

# Modern cosmology

## Inflation and vacuum energy

Paper draft due April 17th

# No static universe

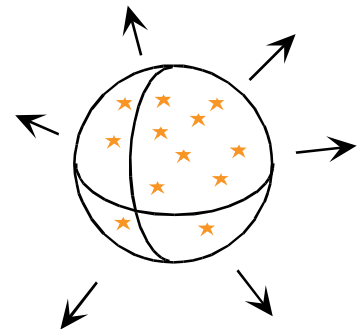
The Perfect Cosmological Principle: the universe looks the same viewed from anywhere and at any time. It does not match what we see.

One of Leibniz' arguments against Newton's absolute space was:

- An infinite and unchanging Euclidean space and an absolute time independent of the stuff that is in it implies either:
  - The stuff is also infinite in extent (in space and time). But that is impossible, because it violates Newton's own laws of motion.
  - The stuff is finite in extent. But then symmetries are violated. There is a center (a preferred position) and a corresponding preferred velocity, which ought to be observable.
- GR extends the problem to spacetime itself. It tells us that the universe must be expanding or contracting. It can't be static. This means that either there is an earliest time or a latest time (or both).
- This is easiest to visualize with our 2-d sphere analogy. The sphere is a balloon which is being blown up.

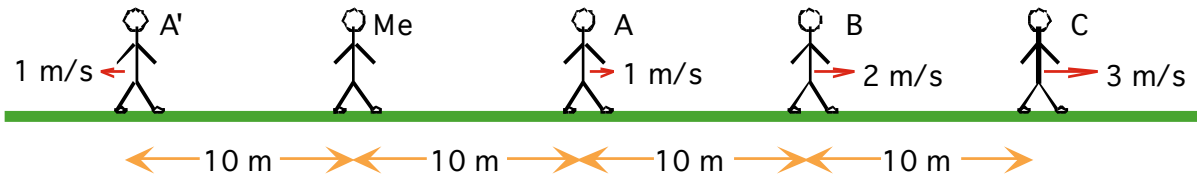
Some time in the past, the radius of the balloon (the area of its surface) must have been zero.

That's the "big bang" singularity.



# The universe is expanding

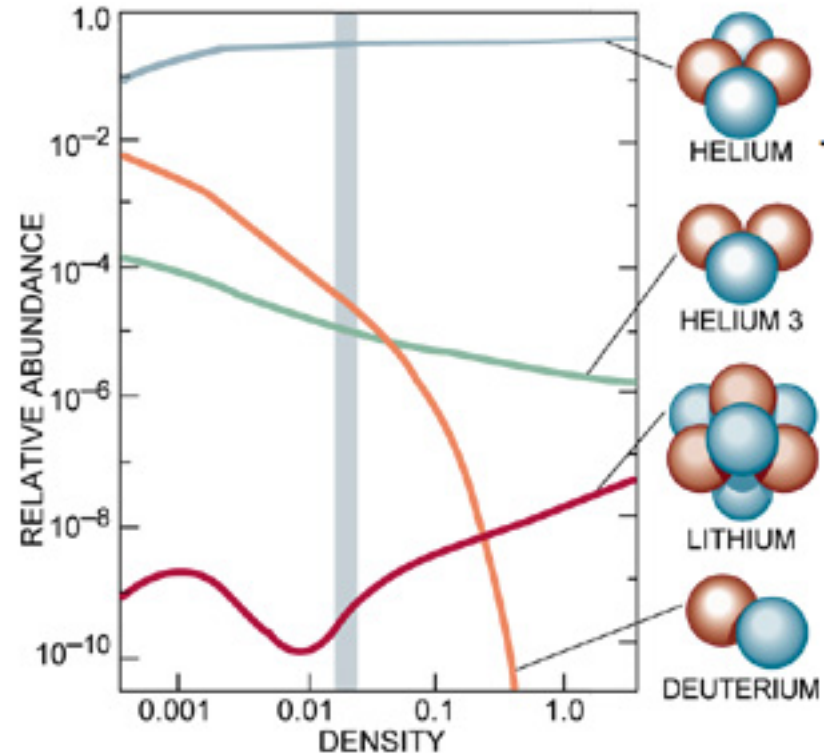
- What is observed? (Hubble, 1932)
- Distant galaxies are moving away from us. The farther they are, the faster they are receding (a linear relationship). This means that at some time in the past, they were all right here ... The whole universe was squashed together. This does not violate relativity. There is no center (preferred location).
- Suppose I have several friends:
  - A is 10 meters from me, moving away at 1 m/s
  - B 20 2
  - C 30 3



- If they have been moving at a constant speed, I can say that 10 seconds ago, each was at my present location. Notice that A sees exactly the same thing that I do. (Different people, but the same relationships.) The quantity that describes this motion is: “ $H = 0.1 \text{ m/s per meter}$ ”.  $H$  is the Hubble expansion parameter.

# Did the Big Bang really happen?

- Besides
  - GR theory and
  - the Hubble expansion
- main evidences for the big bang are
  - The relative abundances of the light nuclei (H, D, He, Li) are  $\sim$ correctly predicted by the BB theory.
  - the cosmic microwave background.



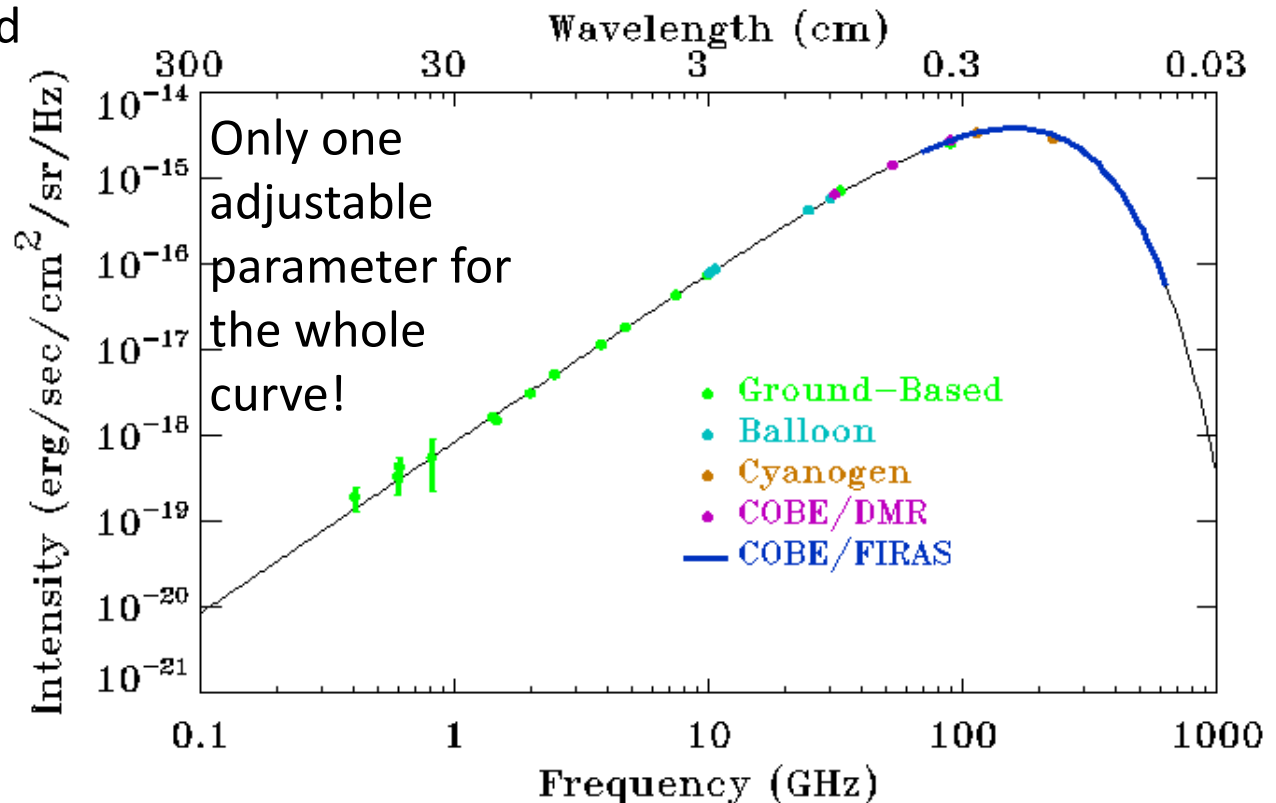
<http://astro.berkeley.edu/~mwhite/darkmatter/bbn.html>

# Cosmic Microwave Background Spectrum

When the universe was much more compressed, it must have been much hotter than now. Hot objects glow with thermal radiation. Before the universe cooled to about 3000 K, it wasn't transparent, since when atoms are heated up above that the electrons fall off. Loose electrons are very good light absorbers/ reflectors, as in metals. So we should see back to the point at which it first became nearly transparent, at about 3000 K and  $\sim 400,000$  years old.

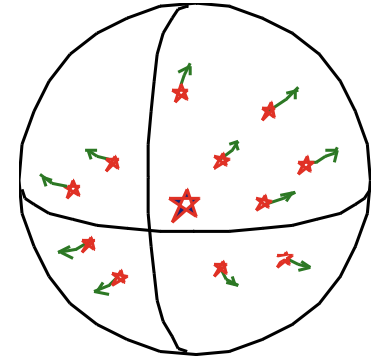
It shouldn't look like a 3000K surface because the universe has expanded diluting the light and stretching out its wavelengths. It should look like it's at  $\sim 2.7$  K.

Predicted by Gamow, Alpher and Herman in the 1940s and accidentally discovered in 1964 by Penzias and Wilson. Many details are now understood in terms of more elaborate BB theories.



# How does GR describe the expansion?

Remember our balloon analogy for curved geometry:  
Think of dots painted on a balloon. As the balloon expands, the dots move apart.



- GR says the balloon must either be expanding or contracting. It is expanding.  
The age of the universe is not quite  $\sim 14$  billion years, due to accelerations. The expansion rate is changing due to the mutual gravitational effects of all the energy in the universe.
- Will the expansion ever stop? If I throw a ball in the air, will it fall down?
- There are two simple possibilities.
  - If the attraction is strong enough, and the speed small enough, then the expansion will stop, and the universe will collapse into a big crunch.
  - If not, or if there is a repulsion, then it will continue to expand forever.
- Right now, it looks as if the expansion will continue forever.

# There is no edge, but there is a horizon

- Even though the universe is expanding, it is not expanding “into” anything. There is not an edge to the matter, beyond which there is only empty space.
- There is a GR analog to the edge, however. There is a horizon, dependent on the observer. The linear relationship between distance and speed tells us that beyond a certain distance ( $\sim c/H \approx 14$  billion light years) the stuff out there “is” moving away at faster than light speed. i.e. space is expanding so fast that it is being carried away faster than the speed of light.
  - Why “is”?
  - In standard “co-moving” coordinates, the distance across “now” is a lot bigger than 28 billion light years.
- Doesn’t this violate special relativity? What's left of the SR speed-limit is the constraint that any *local* measurement of a speed give  $c$  or less. Inferred speeds of parts of the universe with which communication is impossible are not governed by that constraint.

# The Cosmic microwave background (CMB)

- When the universe was small, it must have been hot. It should be possible to see the afterglow. When the universe was about  $10^5$  years old,  $T \sim 3000\text{K}$ . Below this temperature, atoms are not ionized, and the universe becomes transparent. The “relic photons” will have been red-shifted by the expansion of space to an effective temperature of only  $2.7\text{K}$ .
- The CMB is a nearly perfect “black body” spectrum. The only distortion larger than about a part in  $10^5$  is an anisotropy that indicates that our galaxy is moving a few hundred km/s with respect to the matter that emitted the radiation.
- Theories without a “hot big bang” need to propose alternative mechanisms for the CMB. None have been able to reproduce the spectrum.
- At  $10^5$  years the radius of causal connection corresponds to a  $\sim 1^\circ$  circle in the sky. So, why is the CMB the same in every direction? There appears to be a deeper connection .
- The fluctuations tell us something about how lumpy the matter distribution was at that epoch.



# The main features of hot big bang cosmology

- As the universe expands, it cools. The very early universe was very hot, and massive objects could be produced by the heat. Objects that are bound today were liberated then.
- For a given expansion rate, there is a critical energy density,  $\Omega_o$ , for which the geometry is flat. In a simple fixed-mass picture the mass density causes the expansion to *decelerate*. (now,  $\Omega_o \sim 10^{-26}$  kg/m<sup>3</sup>, about 10 protons per cubic meter) In a fixed-density picture, the energy density causes the expansion to *accelerate*. If there were zero background density,  $\Omega_o$  is the density just sufficient to bring the expansion to a halt.  $\Omega > \Omega_o$  would give a big crunch.
- The gravitational dynamics of galactic clusters implies that they contain  $\Omega \gg 0.3\Omega_o$ , mostly non-stellar "dark matter."
- Density fluctuations increase with time. Way back then, the universe was very homogeneous, as shown by the CMB.
- The overall density of the universe evolves away from  $\Omega_o$ , the critical energy density needed for closure. Closer to  $t = 0$ , the density becomes closer to  $\Omega_o$ .
- One can't extrapolate back to  $t = 0$ . Above about  $T=10^{32}$ K, one needs to be able to unify QM and gravity. New phenomena might appear first.

# Dark Matter/Dark Energy

- Dark Matter. An unknown “particle” that only interacts with us via gravity but whose mass is about 6 times more than all matter we can see. We can see its effects on galaxies
- Dark Energy: (cosmological constant). A term in Einstein’s GR equations that makes space fly apart. The Universe is accelerating. *Nobel Prize 2011: accelerating expansion of the universe: Perlmutter, Schmidt, Reiss*

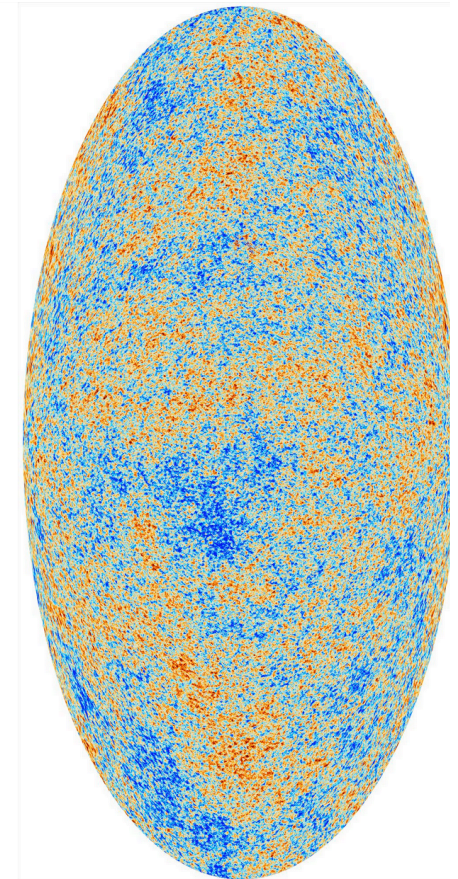
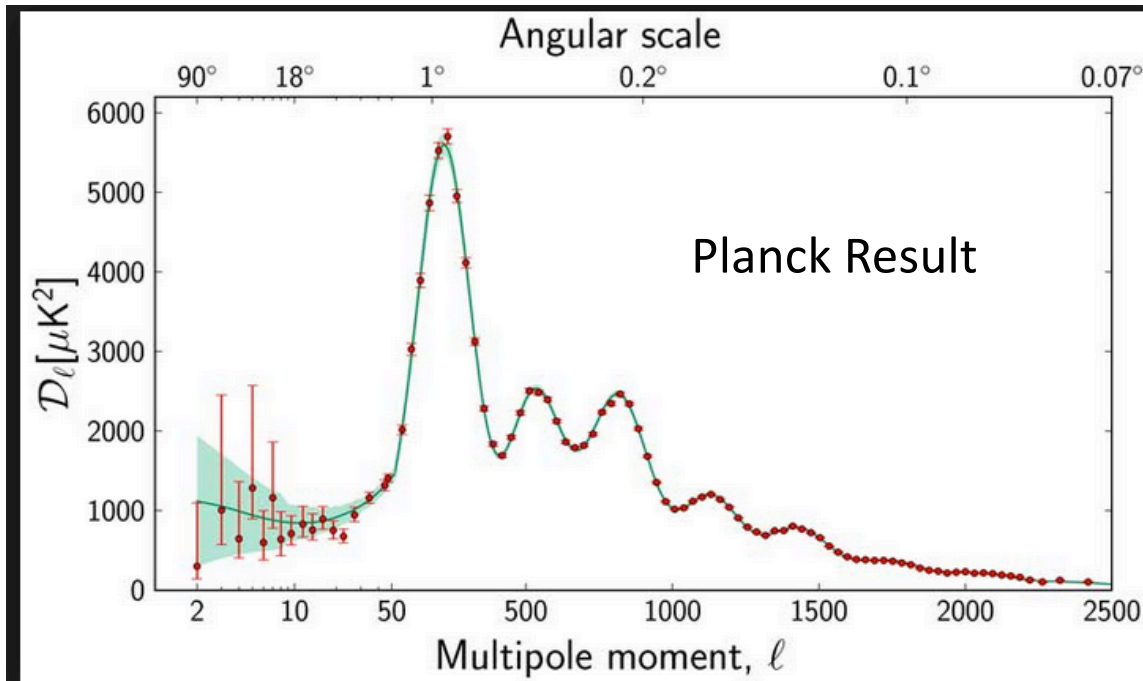
# There are three big issues

1. Why is the universe so homogenous at early times? There hadn't been enough time for the various regions that we can see to have communicated, so why do they look the same?
2. Why did the energy density of the universe start out so close to  $\Omega_0$ ? If it was so close to the critical value then (differing by about one part in  $10^{-42}$  at the earliest times to which we think we can extrapolate known physics) why not exactly 1?
3. Entropy only increases with time. This implies that the universe was in a very low entropy state at early times. How is that consistent with high temperatures?

There is a proposed scenario to explain all this, but the last point needs some preliminary discussion

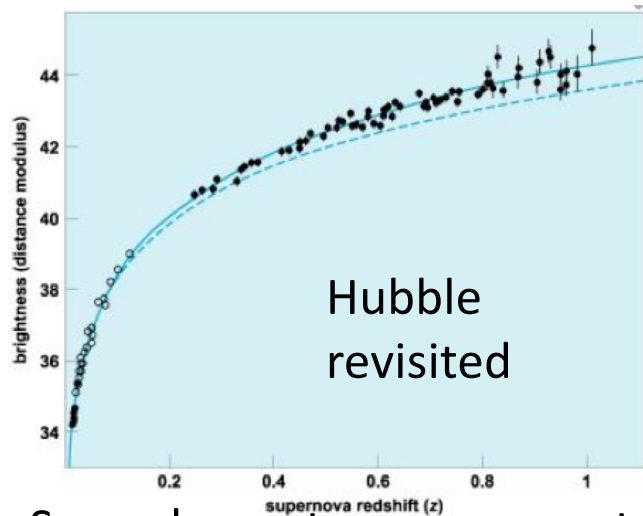
# CMB is not isotropic

- Nobel Prize 2006: CMB is anisotropic: Smoot, Mather
- We see slightly different temperatures in different directions
- The problem is that they are so uniform
- Inflation (curve) did make predictions for the amount of structure of various sizes in the universe, especially in the background radiation.



# CMB Fits Theory

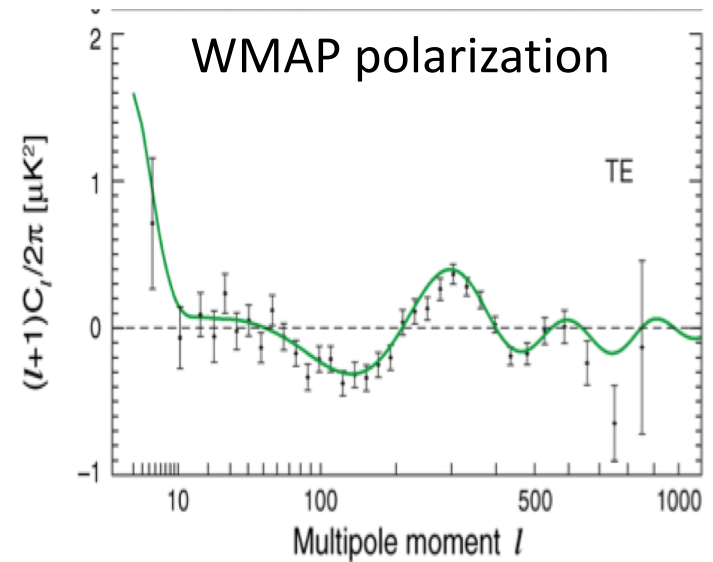
- Does that mean that we are missing 70% of the matter in the universe, when we only find 30% of the critical density in galactic clusters?



No: the expansion of the universe is *still accelerating* according to pretty reliable measurements.

It looks like we're still in a period of weak inflation!

- So we have strong reasons to think that inflation made the total energy density very close to the critical value. If the same inflation that made the universe homogeneous also made it flat, the radius of curvature should be more than  $(10^5)^{1/2}$  as large as the age of the universe times  $c$ . That means that the universe is extremely close to flat: right at the edge between open and closed.

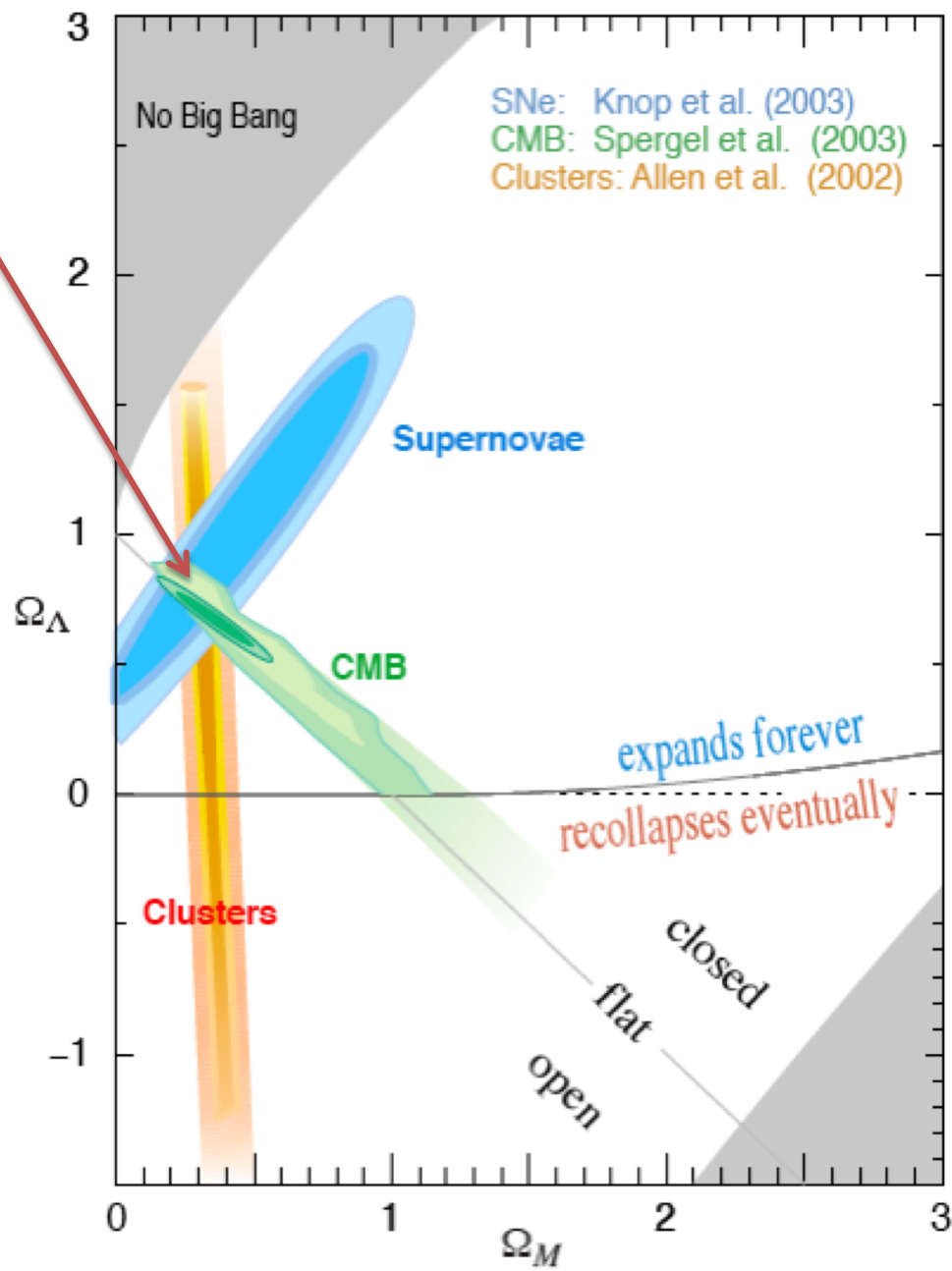


# Parameters

$H_0$	$70.4^{+1.3}_{-1.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$	Hubble constant
$\Omega_b h^2$	$0.02260 \pm 0.00053$	Physical baryon density
$\Omega_c h^2$	$0.1123 \pm 0.0035$	Physical dark matter density
$\Omega_b$	$0.0456 \pm 0.0016$	Baryon density
$\Omega_c$	$0.227 \pm 0.014$	Dark matter density
$\Omega_\Lambda$	$0.728^{+0.015}_{-0.016}$	Dark energy density
$\Delta_R^2$	$2.441^{+0.088}_{-0.092} \times 10^{-9}, k_0 = 0.002 \text{ Mpc}^{-1}$	Curvature fluctuation amplitude
$\sigma_8$	$0.809 \pm 0.024$	Fluctuation amplitude at $8h^{-1} \text{ Mpc}$
$n_s$	$0.963 \pm 0.012$	Scalar spectral index
$z_*$	$1090.89^{+0.68}_{-0.69}$	Redshift at decoupling
$t_*$	$377730^{+3205}_{-3200} \text{ years}$	Age at decoupling

## We're here

- The accelerating expansion from the background energy density, breaks the simple connection between energy density and the fate of the universe.
- Depending on the ratio of the ordinary mass to the background density, you can have:
  - Open/ always expands
  - Closed/Collapses
  - Closed/always expands
  - Open/collapses
- We're almost exactly on the edge between open and closed, very near flat.



# Key unanswered questions

- If the field apparently causing the current acceleration of expansion remains constant, the expansion will continue forever. If it were to fall to zero, the expansion would still continue forever. But we really don't know what it is or what it will do.
- What would make the background energy density so close to the matter density?
  - In cosmological constant case, that would be a special recent historical feature. 1 billion years post BB, the background would be less than 1/1000 of the matter density.
- What fine-tuned the parameters to give it a smooth landing?

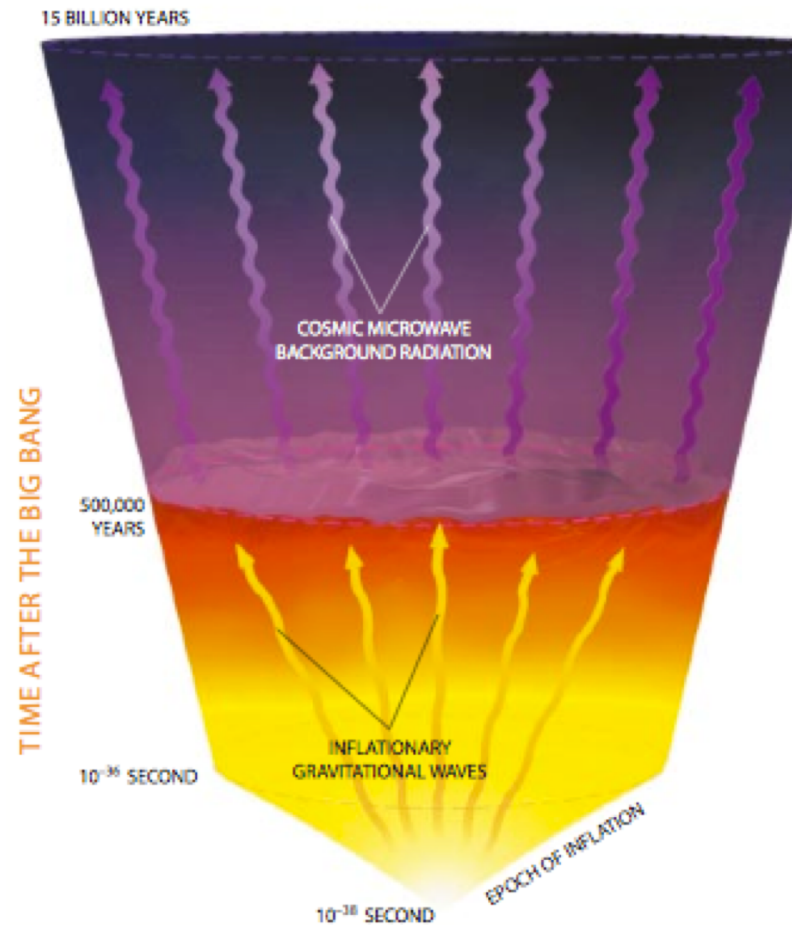


# Entropy in the big bang

- The universe is not in thermal equilibrium. One indicator of low entropy is that there are hot objects and cold ones. Life requires such disequilibrium.
- If the universe was uniformly hot at early times, one would guess that the entropy was very high then, i.e. at thermal equilibrium. If so, how do we explain the low entropy at the present time?
- In the early universe, the matter was very hot and in a high entropy state (thermal equilibrium), but spacetime was in a low entropy state, i.e., the curvature of spacetime was not “wrinkled”. *Geometry itself has entropy.*
  - The formation of gravitationally condensed objects like the Sun, neutron stars, and black holes, increases entropy. So, as long as stuff can keep falling into gravity wells, there will continue to be regions of high and low entropy.
- Why did spacetime start out in this special, low-entropy state?
- If there is to be a big crunch, the universe will collapse back to a singularity, but it will have high entropy. Without some further constraint, there is no known reason why a very dense universe must have low-entropy.

# Inflation

- The other two mysteries (large scale homogeneity and near flatness) might both be accounted for by a single explanation.
- *If "empty" space had a fixed positive energy density, space would expand exponentially. (Inflation)* A period of such an expansion would:
  - Pull causally connected regions far apart, so that simple extrapolation from a later Hubble constant would not reveal how close they had once been.
  - Smooth out wrinkles in space.
  - Dilute the concentration of magnetic monopoles

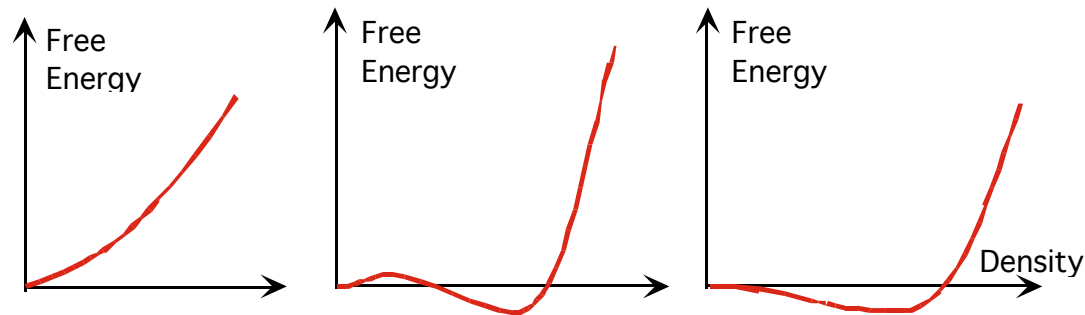


# Spontaneous symmetry breaking in the vacuum

- Our vacuum can have unusual properties that one would not expect from Newton's or Leibniz' (or even Einstein's) space. It now makes sense to ask, "Are the virtual particles in our vacuum aligned in some way?" Do the underlying equations of physics have any symmetry that is not manifested by the world that we see?
- The answer is yes. The symmetry is similar to the one that gives conservation of electric charge. It is not a spatial symmetry, but an "internal" one (*i.e.*, a mathematical symmetry of the equations) called gauge invariance. In addition to enforcing conservation of charge, it also causes the photon to be massless, which is the reason the electrical force follows a  $1/r^2$  law. GR has a gauge invariance, as do the strong nuclear forces (QCD).
- The gauge invariance of the weak nuclear force is spontaneously broken at the temperatures of the current world. The result of this loss of symmetry is that the particles (the W and Z bosons) that mediate the weak force are massive, and the force is not  $1/r^2$ . At high temperature (*e.g.*, in the early universe) the symmetry is restored. (like the symmetry of a magnet, or of a piece of ice.)

# Spontaneous symmetry breaking in field theory

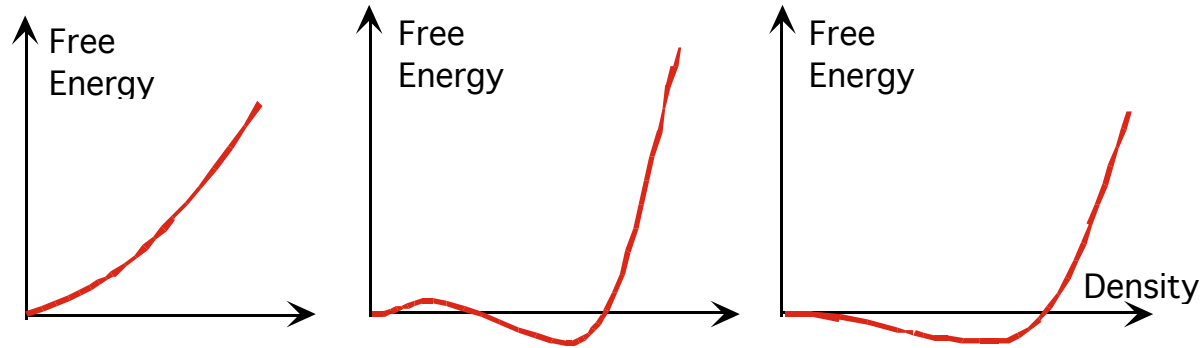
- Let's imagine a universe where every particle is massless. Suppose there is a particle which interacts with the other kinds of particles **and with itself**.
- Consider a box containing these particles. How does the energy of the box vary as we increase the density of particles in the box? Normally, we would expect it to increase:



- The graph is not linear, *because the particles interact*.

# Phase Transitions of Fields

- Suppose the particles have an attractive interaction such that above a certain density they begin to condense. Then the energy vs. density graph could look like one of these:



On the right two, the state of lowest energy has nonzero density!

- There is nothing terribly exotic about these pictures of energy vs. density. Essentially identical pictures occur for ordinary gases, when you try to calculate whether they form dense liquids or stay as rarified gas. The difference arises in that we treat the gas molecules as coming from some reservoir with a fixed number of particles.
- Here, in contrast, we're dealing with particles which can pop in or out of existence. Empty space itself provides the reservoir, and can always produce more particles.

# “Symmetry Breaking”

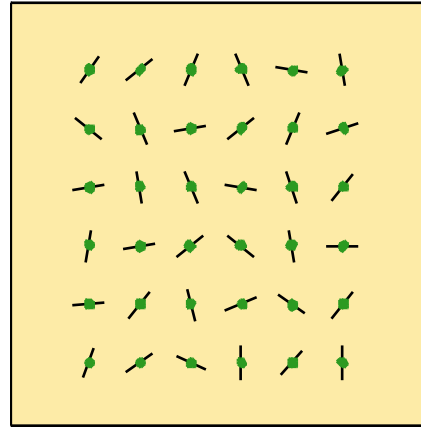
- Recall that the conservation laws follow from symmetries of laws. For example, angular momentum conservation follows from the invariance under rotations of the equations.
- Nevertheless, the state of lowest energy doesn't necessarily have to exhibit the symmetry.

- Let's consider an everyday example – a piece of iron. Each atom behaves like a little magnet, which we'll call a spin.

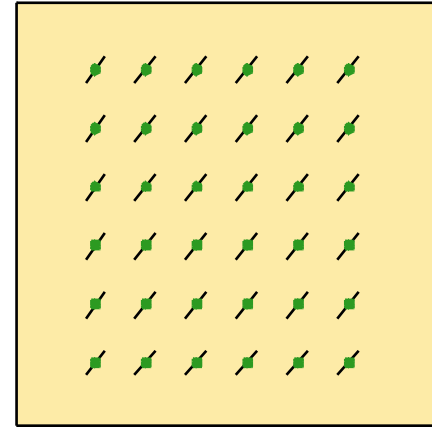
Will the spins line up with each other?

The answer depends on the temperature of the iron:

High Temperature



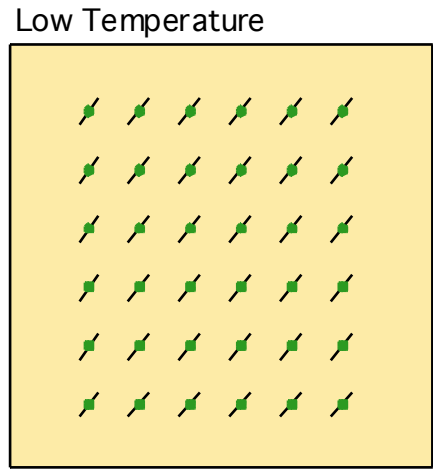
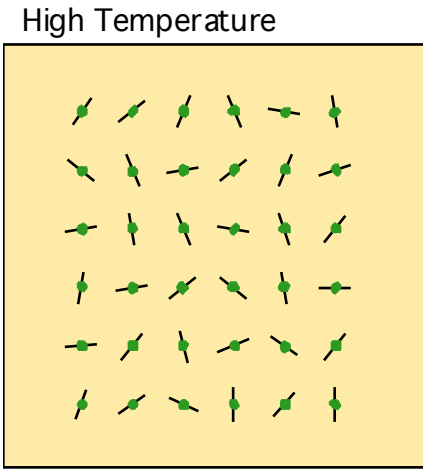
Low Temperature



- At high temperatures, the spins point randomly. That's because there are many more quantum states with random-looking spins than there are with the spins in any simple pattern. The iron is not magnetized oriented and, on average, the material is isotropic.
- What happens at low T?

- The spins have lower energy when they line up. At low T, that energy can make more entropy in the nearby reservoir than the spins lose by lining up. When the iron is cooled below about 770° C (the Curie temperature), the spins do align, maximizing the *total* entropy. The iron becomes magnetized.

- However, they cannot align without picking some particular direction to align along. Now there is a preferred direction, even though the physical equations themselves contained no special direction.

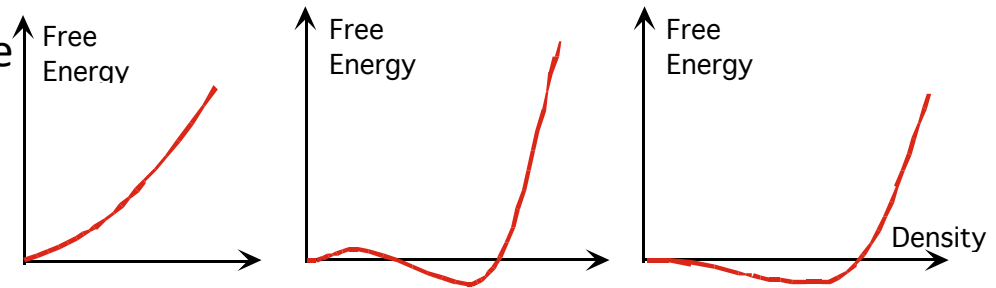


- This process is called spontaneous symmetry breaking.
- Rotational* symmetry is broken in this example.
- So is time reversal, since these are magnets, not little arrows.

# What would drive inflation?

- What energy density is to be used as the source of the gravitational effects? The zero-point energy would in principle be *infinite*. Even if we cut off the zero-point fluctuations at the Planck scale, where our current physics breaks down, the density would be  $\sim 10^{125}$  times the critical density of cosmology. So the energy that counts seems to be only the energy above some reference vacuum state.
- Consider the early, hot universe. Suppose that there is a scalar field which behaves as described earlier. Then, as time progresses, the free-energy-density graph will evolve.
- The density of the field is zero at

very early times, but as the temperature decreases, that is no longer the favored configuration. If the middle energy-density graph is

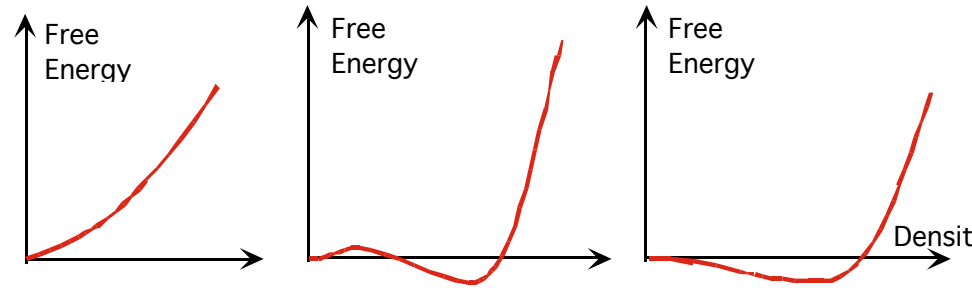


correct, then the universe will become trapped in a **false vacuum** state, i.e. a state in which the free-energy is bigger than it has to be. Even if the last version is right, the universe will not instantly reach the true vacuum, but will spend a little time in false vacuum states. The false vacuum will cause the expansion of the universe to have unusual features.



# Start and End of Inflation

(See Scientific American, Jan. 1999 for articles on the difference between getting stuck for a while in a false vacuum and gradually rolling out of a false vacuum.) The frozen symmetrical field has, at least for a while, a fixed density- driving inflation.



- In this scenario, the inflation was not caused by a change of the actual state of the vacuum but by the appearance of a new *possible* equilibrium state with lower energy. How does the universe know that there's a lower energy "real" vacuum?

Inflation may solve our two big cosmological problems.

- **Homogeneity.** If the inflation lasted for 100 time constants, the universe expanded by a factor of  $e^{100} = 10^{43}$ . The entire visible universe ( $10^{25}$  m) was a basketball ( $\sim 30$  cm) just after inflation, but only a minute speck ( $10^{-43}$  m) just before, much smaller than the causally connected region ( $10^{-23}$  m) then.
- **Flatness.** Suppose the universe wasn't close to the critical density before inflation. This means, in the balloon analogy, that it was curved. Now, increase the radius of the balloon by  $\times 10^{43}$ . It will become indistinguishably close to flat.
- Inflation could also account for the rarity of certain particles (magnetic monopoles) which should have been created, but have never actually been found.
- **Problem:** The inflationary scenario requires some fine-tuning of the strength of competing terms in the interactions, in order for the inflationary period to end smoothly.