String Theory and Inflation

The start of a beautiful relationship?

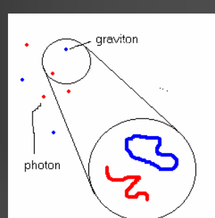
C.P. Burgess

Outline

- String Theory
  - *A Theory looking for observations.*
  - *The D-Brane revolution.*
  - *What is the String Scale?*
- Inflation
  - *Cosmic initial conditions and fluctuations.*
  - *Phenomenology looking for a theory.*
- Inflation in String Theory?
  - *Braneless attempts.*
  - *Brane Inflation?*
- Outlook

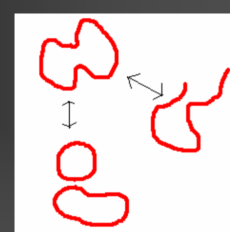
String Theory: the idea

- All matter consists of small one-dimensional objects (strings).
  - Strings look like particles when not resolved closely enough
  - *All* particle types are different normal modes of the string.



String Theory: the interactions

- All interactions consist of the splitting and joining of these elementary strings.
  - This is the *only* known sensible description of the scattering of gravitational waves at very high energies!
  - Looks like General Relativity plus other interactions at low energies.
  - No parameters: string length sets units.

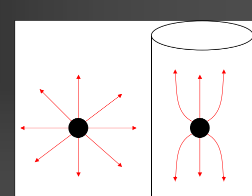


Possible Downsides

- At first sight there appeared to be a number of different kinds of string theories.
  - Open, closed, heterotic, Type I, Type IIA,...
- Predicts we live in 10 spacetime dimensions!
  - *Experimental update:* number of (large) dimensions = *4*
- Very difficult to experimentally test so far.
  - Strings are so short that once the symmetries and spectrum are gotten right, most of the details are usually also right.
  - Calculation gets known masses right, *but*…..
    - experiment m_{exp} = 0.000000000………………..005
    - theory m_{th} = 0.00000000

Gauss' Law in D Dimensions

- String properties are inferred from the strength of gravity and electromagnetic interactions *in 4 dimensions.*
- String theory predicts these *in 10 dimensions.*
- The connection depends on the size of the extra dimensions, since Coulomb's and Newton's Inverse-Square Laws reflect the spread of flux into space.
  - Force law falls faster in higher dimensions because there is more space over which to spread flux.



How Long is a String?

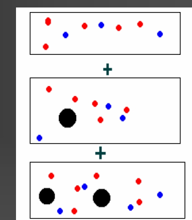
	Electromagnetism	Gravity
for $r \ll a$:	$A_0 \propto \frac{\alpha Q}{r^{n+1}}$	$h_{00} \propto \frac{GM}{r^{n+1}}$
for $r \gg a$:	$A_0 \propto \frac{\alpha Q}{a^n r}$	$h_{00} \propto \frac{GM}{a^n r}$
Effective 4d coupling:	$\alpha_{eff} = \frac{\alpha}{a^n}$	$G_{eff} = \frac{G}{a^n}$

In string theory G and α are related to the string coupling λ and length l_s.

$$\alpha_{eff} = \frac{\alpha}{a^n} = \frac{\lambda \lambda_s^n}{a^n} \approx 0.01 \qquad G_{eff} = \frac{G}{a^n} = \left(\frac{\lambda^2 \lambda_s^n}{a^n}\right)\lambda_s^2 \approx \left(10^{-19}\ \text{fm}\right)^2$$

An Aside on Magnetic Monopoles

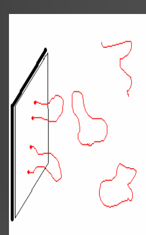
- Field theories can involve more states than are indicated by the fields they involve.
  - For example: QED has fields for electrons, positrons and photons, but it can also describe these interacting with very massive magnetic monopoles.
    - $M = \mu/\alpha$
  - Monopoles arise as solitons of the other fields, and are not described by fields of their own.
    - $g = 4\pi/e$



D-Branes

Polchinski

- String theory is bigger than previously thought.
  - Normally, open strings satisfy Neumann boundary conditions,
    - string ends move at light speed.
  - Dirichlet boundary conditions also make sense
    - string ends live on a surface.
  - This surface is interpreted as a large massive object, a *D-brane*, in spacetime, much like a monopole.



Why Do This?

- Good Things Happen if the theory has both strings and D-branes:
  - Previously-hidden duality symmetries emerge, with all known string theories dual to one another under these symmetries!
  - Some weakly-interacting string theories are the duals of the strong-coupling limit of others!
  - Led to discoveries of similar symmetries amongst ordinary particle theories.
- Conjecture: all known string theories are different solutions to a more fundamental (11-dimensional) theory (M Theory).

Brane vs Bulk States

- Important Brane Facts:
  - At low energies some states are trapped to live near the Brane
    - *eg:* Open strings terminating on a Brane.
  - Other states - *Bulk* states - can ramble:
    - *eg:* Closed strings, including gravitons.
- Trapping is not really so weird.
  - Similar to the trapping of 'zero modes' on defects like vortices and domain walls in solids.
- *Brane-World Scenario:* All known particles are so trapped.

4D Couplings Revisited

- The point: Being trapped on a p-dimensional brane changes how α (but not G) depends on λ and l_s

$$\alpha_{eff} = \frac{\alpha}{a^{p-3}} = \frac{\lambda l_s^{p-3}}{a^{p-3}} \qquad G_{eff} = \frac{G}{a^n} = \left(\frac{\lambda^2 l_s^n}{a^n}\right) l_s^2$$

So if $p=3$ (for example) we have

$$G_{eff} = \alpha_{eff}^2 \left(\frac{l_s}{a}\right)^n l_s^2$$

Experiments no longer require l_s to be so small!

Strings In Your Face

Arkani-Hamad, Dvali & Dimopoulos

- Could strings be as big as they can be: $l_s = l_w$?
  - Non-gravitational physics is characterized by the weak scale: $G_F = l_w^2 = (10^{-3}\ \text{fm})^2$
  - If so, strings may be experimentally discovered 'tomorrow'!
  - If so, does this explain why l_w is so much larger than $l_p = 10^{-19}$ fm?
    - *ie:* Why is gravity so weak? Why are stars so big?
- Gravity would be weak because the extra dimensions are large:

$$a = \left(\frac{\alpha_{eff}\, l_s}{l_{pl}}\right)^{2/n} l_s$$

If $n = 2$ then $l_s = l_w$ requires $a \sim 0.1$ mm!!
If $n = 6$ then $l_s = l_w$ requires $a \sim 10^5$ fm,

Why is the heirarchy a/l_s so large?

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Intermediate-Scale Strings

CB, Ibanez & Quevedo

- Q: Can l_s and a be similar in size?
- A: Yes. $l_s / a = 0.01$ works if:
  - I: $l_s = \sqrt{(l_w\, l_p)} = 10^{-11}$ fm.
    - $l_w = l_s^2 / l_p$ naturally arises if supersymmetry breaks on another brane, and is transmitted to our brane by gravity.
  - II: n = 6 extra dimensions.
- ***No hierarchy need be dialed in.***
- Other nice things also happen if so:
  - *String axions can solve strong CP problem, neutrino masses similar to experiments, etc*

$$\alpha_{eff} = \frac{l_s}{a} = 0.01$$

$$\frac{l_{pl}}{l_w} = \frac{l_{pl}^2}{l_s^2} = \alpha_{eff}^2 \left(\frac{l_s}{a}\right)^n$$

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String Summary

- String theory is the only known theory where gravity and quantum mechanics co-exist at high energies.
  - *Major Lesson of the 20th Century:* Relativity and Quantum mechanics are almost inconsistent, and so together impose extremely strong self-consistency conditions.
- The string length is likely much longer than the Planck length.
  - *Size Matters:* much better prospects for comparison with experiments.
  - The intermediate scale is well motivated on particle-physics grounds: $l_s = \sqrt{(l_w\, l_p)} = 10^{-11}$ fm.
- We may all be *Brane bound*.

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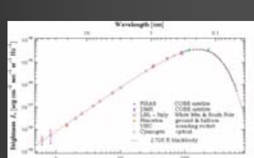
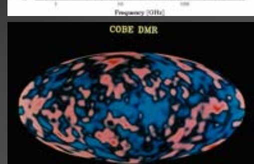
Motivations for Inflation

- The Hot Big Bang Model provides a very successful description of the observed Universe at large.
  - Described by expansion of universe: *R(t)*
  - Requires unnatural initial conditions:
    Flat, homogeneous, isotropic





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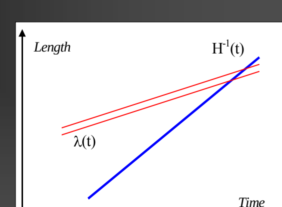
Acausal Correlations?

- Initial correlations cannot be causally understood in the Hot Big Bang since in the past they were not in causal contact with one another!
  - Light has not yet had time to travel across the sky to tell everybody to be at the same temperature!
- *eg:* for radiation:



$$p = \rho/3 \quad \Rightarrow \quad \lambda \propto R \propto t^{1/2}; \quad H^{-1} \propto t$$

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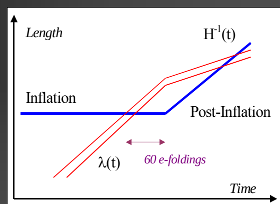
Inflation

Guth

- Initial conditions *can* robustly follow from dynamics if the universe were to become temporarily dominated by vacuum energy:
  - Fluctuation amplitude requires $V \sim (10^{-17} - 10^{-12}\ \text{fm})^{-4}$
- Inflation is an *attractor*!
- *ie:*



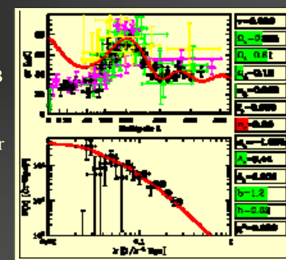
$$p = -\rho \quad \Rightarrow \quad \lambda \propto R = e^{Ht}; \quad H^{-1} = const.$$

Bonus!

Chibisov & Mukhanov / Lukash / Starobinski
Guth & Pi / Bardeen, Steinhardt & Turner / Hawking

- Besides redundantly testing the Hot Big Bang model, current precision measurements of the CMB temperature *anisotropies* are consistent with inflationary predictions for fluctuation properties.
  - *eg:* the ‘tilt’, n_s, of scalar fluctuations

$$n_s = 1 - 6\varepsilon + 2\eta$$

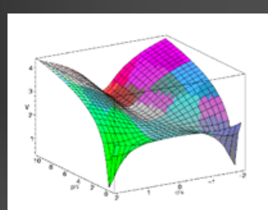


M. Tegmark

The Devil is in the Details…

Albrecht & Steinhardt; Linde….

- It has proven difficult to find microscopic physics which explains the required features of inflationary models:
  - Why is the amplitude of fluctuations what is seen?
  - Why are pre-inflationary initial conditions chosen properly?
  - Why does inflation last as long as it must?
  - *Etc….*



V(φ,χ)

Round Up the Usual Suspects...

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String Theory and Inflation?

Brustein & Steinhardt

Good News:

- There are very many scalar fields (called moduli) whose motion could describe inflation.
- These scalars tend to have very flat potentials, so can give very slow rolls and so lots of inflation.

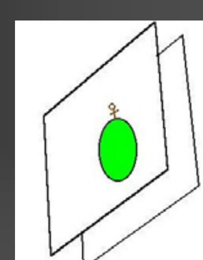
Bad News:

- There are typically *too many* such scalars, whose late-time motion can ruin successes of Hot Big Bang.
- The potentials are *exactly* flat up to non-perturbative corrections, and so are usually incalculable.
- No particular reason to choose successful scale for V, if $\ell_s = \ell_p$

Brane Inflation

Dvali & Tye;
CB, Majumdar, Quevedo, Rajesh & Zhang

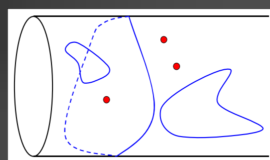
- Brane motion may provide inflation:
  - Branes themselves can break supersymmetry, and so give rise to *calculably weak* interactions.
  - Brane tension has the correct equation of state: $p = -\rho$
  - Inflation can end through intervention of many new degrees of freedom.
  - Fluctuation amplitudes point to ℓ_s fairly close to the intermediate scale.
- *But:*
  - Many other moduli must be eliminated to really successfully produce inflation.



The Brane Gas

Brandenberger & Vafa;
Alexander, Brandenberger & Easson
BMQRZ

- The Brane Gas: The beginnings of a theory of inflationary initial conditions….
  - An initial hot gas of branes may explain why some dimensions initially become somewhat larger than others.
  - The last few collisions of these branes may then exponentially inflate these initially large dimensions.
  - May have observable consequences for the CMB, since it implies the existence of cosmic strings surviving down to the present day.



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Outlook

- CMB measurements reinforce the belief that the Universe underwent a very early inflationary period, but this has proven difficult to understand as a consequence of any known microscopic physics.
  - Because it is difficult, we stand a chance of learning something interesting about the microscopic physics which is responsible.
- String theory is by far the best-motivated theory of physics at the very-high energies which are likely to be responsible for inflation.
  - Due to the discovery of branes, there is now progress in trying to obtain inflation from string theory.
  - Branes dramatically change the nature of the early universe, and may tie inflationary cosmology to our understanding of the sculpting of the extra dimensions.

More work needs to be done - enormous fun is being had!

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Perhaps a beautiful relationship….

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………and a classic ending.

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