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Cosmology (including neutrino mass limits): a particle theorist's viewpoint

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I will present a particle theorist's viewpoint on various aspects of modern cosmology. Necessarily, it will cover a limited selection of topics according to taste and competence.

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1. Do we already have a CSM (Cosmological Standard Model)?

As we have heard repeatedly during this conference, particle physicists have now lived with a Standard Model (SM) for about 30 years, witnessing its successes over and over again. If any they have been deprived of the thrill of surprises and crises. But if we go back 10 or 20 more years (to the fifties and sixties) the situation in High-Energy-Physics (HEP) was totally different: sure enough there was QED, but that was about it: the rest was a bunch of more or less successful models for the weak and the strong interactions, nothing any close to a full theory. It took years of crucial experiments and ingenious theoretical work to turn those models into the precise and predictive framework that defines today's SM of HEP. It was a golden age during which particle physics truly underwent a “phase transition".

What about cosmology? Are its next 30 years going to look like those just elapsed in particle physics? Or like the preceding 20? My belief is that today's cosmology is also heading for a golden age and a phase transition! And yet one could argue that:

- Data are becoming sharper and sharper;
- They appear to support, better and better, a so-called concordance model whereby the energy budget of the Universe is shared among baryonic matter, dark matter, and dark energy, according to a 5%, 25%, and 70% split;
- Dark matter is (quite) cold, dark energy is consistent with a bona-fide cosmological constant, large-scale structure is consistent with a nearly scale-invariant primordial spectrum of adiabatic, gaussian density perturbations. And these are naturally produced during a long, slow-roll inflationary phase.

Why not call this a CSM? Well, because so many questions are left unanswered:

- What makes that dark 95 % of the Universe?
- What is source of inflation (i.e. of early cosmological acceleration)?
- What fixes the initial conditions forcing the Universe to inflate?
- What is source of the late cosmological acceleration?
- etc. etc. (see below)

Indeed, if we did have a CSM, the field would be as theory driven as HEP, see e.g. the LHC experimental programme!

2. More data?

Will more data pin down a CSM? Obviously that would help! Here is an incomplete list of forthcoming important cosmological data:

- Dark matter searches (DAMA, UKDMC, HDMS, . . .);

- Supernovae (SNAP), CMB and cosmic acceleration;
- Ultra high-energy cosmic rays (AUGER);
- Non-gaussianity in CMB (WMAP, PLANCK);
- CMB polarization (B-mode to be measured at PLANCK?);
- 2D and 3D galaxy surveys and large scale structure (SDSS, ...);
- Cosmological GW bkgnd (LIGO, VIRGO, ... LISA).

What is already clear is that cosmological data are already helping particle physics. Let me just give two examples.

2.1 Neutrinos

Neutrino oscillations are only sensitive to mass (actually mass-squared) differences. These are in the range of $10^{-4}\mathrm{eV}^2$ for solar to $10^{-2}\mathrm{eV}^2$ for atmospheric oscillations. Direct laboratory limits on *actual* neutrino masses span a much wider range:

- $\sim$ 2eV for ν_e;
- $\sim$ 170KeV for ν_μ;
- $\sim$ 18MeV for ν_τ.

On the other hand effects of m_ν on the CMB structure (in particular on the acoustic peaks) and on large-scale structure offer much stronger indirect limits: Combination of WMAP, CBI, ACBAR (CMB experiments) and 2dF-GRS (galaxy survey) yields, for the fraction of critical energy density in neutrinos, $\Omega_\nu h^2 < 0.0076$ at 95 % confidence level. Typical bounds on the sum over (light) neutrino masses range between 0.5 and 1 eV (see e.g. [1]).

For a “hierarchical" structure of neutrino masses an upper limit of 0.70 eV has been claimed for the heaviest neutrino, while for three degenerate neutrinos it reduces to $m_\nu < 0.24$ eV. This is of course extremely interesting when compared to direct laboratory limits. It is hoped [1] that, by the time data from the PLANCK satellite will be analyzed, the (sum of) neutrino masses will be known with a 0.1eV precision allowing to discriminate between a democratic and a hierarchical structure.

In the words of the Neutrino Astrophysics and Cosmology working group of the American Physical Society (December 2004):

It is important to precisely measure the cosmological neutrino background through its effects on big-bang nucleosynthesis, the cosmic microwave background, and the large-scale structure of galaxies; weak gravitational lensing techniques offer a very realistic and exciting possibility of measuring neutrino masses down to the scale indicated by neutrino oscillations.

2.2 Dark Matter

Let me simply quote here from a paper by Ostriker and Souradeep [2]:

Cosmological observations . . . are beginning to put interesting constraints on the properties of the Cold Dark Matter. In particular, simulations using canonical collisionless CDM appear to be at odds with observations on small (sub Mpc.) scales:

- *The number of small galaxies that are observed orbiting with a larger unit is less than expected.*
- *The density profile at the centers of CDM halos is predicted to be "cuspier" than observed.*

Alternative variants to collisionless CDM are under active investigation. They include self-interacting dark matter, warm dark matter, self annihilating dark matter, massive black holes, etc.. It is not inconceivable that cosmological observations would pin down the properties of the CDM component well before any direct detection.

3. More theory?

The field is still very much data driven as it was clear from the cosmic-acceleration surprise. The SM example has shown that a combination of good experiments and sound theory can be crucial for progress. Theory has definitely to catch up with experiments if one wants to achieve the kind of balanced situation that prevails since a while in HEP. Where does it stand?

Below is a long (yet incomplete) theorist's shopping list, indicating, in boldface, the items included in the following discussion:

- **Cosmological singularity and time arrow**;
- **Primordial perturbations and transplanckian problem**;
- Initial conditions;
- **Unconventional cosmologies and perturbations**;
- **Fundamental strings as cosmic strings**;
- Reheating;
- Baryogenesis;
- Dark matter;
- **Dark energy**.

I shall now go through the items shown in boldface, following the above (also chronological) order.

3.1 Cosmological singularity and time arrow

We may start from the question: Can we accept the cosmological singularity? Like other infinities in physics, I find this very hard to swallow, for a theorist. In practice, we may be able to retain a lot of predictivity without dealing with that problem, particularly in an inflationary set-up that washes out initial conditions. There is here some similarity with the situation that occurs in (renormalizable) Quantum Field Theories where we learned how to live with infinities through the “renormalization" procedure according to which, once we give up computing certain quantities and take them from experiments, we are still able to compute many other observables.

In cosmology initial conditions lie at (or near) the putative singularity. Hence the issue here is whether we can be predictive without a theory of initial conditions. Superstring theory, as a consistent theory of quantum gravity, should be able to provide an answer; actually that theory can deal with some kinds of (timelike or null) singularities, but is still largely unable to cope with the spacelike singularities that occur in cosmology or in the interior of black holes. In the former, favourable cases singularities are typically resolved not so much by their mere removal, but by changing the description of physics through new relevant degrees of freedom. There is again a similarity here with particle physics: perturbative QCD has an infrared (Landau) singularity, correctly reinterpreted at the non-perturbative level as a transition from the quark-gluon to the hadronic description of strong-interactions.

Which are the most likely theoretical outcomes for the cosmological singularity in superstring theory? I can see two:

- The big bang singularity is replaced by a string phase from which a space-time metric description emerges. So far no concrete models of this type have been proposed;
- A stringy phase joins two classical epochs: the Big Bang becomes the “Big Bounce" since spacetime curvature must grow in the first (pre-bounce) phase and decrease in the second. In most cases, but not always, the bounce actually means contraction followed by expansion. The pre-big bang [3] and ekpyrotic/cyclic [4] scenarios belong to this class.

Note, incidentally, that the notorious problems of hot-big-bang (pre-inflationary) cosmology (homogeneity, flatness) can be solved, in principle, by making the Universe either much smaller (the way chosen by inflation) or much older (the “Big Bounce" way).

However, if one starts from a crunch-like situation, is a bounce into a big bang phase possible? One can give arguments in favour of a positive answer by using the so-called holographic entropy bounds in a cosmological context [5]. These can be simply summarized by saying that the upper bound on entropy density is obtained by allowing one Hubble-size black hole per Hubble volume, a state whose entropy density according to the Bekenstein-Hawking formula for black-hole entropy is immediately computed to be (up to numerical constants):

$$\sigma_{max} = S_{BH}/V_H = H M_P^2 \tag{3.1}$$

It is easy to show that such a bound gets tighter and tighter in the pre-bounce phase, while it becomes looser and looser after the bounce (possibly explaining our arrow-of-time) It is therefore tempting to assume that the bounce occurs when the bound is just saturated in order to prevent

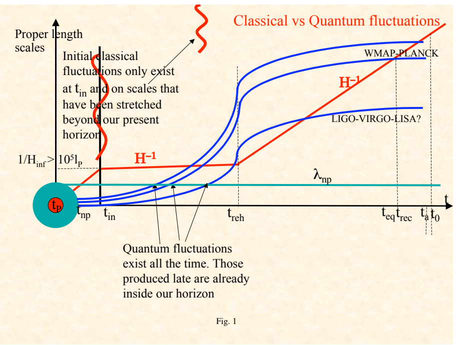

Figure 1: A cartoon of inflationary cosmology showing various interesting physical scales as functions of cosmic time t. We show, in particular, where initial classical fluctuations lie and where continuously generated quantum fluctuations are best given.

its otherwise inevitable violation. The resulting picture [6] for the transition phase is that of a dense gas of “string-holes", critical-mass strings that turn into black holes by even the smallest mass increase. Temperature and curvature also saturate at the bounce, calling for a full (and yet unavailable) stringy description of such a phase transition.

3.2 Primordial perturbations and the transplanckian problem

The issue stems from the simple observation that, in the conventional inflationary setup, practically all length scales of present physical interest were sub-planckian at the beginning of the inflationary phase, unless inflation lasts a bare minimum (incidentally this is not the case in bouncing cosmologies). The question then arises of how robust are inflationary predictions with respect to the unknown short-distance physics that controlled those initial perturbations. This can be seen either as a problem or as an opportunity since present large-scale cosmological observations would represent a “window" on very short-distance physics in the early Universe. There have been several contradictory claims on this issue (see [7] for a representative set), some of them suggesting measurable effects of order H_{inf}/M_P on present CMB anisotropies. In order to address this important issue one can start from a simpler question:

Q: Why does inflation wash out initial classical fluctuations while leaving (or even amplifying) initial quantum fluctuations?

The answer to that question is quite obvious:

A: Initial classical fluctuations start, by definition, at scales that are already (much) bigger than the Planck length and thus have already been stretched beyond our present horizon. By contrast, initial quantum fluctuations are generated all along the inflationary epoch, in fact they are there all the time because quantum mechanics is never turned off.

Their actual size (normalization) is better defined, for each wavelength , at the time at which, following the expansion, it grows above a characteristic length related to whatever new physics takes place at short-distance.

As shown in Fig. 1, while initial classical fluctuations should be assigned at a fixed time, a vertical line, quantum fluctuations should be given on the horizontal “New-Physics Hypersurface".

The size of new-physics effects will depend on our assumption on what the “initial conditions" are on such a “New-Physics Hypersurface".

As an example [8] we may decide to minimize, on such an hypersurface, different canonically-related Hamiltonians. The outcome is that, according to the chosen Hamiltonian, we typically get effects of different order in H_{inf}/M_{NP} (we indicated by M_{NP} the energy scale at which some new physics kiks in, a scale that can be, in principle smaller than M_P). It looks unlikely, however, that one can generate effects larger than $(H_{inf}/M_{NP})^2$ unless the unknown new physics breaks Lorentz invariance. Yet, these effects can be sizeable, if either $H_{inf} \sim M_{NP} \ll M_P$ in conventional inflation, or $H_{max} \sim M_P$ in bouncing cosmologies.

3.3 Perturbations in bouncing osmologies

This is, of course, the acid test of any new cosmological model that wants to challenge conventional (slow-roll) inflation. In that framework (even very) different scales feel roughly the same cosmologiocal background at exit time. This is what leads to a nearly scale-invariant spectrum of scalar and tensor perturbations. Hence the crucial question becomes:

Q: Is the spectrum of Scalar (S) and/or Tensor (T) perturbations nearly scale-invariant also in a bouncing-curvature cosmology?

The naive expectation [9] is that both T and S perturbations have blue spectra since, by the definition of a bouncing-curvature scenario, shorter scales exit the horizon at larger values of H. In spite of this, the proponents of the Ekpyropic scenario claim [10] that they naturally get a blue spectrum for T (and thus practically no tensor perturbations at the scales of relevance for the CMB) but an almost scale-invariant spectrum of S. Since, so far, T perturbations have not been observed, if this claim could be substantiated, it would make the ekpyrotic scenario a serious contender of conventianl inflation. What is the present status of this debate?

For T- perturbations (gravity waves) the theoretical anlysis is easy, since there is just one gauge-invariant perturbation, and the result is, uncontroversially, a strongly tilted, blue spectrum.

S-perturbations are trickier. Several (related) choices of gauge-invariant scalar perturbations are possible [11]:

- $\Phi = \Psi$ i.e. the famous Bardeen potential, corresponding to curvature perturbation on shear-free hypersurfaces and directly related to $\Delta T/T$ via the Sachs-Wolfe effect;
- $\mathscr{R}$, the curvature perturbation on comoving hypersurfaces;
- ζ, the curvature perturbation on constant-density hypersurfaces.

In standard slow-roll inflation it does not make much of a difference to work with Φ, $\mathscr{R}$ or ζ since they are all dominated by the same constant and nearly scale-invariant mode

In bouncing cosmologies the situation is less clear: Before the bounce $\mathscr{R}$ and ζ have an almost constant mode with a blue spectrum while Φ has a *growing* mode with a red or flat spectrum (In the PBB scenario, Φ has a red spectrum $(n = 0)$ and grows so large that linear perturbation theory breaks down in the longitudinal/Newtonian gauge; in the Ekpyrotic case the addition of a suitable potential turns the red spectrum of Φ into an almost flat one $(n \sim 1)$ before the bounce). What matters, however, for CMB anisotropies, is the spectrum at *late* times. If the (red or scale-invariant) spectrum of the pre-bounce growing mode of Φ is *not* going 100 % into the post-bounce decaying mode, then a scale-invariant mode of Φ can survive long after the bounce, till recombination, and give the observed CMB anisotropies in the context of the ekpyrotic/cyclic Universe. If, instead, the scale-invariant mode of Φ all goes into the decaying mode, one cannot explain the observed anisotropies this way.

Various toy models have been studied to check which way things go with mixed claims: Some models [12] [13] lend support to the first alternative, while others [14], [15], [16], in agreement with the general arguments in [17], go in favour of the second. With V. Bozza [18] we investigated a large class of two-fluid, non singular bounces: we found that the spectrum of the growing mode of Φ at $t \ll 0$ is never transferred to the non decaying mode at $t > 0$. At most, one of the two fluids transfers its primordial spectrum to the other, but the whole issue does not appear to be completely settled due to possible counter examples presently under scrutiny.

If the conclusions of Ref.[18] are confirmed the only way to rescue the phenomenological viability of bouncing-curvature cosmologies appears to be by making appeal to the so-called curvaton mechanism [19], [20], [21] [22]. This consists in generating first a scale-invariant spectrum of isocurvature (entropy) perturbations in a subdominant component of the cosmic fluid. If later this component becomes non-negligible (or even dominant) and then decays, its primordial spectrum is transmitted to photons as ordinary adiabatic curvature perturbations. This does look like the best bet for making bouncing cosmologies compete with slow-roll inflation. Another possibility is to use fluctuations of a field that controls the decay rate of the inflaton at reheating [23]. In both cases, the source of inflation and the source of perturbations is *not* the same.

One appealing possibility [19], [22], is to identify the curvaton with the universal axion of string theory, which can easily have a scale-invariant spectrum [24]. Detailed CMB predictions differ from those of standard slow-roll inflation: a very small T/S ratio, some residual isocurvature component, and possibly rather sizeable non-gaussianity. Note that present limits on the non-gaussianity parameter f_{nl} are presently in the range of 300 or so, but should improve to O(a few) in the not-too-distant future.

3.4 F and D-strings as cosmic strings

Conventional cosmic strings are topological defects that occur as a consequence of spontaneous symmetry breaking (SSB), typically of a global or local $U(1)$. They may have very long lifetimes forming a network that approaches a scaling regime with a few tens of Hubble-size strings and many small loops in each Hubble volume. They are characterized by a tension μ or, better, by the dimensionless quantity $G\mu$, where G is Newton's constant. There are upper bounds on $G\mu$ coming from various arguments (contribution of cosmic strings to CMB anisotropies, pulsar timing, $\dots$) at the 10^{-7} level. There are also claims of detection of cosmic strings via their peculiar gravitational lensing, suggesting[1] a $G\mu$ of order 4×10^{-7}.

In some brane-world models fundamental(F) and Dirichlet(D)-strings are produced [25] at the end of inflation (with the separation of a brane-antibrane pair playing the role of the inflaton [26]). They can be long-lived and have a small enough $G\mu$ but not far below the experimental upper bound of $10^{-6} - 10^{-7}$. Even with $G\mu \sim 10^{-7}$ strings can be a powerful source of GW because of

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[1] More recently such evidence seems to have faded away.

the cusps they form while they oscillate [27]. Calculations [27] show that, even at $G\mu \sim 10^{-9}$, the GW signal from the cusps can be within (at least advanced) LIGO's sensitivity. Finally, F and D GW signals can be possibly distinguished from those of more conventional cosmic strings. Damour and Vilenkin [27] have also worked out the stochastic GW signal from oscillating string loops. The results depend on yet unknown parameters but, optimistically, pulsar-timing experiments and LISA –if not already advanced versions of LIGO-VIRGO– could possibly detect such a GW signal.

3.5 Cosmic Acceleration (dark energy)

Evidence of a recent cosmic acceleration [28] is probably the deepest puzzle theoretical physics has encountered since the birth of QM. The problem was there even before cosmic acceleration was found: it just got worse. The puzzle is not unlike the one facing Max Planck when he realized that the total power emitted by a classical black body is infinite. In QFT, vacuum energy (the obvious candidate for cosmic acceleration) is badly ultraviolet divergent and should be somehow regulated. Yet, any reasonable value for the UV cut-off would normally induce much-too-large a cosmological constant . . . unless there are smart cancellations. This has been a long-standing puzzle for theorists.

Since we do not know how the UV cut-off works we cannot draw any solid prediction on the expected amount of loop-generated vacuum energy. The one consistent UV-finite theory we know is superstring theory and has a vanishing cosmological constant (but also unbroken SUSY) to all orders in perturbation theory. We used to ask:

Q1: Is it possible that non-perturbative effects break SUSY without introducing a cosmological constant? A positive answer to the question was, I guess, the string-party-line, until evidence for cosmic acceleration came out. The new question is:

Q2: Is it possible that non-perturbative effects break SUSY while giving a tiny cosmological constant?

One thing to bare in mind while discussing the issue is the UV-IR connection stemming from an almost trivial dimensional argument. The most relevant parameters at low energy have positive (mass) dimensions $d > 0$ (e.g. the cosmological constant, the Planck mass, mass terms); next come the dimensionless parameters (gauge and Yukawa couplings, for instance) with $d = 0$, and, finally, the "irrelevant" parameters with $d < 0$. Each one of these, a priori, receive quantum corrections that scale as Λ_{UV}^{d}. This means that the *most* relevant parameters are *most* sensitive to the UV completion of the theory and thus *most* difficult to predict from any effective field theory approximation. The latter may mask subtle cancellations that depend on the full structure of the theory. The third question is therefore:

Q3: Is this the case for the Higgs mass and the cosmological constant? In the case of an affirmative answer, the case for TeV-scale supersymmetry becomes much less compelling.
Actually the situation for the cosmological constant $\Lambda_{\cos}$ is even worse. Its "measured" value raises several formidable questions:

- Why is $\Lambda_{\cos}$ not much larger than what is observed?
- Why is it not much smaller?
- Why is it just $O(\rho_{cr})$ now? This is the (in)famous coincidence problem.

Tentative answers can be classified in two groups:

- 1. Explain acceleration with dark energy;
- 2. Explain acceleration without dark energy.

3.5.1 Explain acceleration with dark energy

This case splits itself into subclasses:

- 1.1 Dark energy is a bona-fide $\Lambda_{\rm cos}$ (i.e. with equation of state $w \equiv p/\rho = -1$).

  Smallness of $\Lambda_{\rm cos}$ can be argued along different lines:

  1.1.1 SUSY breaking leads to $\rho_{vac} \sim M_{susy}^4 (M_{susy}/M_P)^p$ with some sizeable positive p;

  1.1.2 Anthropic explanation (Cf. S. Weinberg's 1987 "prediction" [29]). This has become a popular attitude in some string-theory circles (the "landscape" craze).

- 1.2 Dark energy is the (residual) potential energy of a light scalar field [30] Q, still slowly rolling down (with equation of state $w \equiv p/\rho \neq -1$, in general).

  In turn one may have:

  1.2.1 Decoupled quintessence (normal ΛCDM models);

  1.2.2 Coupled quintessence (Q couples to CDM, alleviating the coincidence problem [31]).

Quintessence does not really solve the cosmic acceleration problems much better than Λ_{cos} can. Its main advantages are:

- It allows for a strictly vanishing Λ_{cos}, for which we may find, one day, a theoretical explanation;
- It allows for $w > -1$, just in case experiments will show that such is the case;
- The coincidence problem is slightly alleviated (a little better by coupled Q, see above).

On the other hand, since Q is a very light scalar field, one has to watch for possible Q-induced violations of the Equivalence Principle in particular of universality of free-fall on which strong bounds (at the level of 10^{-12} exist. A dilaton- runaway scenario where these violations (as well as variations of "constants") are kept below (but not much below) present bounds has been proposed [32].

3.5.2 Explain acceleration without dark energy

Also this class splits into two subclasses:

- 2.1 Acceleration is produced without modifying gravity , using inhomogeneities inside horizon [33] and the fact that averaging solutions of the Einstein equations is not like solving Einstein's equation for the average metric [34] (in formulae $\langle G_{\mu\nu}(g)\rangle \neq G_{\mu\nu}(\langle g \rangle)$). Such an explanation would be excellent for relating acceleration to the present epoch. Unfortunately, it looks unlikely that the effect of inhomogeneities will be as large as experimentally needed;
- 2.2 Acceleration is due to a modification of gravity at large distance. This can occur in some brane-world scenarios with large extra dimensions, like the one proposed in [35]. It is still unclear whether such models do pass all the necessary consistency checks.

4. Conclusion

Cosmology has entered its own golden age since COBE released its first data on CMB about 15 years ago:

- Improvement in quality and quantity of the data has been spectacular (Cf. WMAP vs. COBE);
- Cosmological parameters are being pinned down with increasing precision, making cosmology a truly quantitative science;
- There have been striking discoveries in the field:
  - Some expected, like Black Holes, and Gravity Waves;
  - Some unexpected, like Dark Matter, UHECR, Dark Energy;
- and we are probably just at the beginning ...

Following yesterday's example by David Gross, I will quote myself on a prophecy. Here is the end of my summary talk at the ICHEP held Warsaw in 1996:

If our field is to keep thriving, we cannot afford the luxury of ignoring any relevant scientific input wherever it may come from: LEP, HERA, COBE, LIGO ... or a conceptual problem in Quantum Gravity. We have to work, hand in hand, theorists and experimentalists, accelerator and astro-physicists, stressing to ourselves –and to the public opinion whose moral and material support we seek– the

BASIC UNITY OF FUNDAMENTAL PHYSICS

This is even more true today than it was nine years ago: furthermore, as time goes on, that wish seems to be slowly getting fulfilled ...

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