when we see those they look remarkably alike. How could this be?

- Monopoles, Cosmic Strings and Domain Walls: a problem: similar to the previous one. We expect several cases of spontaneous symmetry breaking to have occurred in the history of the universe. If the first breaking happens in different directions in different areas of the universe they start relaxing together but then socalled topological defects (similar to the domains in a ferromagnet) can occur and we should have observed these if they existed.

All of these are solved (at least in principle) by inflation. Note that the absolute simplest version of inflation does not work and no simple nice working model is known but many general features are well supported.

6 A really short Big Bang primer from General Relativity

We only discuss here the simple Friedman-Lemaître universes. Assume the universe is homogeneous and isostropic. That means that the energy-momentum tensor can be written in the simple form

$$T^{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \tag{1}$$

and $\rho(t)$ and $p(t)$ are only functions of time. The matter is supposed to be at rest and behave like a socalled perfect fluid. The metric can be written in the general form

$$ds^2 = dt^2 - R(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2 \right) \right). \tag{2}$$

The parameter k can take the values $\pm 1, 0$ leading to the following general geometry of the universe

$k = +1$ Finite in space universe, closed, spherical geometry

$k = 0$ Infinite in space, open, flat geometry

$k = -1$ Infinite in space, open, hyperbolic geometry.

Notice that I have not said anything about whether the universe has a finite lifetime. From Einstein's equations we then get

$$H(t)^2 \equiv \left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{8\pi G_N \rho(t)}{3} - \frac{k}{R(t)^2}\,. \tag{3}$$

The pressure p satisfies

$$d\left(\rho R^3\right) = -pd\left(R^3\right)\,. \tag{4}$$

This has to be supplemented with an equation coupling ρ and p, known as the equation of state. The latter is in general complicated but for most purposes some simplifications are used. Usually it is assumed that

$$p(t) = w\rho(t)\,. \tag{5}$$

The following cases are of interest

- $w = 0$ corresponding to particles at rest, known as a matter dominated universe. $\rho \sim R^{-3}$
- $w = 1$ corresponding to particles moving at the speed of light whose energies is dominated by the kinetic energy and thus gets redshifted, known as a radiation dominated universe. $\rho \sim R^{-4}$
- $w = -1$ Or a cosmological constant. ρ is constant.
- $-1 \leq w \leq 0$ known as quintessence.

Note that in general relativity energy does not need to be conserved.

The later cases are normally realized as being produced by the values of a field ϕ which then obeys the equation of motion

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\partial V(\phi)}{\partial \phi},\,. \tag{6}$$

For $k = 0$ these have the behaviour

matter	$\rho(t) = \rho_0/R(t)^3$	$R(t) = \left(\sqrt{6\pi G_N \rho_0}\, t\right)^{2/3}$
radiation	$\rho(t) = \rho_1/R(t)^4$	$R(t) = \left(\sqrt{32\pi G_N \rho_1/3}\, t\right)^{1/2}$
cosmological constant	$\rho = \rho_2$	$R(t) = e^{\sqrt{8\pi G_N \rho_2/3}\, t}$

So a possibility of exponential expansion exists if at some point we have a constant density. This is known as inflation.

A short history of the universe can now be described as.

1. For very small times all particles are relativistic and they dominate by far the energy density. The universe expands as a radiation dominated one and the particles slowly redshift.

2. The the energies of the ϕ field becomes low enough that the effect of the $V(\phi)$ becomes important and we shift to an exponentially expanding universe. The large inflation here means that the entire observable universe was reall a very small part beforehand.

3. The ϕ has slowly reached the minimum of the potential such that inflation stops and the universe is again radiation dominated.

4. Finally all relativistic particles get redshifted to such low energies that their rest mass dominates and we have the present (almost) matter dominated universe.

5. A newer observation is that we actually again have something like a (now much smaller one) cosmological constant around. This is known as the dark energy.

How does this solve the various problems. Basically all in the same way. Since the entire universe came from a very small pre-inflation area it had ample time to get homogenuous and organize itself. During the inflation any curvature present would also have gotten stretched away so that the universe afterwards will be flat with an incredible precision.

7 Cosmic Microwave Background

The cosmic microwave background has many interesting properties. First its existence by itself was a major success for the Big Bang model and was in fact what really made it universally accepted. Now the fine noninhomogeneities are of major interest see e.g. [2]. In 2003 there was a major step forward with the results from the WMAP satellite.

8 Structure Formation

This is the question how the present structures seen in the universe at scales from galaxies and up are formed from the initial small perturbation caused by quantum effects and/or whatever in very early universe. This is done by galaxy surveys and complements the structures seen in the microwave background by covering different time scales and size scales. Here come names like "the great wall, the gigantic bubble,..."

9 Other

There are many more speculative connections involving strings, extra dimensions gravity and gauge interactions operating in a different number of dimensions, quantum gravity and gravitational radiation,....

References

[1] L. Bergström and A. Goobar, Cosmology and Particle Astrophysics

[2] M. Kamionkowski, http://arXiv.org/abs/hep-ph/0210370