LHC, SSC and the Universe

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ABSTRACT

The geometric mean of the Planck mass and the 2.7^0K background temperature - numerically equal to about a TeV - is the maximum mass that any cosmologically stable perturbatively coupled elementary particle can have or else the density of the Universe exceeds its critical value. Thus, the TeV scale is cosmologically significant for reasons unrelated to the scale of electroweak symmetry breaking; it would persist even if the masses of the W and Z vanished. This implies that the TeV scale emerges cosmologically in many extensions of the Standard Model involving new particles and forces. We derive, for example, upper limits of order of a few TeV to the mass of the lightest supersymmetric particle LSP as well as to the masses of new $U'(1)$ gauge bosons and their associated stable electroweak singlets that can occur in superstring theories. Any dark matter candidate that is perturbatively coupled must also weigh less than a few TeV. Thus, cosmology implies that all these particles should be accessible to multi-TeV colliders. In particular, the dominant dark component of the Universe and its charged electroweak partners could be discovered in such machines. These ideas suggest a cosmological argument for a desert commencing near a TeV. They have implications for unified and superstring models. For example, new $U'(1)$ s accompanied by stable electroweak singlets have to be lighter than a few TeV; they therefore must commute with family rotations or else be in conflict with the $K_L - K_S$ mass difference.

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1. INTRODUCTION

The LHC and the SSC are designed to unravel the mechanism of electroweak symmetry breaking. In this paper we argue that these accelerators have a good chance of discovering much more. We show that any perturbative new physics with cosmologically stable remnants has to occur below a few TeV. The single ingredient from which these conclusions follow is the cosmological requirement that the density of the Universe does not exceed its critical value.

2. TEV FROM COSMOLOGY

Consider a particle X of mass m that is cosmologically stable, *i.e.* its lifetime exceeds the age of the Universe. We begin with an elementary derivation of the contribution of this particle to the density of the Universe [1]

$$\Omega_x \equiv \frac{\rho_x}{\rho_c} \simeq \frac{mn_{xo}}{2 \times 10^4 h_0^2 T_0^4} \quad (1)$$

where ρ_c = critical density of the Universe, $T_0 = 2.7^0 K$ = photon temperature today, n_{xo} = number density of X s today, and $0.4 \leq h_0 \leq 1$ parametrizes the uncertainty in the Hubble parameter. The number of X s per photon has remained approximately constant since the freeze-out temperature T_f below which X s do not annihilate [2]:

$$\begin{aligned} \frac{n_{xo}}{T_0^3} &\simeq \frac{n(T_f)}{T_f^3} \\ n(T_f)\langle\sigma v\rangle &\sim \frac{\dot{R}}{R} \sim \frac{T_f^2}{M_{PL}} \end{aligned} \quad (2)$$

where $M_{PL} = \text{Planck Mass} \simeq 10^{19} \text{ GeV}$, $\sigma = X$'s annihilation cross-section. For

$T_f \lesssim m$, we substitute the Boltzmann formula for $n(T_f)$ and find

$$\frac{m}{T_f} = \lg \frac{M_{PL}}{\mu} \simeq 20 - 28 \quad (3)$$

where $\mu = \frac{T_f^{1/2}}{m^{1/2}\langle\sigma v\rangle}$ is typically of order of $10^7 - 10^{10} \text{ GeV}$ for electroweak cross-sections and masses m in the GeV to TeV range. Combining the above equations, we get

$$\Omega_x h_0^2 \simeq \frac{1}{10^3 \langle\sigma v\rangle} \frac{1}{M_{PL} \times 2.7^0 K} \simeq \frac{1}{10^3 \langle\sigma v\rangle} \frac{1}{T_e V^2} \quad (4)$$

where we used

$$T_e V \simeq \sqrt{M_{PL} \times 2.7^0 K} \quad (5)$$

Equation (5) clearly shows how the TeV scale emerges in cosmology [3] in a way that has nothing to do with the masses of the W and Z . It suggests that the TeV scale emerges cosmologically in a host of applications where the particles and forces involved know nothing of the W and Z masses. We demonstrate this statement in the applications that follow. Sections 3 through 6 are distilled summaries of earlier results.

3. MAXIMUM MASS FOR ANY PERTURBATIVELY COUPLED COSMOLOGICALLY STABLE PARTICLE

Consider first a general particle X that annihilates with its antiparticle into particles and via intermediate particles of much smaller mass. For example, X could be any stable particle with strong and/or electroweak quantum numbers that is heavier than the Z boson. What is the heaviest such a particle can be? Can it be so heavy that it is inaccessible to multi-TeV accelerators?

Since X is the heaviest particle in the problem, its self-annihilation cross-section is

$$\sigma v \simeq \frac{c\alpha^2}{m^2} \quad (6)$$

Here $\alpha = \frac{g^2}{4\pi}$ is the coupling that dominates annihilation. For an electroweak particle $\alpha = \alpha_2$. C is a model-dependent factor that depends on the group theoretic representation of X , the number of annihilation channels, etc. It is typically of order of a few [4]. Combining Eqs. (5) and (6), we get [5]:

$$\begin{aligned} m &\simeq \sqrt{M_{PL} \times 2.7^{0K}} \quad 16\alpha\sqrt{C} \quad \sqrt{\frac{O_x h_0^2}{0.25}} \\ &\simeq TeV \quad 16\alpha\sqrt{C} \quad \sqrt{\frac{O_x h_0^2}{0.25}} \end{aligned} \quad (7)$$

From these equations, we clearly see that for any perturbatively coupled particle, with $g \lesssim 1$ and $\alpha \lesssim (4\pi)^{-1}$, its mass cannot exceed [5]

$$m \lesssim \frac{\sqrt{10C}}{2} TeV \lesssim 5 TeV \quad (8)$$

and should thus be accessible to multi-TeV machines. In particular, any cosmologically stable particle, such as a dark matter candidate, should weigh less than a few TeV provided its properties, such as abundance etc., can be computed in perturbation theory.

4. MAXIMUM MASSES FOR STABLE PARTICLES IN THE STANDARD MODEL

Consider a stable quark or lepton. How heavy can it be without overclosing the Universe? Can it be so heavy that it is inaccessible even to the multi-TeV colliders?

First of all, a quark or lepton whose masses break $SU_{2\text{weak}}$ can never be heavier than $500 GeV$ [6] without implying new physics below 1 TeV [6]; such physics would probably involve a new strong interaction sector and would clearly be a bonanza for multi-TeV machines. The arguments proving this involve the renormalization group [6] and have nothing to do with cosmology.

Quark and lepton masses can exceed $500 GeV$ without implying any strongly coupled sub-TeV sector provided they do not break $SU_{2\text{weak}}$ [7]. In this case the cosmological arguments of the previous section give the following upper bounds [4]:

For quarks [8]:

$$\begin{aligned} \mathcal{M}_Q &\leq 10.7 \sqrt{O h_0^2} TeV \\ &\leq 5.35 TeV \end{aligned} \quad (9)$$

for leptons [8]:

$$\begin{aligned} \mathcal{M}_L &\leq 4.4 \sqrt{O h_0^2} TeV \\ &\leq 2.2 TeV \end{aligned} \quad (10)$$

Actually existing dark matter search experiments [9] already exclude the maximum masses [4] and set slightly better limits than (10) and (9). Thus all such particles are accessible to the multi-TeV colliders.

5. TEV DARK MATTER

The possibility that the dark constituents of the Universe will be discovered at SSC or LHC is very fascinating. The previous section shows that this is a likely possibility.

The minimal standard model has no candidates for non-baryonic dark matter. Perhaps the most economical extension of the standard model [1] had a $\simeq 2 \text{ GeV}$ neutrino as the dark particle. Unfortunately, it has been excluded by SLC and LEP. The next simplest possibility is to have a heavy $\simeq \text{TeV}$ zero electric charge object [4]. It is interesting that existing dark matter searches [9] completely exclude such an object unless it also has zero hypercharge. The simplest such particle belongs to an $SU_{2\text{weak}}$ isotriplet with zero hypercharge. Its mass is [4]:

$$\begin{aligned} \mathcal{M}_{\text{dark}} &= 6.6 \sqrt{\Omega h_0^2} \text{ TeV} \\ &\simeq 3.3 \text{ TeV} \end{aligned} \quad (11)$$

It has two electrically charged electroweak partners that are only $\simeq 300 \text{ MeV}$ heavier.

Will dark matter detectors be able to detect directly such a zero hypercharge dark candidate? Such particles do not couple via a single Z^0 exchange because they have vanishing I_3 and Y ; this is precisely the reason they have not already been seen. They do interact with ordinary matter via the two- W exchange [4]. Their interaction cross-sections with nuclei are therefore down by at least four orders of magnitude; they are difficult to detect via dark matter detectors.

It is therefore interesting that multi-TeV colliders are more likely to reveal at least some dark particle candidates than the direct dark matter detectors themselves.

Next we come to TeV dark matter candidates that can occur in supersymmetric theories.

6. MAXIMUM MASS OF THE LIGHTEST SUPERSYMMETRIC PARTICLE (LSP)

Baryon number conservation in SUSY theories is simply guaranteed via a symmetry that stabilizes the LSP [10]. The most likely candidates for LSP are colourless, neutral particles such as the neutralino or sneutrino; they typically have couplings equal to α_2 . What is the heaviest the LSP can be? Can we push its mass beyond the reach of multi-TeV colliders? Once it is heavier than the Z , it will decay into and via W and Z bosons to which it couples with strength $\sim \alpha_2$ [11]. Thus Eq. (7) with $\alpha = \alpha_2$ is applicable and gives a limit of

$$\begin{aligned} m_{\text{LSP}} &\simeq \text{TeV} \quad 16\alpha_2 \sqrt{C} \\ &\simeq \text{TeV} \end{aligned} \quad (12)$$

Thus we see that an upper limit of a TeV or so to the mass of the LSP is easily obtained from cosmology [12,13]. Such an upper limit cannot be obtained via particle physics since there we can increase the LSP mass to 10^3 TeV or more as long as we are willing to tolerate increasingly more fine tunings of parameters [10]; how much fine tuning is too much is a matter of taste and there is no well-defined threshold beyond which a fine-tuning becomes intolerable. An LSP with a mass of order 1 TeV is a good candidate for the dark matter of the Universe.

7. MAXIMUM MASS OF A NEW $U''(1)$ GAUGE BOSON

Low-energy theories emerging from superstrings frequently have an additional $U''(1)$ gauge boson with coupling constant $g' \sim g_1$ and mass M' that can be near the weak scale. Consider such a theory with a cosmologically stable Dirac fermion X that has a mass m and carries no gauge quantum number other than $U''(1)$ [14]. A simple example is: $U''(1) = U(1)_{B-L}$ is the extra $U(1)$ of $SO(10)$ that commutes with $SU(5)$ and X is the $SU(5)$ singlet right-handed neutrino together with an $SO(10)$ singlet Dirac partner that is in $E(6)$. An upper limit of order of a TeV on both M' and m can be obtained as follows. If $M' < m$, Eq. (7) is applicable with $\alpha \sim \alpha_1$ and thus both $M' < m < 1$ TeV or so; if $M' > m$ then the annihilation cross-section for Xs is [15]

$$\sigma v \sim \frac{g'^4}{32M'^4} m^2 \quad (13)$$

Combining this with (4) we get

$$m < M' < \sqrt{\frac{\Omega_x h_0^2}{32}} g'^2 (300 \text{ TeV}) \quad (14)$$

Taking $\Omega_x h_0^2 \leq 0.25$ [5], we obtain (setting $g' \sim g_1 \sim 1/3$)

$$m < M' \lesssim 3 \text{ TeV} \quad (15)$$

Both X and the $U''(1)$ gauge bosons should be accessible at multi-TeV colliders. A TeV mass electroweak singlet X is a good dark matter candidate.

8. $K_L - K_S$ MASS DIFFERENCE, COSMOLOGY AND LOW ENERGY $U''(1)$

Another important application of these ideas is to constrain and exclude proposed theories. The analysis of the previous section gave upper bounds to the masses of both the stable X as well as the unstable $U''(1)$ gauge boson that directly couples to light quarks and leptons. Thus cosmology puts a lower limit on the size of the effects of such a boson. From Eq. (14) with $\Omega_x h_0^2 \simeq 0.25$ we have

$$\frac{M'}{g'} \gtrsim g' \cdot 20 \text{ TeV} \quad (16)$$

For a $U''(1)$ that does not commute with the family symmetry [14] we typically must have

$$\frac{M'}{g'} \gtrsim 10^3 \text{ TeV} \quad (17)$$

or else the $K_L - K_S$ mass difference is too big [16].

Equations (16) and (17) are in obvious conflict unless g' becomes unacceptably large $g' > 50$.

We thus conclude that such theories, with a cosmologically stable $SU(3) \times SU(2) \times U(1)$ singlet are excluded unless the $U''(1)$ assignments commute with family rotations. This excludes a large class of theories emerging from superstrings [17].

9. MAXIMUM SCALE FOR NEW STRONG INTERACTIONS

Consider a colour-like force that becomes strong at the scale Λ where it forms hadrons of mass $\simeq \Lambda$ and size $\simeq \Lambda^{-1}$. The lightest one will typically be very long-lived, its decay rate suppressed by powers of the grand unification mass. In a pure gauge theory, the lightest hadron will be a glueball; in a theory with fermions, it will be an analogue of the proton. How large can its mass $\simeq \Lambda$ be? The annihilation cross-section for such hadrons is given by their size

$$\sigma v \sim \Lambda^{-2} \quad (18)$$

Thus, from (4)

$$\begin{aligned} \Lambda &\simeq 300 \text{ TeV} \sqrt{O h_0^2} \\ &\lesssim 150 \text{ TeV} \end{aligned} \quad (19)$$

We conclude that a new QCD-like force cannot become strong at a scale above 150 TeV without overclosing the Universe [18]. The stable hadron of such a force with $\Lambda \simeq 150 \text{ TeV}$ would be a good dark particle candidate.

10. THE DESERT BEGINS NEAR A TeV

New sectors in physics typically imply a stable remnant. This is true, for example, in both supersymmetry and technicolour where the LSP and the lightest techni-baryon are stable in most versions. Since stable remnants cannot be much heavier than a TeV, if perturbatively coupled, or heavier than $\simeq 150 \text{ TeV}$ if strongly coupled, these arguments imply that one cannot have new sectors above 150 TeV unless they happen to leave no stable remnant. Of course, by stable, here we mean cosmologically stable, *i.e.*, with lifetimes exceeding the age of the Universe; physics at the Planck scale invariably leads to decays of these particles since their stability is not guaranteed by an absolute conservation law valid at all energies. This point is very important since it shows that one cannot exclude the

possibility of new sectors near the Planck scale; such sectors would simply not have any cosmologically stable particles.

Consider, for example, a new strong force with a characteristic scale Λ . The lightest hadron in such a theory will typically decay via a dimension-six operator with a lifetime

$$\tau \sim \frac{M_{PL}^4}{\Lambda^5} \quad (20)$$

If $\Lambda > 2 \times 10^{12} \text{ GeV}$ such a particle will never dominate the energy density of the Universe. For

$$\Lambda > 3 \times 10^{10} \text{ GeV} \quad (21)$$

it will have decayed before nucleosynthesis commences. This guarantees that the lightest state of the new sector will decay rapidly enough to leave all the solid predictions of the Big Bang theory intact.

We thus see that cosmology suggests the existence of a desert commencing at 150 TeV. For perturbative sectors the desert commences at a few TeV. It is not possible to say, in general, when the desert ends. For particles decaying via Planck-suppressed dimension-six operators, it can end as early as $3 \times 10^{10} \text{ GeV}$; if the decay is caused by lower scale or lower dimension operators, the desert can end sooner, or even be absent.

11. TEV FROM COSMOLOGY: A TIME-INDEPENDENT FORMULA

Equation (5) that shows how the TeV scale emerges in cosmology contains the time-dependent quantity T_0 which today equals $2.7^0 K$. This is because the expression $\rho_c = 2 \times 10^4 \rho_\gamma$ is only valid today.

A cosmological expression for a "TeV" that has no time-dependent quantities can be obtained by writing

$$\rho_c \simeq \underline{Q}_B^{-1} \rho_B h_0^2 = \underline{Q}_B^{-1} \eta h_0^2 m_p T_\gamma^3 \quad (22)$$

where, η is the baryon to entropy ratio. Substituting this in Eqs. (1) to (9), we obtain

$$\underline{Q}_x h_0^2 \simeq \frac{\alpha^2}{m^2 \langle \sigma v \rangle} \frac{m^2}{\alpha^2 \frac{1}{20} \eta \underline{Q}_B^{-1} m_p M_{PL}} \quad (23)$$

The TeV scale emerges because of (6) and

$$TeV \sim \sqrt{\frac{1}{20} \eta m_p M_{PL} \underline{Q}_B^{-1} \alpha^2} \quad (24)$$

which involves no time-dependent quantities.

12. LOOP HOLES, CAVEATS, ETC.

One way to avoid all of the conclusions of this paper is to introduce a new inflaton sector that would inflate the Universe at a temperature of a few hundred GeV. This would dilute the X 's and render them harmless, no matter how heavy they are. The degree of inflation could also be fine tuned to make X 's critically close the Universe and therefore be the dark matter. Of course, such an era of late inflation would also dilute the baryon excess of the Universe; so baryogenesis would need to happen near the weak scale or the amount of inflation should be small, which is unnatural. Such scenarios are extremely unappealing logical possibilities that cannot be excluded. In general, introducing any new physics - not necessarily inflation - that would dilute the density of the X 's, together with that of baryons, near the weak scale would avoid all of our conclusions. If X annihilates via a narrow gauge boson whose mass is very precisely twice that of X , then its mass could exceed a few TeV even though it could not exceed the general unitarity limit of $\simeq 150 \text{ TeV}$ [18].

A purely gravitationally coupled cosmologically stable particle, such as the gravitino, does not obey our constraints; it is also terribly uninteresting since it is undetectable by LHC, SSC or any other direct experiment.

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