The Big Bang, Cosmic Inflation, and the Latest Observations

8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 7 December 2020
1. Successes of the Big Bang Model

2. Shortcomings of the Big Bang Model

3. Cosmic Inflation and Large-Scale Structure
Large-Scale Structure

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Ingredients

Matter,
including —
hurray! — the
Higgs boson

General Relativity:
warping spacetime
Warping Spacetime

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} \]

curvature of spacetime = distribution of matter and energy

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Expanding Universe

age of the universe = 13.8 billion years
If the universe is expanding today, it must have been smaller in the past.

The universe began in a very hot, dense state and has been expanding ever since.
Remnant Glow

At early times, the universe was so hot that individual photons carried more energy (on average) than the binding energy of a hydrogen atom.

Photons are \textit{trapped} between charged particles.

Only around \( t = 380,000 \) years could neutral atoms form:

Photons are \textit{free}. As the universe expands, their wavelengths get \textit{stretched}.

Today the universe is filled with this radiation:

\textit{Cosmic Microwave Background Radiation}
Like a Dance Party…

$T > 10^4 \text{ K}$
$t < 380,000 \text{ years}$

$N^+$, $e^-$

$T < 10^4 \text{ K}$
$t > 380,000 \text{ years}$

[Still image from Harry Potter removed due to copyright restrictions.]
Accidental Discovery
Questions?
Clocks and Rulers

It is convenient to use coordinates that take into account the stretching of space:

\[ x = a(t) r \]

\[ \tau = \int_0^t \frac{dt'}{a(t')} \]
**Flatness Problem**

A flat universe has \( \Omega = 1 \)

From Einstein’s equations:

\[
\frac{|\Omega - 1|}{\Omega} = \frac{1}{a^2 \rho} \sim a(t)
\]

Over time, \( \Omega \) should flow away from 1. After 14 billion years, why do we see anything even close to 1 today?
Robert Dicke and James Peebles, 1979
Horizon Problem

\[ x = a(t)r \]
\[ \tau = \int_0^t \frac{dt'}{a(t')} \]

\[ \frac{\Delta T}{T} = 10^{-5} \]

We receive CMB photons today

Plus: Why the Lumps?

CMB photons emitted

At \( t_{\text{cmb}} \), \( \Delta r \gg d_{\text{horizon}} \)

Robert Dicke and James Peebles, 1979

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Questions?
Inflation

From general relativity, if $\rho \sim \text{constant}$, then $a(t) \sim e^{\sqrt{\rho} t}$.

This happens naturally with Higgs-like matter; it doesn’t occur for matter like protons and electrons.
Inflation

This happens naturally with Higgs-like matter; it doesn’t occur for matter like protons and electrons.

\[ \ddot{\phi} + 3H \dot{\phi} + V,\phi(\phi) = 0 \]

\[ a(t) \approx a_0 e^{Ht} \]
Inflation Solves the Flatness Problem

so as \( a(t) \) gets big and \( \rho \) remains constant, \( \Omega \to 1 \).

Latest measurement:

\[ \Omega = 1.0007 \pm 0.0037 \]

Planck collaboration, arXiv:1807.06211
Inflation Solves the Horizon Problem

We receive CMB photons today

CMB photons emitted

We receive CMB photons today

CMB photons emitted

Inflation

$\tau_0$

$\tau_{\text{cmb}}$

Inflation

$\Delta r$

$d_{\text{horizon}}$
Inflation Solves the Horizon Problem

We receive CMB photons today

CMB photons emitted
Inflation Solves the Horizon Problem

We receive CMB photons today

CMB photons emitted

$\tau_0$

$\tau_{\text{cmb}}$

Inflation

$r$
Inflation Solves the Horizon Problem

We receive CMB photons today

CMB photons emitted

$d_{\text{horizon}}$

$\Delta r$

$\tau_0$

$\tau_{\text{cmb}}$

Inflation
Inflation Solves the Horizon Problem

\[ t \sim 10^{-36} \text{ sec} \]

We receive CMB photons today

CMB photons emitted

\[ \Delta t \sim 10^{-36} \text{ sec} \]

\[ a(t) \text{ grows by } 10^{30}! \]
Inflation Solves the Horizon Problem
Gravity stretches and amplifies quantum fluctuations

\[ \delta \ddot{\phi}_k + 3H \delta \dot{\phi}_k + \left[ \frac{k^2}{a^2} + m_{\text{eff}}^2(t) \right] \delta \phi_k \geq \frac{\Delta x \Delta p}{\hbar} \]
Primordial Wiggles

$\alpha(t)$ grows by $10^{30}$!

Gravity stretches and amplifies quantum fluctuations
From $\delta \phi$ to Bumps on the Sky

$$\frac{\Delta T}{T} = 10^{-5}$$

Photons released at $t_{\text{cmb}}$ map the distribution of matter and energy at $t_{\text{cmb}}$.

$\delta \phi \rightarrow \Phi \rightarrow \Delta T$
From $\delta \phi$ to Bumps on the Sky

$$\frac{\Delta T}{T} = 10^{-5}$$

Photons released at $t_{\text{cmb}}$ map the distribution of matter and energy at $t_{\text{cmb}}$.

$\delta \phi \longrightarrow \Phi \longrightarrow \Delta T$
Primordial Spectrum

\[ D_\ell [\mu K^2] \]

\[ \Omega_K = 0.0007 \pm 0.0037 \]
\[ n_s = 0.965 \pm 0.004 \]
\[ \beta_{iso} \lesssim \mathcal{O}(0.1) \]
\[ |f_{NL}^{\text{local}}| \leq 1.25 \]

Planck collaboration,
arXiv:1807.06211
Spacetime can wiggle in a different way, too: *gravity waves* periodically stretch and squeeze objects as they pass through a region.
Primordial Gravity Waves

Spacetime can wiggle in a different way, too: gravity waves periodically stretch and squeeze objects as they pass through a region.

LIGO graph Courtesy of Abbott et al, American Physical Society. Used under CC BY.
Primordial Gravity Waves

Gravity waves from inflation would stretch and squeeze the spacetime in which hydrogen atoms were first forming, adding a *polarization* or corkscrew pattern to the emitted light.
Gravity Waves Detected?

BICEP2: B signal

Declination [deg.]

Right ascension [deg.]

0.3 μK

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The B-mode signal detected by BICEP is consistent with late-universe dust ("foregrounds"), rather than primordial gravitational waves.
Gravity Waves Detected?

Planck-BICEP-Keck collaborations, arXiv:1606.01968
Simons Observatory collaboration, arXiv:1808.07445
Conclusions

Cosmic inflation arises from types of matter and interactions that we now know to exist — hurray, Higgs boson! — and it addresses several long-standing cosmic puzzles.

Inflation makes several specific predictions for what the universe should look like today.

Simple models fit the latest observations to astonishing accuracy.
So Why is the Universe Lumpy?

Because spacetime is wiggly...

... and matter is jiggly.

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