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Inflationary Cosmology and Particle Physics

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The Conventional Big Bang Theory

What it is: The theory that the universe as we know it began 13-15 billion years ago. (Latest estimate: 13.8 ± 0.05 billion years!) The initial state was a hot, dense, uniform soup of particles that filled space uniformly, and was expanding rapidly.

What it describes: How the early universe expanded and cooled, how the light chemical elements formed, and how the matter congealed to form stars, galaxies, and clusters of galaxies.

What it doesn't describe:

- ☆ What caused the expansion? (The conventional theory describes only the **aftermath** of the bang. It says nothing about what banged, why it banged, or what happened before it banged.)
- ☆ Where did the matter come from? (The theory assumes that **all matter** existed from the very beginning.)

Cosmic Inflation

- ☆ Inflation is a modification of the standard big bang theory, providing a very brief "prequel".
- ☆ Inflation can explain the bang of the big bang (i.e, the outward propulsion), in terms of

☆ **Miracle of Physics #1:**

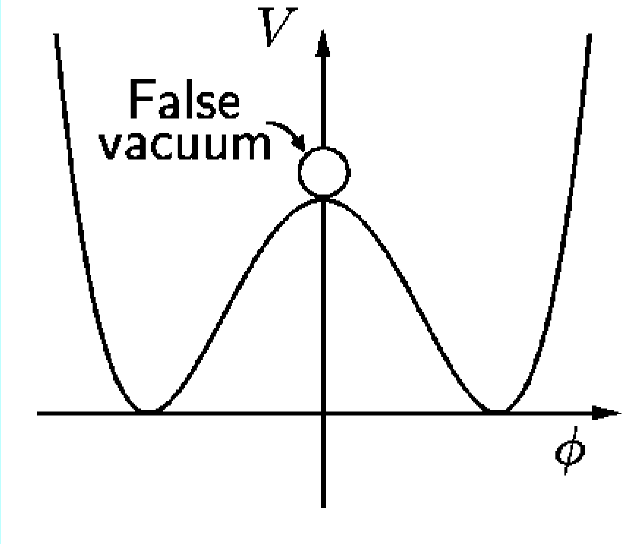
Gravitational Repulsion!

- ☆ According to general relativity, pressures as well as energy densities can create gravitational fields, and a negative pressure creates a repulsive gravitational field.

Inflationary Scenarios

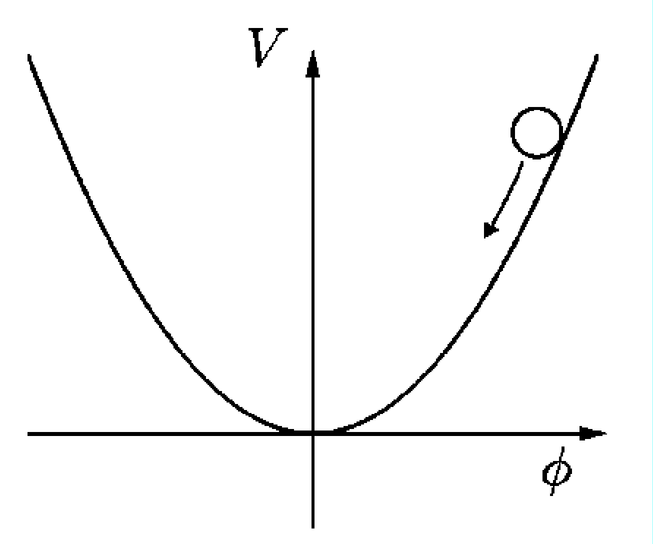
☆ **Negative Pressure $\Longrightarrow$ Repulsive Gravity.**

☆ State dominated by scalar field potential energy $\Longrightarrow$ Negative Pressure.



New (Small Field) Inflation

Linde; Albrecht & Steinhardt (1982)



Chaotic (Large Field) Inflation

Linde (1983)

- Inflation proposes that a patch of negative pressure existed in the early universe — for inflation at the grand unified theory scale ($\sim 10^{16}$ GeV), the patch needs to be only as large as 10^{-28} cm. (Since any such patch is enlarged fantastically by inflation, the initial density or probability of such patches can be very low.)
- The gravitational repulsion created by the negative pressure was the driving force behind the big bang. The patch was driven into exponential expansion, with time constant $\sim 10^{-38}$ second.
- The patch expanded exponentially by a factor of at least 10^{28} (65 time constants), but it could have expanded much more.
- The scalar field eventually rolled down the hill and oscillated about the energy minimum. The energy from the false vacuum produced a hot soup of "ordinary" particles, which quickly reached thermal equilibrium. Standard cosmology began.

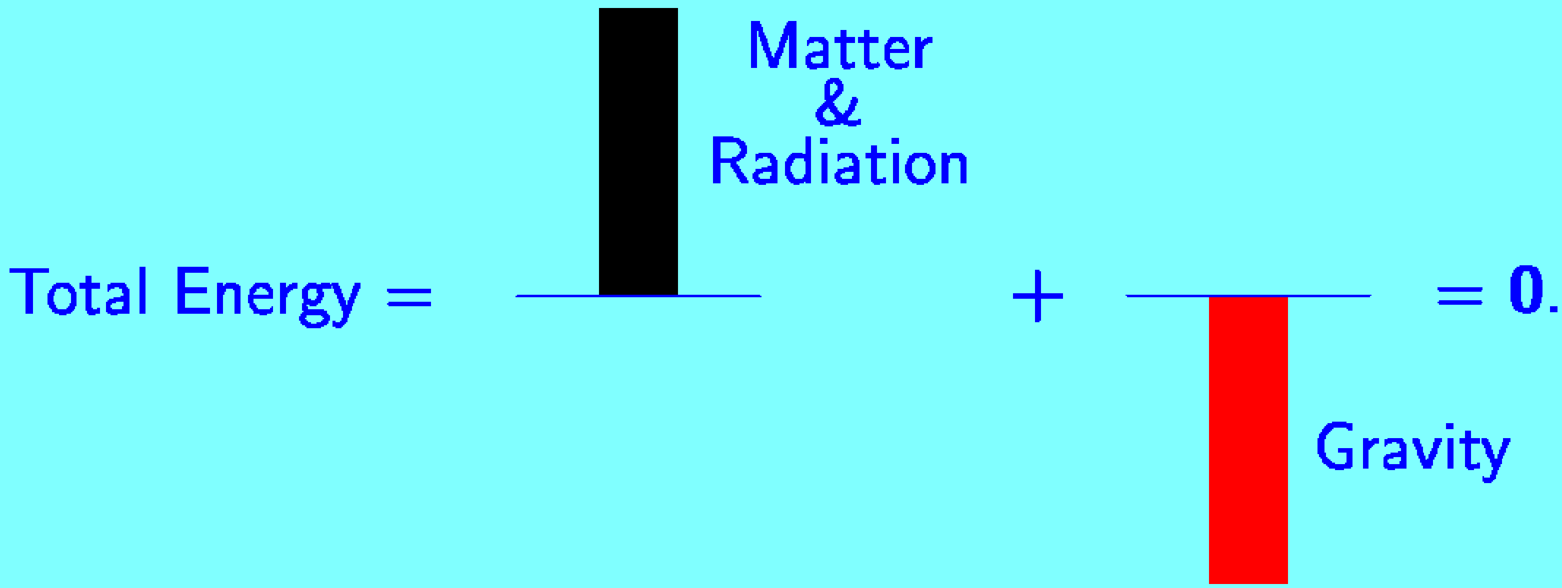
- ☆ As the region inflated, the energy density of the scalar field was **not lowered**.
- ☆ Although more and more mass/energy appeared as the region of scalar field energy expanded, total energy was conserved!

☆ Miracle of Physics #2:

The energy of a gravitational field is negative!

- ☆ The positive energy of the scalar field was compensated by the negative energy of gravity. The TOTAL ENERGY of the universe may very well be zero.

Schematically,



Evidence for Inflation

1) **Large scale uniformity.** The cosmic background radiation is uniform in temperature to one part in 100,000. It was released when the universe was about 380,000 years old. In standard cosmology without inflation, a mechanism to establish this uniformity would need to transmit energy and information at about 100 times the speed of light.

Inflationary Solution: In inflationary models, the universe begins so small that uniformity is easily established — just like the air in the lecture hall spreading to fill it uniformly. Then inflation stretches the region to be large enough to include the visible universe.

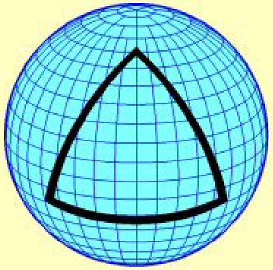
2) **"Flatness problem:"**

Why was the early universe so **FLAT?**

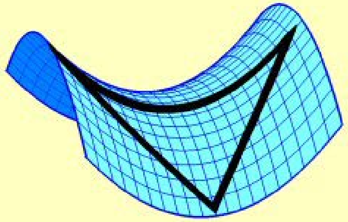
- ☆ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.
- ☆ According to general relativity, the flatness of the universe is related to its mass density:

$$\Omega(Omega) = \frac{\text{actual mass density}}{\text{critical mass density}} \, ,$$

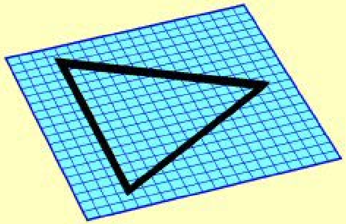
where the "critical density" depends on the expansion rate. $\Omega = 1$ is flat, $\Omega > 1$ is closed, $\Omega < 1$ is open.



Closed Geometry

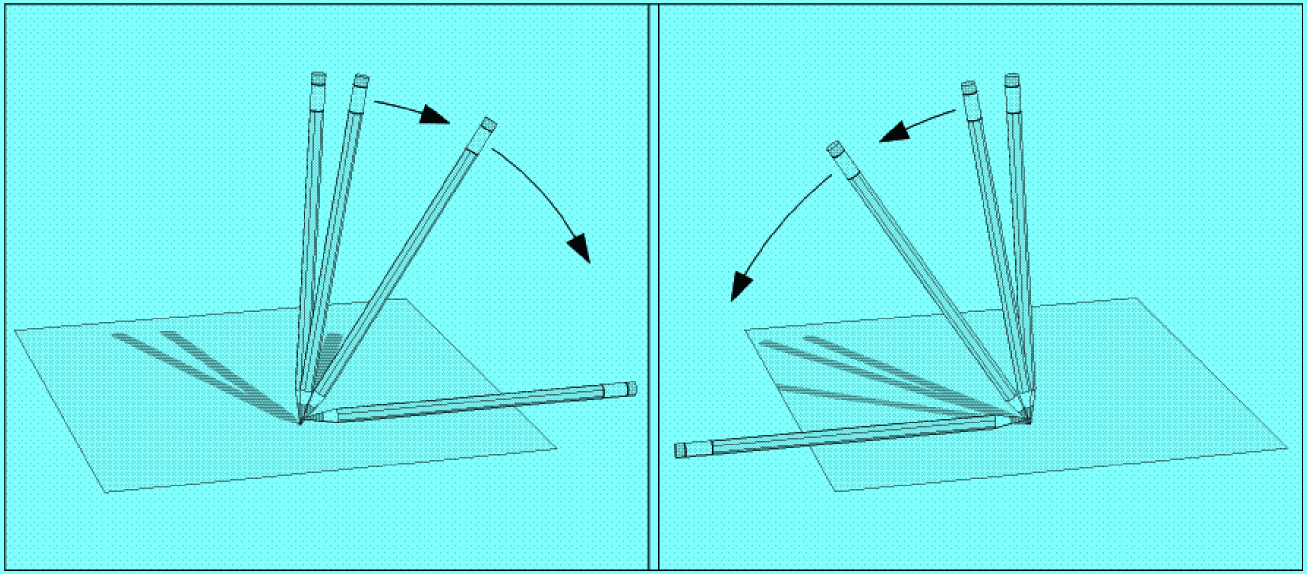


Open Geometry



Flat Geometry

- A universe at the critical density is like a pencil balancing on its tip:



- If Ω in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.
- If Ω was slightly greater than 1, it would rapidly rise to infinity, the universe would recollapse, and no galaxies would form.
- To be as close to critical density as we measure today, at one second after the big bang, Ω must have been equal to one **to 15 decimal places!**

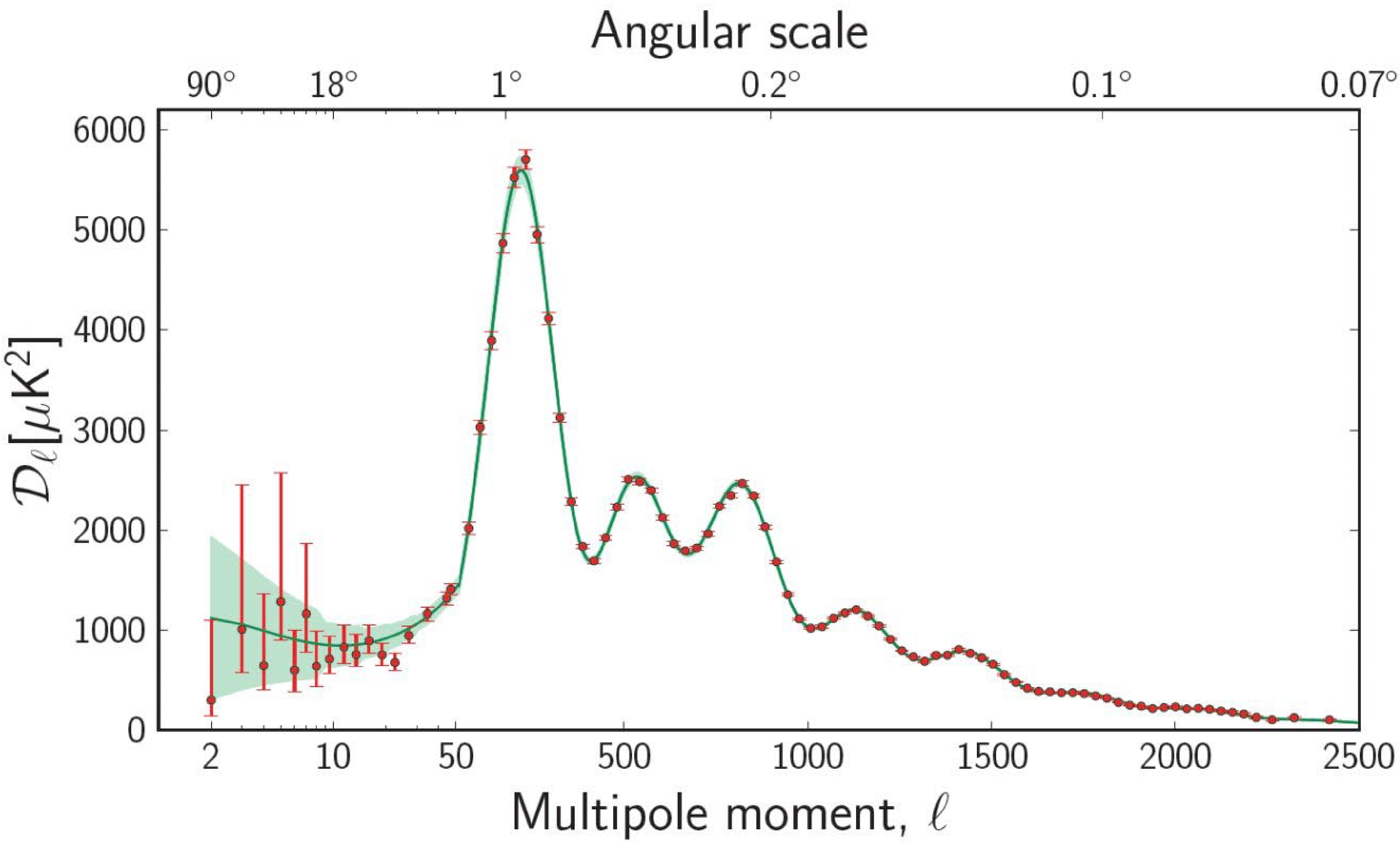
- **Inflationary Solution:** Since inflation makes gravity become repulsive, the evolution of Ω changes, too. Ω is driven towards one, extremely rapidly. It could begin at almost any value.
- Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, it predicts that even today the universe should have a critical density.
- Until 1998, observation pointed to $\Omega \approx 0.2$–0.3.
- Latest observation by Planck satellite (combined with other astronomical observations):

$$\boxed{\Omega = 1.0010 \pm 0.0065}$$

- New ingredient: Dark Energy. In 1998 it was discovered that the expansion of the universe has been accelerating for about the last 5 billion years. The "Dark Energy" is the energy causing this to happen.

3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?

Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.



Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

4) **Gravitational Waves Found by BICEP2(!):** If corroborated, this observation is an additional, strong piece of evidence in favor of inflation.

- ☆ Along with density perturbations, inflation also predicts gravitational waves.
- ☆ Quantum effects on very short length scales imply that the gravitational field — i.e., the metric of spacetime — is constantly fluctuating.
- ☆ Inflation stretches these fluctuations from microscopic to astronomical wavelengths, where they behave as classical gravitational waves (as described by general relativity).
- ☆ The gravitational waves perturb the plasma of the early universe, imprinting a swirling pattern in the polarization of the cosmic microwave background, called B-modes. BICEP2 reported the observation of these B-modes.

Significance of Gravitational Waves

- First experimental evidence that gravity is quantized.
- First image of a gravitational wave. Previously we have detected missing energy attributed to gravitational radiation, but this is the first confirmation that gravitational waves look like what GR predicts.
- Determines the energy scale of inflation. BICEP2 found that $r = 0.20^{+0.07}_{-0.05}$, where r is the ratio of the power in gravitational wave perturbations to the power in density perturbations. If ρ_{inf} is the energy density of the universe at the time of inflation, then

$$\boxed{\rho_{\text{inf}} = \left[2.2 \times 10^{16}\ \text{GeV}\right]^4 \left(\frac{r}{0.2}\right) ,}$$

  in units where $\hbar = c = 1$. So ρ_{inf} is right at the scale of grand unified theories!

What if the BICEP2 observations turn out not to be primordial B-modes?

- ☆ Inflation is still OK!! Many plausible, simple inflationary models predict gravitational waves that have r smaller than 0.20, by many orders of magnitude. Furthermore, inflation still
  1) Explains uniformity of the universe.
  2) Explains the flatness of the universe, and predicts the mass density within 1/2%.
  3) Predicts the spectrum of the density perturbations seen in the cosmic microwave background.
  4) Predicts that the perturbations in the CMB should have a Gaussian probability distribution.
- ☆ If BICEP2 has not seen primordial gravitational waves, it is quite possible that they will not be seen in the foreseeable future.

Inflation Hints the Existence of a Multiverse

Almost all detailed models of inflation lead to "eternal inflation," and hence to a multiverse.

Roughly speaking, inflation is driven by a metastable state, which decays with some half-life.

After one half-life, half of the inflating material has become normal, noninflating matter, but the half that remains has continued to expand exponentially. It is vastly larger than it was at the beginning.

Once started, the inflation goes on FOREVER, with pieces of the inflating region breaking off and producing "pocket universes."

We would be living in one of the infinity of pocket universes.

Do Physicists Take This Seriously?

Martin Rees (Astronomer Royal of Great Britain and (former) President of the Royal Society) has said that he is sufficiently confident about the multiverse to bet his dog's life on it.

Andrei Linde (Stanford University) has said that he is so confident that he would bet his own life.

Steven Weinberg (1979 Nobel Prize in Physics): "I have just enough confidence about the multiverse to bet the lives of both Andrei Linde *and* Martin Rees's dog."