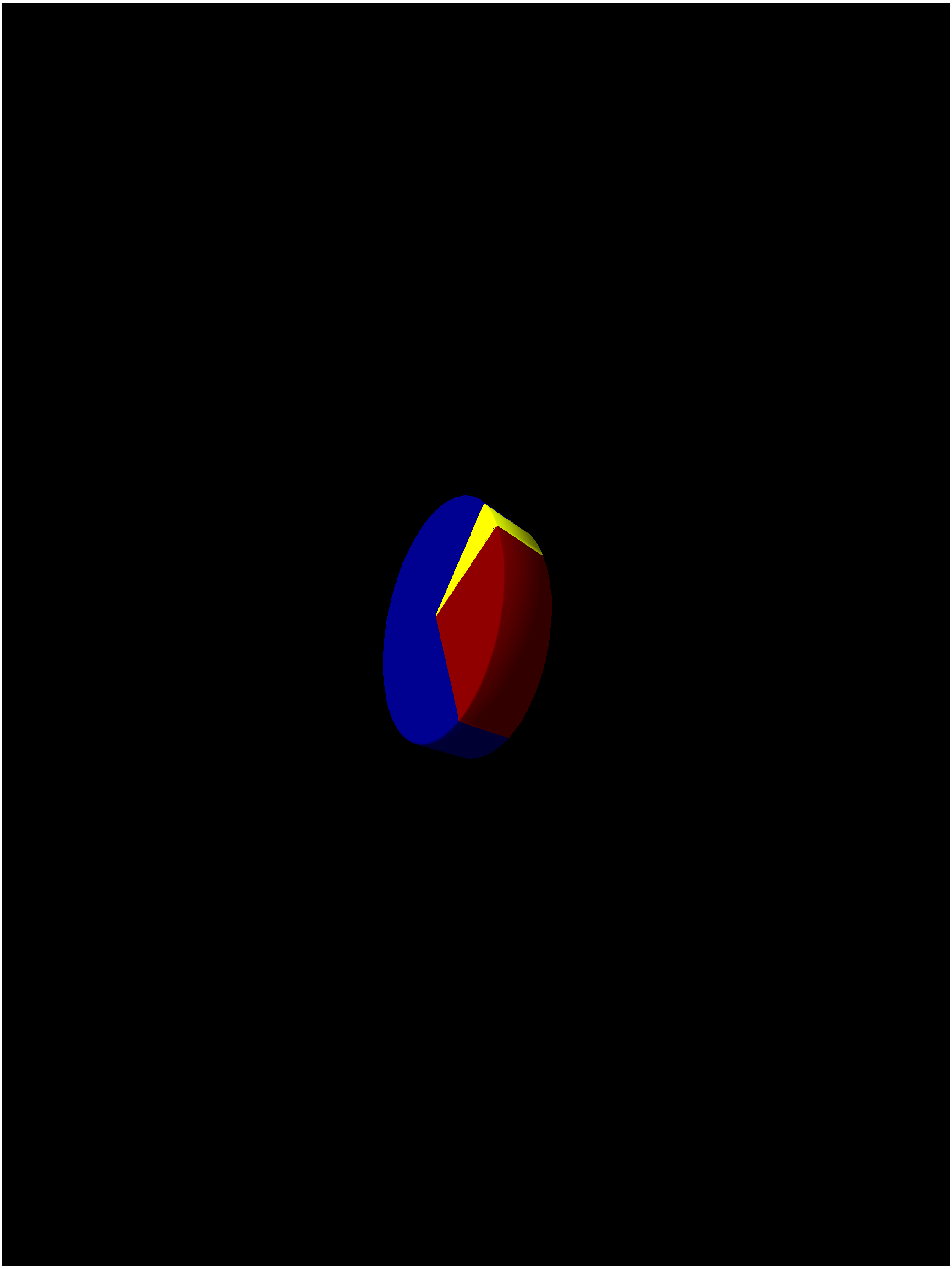
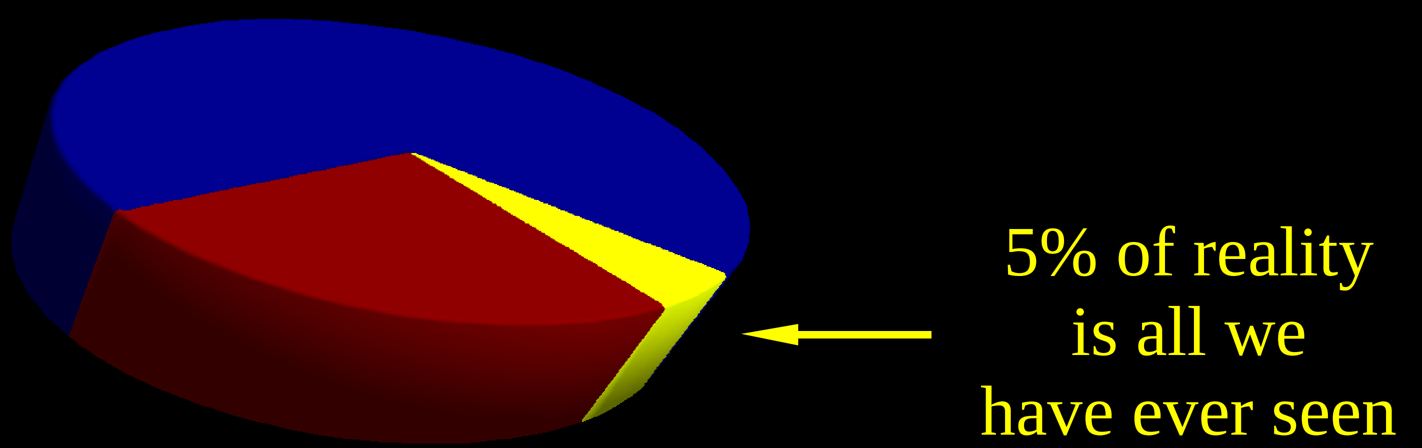


Our Preposterous Universe

Sean Carroll

University of Chicago

http://pancake.uchicago.edu/



Outline

- What does the universe look like?

  stars and galaxies; uniform, expanding

- What is the universe made of?

  ordinary matter, dark matter, dark energy

- Why is it like that?

  we don't know. inflation? string theory?

What does the universe look like?

Start by looking at the sky on a clear night. We live at the outskirts of a huge, disk-like collection of stars: the Milky Way galaxy.

An enhanced view:

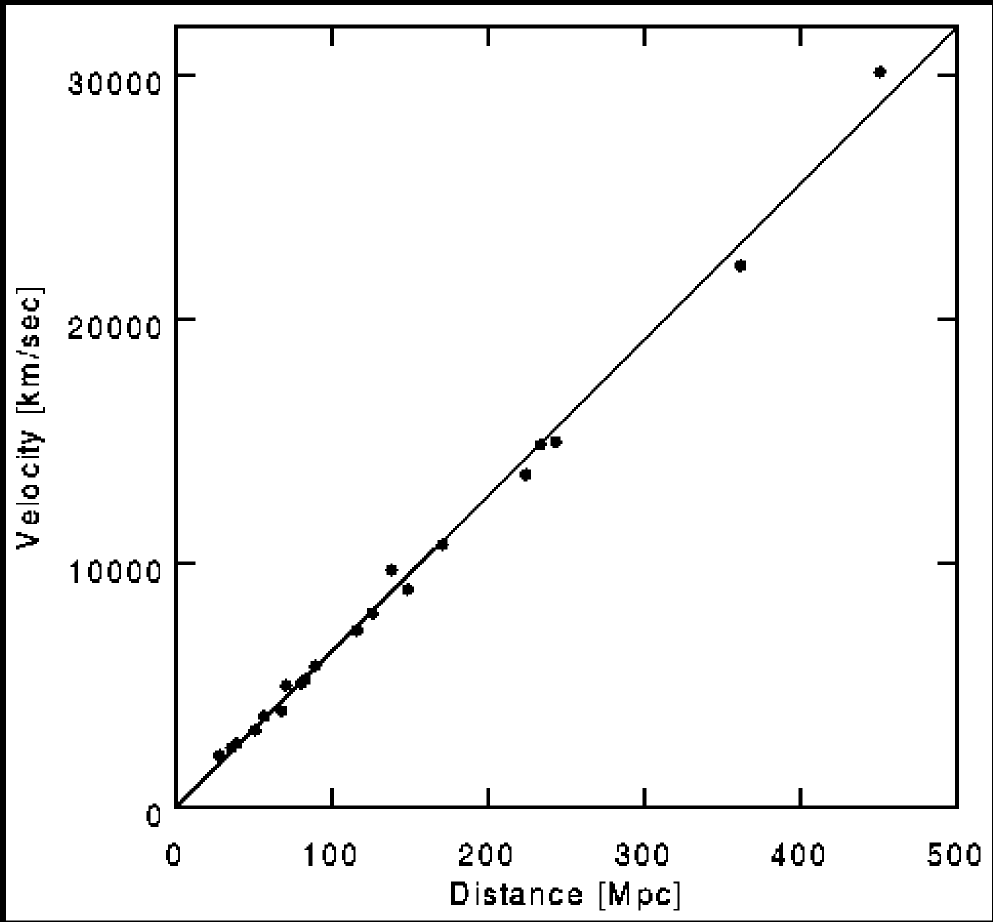
The Milky Way contains about one trillion (10^{12}) stars.

Looking more deeply, we see the universe is filled with galaxies.

1924: Edwin Hubble shows that each galaxy is a collection of stars, just like the Milky Way.

In other words: <u>the universe is expanding</u>.

1929: Hubble again, this time showing that the further away a galaxy is, the more rapidly it is moving away from us.

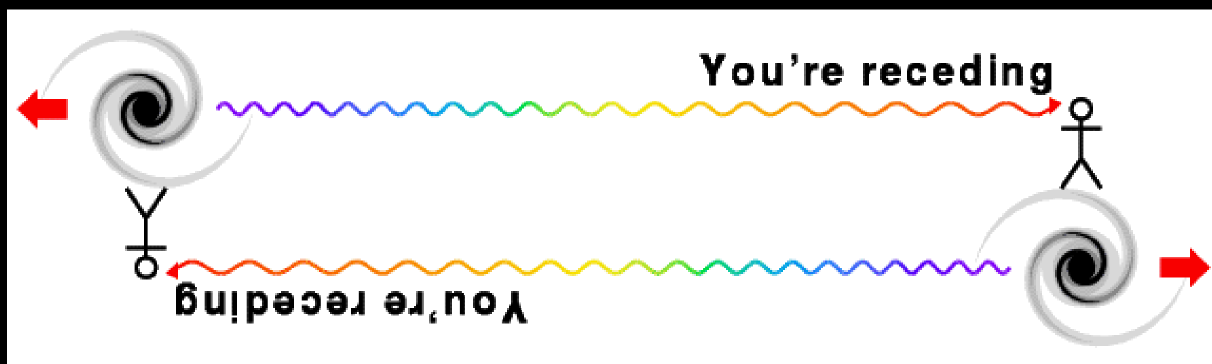


Modern version of Hubble's diagram.

What does "expanding" mean?

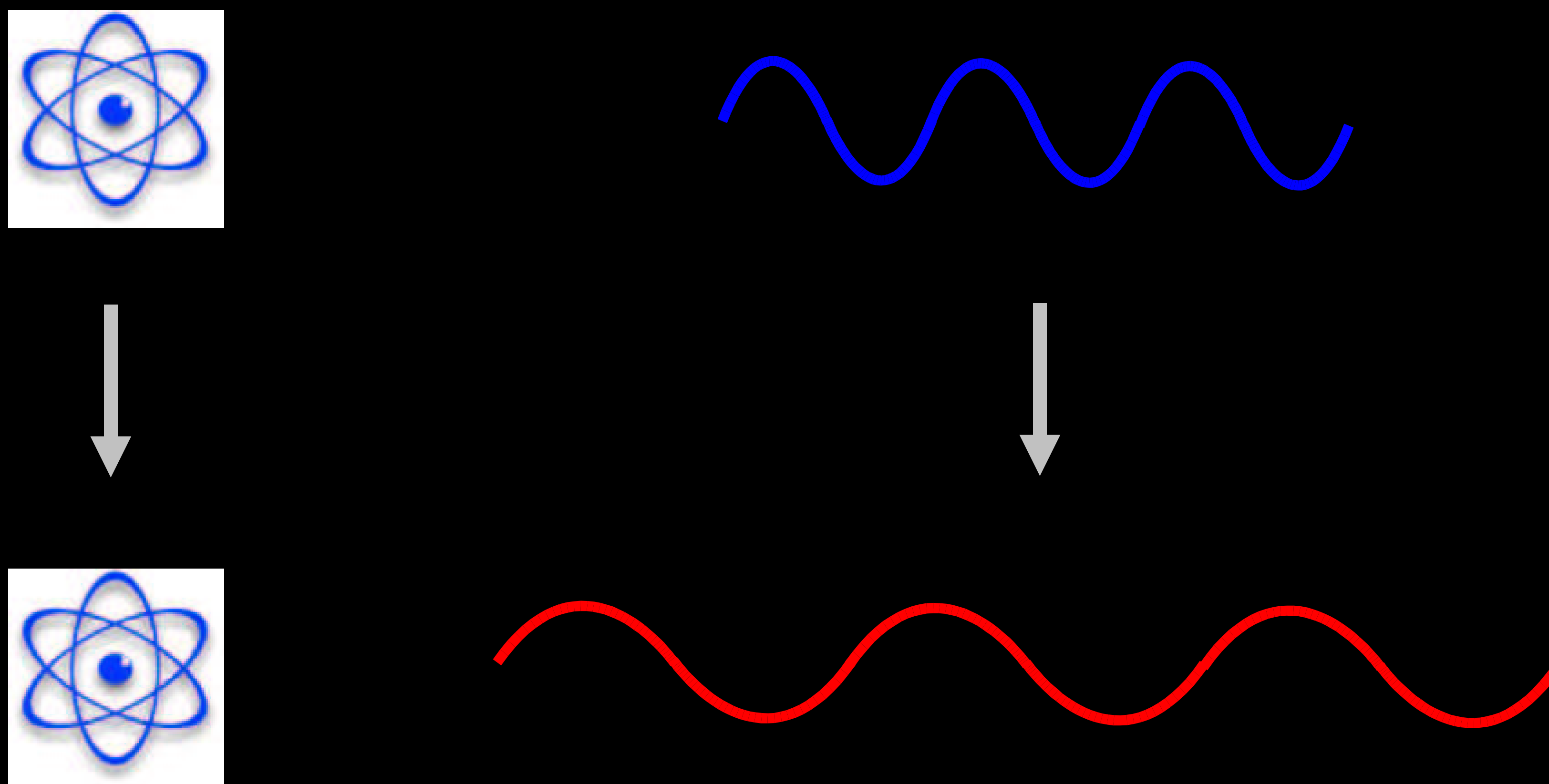
Distant galaxies are receding; the more distant, the faster the recession.

Nothing more or less than that!

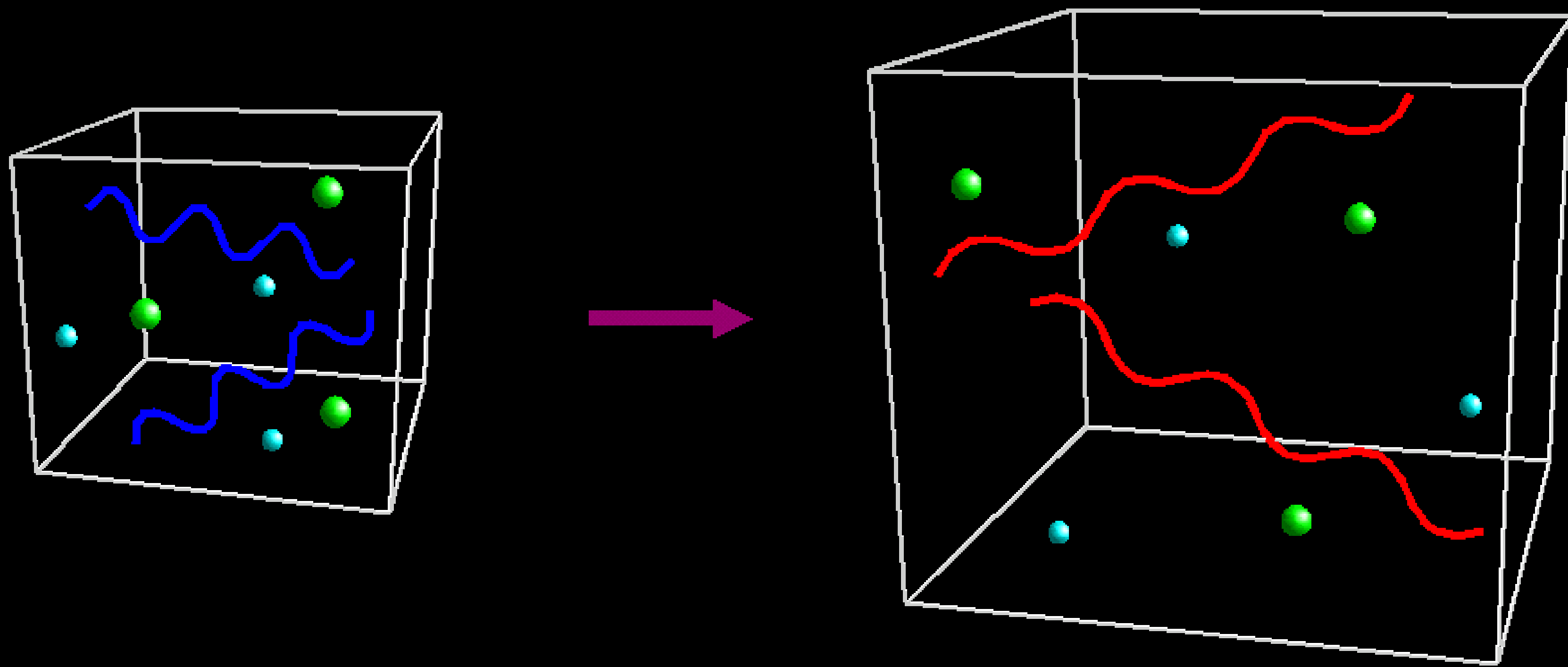


The space in between galaxies is getting bigger; everyone sees everyone else moving away.

Individual objects (galaxies, atoms) do not expand, although light waves do: we say that they redshift.

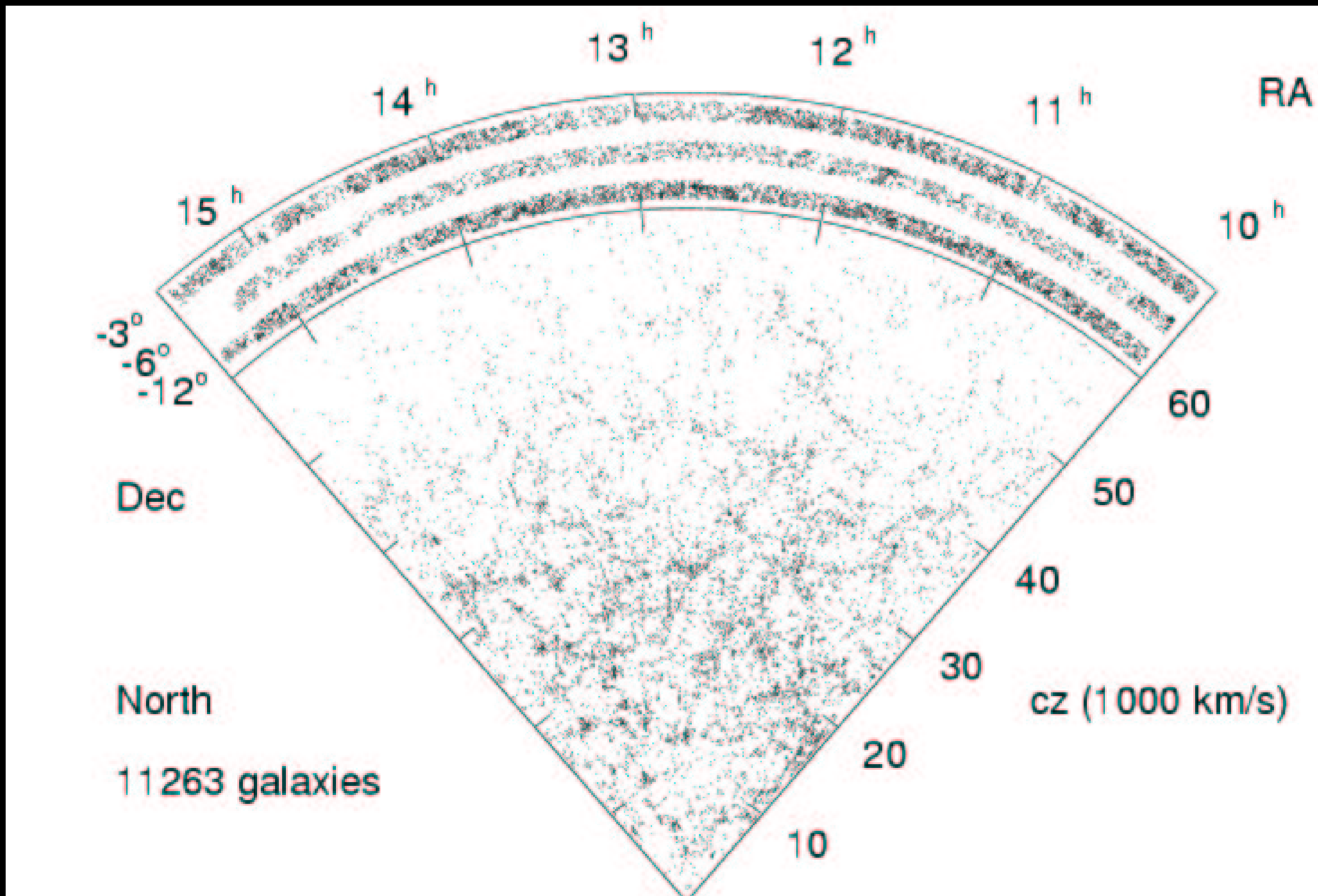


Expansion dilutes the number of particles and redshifts radiation.



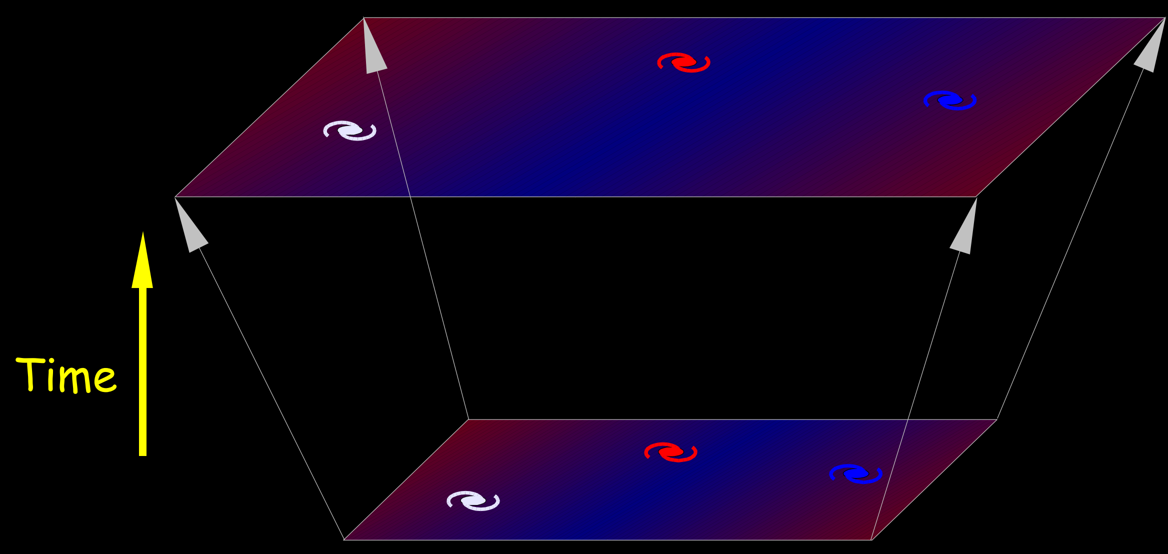
Thus, the early universe was dense and hot.
It began expanding 13 billion years ago: the Big Bang.
Radio telescopes can detect the leftover radiation from
this hot, dense phase: the Cosmic Microwave Background.

The universe possesses a crucial simplifying feature: the distribution of matter is pretty much the same everywhere (on sufficiently large scales).



The distribution of galaxies in one slice of the sky.

So the universe looks like a uniformly distributed collection of galaxies, filled with stars, gas and dust, expanding from an initially hot, dense state 13 billion years ago.



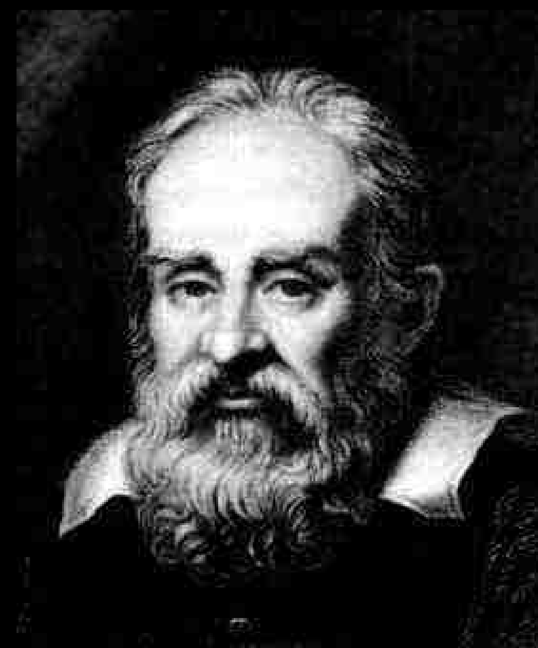
There's no rule that says the entire universe needs to be easily visible. Can we be sure that the matter we see is really all there is?

What is the universe made of?

There may be stuff in the universe we can't see -- invisible (not emitting light) and transparent (not reflecting or absorbing).

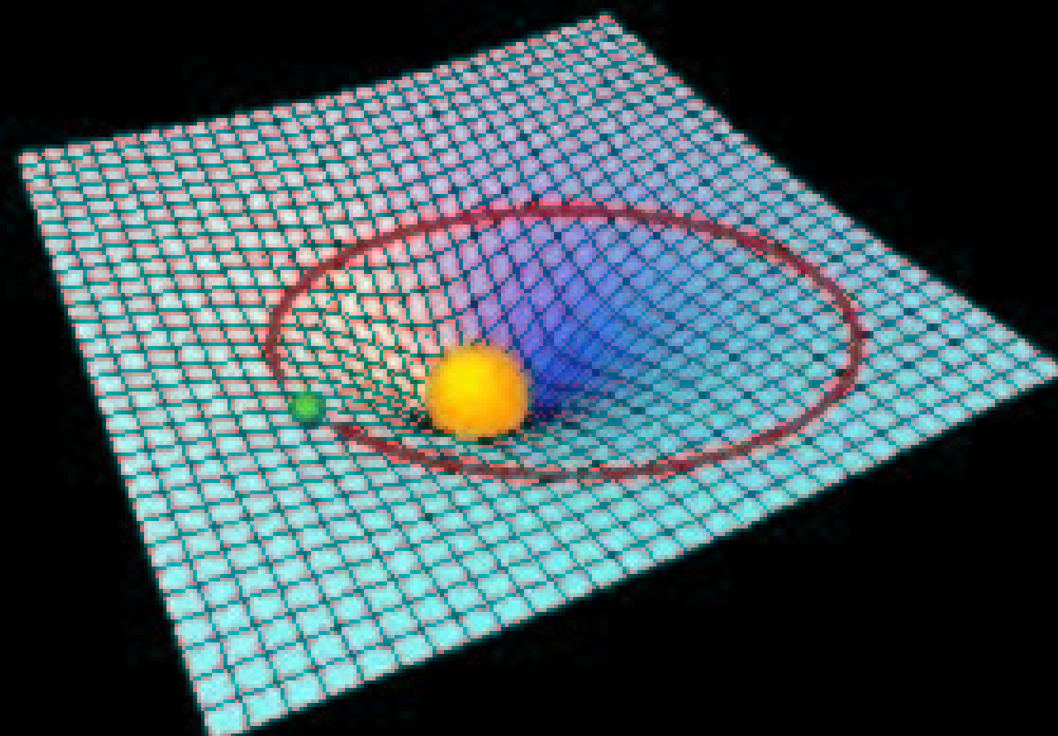
How could we detect such stuff?
Gravity.

The special feature of gravity is that everything causes a gravitational field, in direct proportion to how much mass it contains (or, we would now say, how much energy: $E=mc^2$).



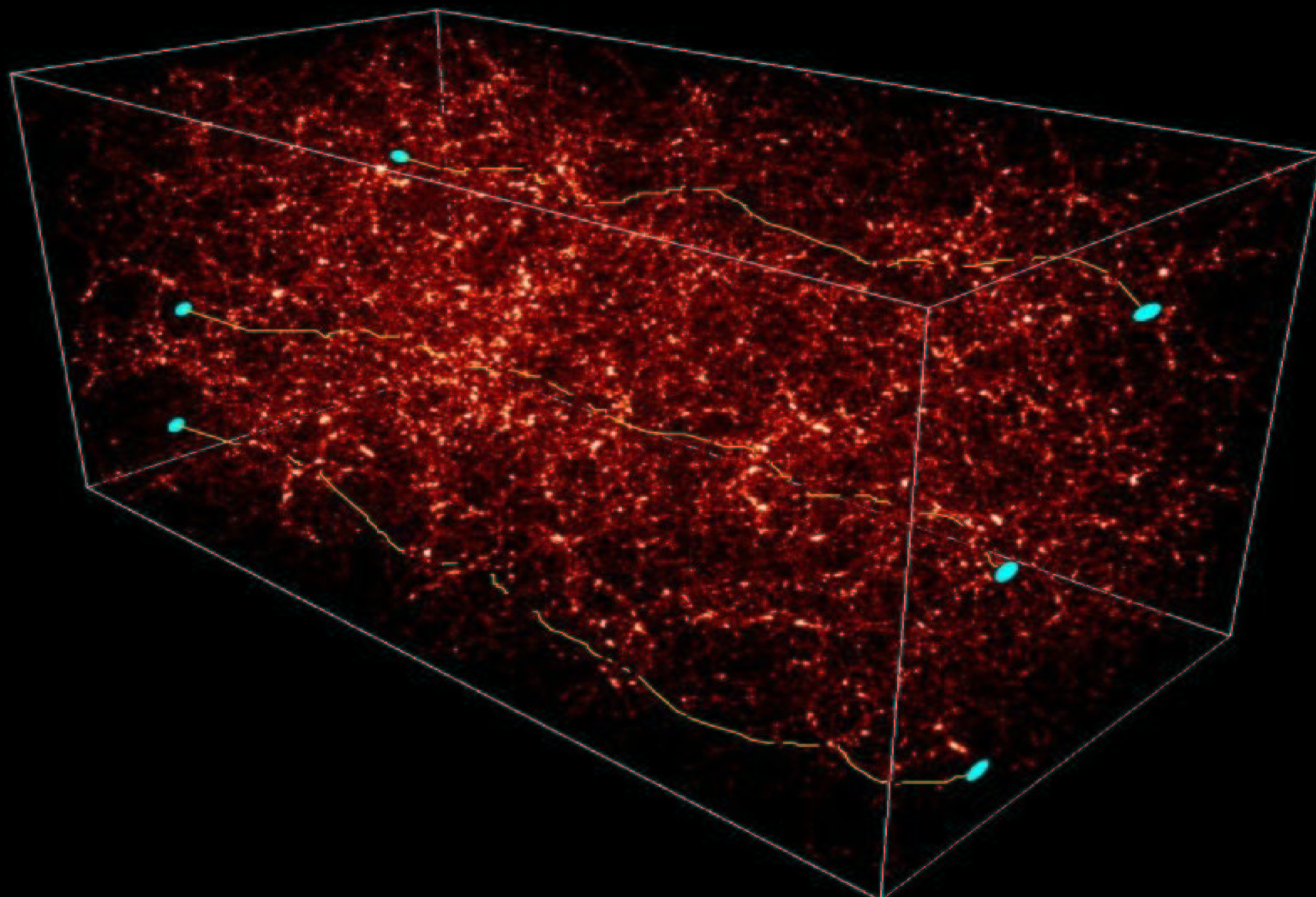
Galileo Galilei

Gravity is described by Einstein's theory of General Relativity.
His profound insight: "Gravity is the curvature of spacetime."



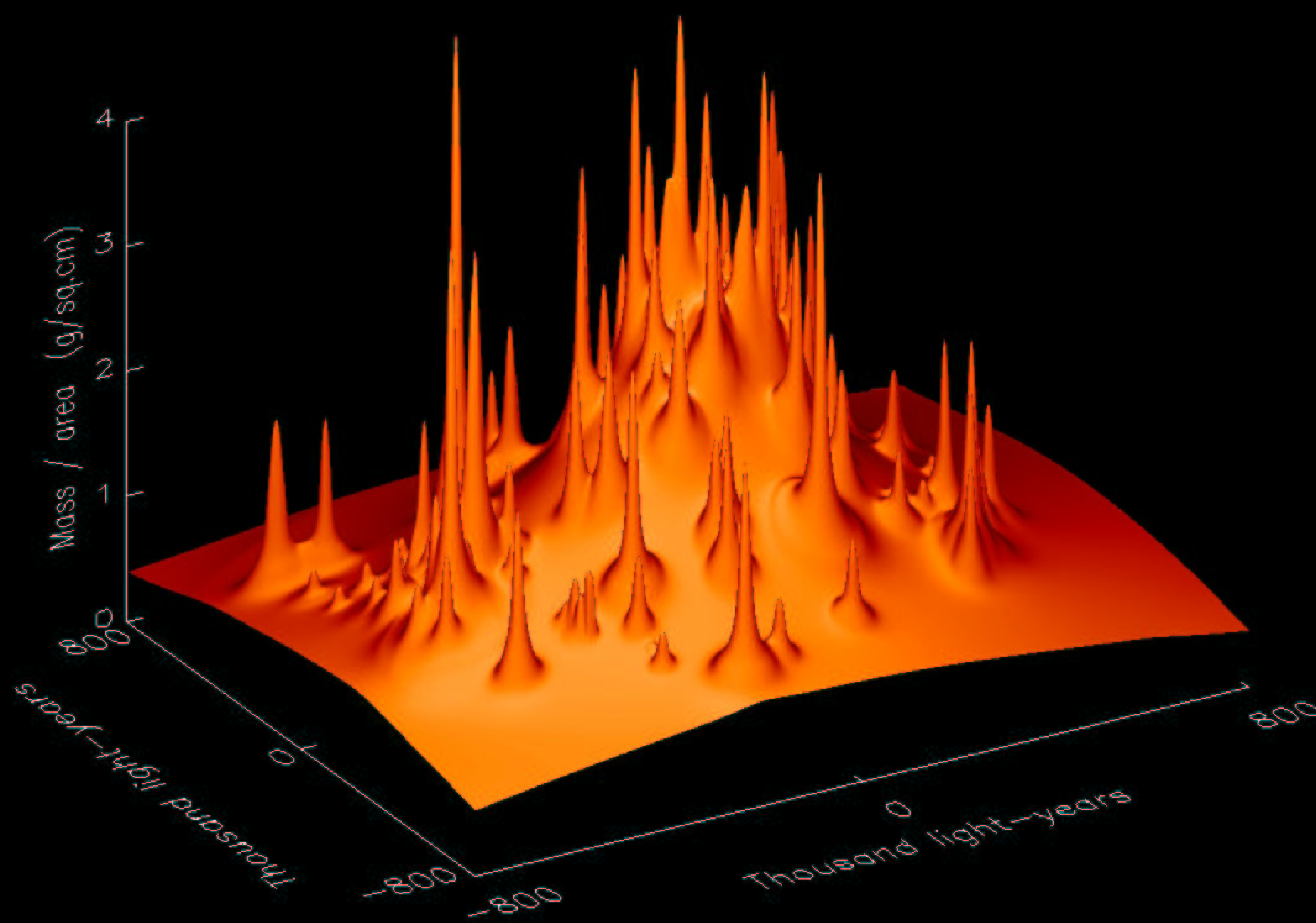
All forms of matter and energy warp the spacetime around them, and objects are deflected by the warped geometry.

This suggests a way to search for invisible matter:
gravitational lensing.



The gravitational field of a galaxy (or cluster of galaxies) deflects passing light; the more mass, the greater deflection.

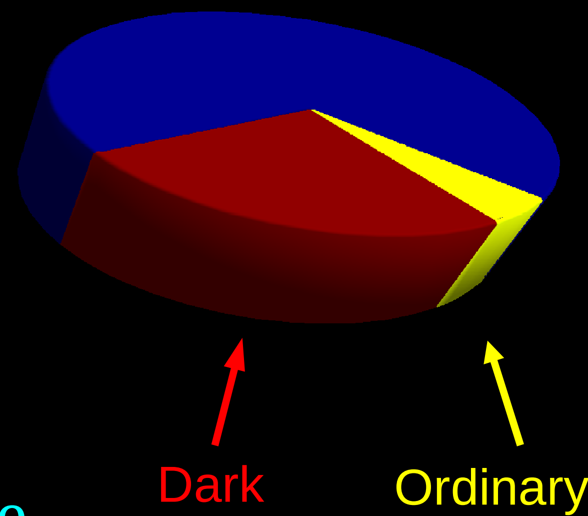
Hubble Space Telescope image of a cluster of galaxies.
An irregular blue galaxy in the background is multiply-imaged.



Mass reconstruction of the cluster. Note the large, smooth distribution of (apparently invisible) matter.

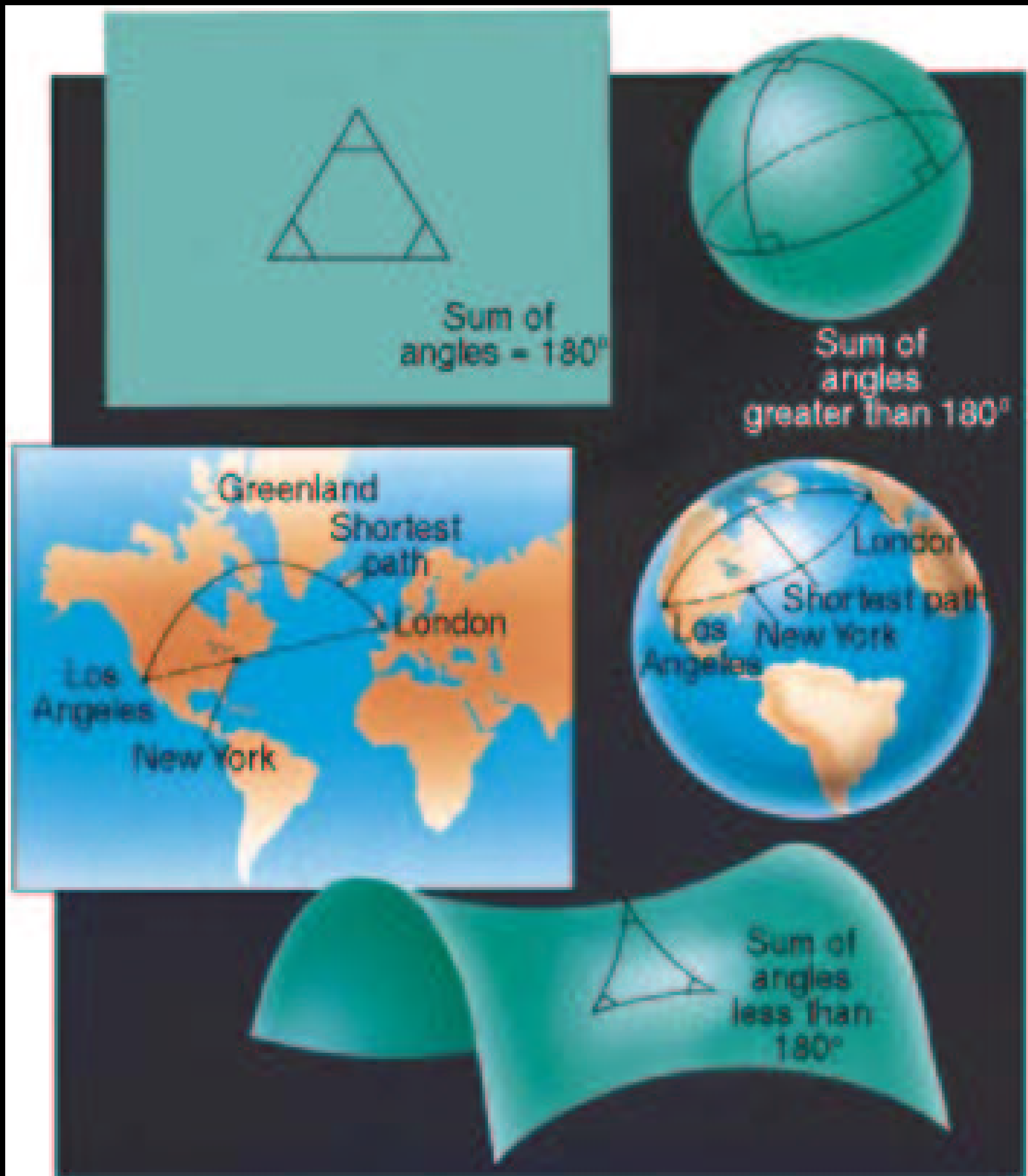
Lensing studies (and many other techniques) reveal that there is much more matter (at least 5 times as much) in the universe than can be accounted for by "ordinary" matter (stars, gas, dust, planets).

We conclude that there must be something else: Dark Matter.



Independent methods (using primordial nucleosynthesis & the microwave background) convince us that the dark matter is a completely new kind of particle. (Axions? Supersymmetric neutralinos?)

Still: can we be sure we've found everything? What if some form of matter/energy doesn't collect into galaxies and clusters?

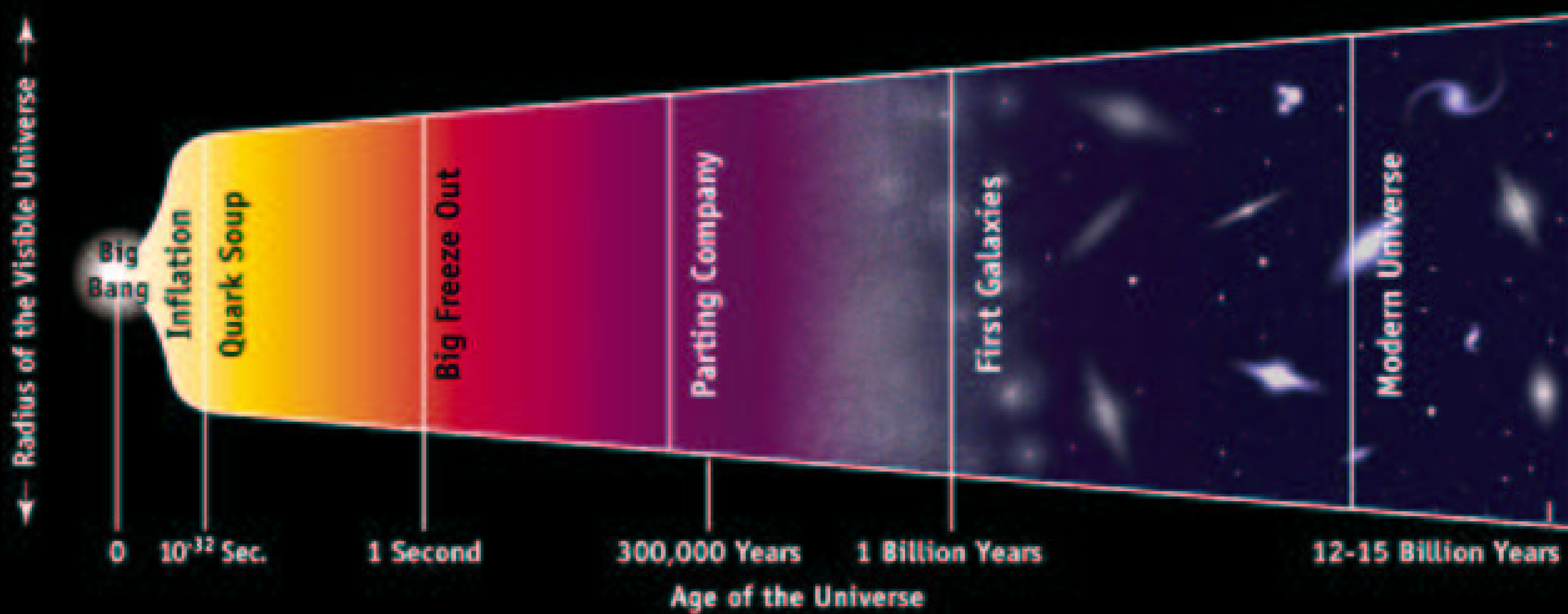


To get the final answer:
look at the overall
curvature of space.

What we need is a standard ruler: something that we know both how big it is, and how far away it is.

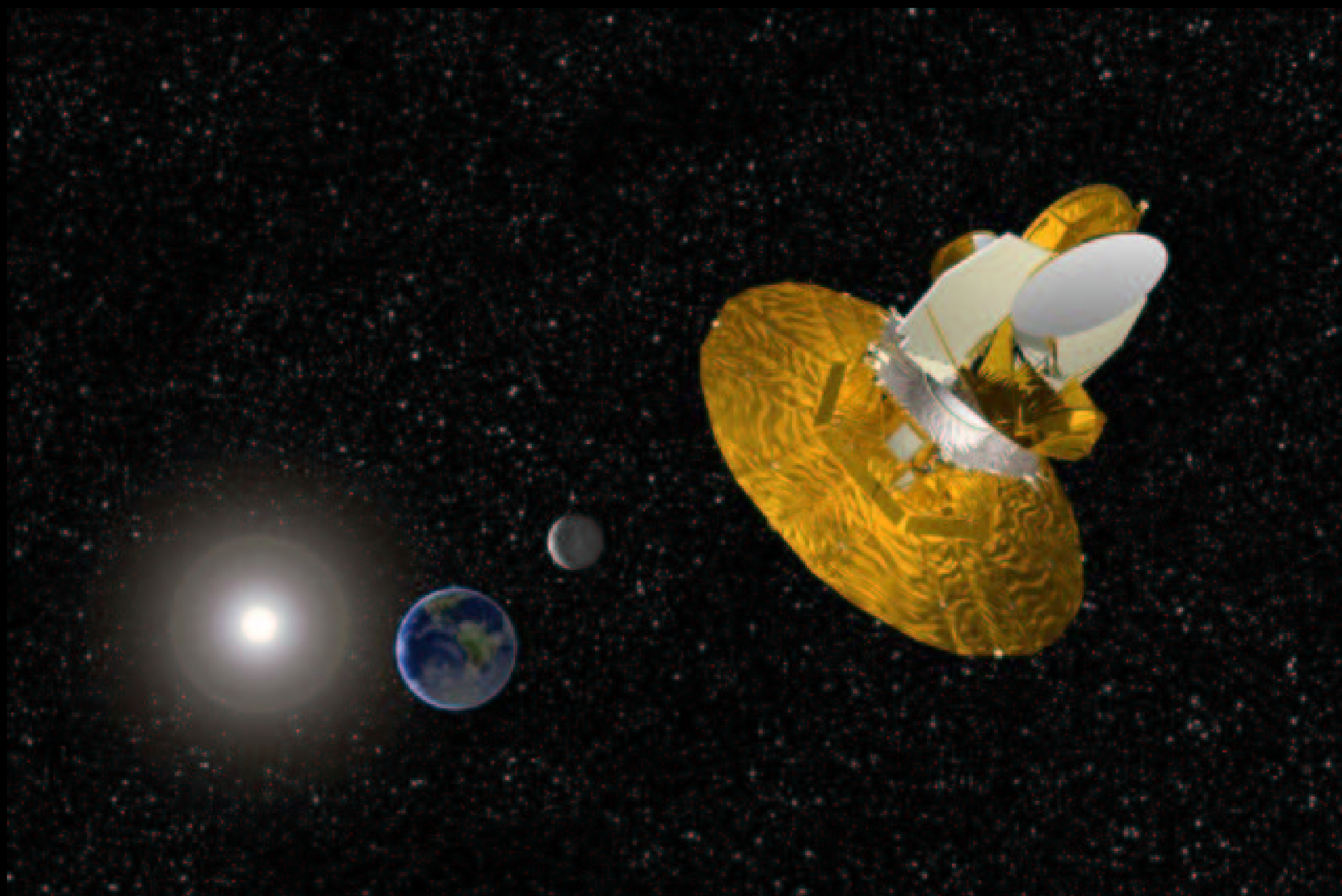
Then, if we determine how big it appears, we can deduce the curvature of space (and hence the total amount of energy in the universe).

Happily, nature provides us with an ideal standard ruler. The Cosmic Microwave Background is a snapshot of the universe at 300,000 years old (when it became transparent).

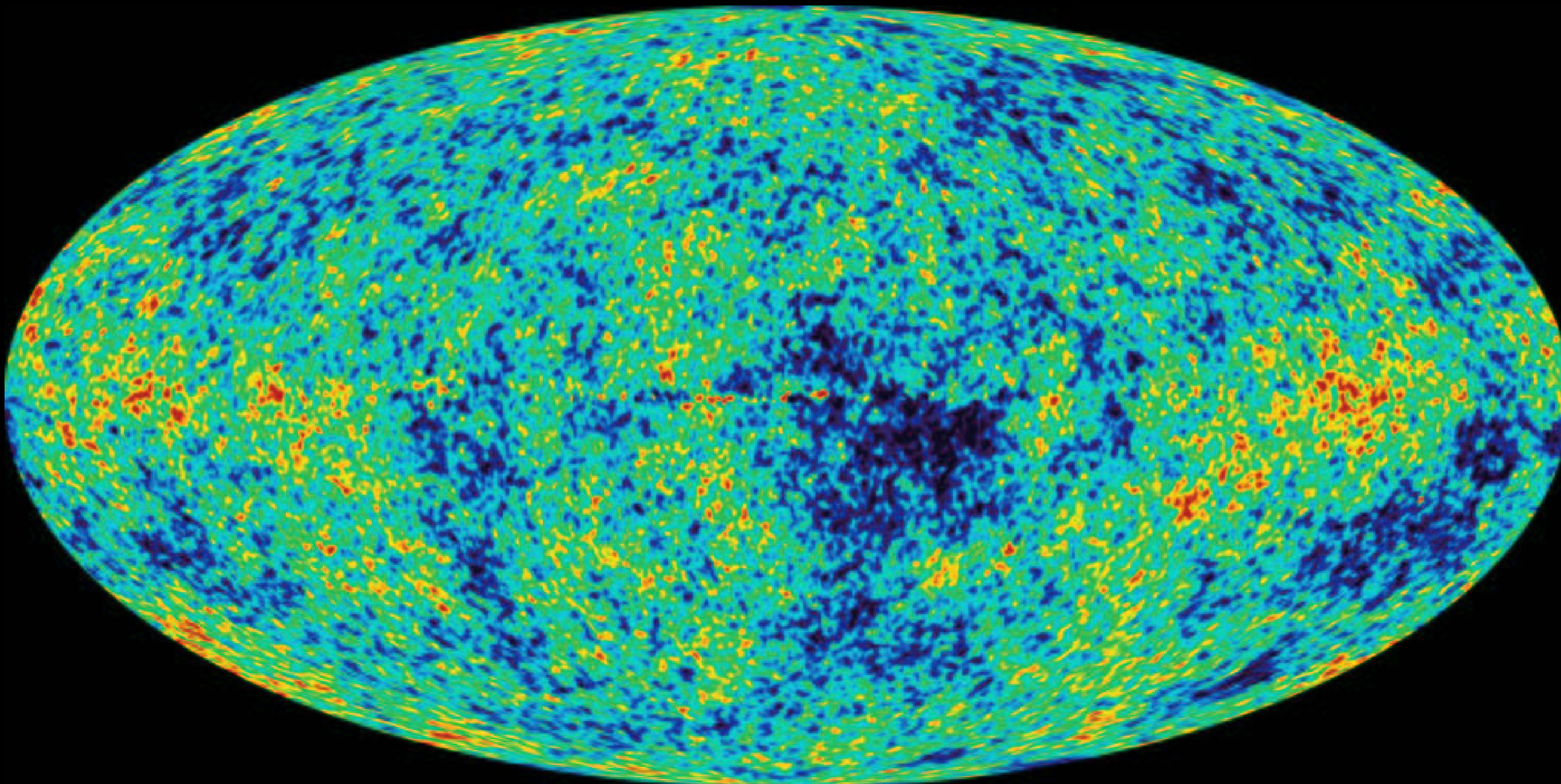


Fluctuations in the microwave background temperature have a characteristic length scale: 300,000 light years! Measuring their apparent (angular) size reveals the geometry of the universe.

The Wilkinson Microwave Anisotropy Probe (WMAP), orbiting the Sun somewhat behind the Earth's orbit, is one of several recent measurements of microwave background fluctuations.



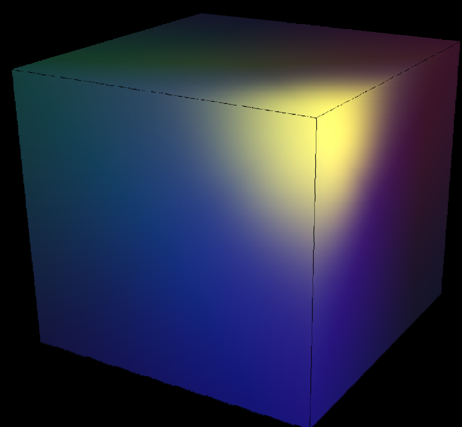
Observed pattern of temperature fluctuations
on the sky from WMAP.



The apparent size of the fluctuations reveals the curvature of space through which the radiation traveled (and thus the total energy of the universe).

Result: the matter (ordinary + dark) we have discovered is not enough to account for the observed curvature of space. In fact, it is only 30% of what we need.

We conclude that there must be something new, which doesn't fall into galaxies: Dark Energy.



(artist's impression of vacuum energy)

Leading candidate for dark energy: vacuum energy, which Einstein called the "cosmological constant" (and also "my greatest blunder").

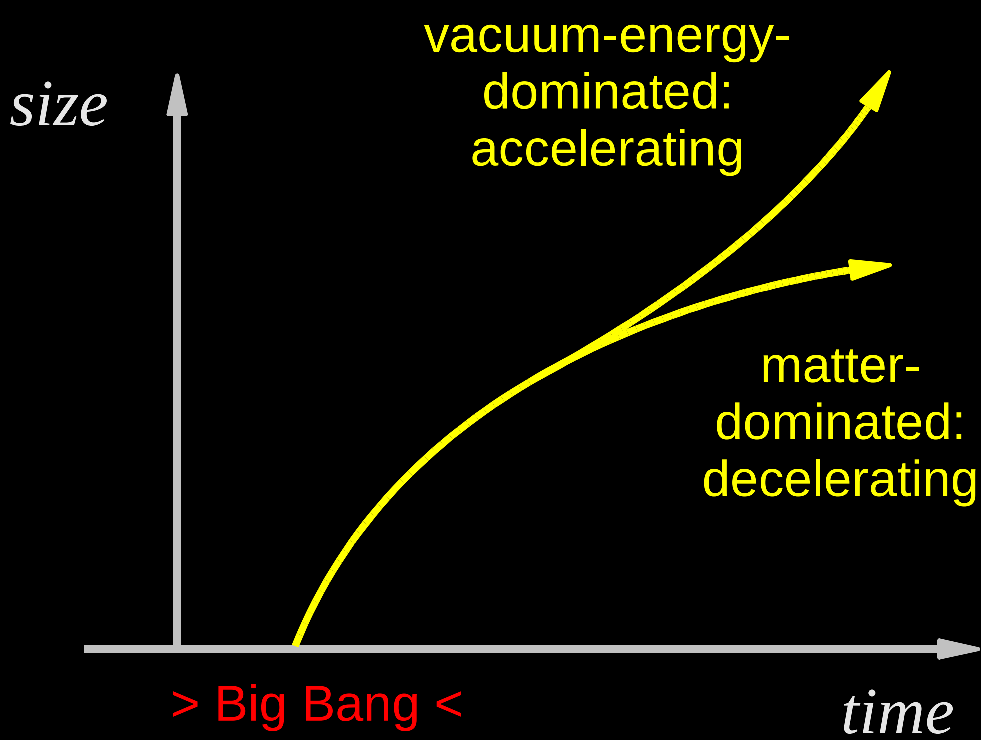
It would be a fixed amount of energy inherent in every bit of spacetime. (10^{-8} ergs per cubic centimeter, to be precise.)

Vacuum energy is spread thinly throughout space.

If we could convert all the vacuum energy within the volume of the earth into electricity, it would equal the same amount as a typical U.S. citizen uses in a single day.

But we can't. Since it's perfectly uniform, the vacuum energy is completely useless.

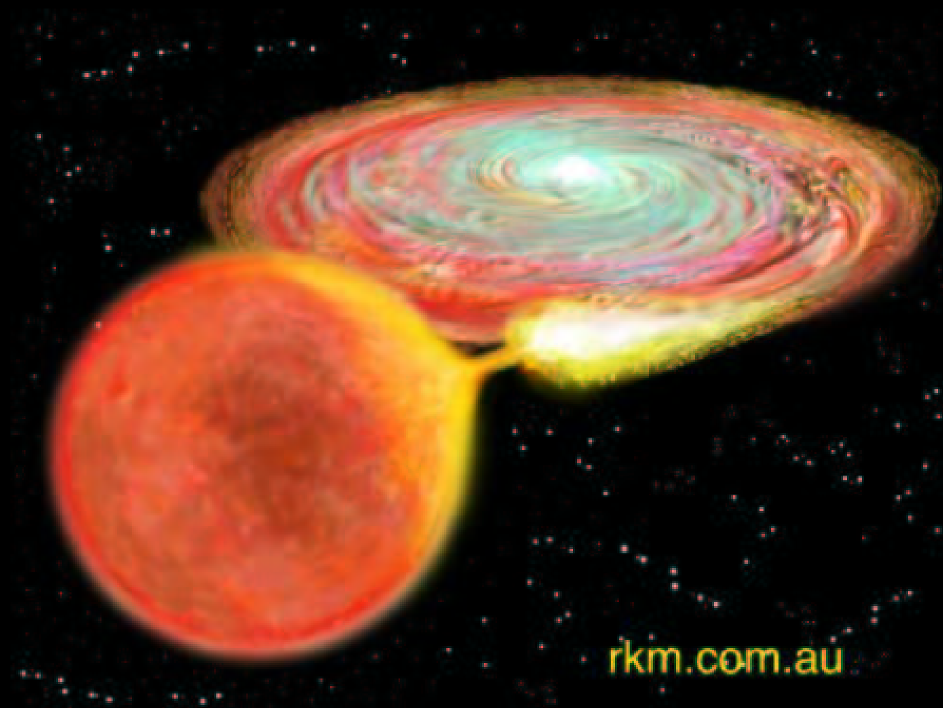
A characteristic feature of vacuum energy: it makes distant galaxies appear to accelerate away from us.



The expansion of the universe is driven by its energy density. Since vacuum energy doesn't diminish with time, the expansion accumulates, and the universe actually speeds up.

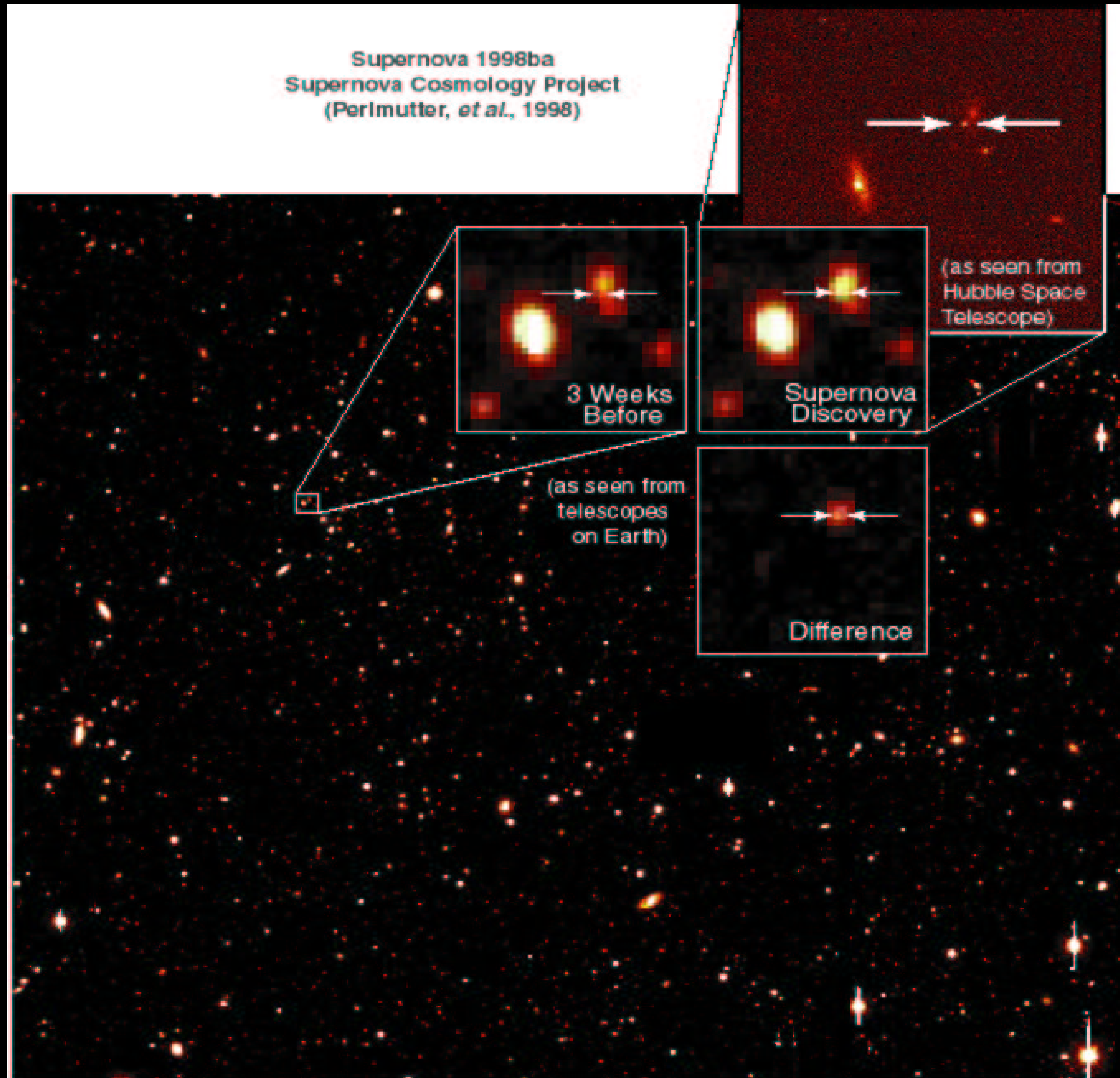
We can search for this effect by measuring the expansion rate in the past, i.e. at very large distances.

To measure the expansion rate at large distances, we search for events that are very bright, and predictably so: Type Ia Supernovae.

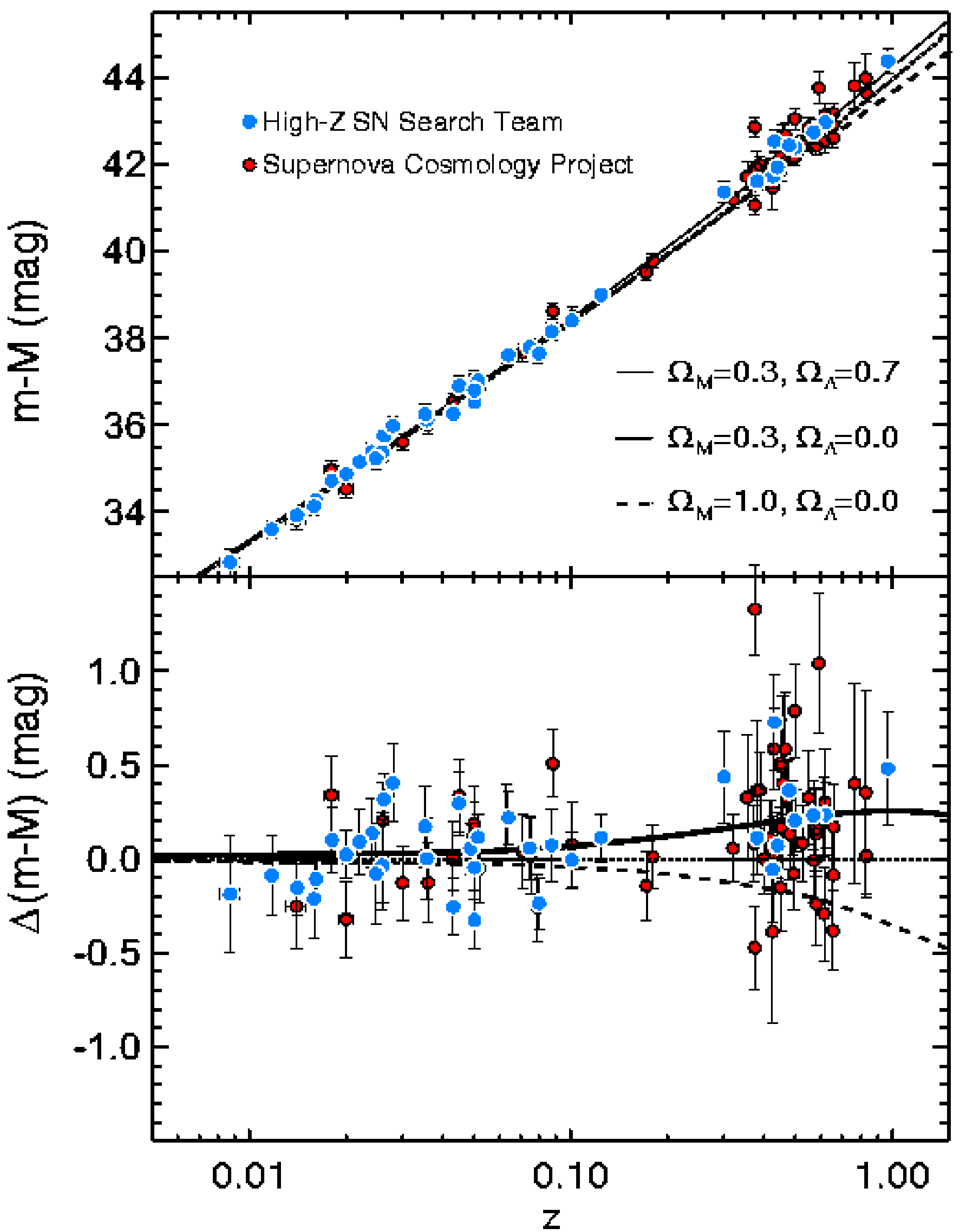


Matter gradually accretes onto a compact white dwarf star, until the gravitational pull becomes too great (at the Chandrasekhar limit) and the star collapses and explodes.

Strategy: stare at one tiny patch of the sky for a long time, waiting for the right event.



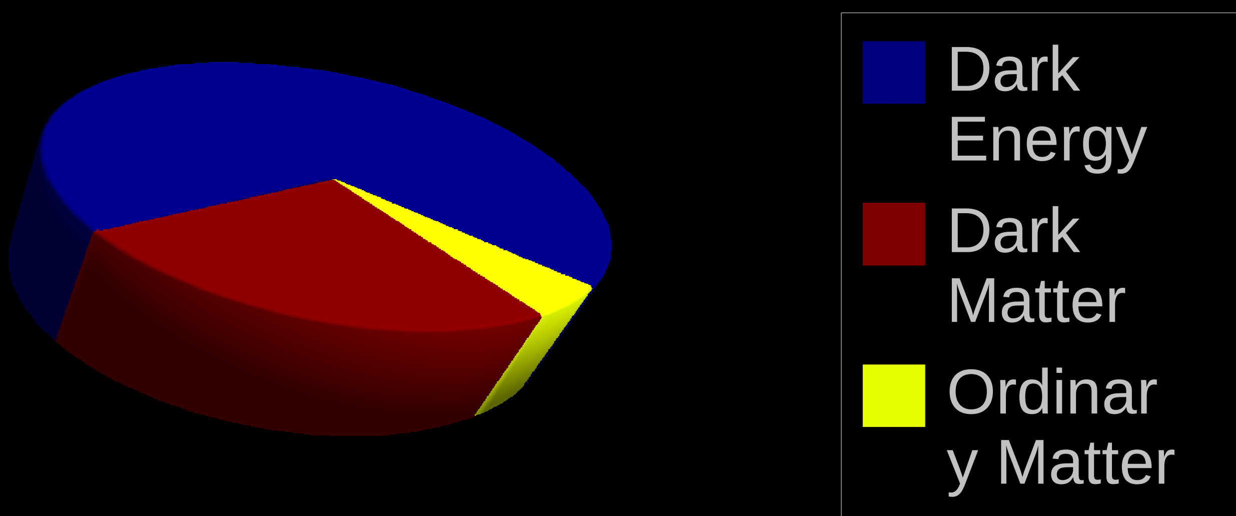
Result: the universe is, as expected, accelerating!



accelerating
coasting
decelerating

We therefore seem to have a complete inventory of the stuff of which the universe is made:

5% Ordinary Matter
25% Dark Matter
70% Dark Energy



Mark Rothko,
Orange & Yellow

Jackson Pollock, *Convergence*

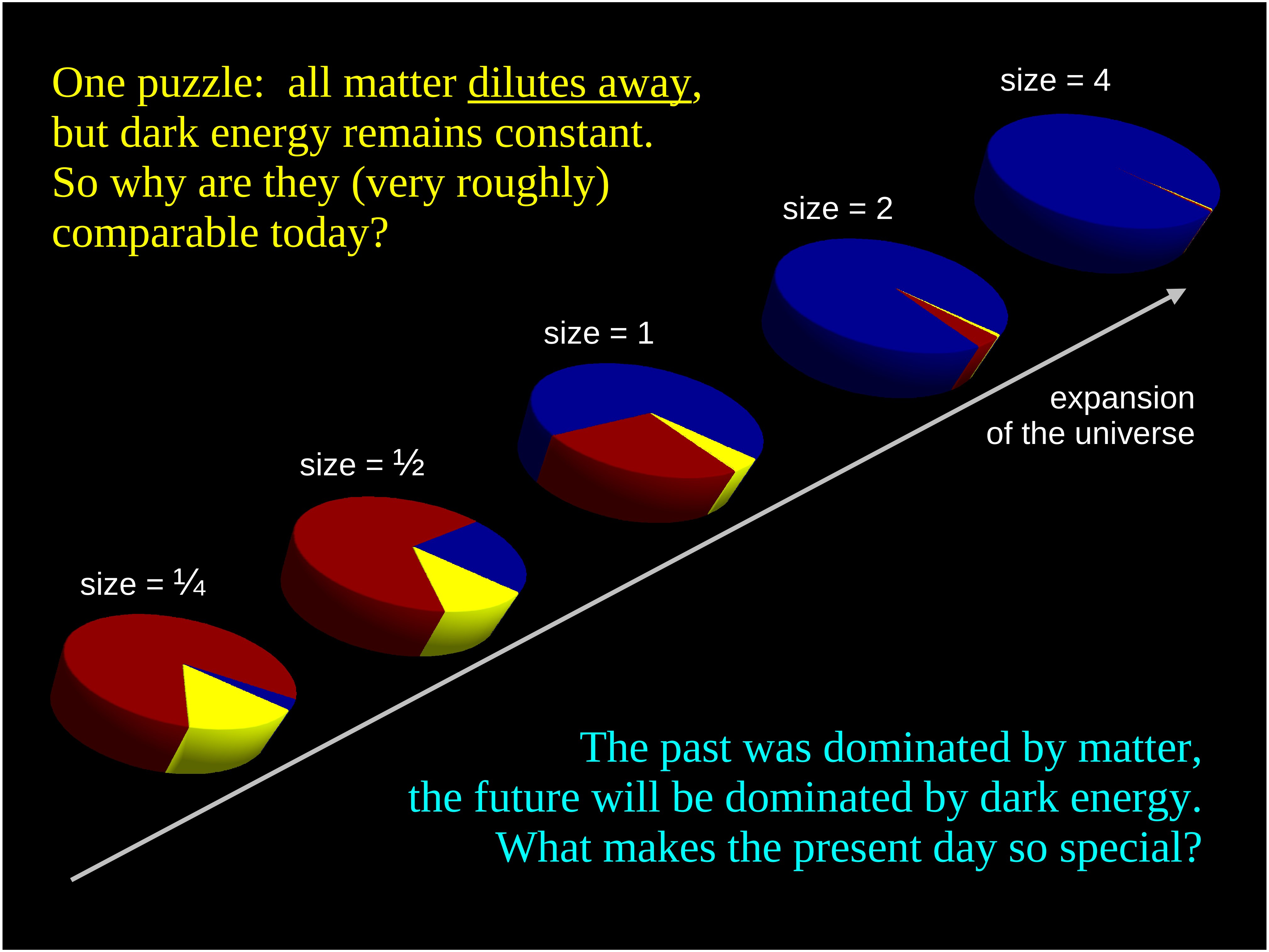
Why is it like that?

We have no clue. Things we don't (yet) understand:

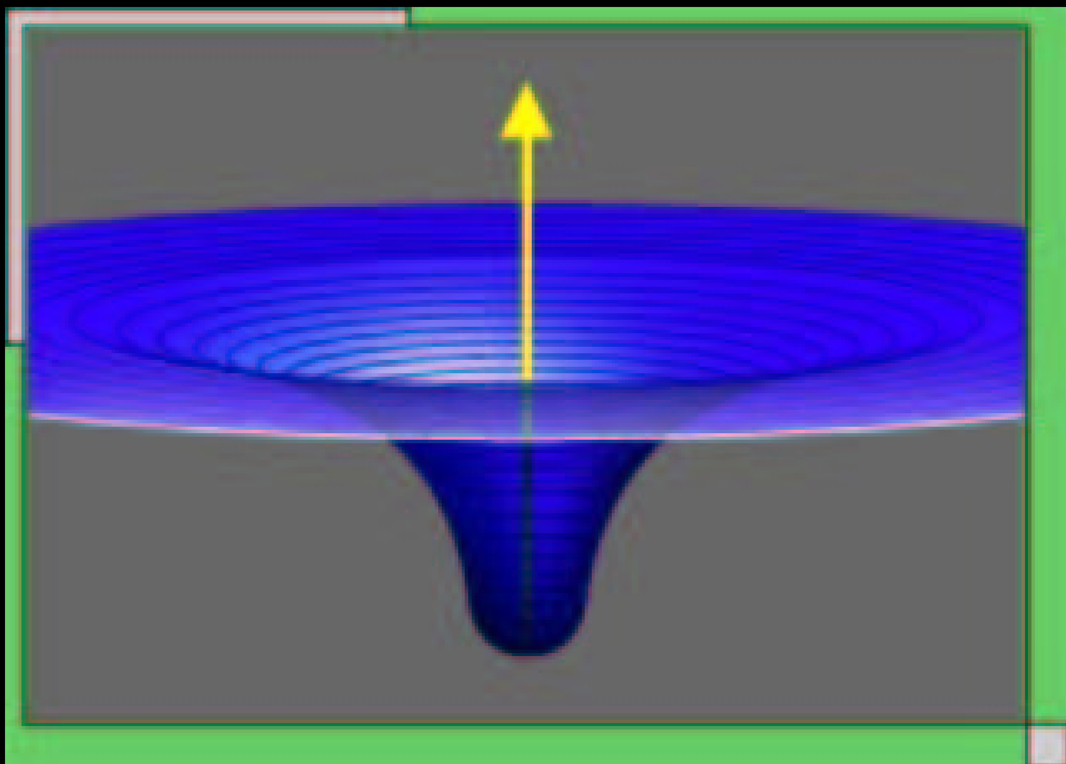
- Why is there more matter than anti-matter?
- What is the dark matter?
- What is the dark energy?
- Why is the vacuum energy so small?
- Why is the universe smooth on large scales?
- Where did the small fluctuations come from?
- Why are matter & dark energy comparable today?

Not to mention:

- What came before the Big Bang?


One puzzle: all matter dilutes away,
but dark energy remains constant.
So why are they (very roughly)
comparable today?
size = ¼
size = ½
size = 1
size = 2
size = 4
expansion
of the universe
The past was dominated by matter,
the future will be dominated by dark energy.
What makes the present day so special?

We don't have answers, but we have plenty of ideas.
Let's just mention two: Inflation and String Theory.

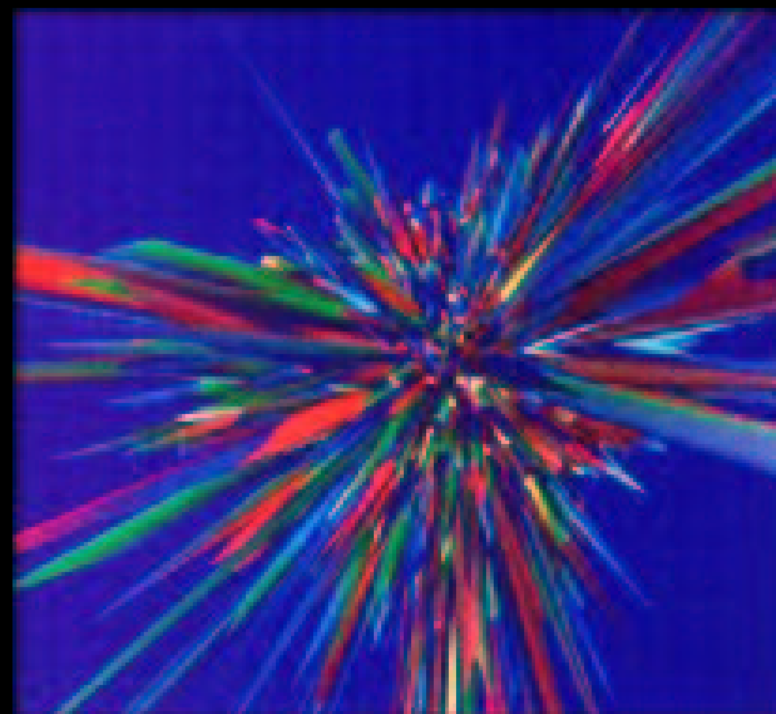


Alan Guth

Inflation is a brief period of intensely accelerated expansion at the very beginning of the universe (driven by super-dark-energy). This makes the universe big and smooth; it also removes our post-inflationary region from contact with the rest of the universe.

An intriguing consequence of inflation: separate parts of the universe can inflate at different rates, and even end up with apparently distinct "laws of physics."

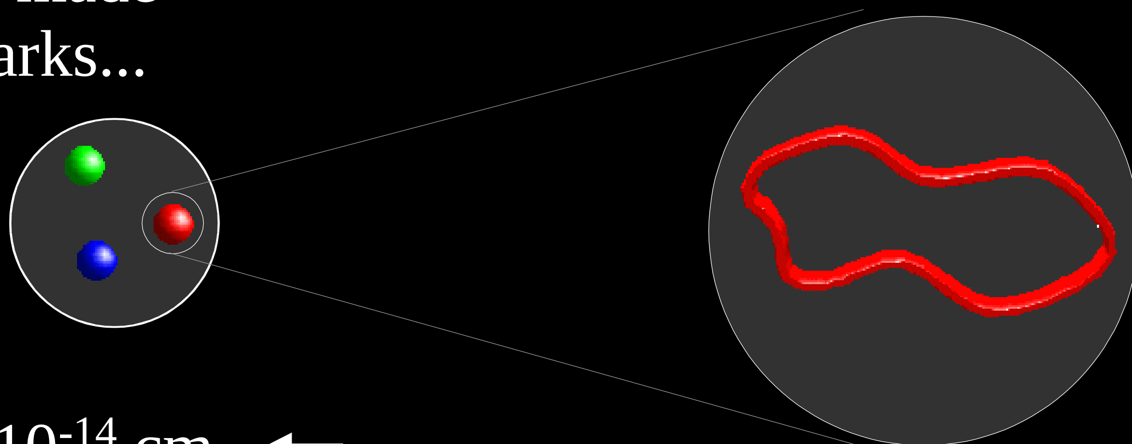
Even though the universe we see is smooth throughout, the larger universe may consist of wildly disparate disconnected regions: different matter content, different vacuum energy, even different numbers of dimensions of spacetime.



Is our region special because it allows intelligent life?

String Theory proposes that all elementary particles (electrons, quarks, etc.) are really small pieces of string.

A proton is made of three quarks...



... and each quark is a string.

$\rightarrow$ 10^{-14} cm $\leftarrow$

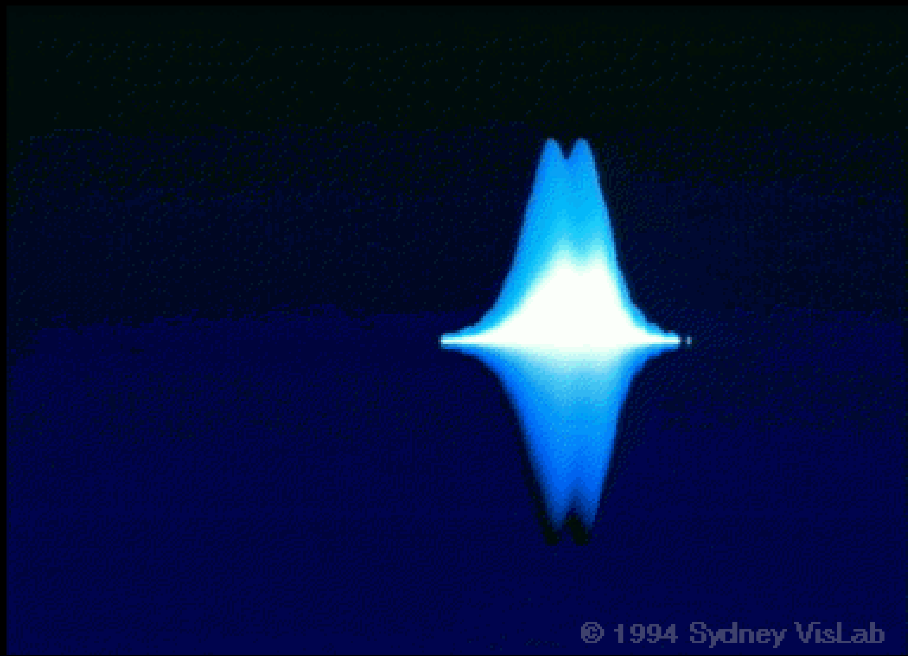
$\rightarrow$ 10^{-33} cm $\leftarrow$

("Planck length")

Why would anyone imagine such a thing?

To reconcile General Relativity with Quantum Mechanics, which underlies our current understanding of particle physics and all microscopic phenomena.

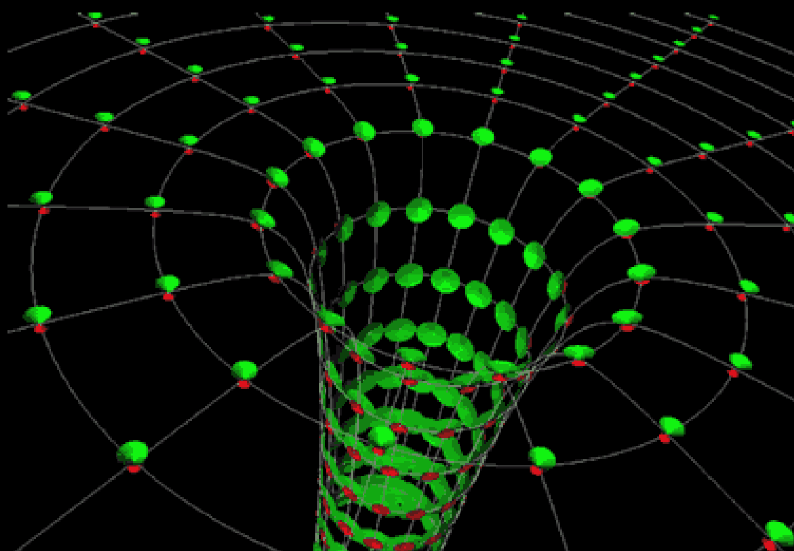
Werner Heisenberg and Niels Bohr



The essence of quantum mechanics:

**What we <u>observe</u> is derived from,
but not in one-to-one correspondence with,
what actually <u>exists</u>.**

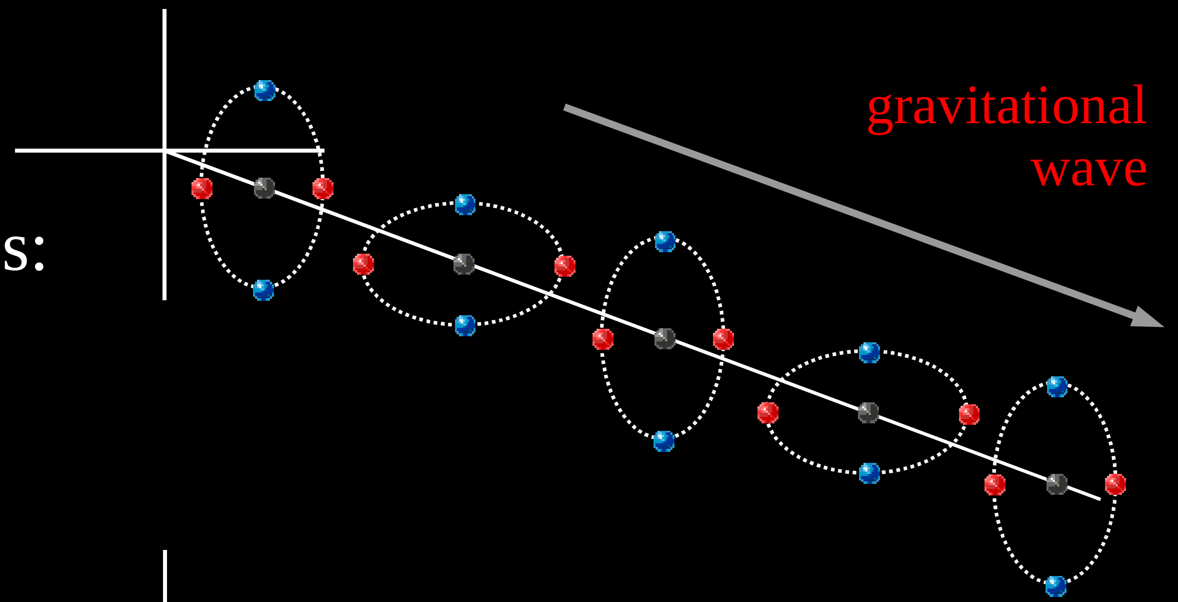
What exists are "wave functions" describing the probability of obtaining various outcomes when measurements are made.



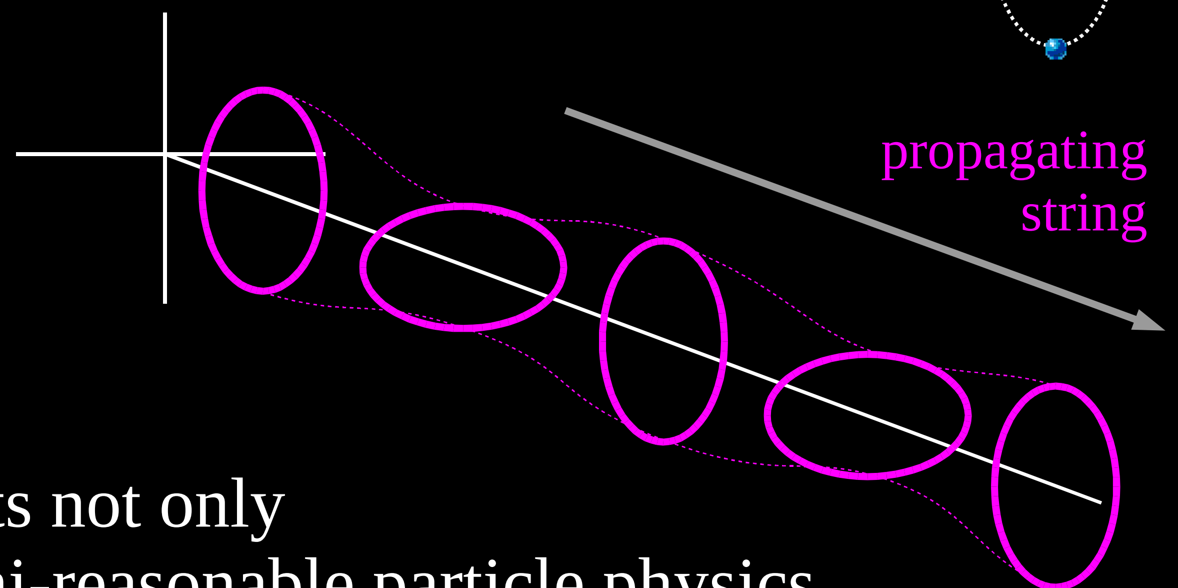
This is hard to reconcile with general relativity. What would it mean for spacetime itself to exist in a superposition of possible geometries?

String theory is a consistent quantum theory that predicts gravity.

Compare the effect of a gravitational wave on test particles:

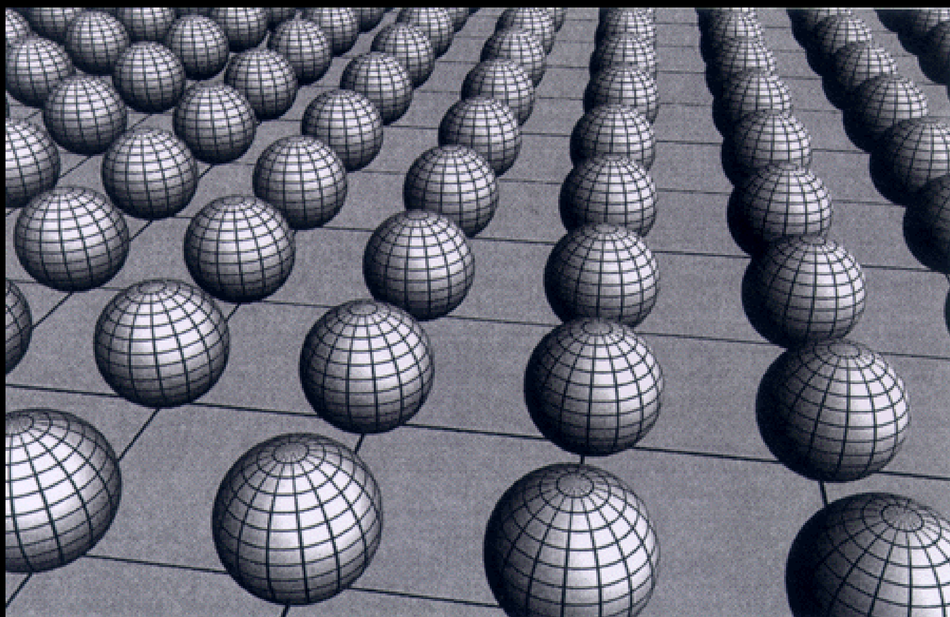


to the propagation of an oscillating string:



String theory predicts not only gravity, but also semi-reasonable particle physics.

An exciting prediction of string theory: extra dimensions.

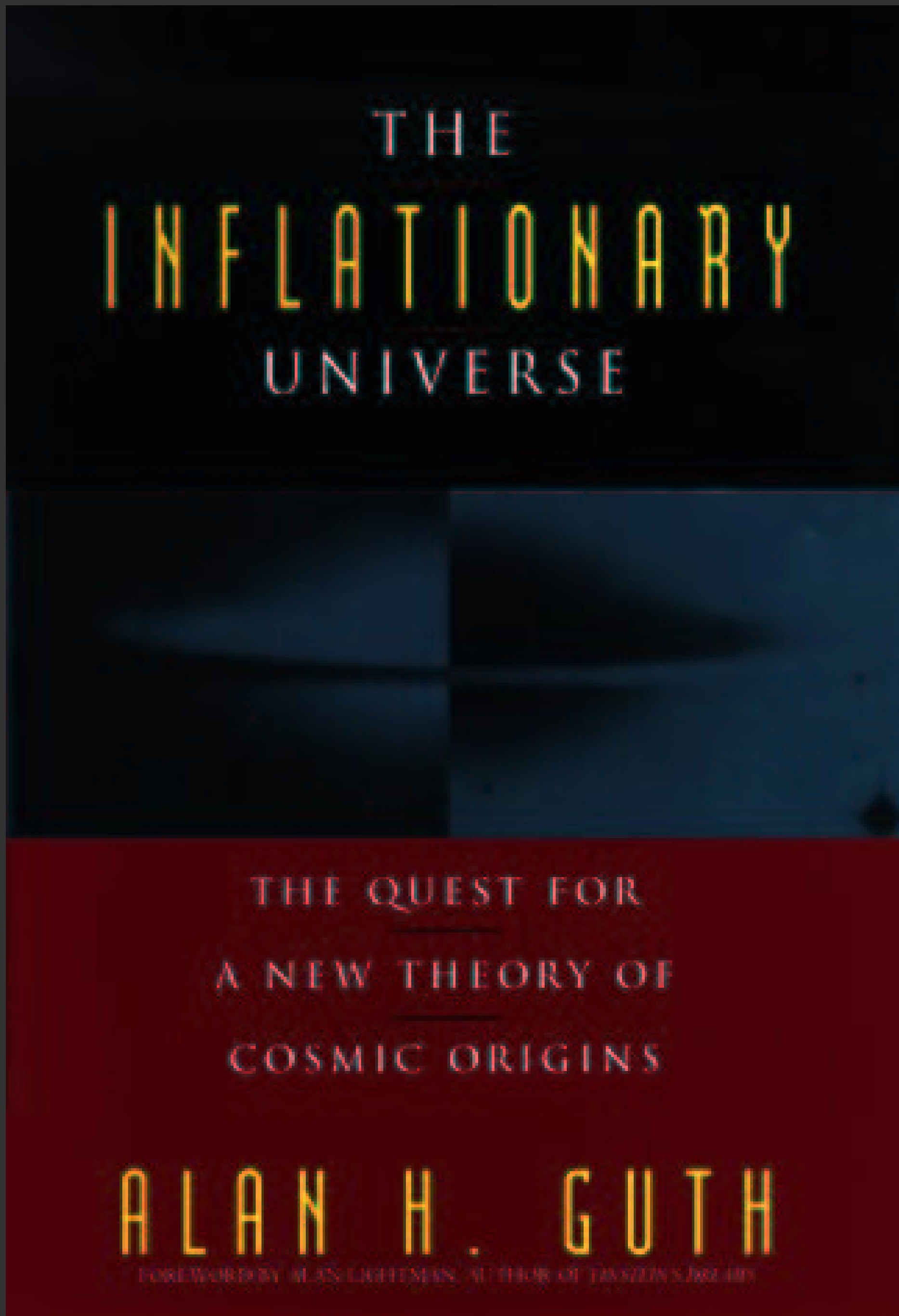


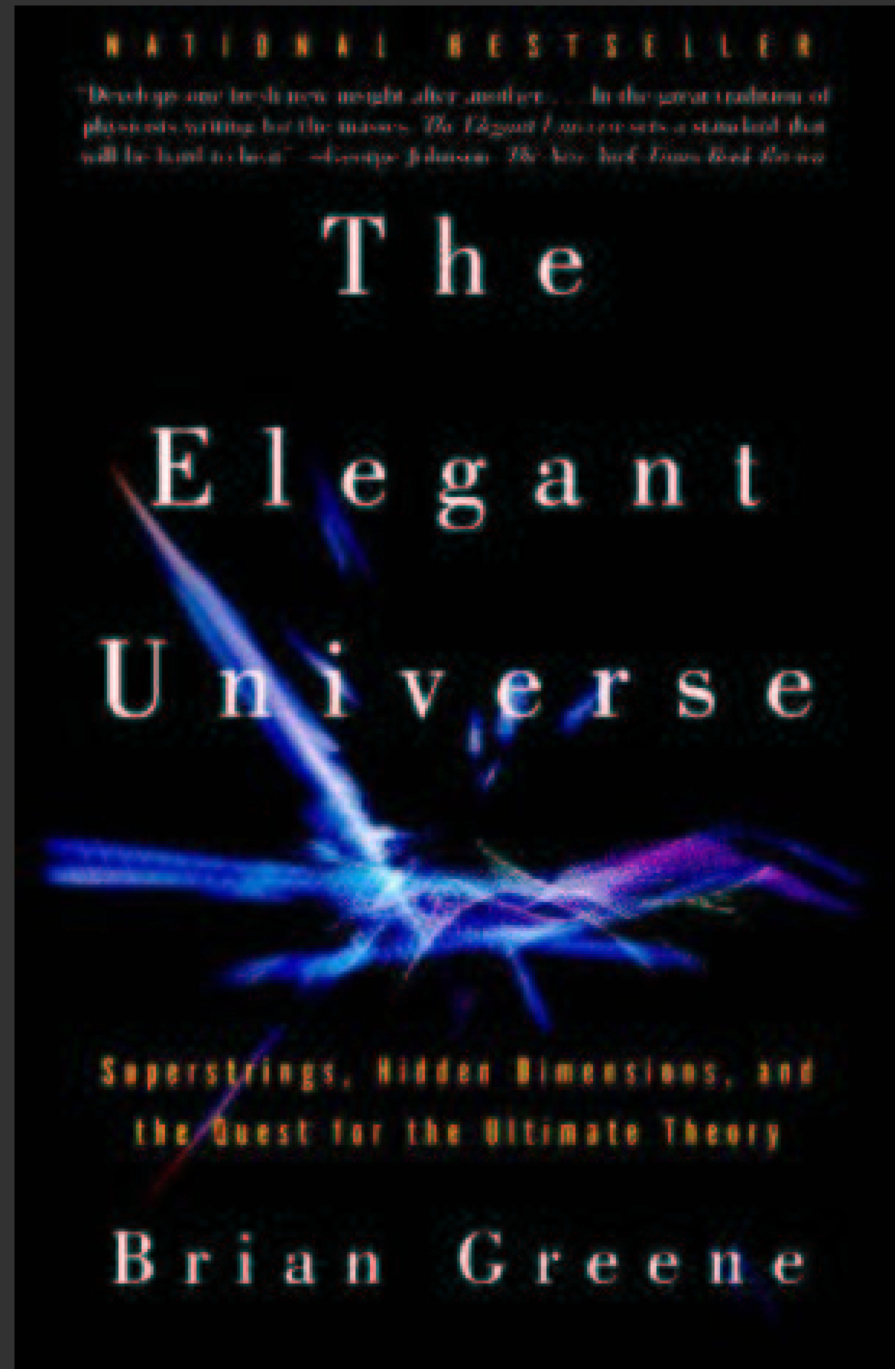
The spacetime we see has four dimensions (3 space, 1 time). But string theory requires eleven dimensions. The extra dimensions may be curled into an ultra-tiny ball, existing at every point in our macroscopic space.

If we get lucky, new dimensions might be just big enough to be detectable at major particle accelerators -- Fermilab outside Chicago and CERN outside Geneva, Switzerland. (We would need to get *extremely* lucky.)

Where does this leave us?

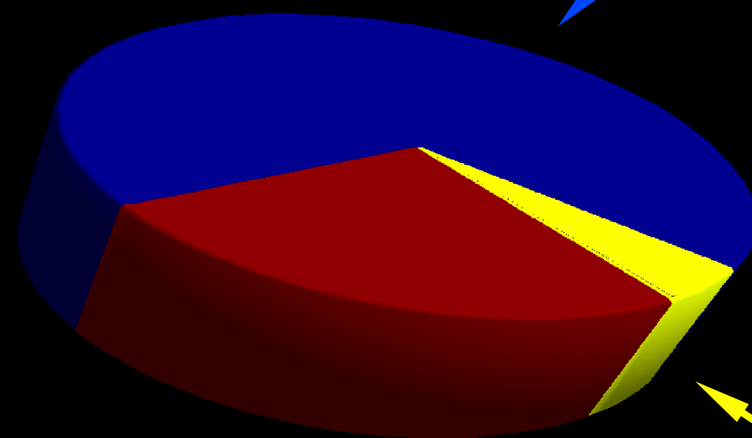
- We can describe the constituents and patterns of the universe. But the description makes no sense. The next challenge is to move from *inventory* to *understanding*.
- A new generation of experiments will provide crucial clues: satellites, observatories, laboratory experiments, large particle accelerators.
- One century ago, physics seemed almost settled, with only a few loose ends to be figured out. What followed was a revolutionary upheaval. What's next for us?


THE
INFLATIONARY
UNIVERSE
THE QUEST FOR
A NEW THEORY OF
COSMIC ORIGINS
ALAN H. GUTH


NATIONAL BESTSELLER
The
Elegant
Universe
Superstrings, Hidden Dimensions, and
the Quest for the Ultimate Theory
Brian Greene

The Preposterous Universe

70% of the universe is
the energy of empty space
(dark energy)



5% of the
universe is
ordinary matter

25% of the universe
is a mysterious new particle
(dark matter)

While the Earth wheeled around its sun, I was privileged to hear that earth and its moon wheeled around each other, and at the same time our whole local star system moved, and at no mean pace, within the framework of a vaster but still very local star group. This gravitating system in turn wheeled with almost vulgar velocity within the Milky Way; the latter, moreover, our Milky Way, was travelling with unimaginable rapidity in respect to its far-away sisters, and they, the most distant existing complexes, were, in addition to all their other velocities, flying away from one another, at a rate that would make an exploding shell seem motionless --- flying away in all directions into Nothingness, thereby in their headlong career projecting into it space and time.

---from *Confessions of Felix Krull, Confidence Man*, Thomas Mann