Quantum Jitters in the Sky

The Big Bang, Cosmic Inflation, and the Latest Observations

David Kaiser
A Group Effort

Guth-Kaiser group, MIT, summer 2014
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The New York Times

9 Scientists Receive a New Physics Prize

By KENNETH CHANG
Published: July 31, 2012
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\[ 10^{-36} = 3 \times 10^6 \]
Large-Scale Structure
Ingredients

General Relativity:
warping spacetime
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
Warping Spacetime

The curvature of spacetime is equal to the distribution of matter and energy.

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

curvature of spacetime = distribution of matter and energy
Expanding Universe

Hubble, 1929

Figure 1

How Old Is the Universe?
Expanding Universe

Hubble, 1929

age of the universe = 13.8 billion years
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 trapped between charged particles.

\( T > 10^4 \text{ K} \)
\( t < 380,000 \text{ years} \)
**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 *trapped* between charged particles.

Only around $t = 380,000$ years could neutral atoms form:

Photons are *free*. As the universe expands, their wavelengths get *stretched*:

$$\lambda_{\text{obs}} = a(t) \lambda_{\text{emit}}$$

Today the universe is filled with this radiation, cooled down to 3K:

*Cosmic Microwave Background Radiation*
Like a Dance Party…

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Accidental Discovery

In 1964, two researchers from Bell Labs in New Jersey were working on a new satellite antenna for communications. They couldn’t remove an annoying, residual “hum”—even after removing pigeons’ “dielectric material.”

They were “hearing” the big bang! CMB first detected…
Clocks and Rulers

It proves convenient to adopt coordinates that take into account the stretching of space:

\[ x = a(t) r \]

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

\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]

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

From Einstein’s equations:

\[
\frac{|\Omega - 1|}{\Omega} = \frac{1}{a^2 \rho} \sim \begin{cases} a(t) & \text{matter} \\ a^2(t) & \text{radiation} \end{cases}
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Over time, \( \Omega \) should flow away from 1. After 13.8 billion years, why do we see anything even close to 1 today?
Horizon Problem

We receive CMB photons today

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

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

\[
d_{\text{horizon}}(t) = \int_{0}^{t} \frac{dt'}{a(t')}
\]
Horizon Problem

\[
\Delta r (t_{\text{cmb}}) \gg d_{\text{horizon}}(t_{\text{cmb}})
\]

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\]

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

We receive CMB photons today

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

Plus: Why the Lumps?

At \( t_{\text{cmb}} \), \( \Delta r \gg d_{\text{horizon}} \)
From general relativity, if $\rho \sim \text{constant}$, then $a(t) \sim e^{\sqrt{\rho}t}$. 

Inflation
Inflation

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

This is only possible with Higgs-like matter; it doesn’t occur for matter like protons and electrons or like $W$ and $Z$ particles.
Inflation Solves the Flatness Problem

\[ \frac{|\Omega - 1|}{\Omega} = \frac{1}{a^2 \rho} \]

so as \( a(t) \) gets big and \( \rho \) remains constant, \( \Omega \to 1 \).
Inflation Solves the Flatness Problem

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\[
\frac{|\Omega - 1|}{\Omega} = \frac{1}{\alpha^2 \rho}
\]

Latest measurement:

\( \Omega = 1.0001 \pm 0.0054 \)

*Planck* collaboration,
arXiv:1502.01589
Inflation Solves the Horizon Problem

We receive CMB photons today

CMB photons emitted

$\Delta t \sim 10^{-35} \text{ sec}$

$\frac{a(t_{end})}{a(t_i)} > e^{70} \sim 10^{30}$
Inflation Solves the Horizon Problem

We receive CMB photons today

Inflation

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Primordial Wiggles
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\[ \Delta x \Delta p \geq \frac{\hbar}{2} \]
Gravity stretches and amplifies quantum fluctuations

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\[ \delta \dddot{\phi}_k + 3H \delta \dot{\phi}_k + \left[ \frac{k^2}{a^2} + m_{\text{eff}}^2(t) \right] \delta \phi_k = 0 \]

Primordial Wiggles
Gravity stretches and amplifies quantum fluctuations

$$\lambda_{\text{phys}}(t) = a(t) \lambda_{\text{com}}$$

$$\phi_k'' + 3H \dot{\phi}_k + \left[ \frac{k^2}{a^2} + m_{\text{eff}}^2(t) \right] \phi_k = 0$$

$$\frac{a(t_{\text{end}})}{a(t_i)} > e^{70} \sim 10^{30}$$

Primordial Wiggles
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 $t_{\text{cmb}}$.

$\delta \phi \iff \Phi \iff \Delta T$
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 $t_{\text{cmb}}$.

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

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

\( \Omega_K = 1.0001 \pm 0.0054 \)
\( n_s = 0.968 \pm 0.006 \)
\( \beta_{\text{iso}} \leq \mathcal{O}(0.1) \)
\( f_{NL} = 2.7 \pm 5.8 \)
Primordial Gravity Waves

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

Auriga detector group, INFN, Italy
**Primordial Gravity Waves**

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**Gravitational Waves Detected, Confirming Einstein’s Theory**

The New York Times

LIGO
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.
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Gravity Waves Detected?

BICEP2: B signal

Right ascension [deg.]

Declination [deg.]

\(0.3\mu K\)

Gravity Waves Detected?

Flauger, Hill, Spergel, 1405.7351
Gravity Waves Detected?
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.
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Inflation makes several specific predictions for what the universe should look like today.

The simplest models fit the latest observations to astonishing accuracy, about 0.5%.
So Why is the Universe Lumpy?
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Because spacetime is wiggly…
So Why is the Universe Lumpy?

Because spacetime is wiggly…

… and matter is jiggly.