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Inflationary Cosmology and Particle Physics

— Alan Guth —

Massachusetts Institute of Technology

37th International Conference
on High Energy Physics
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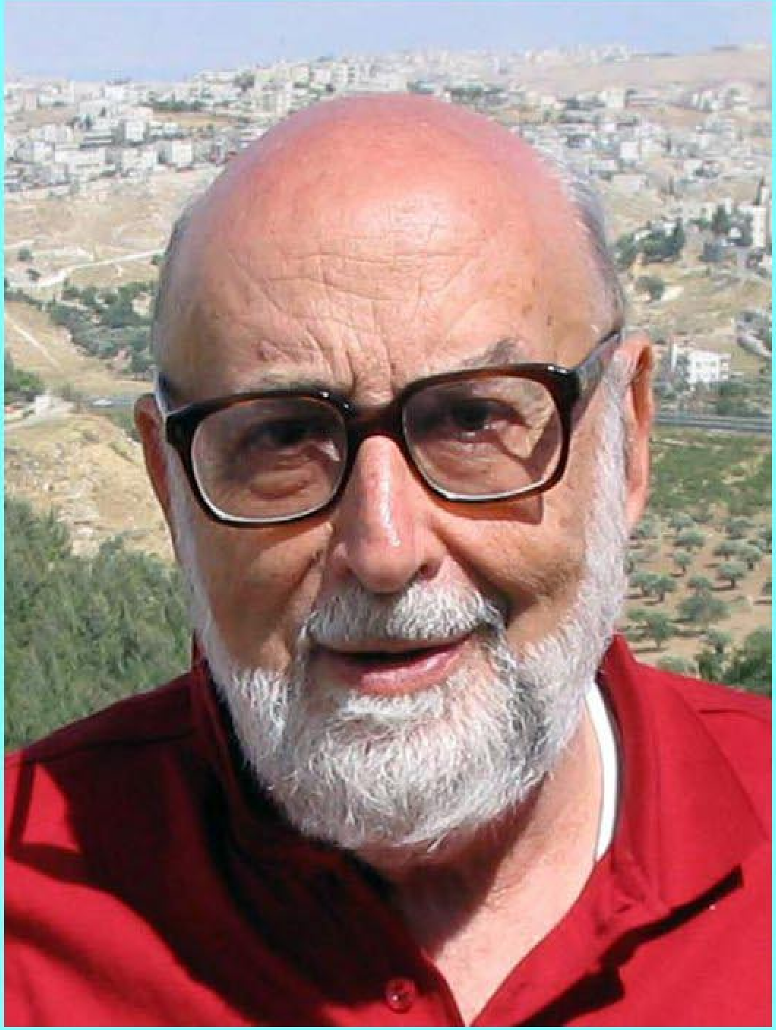
Valencia, Spain
Auditorium 1
July 7, 2014

François Englert



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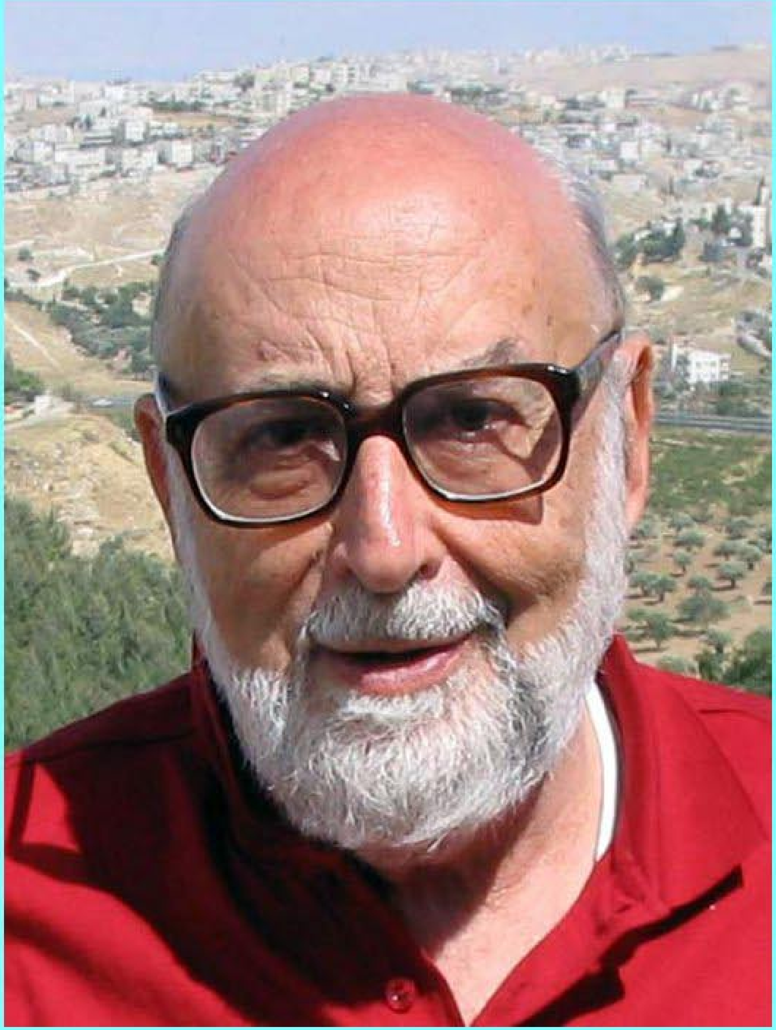

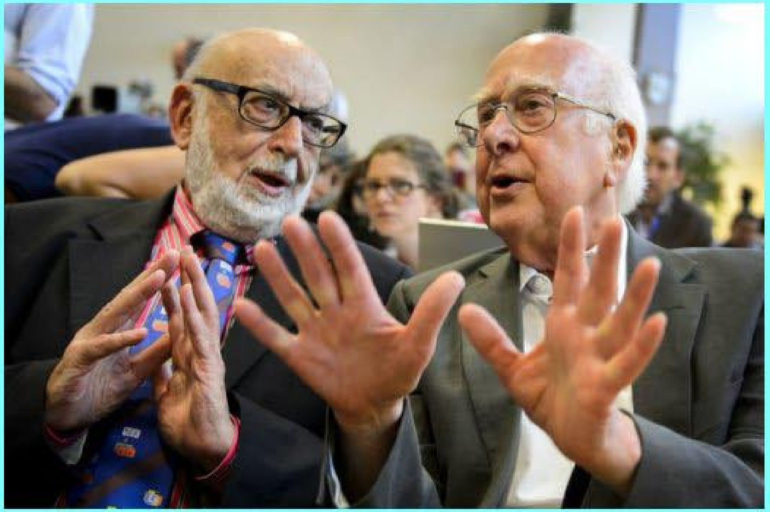

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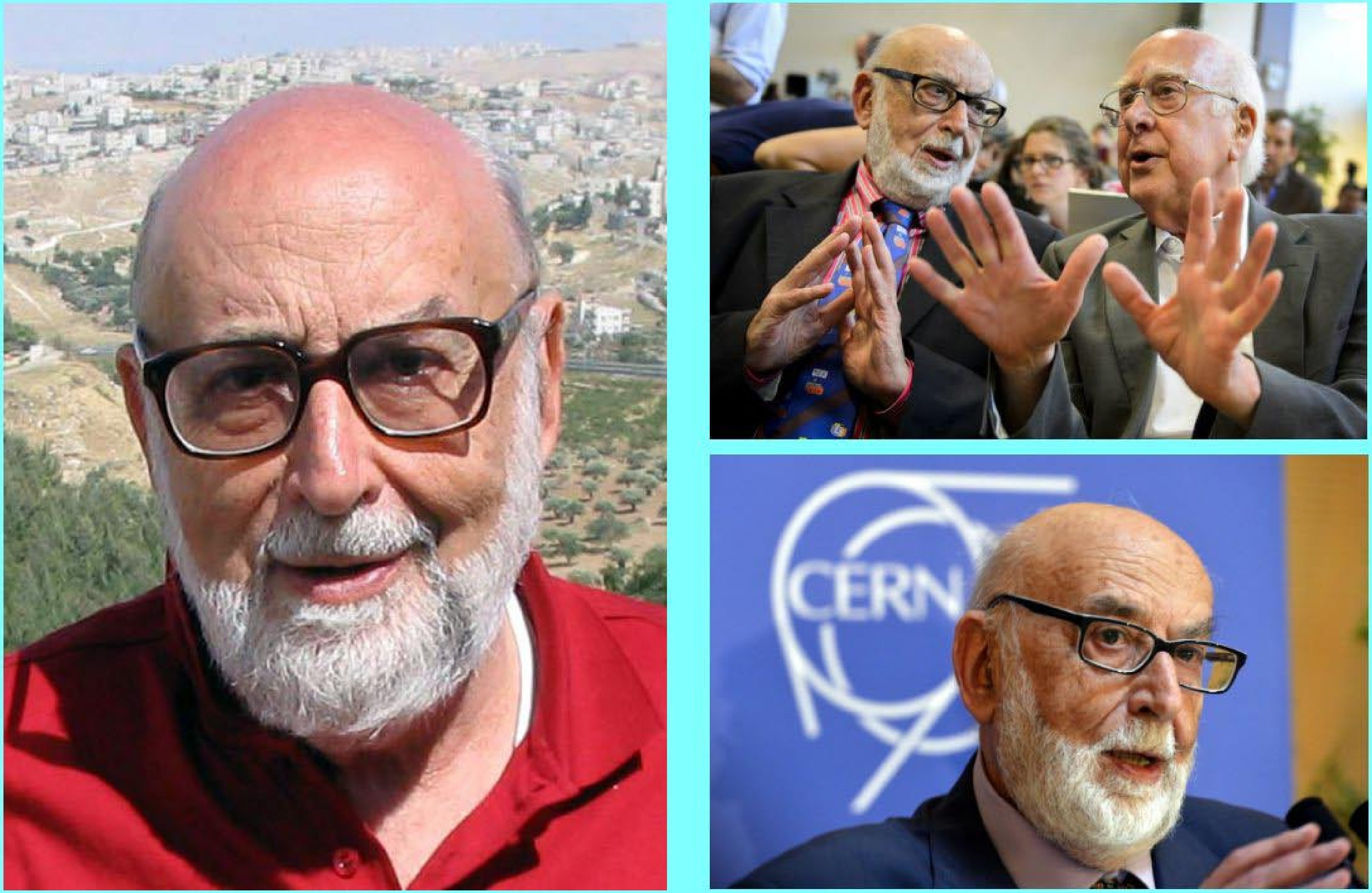

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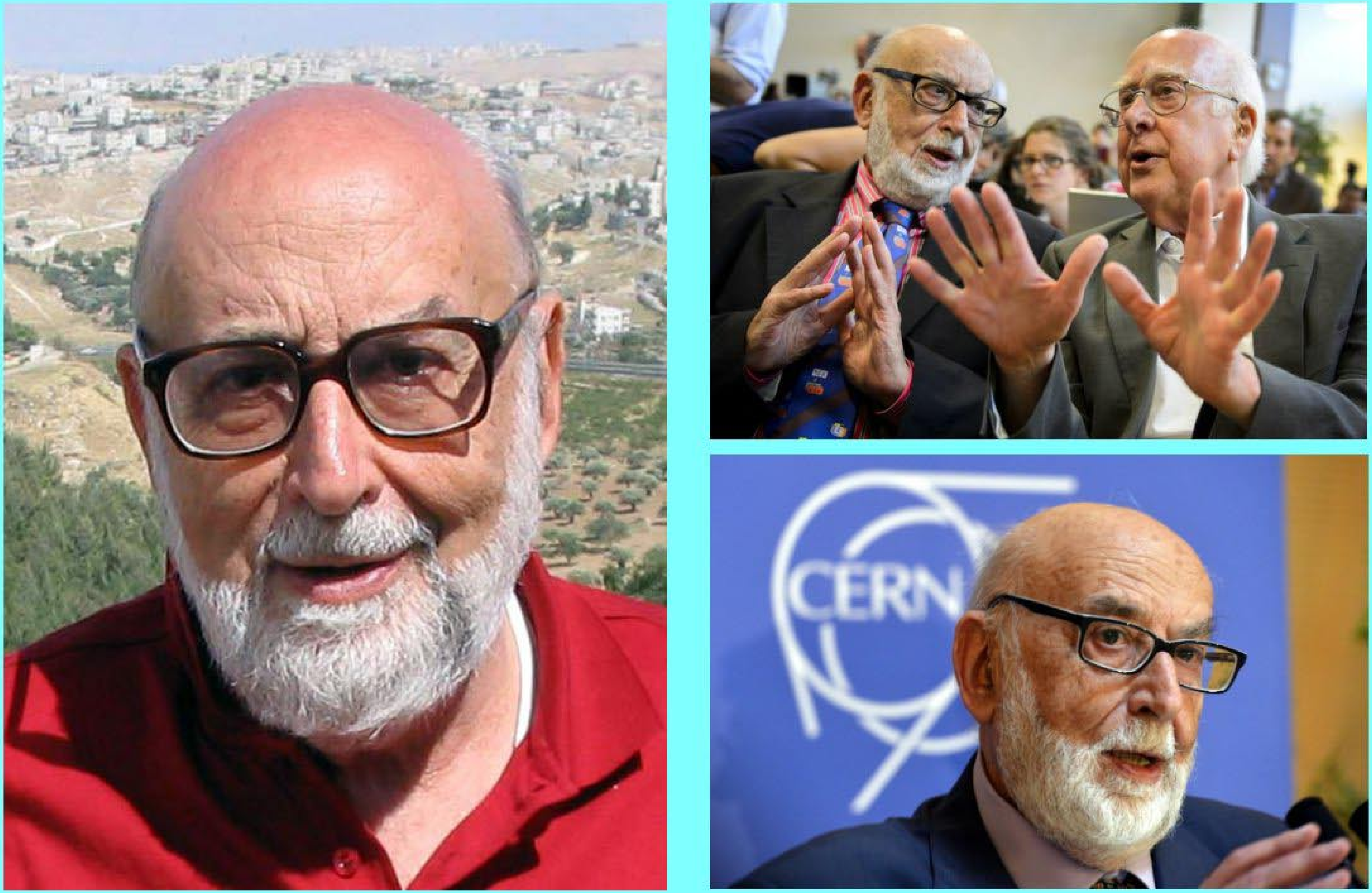

Best wishes to François —

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.

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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.)

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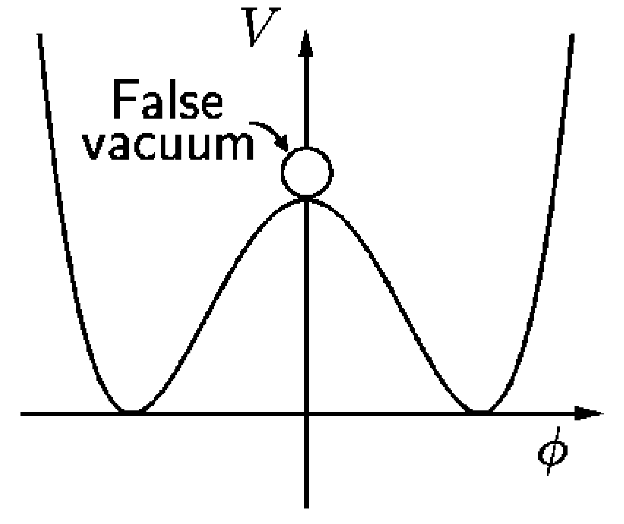
Gravitational Repulsion!

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

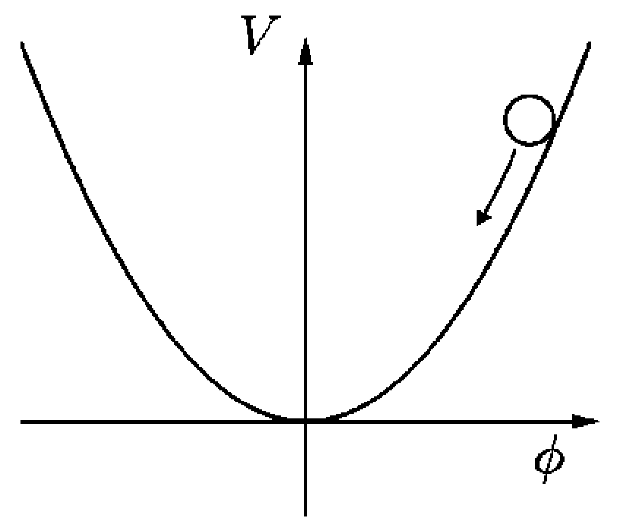
Inflationary Scenarios

- ☆ **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.

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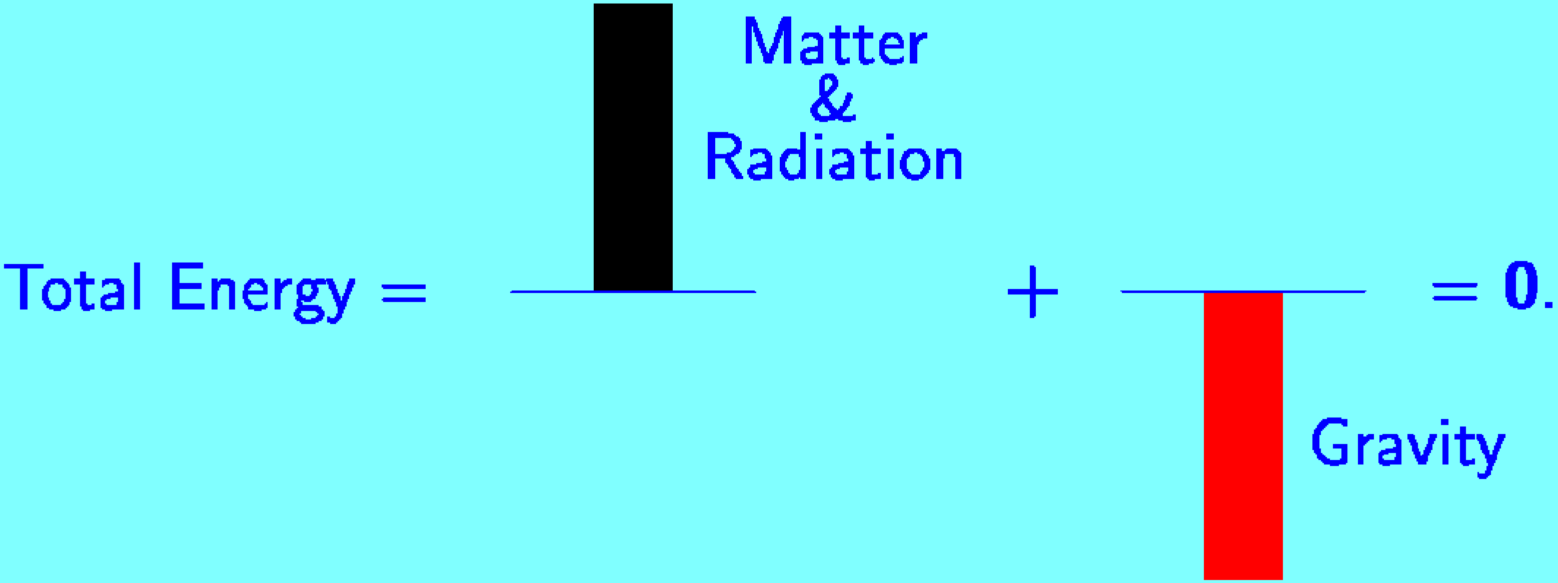
The energy of a gravitational field is negative!

- ☆ 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.

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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:”**

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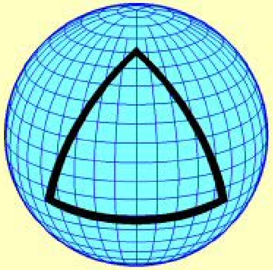
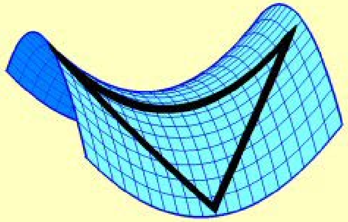
- ☆ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.



Closed Geometry



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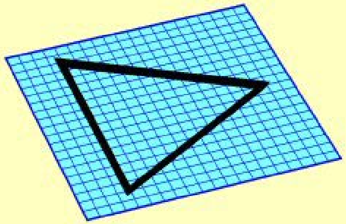

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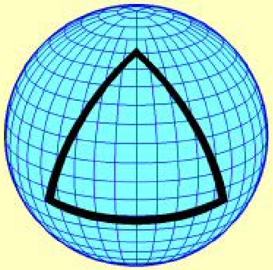
- If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.
- According to general relativity, the flatness of the universe is related to its mass density:

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

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



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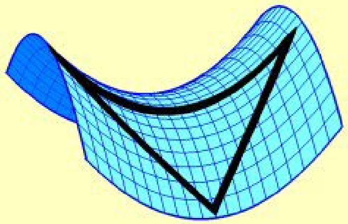

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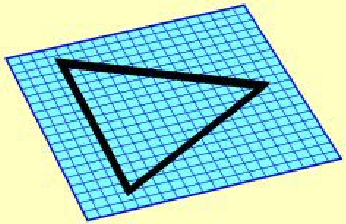
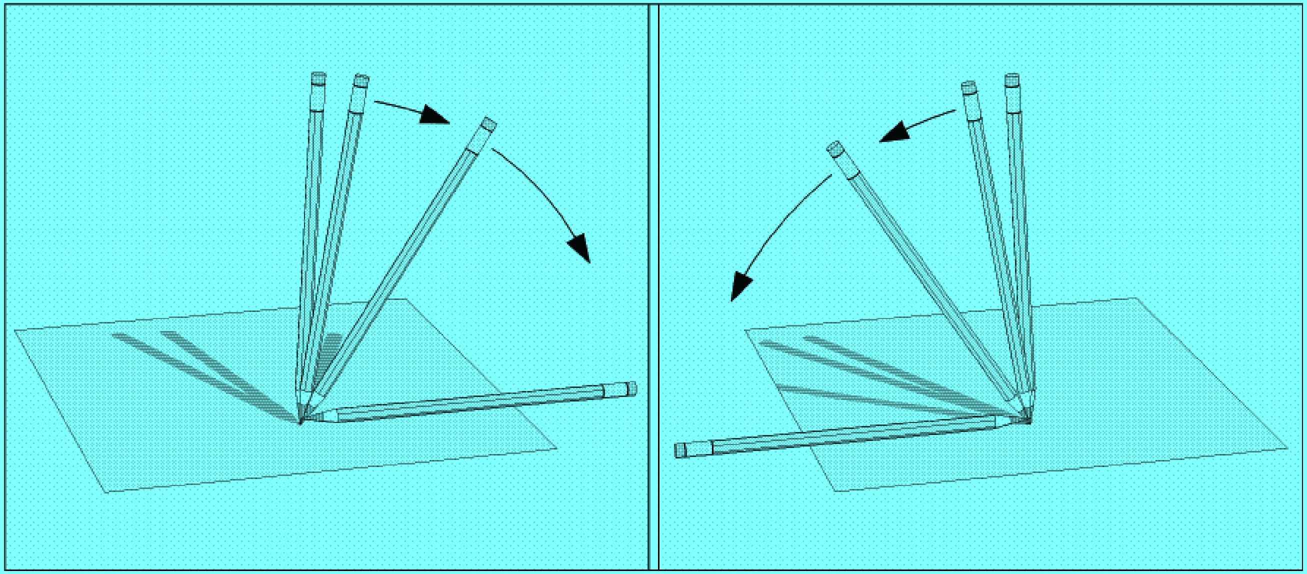


Flat Geometry

- 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.

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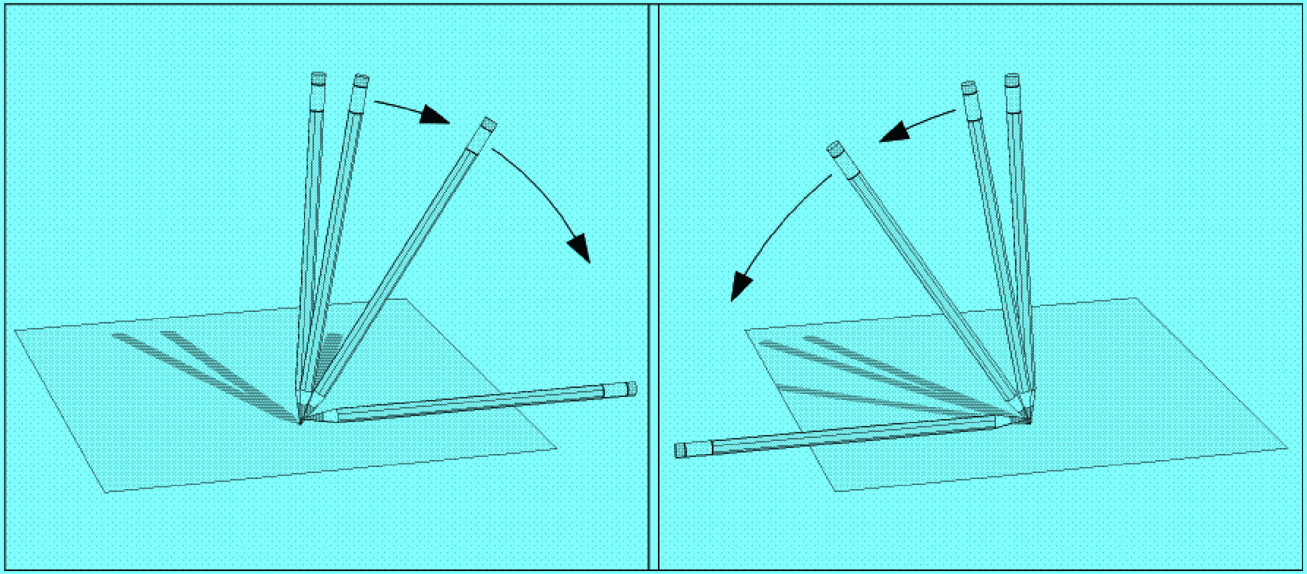

- If Ω in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.
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- To be as close to critical density as we measure today, at one second after the big bang, Ω must have been equal to one **to 15 decimal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

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- ☆ 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?

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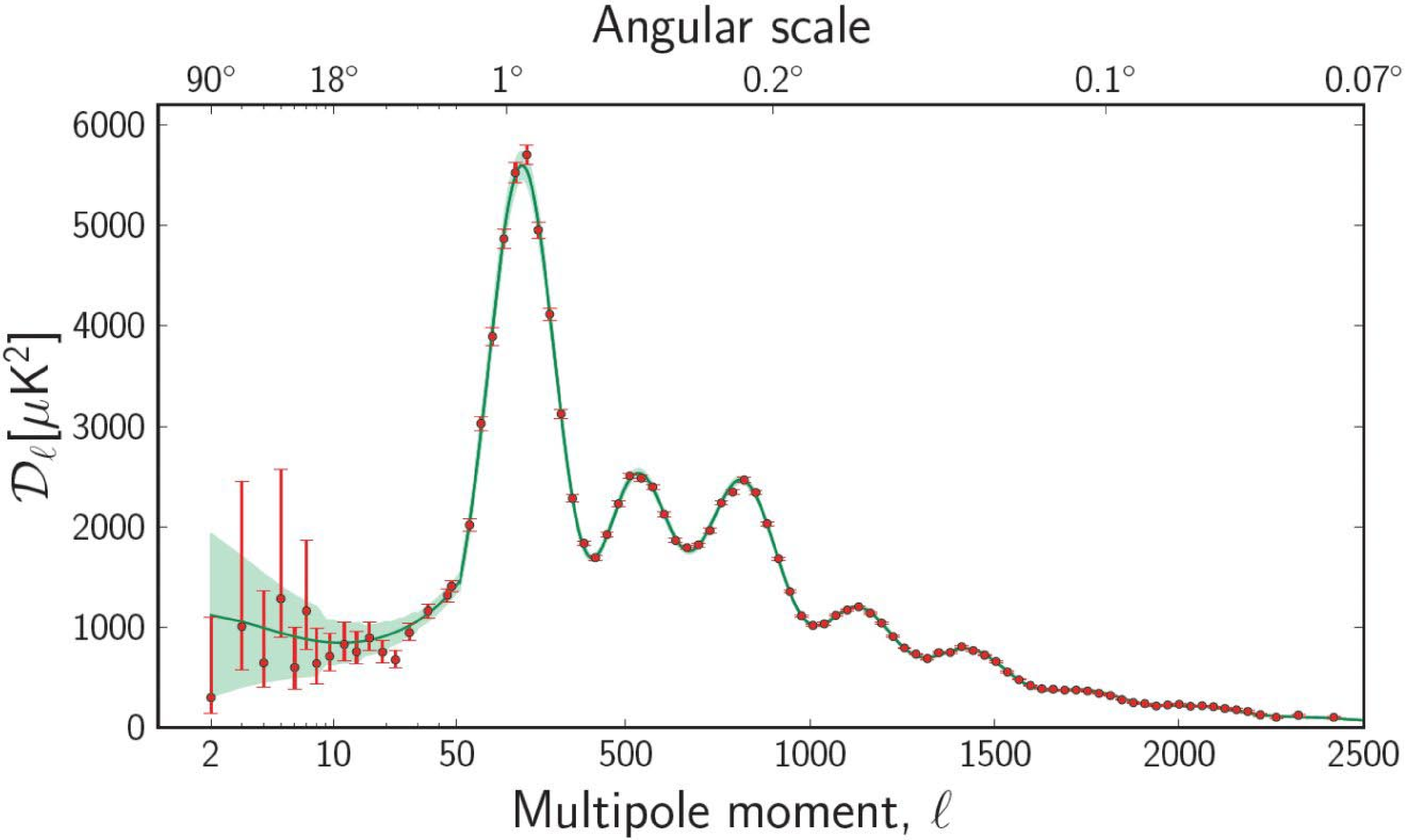
Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.

Planck Collaboration: The *Planck* mission



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 $\rho_{\rm inf}$ is the energy density of the universe at the time of inflation, then

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

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

BICEP2 Roller Coaster Ride

March 17, 2014: The BICEP2 press conference announces the detection of primordial B-modes in the polarization of the CMB. Posted paper: “The observed B-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with r = 0 disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.”

May 15, 2014: Raphael Flauger gave a talk at Princeton (video posted on the web), concluding that “According to all estimates, foregrounds may be small enough to detect a (large) primordial signal at 150 GHz without foreground subtraction, but the uncertainty on foregrounds is large and measurements at other frequencies (especially above 150 GHz e.g. from Planck) seem important for a definitive measurement.”

May 16-17, 2014: At a Caltech workshop (with video on the web), Matias Zaldarriaga concluded: “I believe the case in favor of a detection of primordial B modes is not convincing (hopefully just temporarily).

May 22, 2014: Paper by Morton and Seljak: Similar conclusions.

May 28, 2014: Paper by Flauger, Hill, and Spergel: Similar conclusions.

June 19, 2014: Revised BICEP2 paper published in Phys. Rev. Lett.: “We also examine a number of available models of polarized dust emission and find that at their default parameter values they predict power 5–10× smaller than the observed excess signal (with no significant cross-correlation with our maps). However, these models are not sufficiently constrained by external public data to exclude the possibility of dust emission bright enough to explain the entire excess signal.”

Current rumors: The Planck team is working on a paper describing their dust measurements in the BICEP2 field, which could be released in days or weeks. They intend to release a full paper on polarization in October or November. The BICEP2 and Planck teams are negotiating to collaborate on a paper that pools their data, possibly to be finished by the end of this year.

At this conference, tomorrow, at 18:30 Roger O'Brient will speak for BICEP2, and Enrique Martinez-Gonzalez will speak for Planck.

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

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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.

The Multiverse and the Cosmological Constant Problem

- One of the thorniest problems in particle theory is to understand why the energy density of the vacuum (equivalent to the cosmological constant) is 120 orders of magnitude smaller than the Planck scale.
- The multiverse offers a possible (but controversial) solution.
- If there are 10^{500} different types of vacuum, there will be many with energy densities in the range we observe.
- The vacuum energy affects cosmic evolution: if it is too large and positive, the universe flies apart too fast for galaxies to form. If too large and negative, the universe implodes.
- It is therefore plausible that life only forms in those pocket universes with incredibly small vacuum energies, so all living beings would observe a small vacuum energy. (Anthropic principle, or observational selection effect.)

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