4.1 Introduction:

General relativity is a tremendously complex theory, even if we restrict attention to the purely classical regime. The field equations

\( G^{ik} = 8\pi GT^{ik}, \)

On the left hand side, the Einstein tensor \( G^{ik} \) is enough complicated by itself. But, it seems, atleast a universal function of the spacetime geometry. The stress-energy tensor \( T^{ik} \), in contrast, is not universal but depends on the particular type of matter and interactions we select to insert in the model. In view of the above situation, we must either give up to performing an immense catalog of special case calculations, one special case for each conceivable matter Lagrangian we may write down, or attempt to decide on some generic properties that all reasonable stress-energy tensors should satisfy, and then
attempt to use these generic properties to describe general theorems concerning the strong field behaviour of gravitational fields. The key generic property of most matter seems to have always positive energy density. Hawking and Ellis (1973), Wald (1984) Visser (1995) presented a variety of different ways of making notion of locally positive energy density more precisely. The pointwise energy conditions assume the form of assertions that various linear combinations of components of energy momentum tensor should be positive or at least nonnegative. The so-called averaged energy conditions are somewhat weaker, permitting localised violations of the energy conditions, as long as on average the energy conditions hold when integrated along null or timelike geodesics.

The variety of energy conditions are used in the relativity workers are driven by reverse engineering based on the physical and technical requirements of how much they have to assume to prove easily their results. By assuming some form of energy condition, some notion of positivity of the stress-energy tensor, as an input hypothesis, it has been possible to prove theorems circumstances, gravitational collapse and/or the existence of big bang singularity. The positive energy theorem guaranteeing the mass of the complex gravitating system as seen from infinity is always positive, the topological
censorship theorem, guaranteeing nonexistence of traversable wormholes or the superluminal censorship theorem, limiting the extend to which light comes may tip-over in strong gravitational fields. Conversely, the violation of some or all these energy conditions would point towards exotic physical possibilities as presented by Bondi (1957), Morris and Thorne (1988), Visser (1989), Alcubirre (1994).

All known forms of classical matter obey the weak energy condition (WEC)

\[ T_{ik} u^i u^k \geq 0, \]  

for all timelike vector \( u^i \). By continuity, this pointwise condition also holds for all null vectors. Physically, this condition shows that the energy density of matter seen by any observer is non-negative. The weak energy condition is crucial ingredient for proving the focusing of null geodesic congruences in some of the singularity theorems. Two important examples are Penrose's original (1965) theorem. Hawking and Ellis (1973), which gives the occurrence of a singularity at the end point of gravitational collapse, and Hawking (1965) extension of the theorems for inflationary cosmologies and for certain classes of closed Universe as shown by Borde and Vilenkin (1994), Borde (1994).
4.2 The Energy Conditions:

For a Friedmann-Robertson-Walker spacetime and a diagonal stress-energy tensor

\[ R_{ik} = (\rho, -p, -p, -p) \]

with \( \rho \) being the energy density and \( p \) be the pressure of the fluid, the energy conditions read

<table>
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<tr>
<th>S.N.</th>
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<td>Dominant Energy</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho \pm p \geq 0 )</td>
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Then, these are linear relationships between the energy density and the pressure of the matter of fields generating the spacetime curvature. Violations of the energy conditions have sometimes been presented as only being produced by unphysical stress energy tensors. If the null energy condition is violated, and then weak energy condition is violated as well, negative energy densities— and so negative masses—are thus physically admitted. However, although the energy conditions are widely used to prove theorems concerning singularities and black holes thermodynamics, such as the area increase theorem, the topological censorship theorem, and the singularity theorem of stellar collapse as presented by Visser (1996), they lack a rigorous proof from fundamental principles. Moreover, several situations in which they are violated are known, perhaps the most quoted being the Casimir effect. Observed violations are produced by small quantum systems, resulting in the order of $\hbar$. It is currently far from clear whether there could be macroscopic quantities of such as exotic, e.g. weak energy conditions— violating, matter/fields may exist in the Universe. A program for imposing observational bounds (basically using gravitational micro and macrolensing) on the existence of matter violating some of the energy conditions has been already initiated, and experiments are beginning to actively search for predicted signatures.
Worm-hole solutions to the Einstein field equations, extensively studied in the last decade, Visser (1996), Barcelo and Visser (1999, 2000), Sovonova et al (2002), Eirora et al (2001) and others, violate the energy conditions, particularly null energy conditions. Wormholes are probably the most interesting physical entity that could exist out of a macroscopic violation of the energy conditions. It is interesting to analyse what does super quintessence imply concerning the validity of energy condition. Super quintessence is represented by a cosmic equation of state

\[(4.4) \quad p/\rho < -1,\]

and so different situations may come in picture depending on the sign of the energy density \(\rho\). If \(\rho > 0\), superquintessence implies

\[(4.5) \quad p + \rho < 0,\]

and thus the violation of all the pointwise energy conditions quoted above. It is to be noted that weak energy condition is violated because of the violation of

\[(4.6) \quad \rho + p \geq 0.\]

If, on contrary, already \(\rho < 0\), then null energy condition may be sustained, but weak energy condition is violated. Then,
superquintessence implies strong violations of the energy conditions. Calwell (1999) presented that to day superquintessence equations of state are not discarded, and may be even favoured by experimental data. In addition, recently, the consequences of the energy conditions were confronted with possible values of Hubble parameter and the gravitational redshifts of the oldest stars in the galactic halo as shown by Visser (1997). It was deduced that for the currently favoured value of $H_0$, the strong energy condition should be violated sometimes between the formation of oldest stars and the present epoch.

Strong energy condition violation may or may not imply the violation of the more basic energy condition i.e. null energy condition and weak energy condition, something that has been impossible to determine yet to. In any case, superquintesence could be a nice theoretical framework for explaining observational data opposing the energy conditions.

Views have changed as to low fundamental some of the specific energy conditions are, ever the years. One particular energy condition, the trace energy condition

$$\rho - 3p \geq 0,$$

(4.7)
has been completely abandoned and forgotten. The trace energy condition says that the trace of stress-energy tensor must always be negative or positive depending on metric conventions, and was popular for a while during the 1960s. However, one it was thought that stiff equations of state, such as those for neutron stars, violate the trace energy condition, this energy condition fell into disfavour. It has been now completely abandoned and is no longer put as example in literature. We put it here as a concrete example of an energy condition being outright abandoned. This is also general agreement that the strong energy condition is dead:

(a) The most naive scalar field theory we may write down, the minimally coupled scalar field, violates the strong energy condition

\[(4.8) \quad \rho + 3p \geq 0,\]

\[(4.9) \quad \rho + p \geq 0,\]

and indeed curvature-coupled scalar field theories also violate the strong energy condition. There are fermionic quantum field theories where interactions engender strong energy condition violations. The specific models of point-like particles with two-body interactions also violate the strong energy condition.
(b) The strong energy condition must be violated during the inflationary epoch, and need for this strong energy condition violation is why inflationary models are typically driven by scalar inflation fields.

(c) The recent observational data regarding the accelerating Universe, the strong energy conditions are violated on cosmological scales.

(d) Visser (1997) showed that the tension between the age of the oldest stars and the measured present day Hubble parameter makes it very difficult to avoid the conclusion that the strong energy conditions must have been violated in the cosmologically recent past, sometime between redshift 10 and the present.

Under these situations it would be rather quixotic to take the strong energy conditions seriously as fundamental physics

\begin{align*}
\rho + p &\geq 0, \\ &\quad (4.10) \\
\rho &\geq, \quad \rho_p \geq 0, \\ &\quad (4.11) \\
\rho &\geq 0, \quad p \in [-\rho, +\rho], \\ &\quad (4.12)
\end{align*}
are on the verge of dying. Over the last decade, or so it has become obvious that there are quantum effects that are capable of violating all the energy conditions, even the weakest of the standard energy conditions. Despite the fact that they are moribund, for lack of truly successful replacements, the null energy conditions, weak energy conditions, and dominant energy conditions are still extensively used in general relativity. The weakest of these is the null energy condition, and it is in many cases also the easiest to work with and analyse. The standard wisdom for many years was that all reasonable forms of matter should at least satisfy the null energy condition. It became now clear that the null energy conditions or even the average null energy condition was violated by quantum effects:

(a) Many workers simply decided to ignore quantum mechanics, relying on the classical null energy condition to prevent grossly weird physics in the classical regime, and hoping that the long sought for quantum theory of gravity would eventually deal with the quantum problems. It is not really satisfactory response in that null energy condition violations already show up in semiclassical quantum gravity where as quantise the matter fields and keep gravity classical, and show up at first order in $\hbar$. Since semiclassical gravity (quantum) is certainly a good approximation, it is somewhat disturbing to see
widespread violations of the energy conditions. However, to avoid the conclusion that quantum effects may and do lead to locally negative energy densities, and even violations of the average null energy condition, requires truly radical surgery to modern physics.

(b) Ford and Roman (1995) presented quantum inequalities based on the fact that while quantum-induced violations of the energy conditions are widespread they are also small, and on the observation that a negative energy in one place and time always seems to be compensated by positive energy elsewhere in spacetime. This is known as Quantum Interest Conjecture. While the positive payback is not enough to prevent violation of the average null energy condition i.e. based on averaging the null energy condition along a null geodesic, the hope is that it will be possible to prove more improved type of spacetime averaged energy condition from first principles, and that such spacetime averaged energy condition might be sufficient to enable us to recover the singularity/positive mass/censorship theorems under weaker hypothesis than currently used.

Bekenstein (1974, 1975), Deser (1984), Flanagan and Wald (1996) presented that a fundamental problem for this type of approach that is now becoming acute is the realisation that there are also serious
classical violations of the energy conditions. Recently, it has become obvious that there are quite reasonable looking classical systems, field theories that are compatible with all known experimental data, and that are in some sense very natural from a quantum field theory point of view, which violate all the energy conditions. Because these are now classical violations of energy conditions they may be made arbitrarily large, and seem to lead rather weird physics. For example, it is possible to demonstrate that Lorentzian-signature traversable wormholes arise as unstable classical solutions of the field equations. These classical energy condition violations are due to the behaviour of scalar fields when coupled to gravity.

There is another area in which one is confronted with energy condition violations namely negative tension braneworlds. Negative tension branes provide classical violations of all energy conditions in higher dimensional spacetime.

4.3 The Energy Conditions and Density Bounds:

Let us consider the standard FRW model which is described by the metric

\[
(4.13) \quad ds^2 = -dt^2 + a(t)^2 \left[ \frac{dr^2}{1-kr^2} + r^2 \left( d\theta^2 + \sin^2 \theta d\phi^2 \right) \right]
\]
with

\[ k = \begin{cases} 
+1, & \text{closed}, \\
0, & \text{flat}, \\
-1, & \text{open}. 
\end{cases} \]  

(4.14)

The two nontrivial components of Einstein equations read

\[ \rho = \frac{3}{8\pi G} \left( \frac{\dot{a}^3}{a} + \frac{k}{a^2} \right), \]

(4.15)

\[ p = \frac{1}{8\pi G} \left( 2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a} + \frac{k}{a^2} \right). \]

(4.16)

They may be combined to obtain the conservation of stress energy

\[ \dot{\rho} = -3\frac{\dot{a}}{a}(\rho + p). \]

(4.17)

Let us discuss some consequences of the energy conditions:

1. **The null energy condition (NEC):**

   It is sufficient to guarantee that the density of the Universe decreases at its size increases.

\[ NEC \iff \text{sign}(\dot{\rho}) = -\text{sign}(\dot{a}) \]

(4.18)
It is obtained from the equation of stress-energy conservation combined with the definition of the null energy condition. It one violates the null energy condition the density of the Universe must grow as the Universe grows- so something has gone very seriously wrong. In particular, not even a cosmological constant will let one violate the null energy condition. It is to be noted that one may not even need to know if the Universe is spatially open, flat, or closed to obtain this result. In view of null energy condition

\begin{equation}
\rho \geq -p.
\end{equation}

If \( p = 0 \), we get

\begin{equation}
\rho \geq 0.
\end{equation}

(ii) **The weak energy condition:**

\begin{equation}
\text{WEC} \iff \rho \geq 0 \quad \text{and} \quad (\rho + p) \geq 0.
\end{equation}

It gives us that the density is not only nonincreasing, it is positive. In a FRW model the weak energy condition does not give any stronger bound on the energy density as a function of scale parameter.

(iii) **The strong energy condition:**

In view of Einstein equations, one may obtain
(4.22) \[ \frac{d}{dt}(\rho a^2) = -a\dot{a}(\rho + 3p), \]

Hence,

(4.23) \[ SEC \Leftrightarrow \text{sgn}\left[\frac{d}{dt}(\rho a^2)\right] = -\text{sgn}(\dot{a}). \]

It gives that

(4.24) \[ SEC \Rightarrow \rho(a) \geq \rho_0\left(\frac{a_0}{a}\right)^2 \text{ for } a < a_0, \]

which is in terms of redshifts

(4.25) \[ \text{Strong energy condition } \Rightarrow \rho(Z) \geq \rho_0(1+Z)^2, \]

where the subscript zero stands for present day values, and the strong energy condition gives us with a model-independent lower bound on the density as one extrapolates to the big bang. This bound is again being independent for \( k = 1, 0, -1. \)

Let us consider the quantity \((\rho + 3p),\) we get

(4.26) \[ +3p = -\frac{3}{8\pi G}\left(\frac{\ddot{a}}{a}\right) \]

It gives
(4.27) \[ SEC \Rightarrow \ddot{a} < 0. \]

In otherwords, the strong energy condition gives that the expansion of the Universe is decelerating, and this result holds independent of whether the Universe is open, flat, or closed. Let us define a decelerating parameter

(4.28) \[ q = -\frac{\ddot{a}a}{a^2}, \]

and in this case

(4.29) \[ SEC \Rightarrow q > 0. \]

In particular, any analysis of galaxy distribution that implies a negative deceleration parameter also implies, ipso facto, violations of the strong energy condition, as shown by Misner, Thorne and Wheeler (1973). It is to be noted that these SEC violations are all by definition going on at relatively low redshift \( z < 7 \), since there are no viable galaxies beyond this range.

Let us define critical density

(4.30) \[ \rho_{\text{critical}} = 3H^2/(8\pi G), \]

one obtains
(4.31) \[ q = \frac{1}{2} \left( \frac{\rho + 3p}{\rho_{\text{critical}}} \right). \]

(iv) **Dominant Energy Condition (DEC):**

Let us evaluate

(4.32) \[ \frac{d}{dt} (\rho a^6) = 3a^5 \dot{a} (\rho - p). \]

Hence,

(4.33) \[ DEC \Rightarrow \text{sgn} \left[ \frac{d}{dt} (\rho a^6) \right] = + \text{sgn} (\dot{a}). \]

Therefore, the DEC gives an upper bound on the energy density

(4.34) \[ DEC \Rightarrow \rho (a) \leq \rho_0 \left( \frac{a_0}{a} \right)^6 \quad \text{for} \quad a < a_0. \]

In terms of redshifts, it gives

(4.35) \[ DEC \Rightarrow \rho (z) \leq \rho_0 (1 + z)^6. \]

(v) **Standard Toy Models:**

Let us compare these bounds to the standard toy models for the density: dust, radiation and cosmological constant. One obtains
Again for a mixture of dust, radiation and cosmological constant types of matter, we obtain

\[ \rho(z) = \rho^0_{\text{critical}} \left[ \Omega_{\text{dust}} (1+z)^3 + \Omega_{\text{rad}} (1+z)^4 + \Omega_{\Lambda} \right]. \]

It gives the definition of the partial \( \Omega \) parameters: \( \Omega_{\text{dust}}, \Omega_{\text{rad}}, \Omega_{\Lambda} \). Hence, we get

\[ \Omega = \Omega_{\text{dust}} + \Omega_{\text{rad}} + \Omega_{\Lambda}. \]

It is to be noted that

\[ (\rho + 3p)_{\Lambda} = -2\rho_{\Lambda}, \]

\[ (\rho + 3p)_{\text{dust}} = \rho_{\text{dust}}, \]

\[ (\rho + 3p)_{\text{rad}} = 2\rho_{\text{rad}}. \]

Hence, if we restrict to mixtures of these three types of matter, the deceleration parameter reads
(4.44) \[ q_0 = \frac{1}{2} \Omega_{\text{dust}} + \Omega_{\text{rad}} - \Omega_{\Lambda}. \]

4.4 Look-back time as a function of Redshift:

Let us consider the look-back time as a function of redshift and define look-back time

(4.45) \[ \tau = \left| t - t_0 \right| \]

as the difference between the age of the universe when a particular light ray was emitted and the age of universe now as we are receiving it. Now, we obtain

(4.46) \[ \tau(a; a_0) = \left| t - t_0 \right| = \int_{a_0}^{a} \frac{da}{a(a)}. \]

One may obtain an upper bound on look-back time by fixing a lower bound on a, whereas from an upper bound on a one obtains lower bound on the look-back time.

(i) Strong Energy Condition:

As the strong energy condition implies that the expansion is decelerating i.e.
(4.47) \[ SEC \Rightarrow \tau(a; a_0) \leq \frac{a-a_0}{\dot{a}(a_0)}. \]

Hence,

(4.48) \[ SEC \Rightarrow \tau(a; a_0) = |t-t_0| \]

\[ \leq \frac{1}{H_0} \frac{a_0-a}{a_0}, \]

and this relation being independent of whether k = 1, 0, -1. In terms of redshift, we obtain

(4.49) \[ SEC \Rightarrow \tau(z) = |t-t_0| \]

\[ \leq \frac{1}{H_0} \frac{z}{1+z} \leq \frac{1}{H_0}, \]

which gives upper bound on the Hubble parameter

(4.50) \[ SEC \Rightarrow \forall z; H_0 \leq \frac{1}{\tau(z)} \frac{z}{1+z} \leq \frac{1}{\tau(z)}. \]

(ii) **Null Energy Condition for k = 0:**

For a spatially flat universe i.e. k = 0, we easily obtain

(4.51) \[ \frac{\dot{a}}{a} = H(a) \leq H_0 (t_0-t) \]
In terms of redshift

\[(4.52) \quad NEC + (k = 0) \Rightarrow \tau = |t - t_0| \leq \frac{\ell n(1 + z)}{H_0}, \]

\[(4.53) \quad NEC + (k - 0) \Rightarrow \forall \; z; H_0 \leq \frac{\ell n(1 + z)}{\tau(z)}. \]

(iii) Dominant Energy Condition for \( k = 0 \):

The DEC gives us with a upper bound on the energy density and hence an upper bound on the rate of expansion.

\[(4.54) \quad DEC + (k = 0) \Rightarrow \left( \frac{\dot{a}}{a} \right)^2 \leq H_0^2 \left( \frac{\pi a_0}{a} \right)^6. \]

Integrating this constraint

\[(4.55) \quad DEC + (k = 0) \Rightarrow \tau = |t - t_0| \geq \frac{1}{3H_0} \]

\[\frac{a_0^3 - a^3}{a_0^3} \leq \frac{1}{3H_0}.\]

In terms of redshift, one obtains
(4.56) \[ DEC + (k = 0) \Rightarrow \tau = |t - t_0| \]

\[ \geq \frac{1}{3H_0} \left( 1 - \frac{1}{(1 + z)^3} \right) \leq \frac{1}{3H_0}, \]

(4.57) \[ DEC + (k = 0) \Rightarrow \forall z; H_0 \geq \frac{1}{3\tau(z)} \left( 1 - \frac{1}{(1 + z)^3} \right) \leq \frac{1}{3\tau(z)}. \]

If one may evaluate \( \tau(\infty) \), the look-back time all the way to the big bang, then

(4.58) \[ DEC + (k = 0) \Rightarrow H_0 \geq \frac{1}{3\tau(\infty)}. \]

(iv) Some Standard Results:

(a) Dust case

(4.59) \[ Dust + (k = 0) \Rightarrow \tau = |t - t_0| \]

\[ = \frac{2}{3H_0} \left( 1 - \frac{1}{(1 + z)^{3z}} \right) \leq \frac{2}{3H_0}, \]

(4.60) \[ Dust + (k = 0) \Rightarrow \forall z; H_0 \]
\[
\tau = |t - t_0| = \frac{1}{2H_0} \left(1 - \frac{1}{(1 + z)^2}\right) \leq \frac{1}{2H_0},
\]

(b) Radiation Case:

Radiation + \((k = 0)\) \Rightarrow

\[
H_0 = \frac{1}{2\tau(z)} \left(1 - \frac{1}{(1 + z)^2}\right) \leq \frac{1}{2\tau(z)}.
\]

(c) Linear Fluid Case:

Let us define linear fluid by the equation of state

\[
p = \gamma \rho,
\]

with \(\rho > 0\) and \(\gamma \in [-1, +1]\) to satisfy the dominant energy condition, and strong energy condition is violated over the range of \(\gamma \in [-1, -1/3]\), where as the fluid is normal in the range \(\gamma \in [-1/3, +1]\). One may obtain for linear fluid implies that
(4.64) \[ \text{Linear fluid} \Rightarrow \rho = \rho_0 (1 + z)^{3(1+\gamma)}, \]

(4.65) \[ \text{Linear fluid} + (k = 0) \Rightarrow \tau = |t - t_0| \]

\[ = \frac{2}{3} (1+\gamma) H_0 \left[ 1 - \frac{1}{(1+z)^{3(1+\gamma)/2}} \right], \]

\[ \leq \frac{2}{3} (1+\gamma) H_0, \]

Linear fluid + \( (k = 0) = \forall \xi; \)

(4.66) \[ H_0 = \frac{2}{3} (1+\gamma) \tau(z) \left( 1 - \frac{1}{(1+z)^{3(1+\gamma)/2}} \right) \]

\[ \leq \frac{2}{3} (1+\gamma) \tau(z). \]

For \( \gamma = -1 \) is a cosmological constant, and for suitable choice of the other cosmological constant may lead to hesitation universe as presented by Misner, Thorne and Wheeler (1973). For the range

(4.67) \[ \gamma \in (-1, -1/3), \]

describes loitering Universe. The point \( \gamma = -1/3 \) corresponds to the low density closed Universe, while
(4.68) \( \gamma \in (-1, 0) \)

describes the decaying cosmological constant

(d) de Sitter Case:

Let us consider the case of no other matter only with cosmological constant

(4.69) \( \text{de Sitter } + (k = 0) \Rightarrow \tau = |t - t_0| \)

\[ = \frac{\ell r (1 + z)}{H_0}, \]

(4.70) \( \text{de Sitter } + (k = 0) \Rightarrow \forall z : H_0 = \frac{\ell r (1 + z)}{\tau (z)}. \)

(e) Milne Universe Case:

The Milne Universe is intrinsically open, \( k = -1 \) and with metric

(4.71) \( ds^2 = -dt^2 + t^2 \left[ \frac{dr^2}{1 + r^2} + r^2 (d\theta^2 + \sin^2 \theta d\varphi^2) \right] \)

It is now obvious

\( \text{Milne } \Rightarrow \tau(a; a_0) = |t - t_0| = \frac{1}{H_0} \left( \frac{a_0 - a}{a_0} \right), \)
\[(4.72) \quad \text{Milne} \Rightarrow \forall z; H_0 = \frac{1}{\tau(z)} \frac{z}{1+z} \leq \frac{1}{\tau(z)}.\]

### 4.5 Concluding Remarks:

There are several responses to the current state of affairs: either one may lead to live with wormholes, and other strange physics engendered by energy condition violations, or one needs to patch up the theory. A simple way of dealing with all these problems is to banish scalar fields from the theories. Alternatively, one could forbid non-minimal couplings, or forbid trans-Planckian field values. Each one of these particular possibilities is in conflict. The conflict between quantum physics and gravity is now becoming acute. Problems are no longer confined to Planck scale physics but are leaking down to arbitrarily low energies and even into the classical realm. We have presented general relativistic energy conditions and obtained much informations from classical general relativity without enforcing a particular equation of state for the stress energy. It is shown that the energy conditions provide simple and robust bounds on the behaviour of both the density and look-back time as a present discussions that so-called strong energy condition (SEC) is violated at some time between the epoch of galaxy formation and the present showing that no possible