Cosmic Inflation and Quantum Gravity

Planck

BICEP2

Angular scale

$D_\ell [\mu K]$ vs $\ell$

Multiplicity moment, $\ell$

90° 18° 1° 0.2° 0.1° 0.07°
In addition to mapping out the universe with amazing precision, observations from the latest telescopes are beginning to confront very high energy physics and (quantum!) gravity theory, via Primordial Cosmology:

Outline
* The expanding universe, the big bang and Cosmic Inflation
* Quantum mechanics and the origin of structure
* Cosmic radiation (``CMB''"
* Sensitivity to quantum gravity effects and string theory inflation
Astronomers have strong evidence that the universe is expanding:

We can tell how fast an object is moving by the color of light it emits to us.

- **Blue** (closer together): Emits pulses closer together.
- **Green** (intrinsically green): Emits pulses further apart.
- **Red** (further apart): Emits pulses further apart.
We can tell how far away it is (given an intrinsic luminosity) by the intensity of the light reaching us.
This leads to a distance-redshift relation (Hubble...) showing that galaxies farthest away from us are moving away the fastest. \( \Rightarrow \) If we refrain from placing ourselves at the center of the universe, this suggests that Space is expanding:

\[ \uparrow \text{Time } t \]

* The expansion itself causes the wavelength of light to stretch.
There is strong evidence for accelerated expansion ("inflation"):

Increasing rate of growth of $a(t)$ $\rightarrow$ (Guth, Linde, Albrecht, Steinhardt)

in the early universe.

Early motivations: extrapolating known expansion back in time
$\rightarrow$ causality puzzle

$\begin{array}{c}
t_0 \quad \ldots \quad A \quad \ldots \quad \text{present day} \\
\uparrow \\
\uparrow t_p \\
\uparrow t_R \\
1 \quad \text{light} \\
\end{array}$

$\leftarrow$ Atoms form $\leftarrow$ densest matter we understand

Temperature $1 = \text{Temperature} 2$

but $1 \neq 2$ can't communicate
In other words, we see the same temperature $T$ from regions which never had time to interact with each other (since nothing moves faster than light).

(Cold) (Need to mix to become warm) (hot)
A resolution is to postulate an early period of accelerated expansion: \( a(t) \propto e^{Ht} \)

Universe older, giving \( 0 + \oplus \) a chance to communicate.
This also makes space flatter and dilutes any heavy particles from the dense conditions in the very early universe.

highly curved, dense

→

nearly flat, dilute
What determines how the universe expands?

Einstein's theory of gravity:

\[
(\text{shape and size of space-time}) \leftrightarrow (\text{energy and pressure})
\]

Dense matter curves space into black hole

"\( R = E \)"

curvature energy
The inflationary expansion must end in order to match the slower expansion we see now.

This is modelled by a changing source of energy on the right-hand side of Einstein's equation “\( R = E \)”, where \( R \) is curvature and \( E \) is energy.
"R = E" potential energy $V(\phi)$

Curvature inflation

Potential energy $V(\phi)$ drives inflation

Energy of motion $\frac{1}{2}m(\frac{d\phi}{dt})^2$ drives ordinary expansion
This new degree of freedom $\phi$, known as the "inflaton", has another important consequence (beyond its role in ending inflation):

$$\phi = \phi_0(t) + \delta \phi(t, x)$$

- Rolling down the hill
- Fluctuations
- Seed Structure
via Quantum Mechanics:

Heisenberg's uncertainty principle:

\[ \Delta \phi \Delta p \geq \frac{\hbar}{2} \]

uncertainty in position  uncertainty in momentum  fundamental constant

ball cannot sit still at bottom of the bowl

The "inflaton" cannot sit still, and varies from point to point.
In cosmology this means:

- Inflation: $a(t) \propto e^{Ht}$
- Fluctuation $\delta \phi$ with wavelength $\lambda$
- $\delta \phi$ freeze out with wavelength $\lambda e^{Ht}$

Amplitude fixed by uncertainty principle to be about $\delta \phi \approx H = \text{constant}$

Intrinsic Quantum fluctuations in inflaton $\phi$
Similar results hold for fluctuations in the spacetime geometry itself: $\delta \text{ (lengths)} \lesssim \sqrt{V(\phi)}$

Quantum Gravity

"graviton" = quantum of gravitational waves

like "photon" = quantum of light (electromagnetic waves)

* We will see another important role of QG (a string theory) later
When inflation ends, the fluctuations $\delta \Phi$ re-enter the "Hubble horizon" and seed structure.

Extensive calculations show how this initial seed evolves to the distribution of structure (galaxy clusters, galaxies, ...) which we see.
Accelerated expansion of space + quantum fluctuations + gravity + other forces → Structure in the universe (Bryan & Norman)
The cosmic light ("CMB") emanates from the earliest times (largest scales) at which the light can move freely, soon after the universe was born into a universe of hydrogen and electrons. When the universe was roughly 380,000 years old, the first structures began to form. These were the seeds of the galaxies and the large-scale structures we see today. The cosmic microwave background (CMB) is the afterglow from this early universe, and it provides a snapshot of the conditions at that time. The CMB is a powerful tool for understanding the early universe.
The Big Picture

Cosmic Microwave Background (CMB)

Planck Satellite

The temperature $T$ of the light is approximately the same in all directions

$$\frac{\Delta T}{T} \approx 10^{-5} \ll 1$$
So far, observations have confirmed the basic predictions of inflation:

- Universe flat

- The fluctuations are approximately independent of wavelength

Experiments are reaching sensitivity to (quantum!) gravitational waves for some simple models
Gravity waves (fluctuations of the shape of Space)

BICEP2 recently got sensitivity to part of this range

Slight dependence on wavelength because of slowly decreasing energy \( V(\phi) \)

But must disentangle from other sources
Polarization of cosmic radiation

In the presence of the inflaton and graviton perturbations, CMB has net polarization, with different symmetry structure.
Foreground Sources

extinction // to B

emission ⊥ to B

J.-P. Bernard
BICEP2 Detected B modes (2-years of observations at the South Pole, released March 2014).

Planck Polarization release coming: less sensitive but all sky, more colors for foreground discrimination
What is at stake is not inflation itself, or the big bang, but a unique empirical lever to high energy physics and quantum gravity.
To see this, consider again

In order to explain \( T_{\text{light}} \), flatness, and homogeneity of our universe we need a long period of inflation.

\[
\text{(Size at end)} \geq 10^{26} \times \left( \frac{\text{Size at Start}}{10^{0}} \right)
\]
\[ \frac{\text{end size}}{\text{start size}} \geq 10^{26} \]

This corresponds to a **boring** roller coaster with a very flat potential energy function

\[ V(\alpha) \]

* \( V(\alpha) \) is sensitive to "quantum gravity" effects:

↑ exit from inflation is fun...
Quantum Gravity & String Theory

General Relativity (Einstein's theory of gravity) breaks down at short distances; cf. J. Polchinski (last week).

Space-time typically becomes highly curved in some regions.

Far past: Short-distance singularity
String theory, a candidate completion of general relativity and particle physics, smooths out spacetime singularities via new degrees of freedom:

\[ \text{singular} \quad \rightarrow \quad \text{non-singular} \]

In addition to ordinary particles and gravitational fluctuations, string theory introduces a tower of oscillating strings ...
... and extra dimensions,

\[ \uparrow \text{D-4 dimensions} \]

\[ \leftarrow \text{our 4 dimensions} \rightarrow \]

higher-dimensional "membranes",

and new types of particles and forces.
Parameterized Ignorance of Quantum Gravity Effects

$\sim M_p \quad \phi \phi, \quad m_x \sim \phi$

$V(\phi)$ could be strongly corrected by $\phi$'s interactions with the new degrees of freedom that complete gravity.
We needed $V(\phi)$ to be very flat:

$$V(\phi)$$

But quantum gravity can affect $V(\phi)$ strongly enough to directly influence inflation.

Turning this around, inflation and observations are sensitive to some quantum gravity/string-theoretic effects!
The strongest sensitivity to high energy effects occurs in two basic cases.

1. Large-field inflation $V(\phi) \rightarrow \phi$

   $\phi \geq \text{Energy of lightest black hole} > \text{Energy of strings, etc.}$
Large-field inflation corresponds to large potential energy $V(\phi)$.

... and larger potential energy means larger fluctuations in spacetime geometry ("Gravity Waves"): 
Parameterized ignorance of quantum grav.

New degrees of freedom each $\Delta \Phi \sim M_P$

No continuous global symm. in QG

String Theory

axions (and duals)

From ubiquitous Axion-Flux couplings

Discrete shift symm., $f \ll M_p$

[cf Chaotic Infl. (Linde), Natural Infl. (Freese et al)]
Large-field inflation arises for simple fields called axions in string theory. Glossing over details, one has a wind-up toy in the extra dimensions.

Falsifiable with observations: this mechanism requires Primordial Gravitational Waves at a level detectable by near-term B mode experiments.
An example:

Without string theory:

\( V(\phi) \) is a parabola

With string theory, the added heavy degrees of freedom can adjust, producing a flatter potential.

\( V \propto \phi \propto \phi^{2/3} \ldots \)

* All predictions we can make are "model-dependent," but still highly constrained by the structure of string theory.
Other possibilities in string theory

Now many more examples and more data

BICEP2, SPT, ACT, Keck Array, SPIDER, ...
Other Observables (More Exotic)

- Interactions of the fields
- (Residual) Cosmic Strings another grav. wave signature
- "Multiverse": Different shapes of extra dimensions, different expansion in different regions ...
This is a new connection between String Theory and data.

- Although we have no sweeping predictions of String theory as a whole, we have well-motivated mechanisms and models within the framework of String theory which are falsifiable.
- These have helped stimulate a more thorough understanding of inflation and its signals.
Many open questions, such as:

- horizons

accelerated expansion \implies lose contact

No one can collect all the data from all experiments

\rightarrow how formulate physics in this situation?

A subject of active research.