Accelerating Universes
and
The Emerging Landscape of String Theory

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Outline

• Introduction: The Accelerating Universe!
• String Theory and Accelerating Universes
• The Landscape and Conclusions
New Discovery

• The Universe is Accelerating.
• The Rate at which Galaxies are flying apart is increasing with time.
Observational Data

The Universe is Expanding
Noble Prize 2011 Physics

Saul Perlmutter, Brian Schmidt, Adam Reiss
Noble Prize 2011 Physics

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"
The Accelerating Universe

• The Acceleration is surprising.

• Gravity is universally attractive. This suggests that the rate of expansion should be slowing down. Not Accelerating.
A mysterious form of energy must be dominating the universe. We do not know what it is. It is called Dark Energy.
The acceleration is thought to be driven by dark energy, but what that dark energy is remains an enigma - perhaps the greatest in physics today.
How Do We Know That The Universe is Accelerating?

By Observing the Universe at Large

- Cosmic Microwave background
- SuperNovae
- Large Scale Galaxy Surveys
- Hubble Space Telescope
Etc.
Dark Energy and Dark Matter

Most of the Universe is made up of unknown forms of matter and energy:

• 67% : Dark Energy – completely unfamiliar. Must have negative pressure!

• 29% Dark Matter (will be tested at the LHC experiment that is now underway)

• 4% Familiar Baryonic Matter.
Matter and Energy in the Universe: A Strange Recipe

- Baryons: 4 ±1%
- Neutrinos: 0.1% – 5%
- Cold Dark Matter: 29 ± 4%
- CMB: 0.01%
- Dark Energy: 67 ± 6%
Therefore the findings of the 2011 Nobel Laureates in Physics have helped to unveil a Universe that to a large extent is unknown to science. And everything is possible again.
Cosmic Microwave Background Radiation

• Discovered by Penzias and Wilson.

• COBE:

\[ T = 2.728 \pm 0.004 \, K \]

Confidence level of fit better than any terrestrial experiment!
COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE

Theory and observation agree.

Intensity, $10^{-4}$ ergs/cm² sr sec cm⁻¹

Waves / centimeter
• **Temperature Anisotropy:**

Small differences in the temperature of the Cosmic Microwave Background coming to us from different directions in sky have been measured, with a precision:

\[
\frac{\Delta T}{T} \sim 10^{-5} - 10^{-6} \text{ Kelvin}
\]
WMAP Map of the Sky
WMAP: Angular power spectrum
In fitting the data one takes a theoretical model with about six parameters including:

\[ \Omega_{\text{matter}}, \quad \Omega_{DE} \]

- Fraction of energy density in matter
- Fraction of energy density in dark energy
Constraints on $\Omega_\Lambda$, $\Omega_M$ (Kowalski et. Al.)
Kowalski et. Al. Taken From Particle Data Book
WMAP 7 Year Results
The Cosmological Constant

• The leading theoretical candidate for Dark Energy.
• It is the ground state energy density.
• If this energy is positive it gives rise to acceleration
• Consistent with Data (so far)
The Cosmological Constant

Cosmological Constant.
Equation of State:

\[ p = \omega \rho \]

Energy density

Pressure

- Cosmological Constant

\[ p = -\rho \]
\[ \rho > 0, \ p < 0 \]

- This means Dark Energy has negative pressure.
$\rho = w \rho$

Constraints on $\omega$, $\Omega_M$; Blue: SNe, Orange: CMB, Green BAO (Kowalski et. Al. (2008)).
• Negative pressure is strange!

• Intuitively one might have thought it leads to an instability and would cause an implosion.

• Instead, in General Relativity, it leads to acceleration!
Einstein Equation:

\[ \frac{\ddot{R}}{R} = -\frac{4\pi G_N}{3} (\rho + 3p) \]

Cosmological Constant:

\[ \frac{\ddot{R}}{R} = +\frac{8\pi G_N}{3} \rho \]
The Cosmological Constant

• It is well motivated theoretically.
• But required value $2 \times 10^{-29}$ gm/cc very small.
• Of order $10^{-120}$ in Planck units!
• This smallness is the famous Cosmological Constant problem.

(We will have more to say about this later.)
The Harmonic Oscillator
The Harmonic Oscillator
Ground State Energy

Example: Harmonic oscillator

\[ E = E_0 + \frac{1}{2} \hbar \omega \]

• Nothing depends on the constant \( E_0 \) (except for gravity).

• Quantum Mechanics is essential to calculate the answer.
The Cosmological Constant and Gravity

To calculate the cosmological constant from first principles we need a theory of gravity consistent with the rules of quantum mechanics.

Enter String Theory!
The Serpent eats its Tail!

Physics at the longest of distance scales is intimately tied to physics at the shortest of distance scales!
Another Motivation:

Preliminary attempts resulted in no-go theorems saying that string theory could not give rise to accelerating universes.

Gibbons, Maldacena, Nunez
Accelerating Universe in String Theory

Closer Thought Showed that this problem was related to another important problem in String Theory: Moduli Stabilisation.
Moduli Stabilisation

• Typically Many Flat Directions in String Compactifications. (~100)

• Different Sizes and Shapes of the compact space

\[ V(\phi) \]

\[ \phi \]

Physical Parameters, e.g, \( G_N \), vary along these directions
Internal directions

Non-compact directions
• As one moves along the flat directions physical parameters, like $\alpha_{em}, G_N$ change.

• The flat directions correspond to an infinite degeneracy.

• Without a good symmetry reason the degeneracy is lifted.

• But resulting potential is hard to control.
Degeneracy is unusual in Quantum Mechanics.

E.g.

In the double well potential tunneling lifts the classical degeneracy.
Double Well Potential

Quantum Tunneling Lifts Degeneracy
Moduli Stabilisation

• The degeneracy in string theory is due to Supersymmetry.

• A general argument shows that supersymmetry must be broken to get a positive cosmological constant.
Moduli Stabilisation

• Without a good symmetry reason the degeneracy is lifted.
• But resulting potential is hard to control.
In regions of moduli space where the potential can be calculated one gets typically runaway like situations.
The moduli needs to be stabilised at a minimum with a positive value for the potential.
The No-go theorems were a consequence of not stabilising the flat directions.

This was resulting in runaway behavior in the potential.
Flux Compactifications

• A new technical advance was needed.
• Turn on Fluxes along the small extra directions.
• Flux: Generalisations of Magnetic Flux (Including Higher Forms, $F_3, F_4$...)
• Gives extra potential energy depending on size and shape of compactification.
Internal directions

Non-compact directions
**FLUX COMPACTIFICATION**

- Why Does Flux Help?

\[ S = \int \sqrt{g} R d^6 x \]

Any Value of R1, R2 Allowed: Moduli

Torus Is Flat, Curvature Vanishes.
Flux Compactifications

Size Modulus: \( A = R_1 R_2 \)

Shape Modulus: \( R_1 / R_2 \)
Now Choose a Sphere

Area $A = 4\pi R^2$

Turn On Magnetic Field Threading the sphere

Flux: quantised

$\Phi = \int F dA = 2\pi n$
Sphere With Magnetic Flux

Potential energy:

\[ V = \left( -\frac{2}{R^4} + \frac{n^2}{8R^6} \right) \]

Curvature

Flux

\[ R_{min} = \sqrt{\frac{3}{32}} \ n \]
Turn On Magnetic Field

\[ S = \int \sqrt{g} \left( R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right) d^6 x \]

\[ S = \int \sqrt{g} \left( R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right) d^6 x \]

A=R1 R2

Dirac Quantisation :

\[ F_{12} A = N \]

Extra Cost In Energy:

\[ \left( F_{12} \right)^2 A = \frac{N^2}{A} \]
``De Sitter vacua in string theory,''
S. Kachru, R. Kallosh, A. Linde, S. P. Trivedi,

Result:
Positive Values for the Cosmological Constant Can Indeed Arise in String Theory.
The Construction

Has several ingredients:

1) An internal manifold: Calabi-Yau Manifold.

2) Fluxes

3) Non-perturbative effects

4) Anti-Branes.
Subsequent research has focused on understanding these different ingredients in greater depth.

What we have learnt gives greater confidence that the construction, and others like it, do make sense.
• However, the last word has not been said.

• Much more needs to be done to rigorously ensure deSitter vacua do exist in string theory.

• To be totally sure we will probably need a deeper understanding akin to what we have today for negative cosmological constant vacua.
Many, Many, Universes

• Such constructions lead to many different vacua.

• The essential reason is that many different fluxes can be turned on.

• Preliminary estimate,

\[ N_{vac} \sim 10^{100} - 10^{1000} \]

(Douglas, Denef,..).
• \( \sim 100 \) Directions.

• \( \sim 10^{100} - 10^{1000} \) different vacuua.

• Varying cosmological constants.

• Transitions among vacua possible: Through tunneling and possibly due to the thermal fluctuation in deSitter space.
Landscape
Yorkshire Dales
David Hockney: Yorkshire Dales
The Small Value of the Cosmological Constant

Observed value is about $10^{-120}$ in natural units.

The Landscape suggests an “unconventional” explanation for this smallness.
D. Hockney: Looking At A Landscape
An Anthropic Explanation for the Small Cosmological Constant:

• A large range of values is allowed for $\Lambda$
• But values very much bigger than the one observed would not lead to life.
• Galaxies would not form. (Weinberg 1987).
For Small Cosmological Constant,

Number of vacua,

\[ \Lambda = 10^{-120} \]

\[ N(\Lambda) \sim 10^{940} \]
More on the Landscape and Anthropic Principle

• In what sense is this an explanation?
• Is it predictive?
• Do we have to resort to Anthropic Principle for the other constants of Nature as well?
• In what sense then is string theory predictive?
• Who ordered the extra vacuua?
Implications of the Landscape Cont’d

Personal Views:

• An anthropic explanation must be the one of last resort.

• Conventional explanations, e.g. based on symmetries, are superior because they are predictive.

• For the cosmological constant today there is no other reasonable explanation for the cosmological constant.
Much more needs to be done to develop string theory more fully.

- Including a deeper understanding of time dependent situations
- And vacua with positive cosmological constants, especially small values.
- Such an understanding is needed to help find vacua of the kind we live in and allow us to test string theory.
Cosmologists have discovered that the universe is accelerating.

Such accelerating universes do arise in string theory. Their construction is based on turning on fluxes.
Summary

• This construction reveals a rich set of possibilities described by a landscape.

• And provides an unconventional explanation for the cosmological constant problem.
In fitting the data one takes a theoretical model characterised by some value for $\rho_{\text{matter}}$, k, $\rho_{\text{DE}}$, $\omega_{\text{DE}}$, and a few other parameters.

And fits the data.
Personal Views:

• Hopefully string theory will be capable of many predictions.

• More generally, conventional ways of thinking in particle physics, based on symmetries, are quite likely to continue to be of great relevance.
Facts To Remember

• Age 13.7 Billion Years

• Last Scattering 380,000 years after big bang

\[ M_{pl}^2 = \frac{\hbar c}{G_N} \]
Lambda CDM Model

Six Parameters:

\[ \Omega_b h^2, \Omega_c h^2, \Omega_\Lambda \]

\[ \Delta^2_R, n_s \]

\[ \tau \] (reionisation depth)

\[ H = 100h \text{Km/s/Mpc} \]
$\sigma_{cr} \approx 100$

FIG. 1: Potential (multiplied by $10^{15}$) for the case of exponential superpotential with $W_0 = -10^{-4}$, $A = 1$, $a = 0.1$. There is an AdS minimum.

$\sigma_{cr} >> 1$ if $W_0 << 1$. With $10^{(100)}$ vacua this leaves many possibilities.
Implications of the Landscape

• Who ordered the extra vacua?
• In what sense is String Theory predictive?
• Do we have to resort to the Anthropic Principle?
Personal Views:

1. Too early to give up on the original goals of string theory.

2. Perhaps with some input we might be able to predict a lot.

3. Real question: Is string theory correct? For this we need to make a prediction which is borne out.