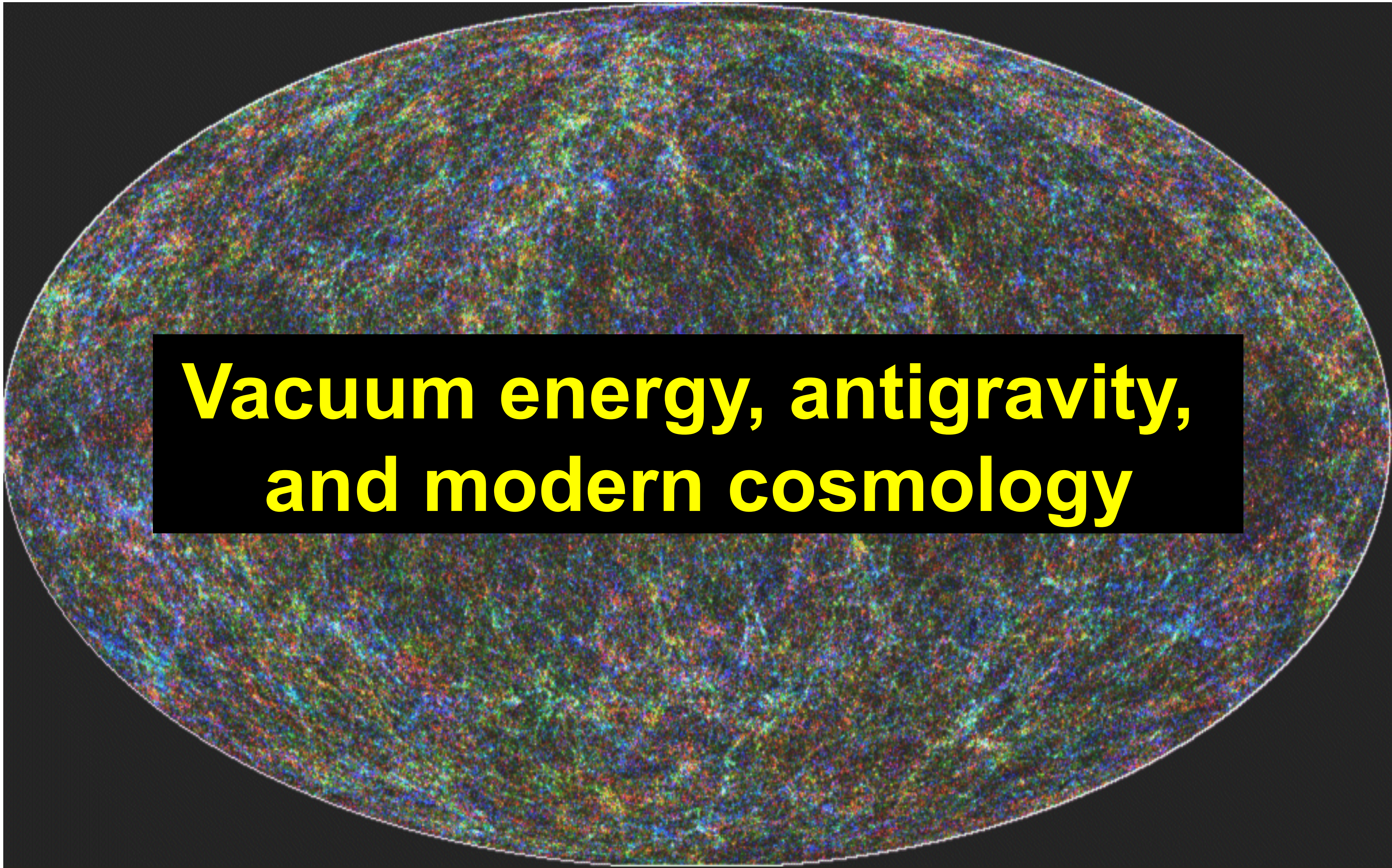
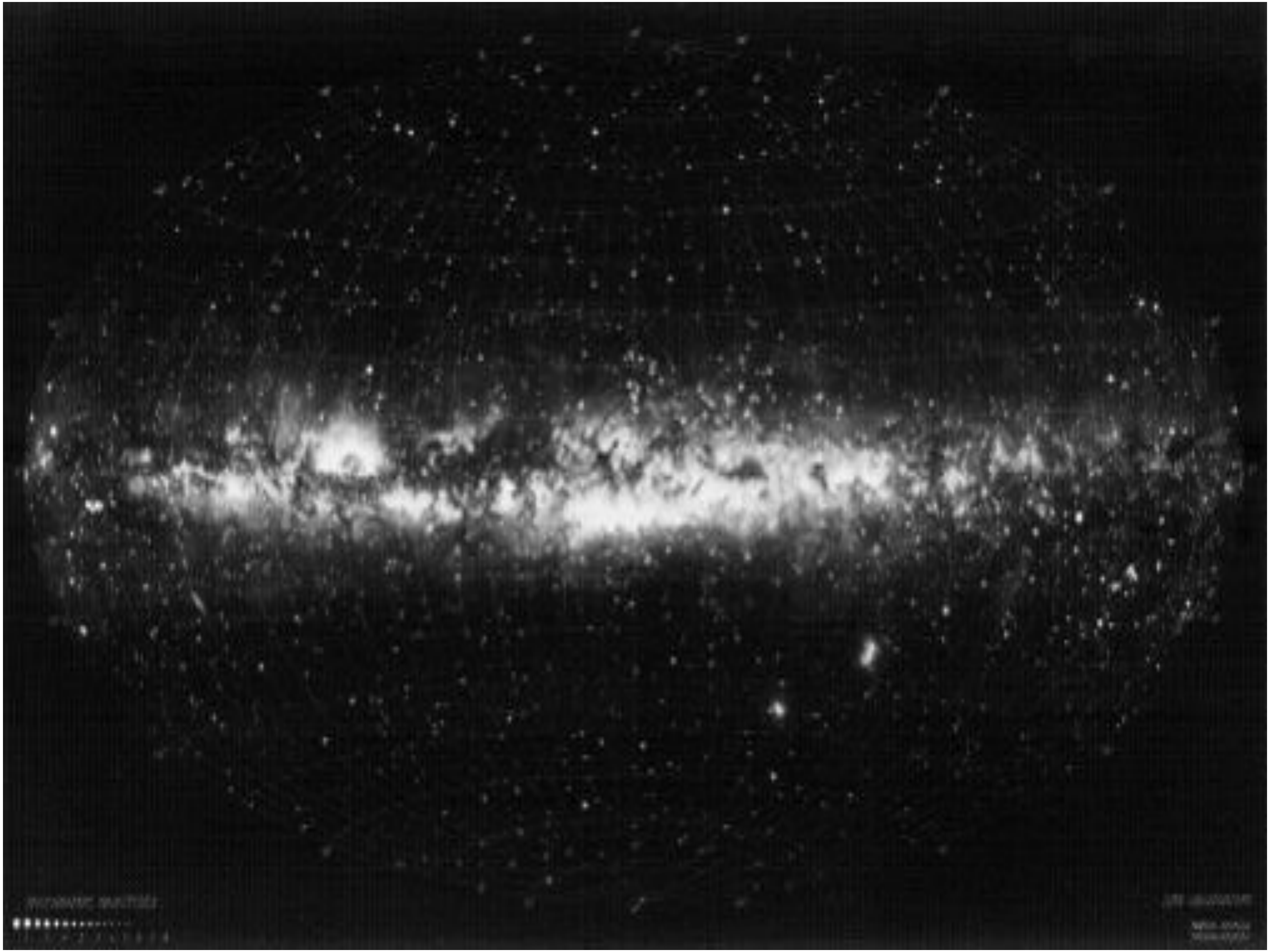


Vacuum energy, antigravity, and modern cosmology

John Peacock, University of Edinburgh

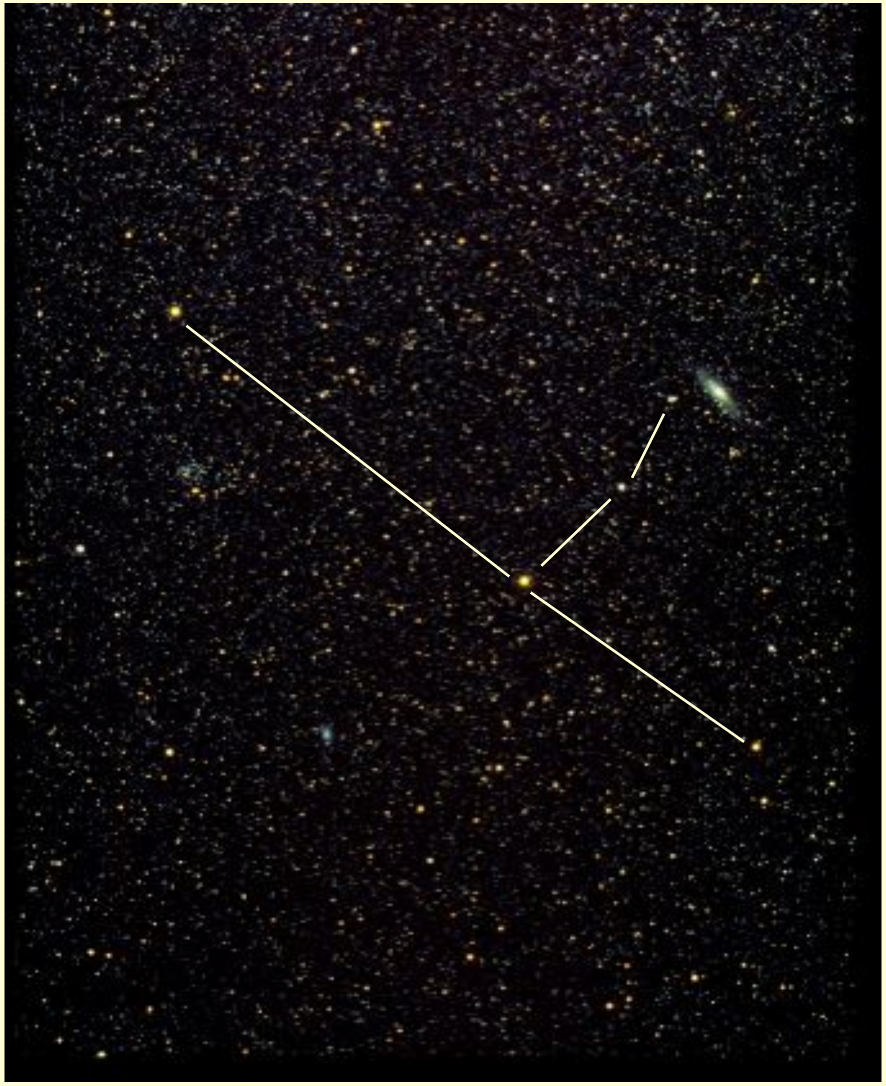
Loretto School, 1 November 2012



Nebulae

Orion

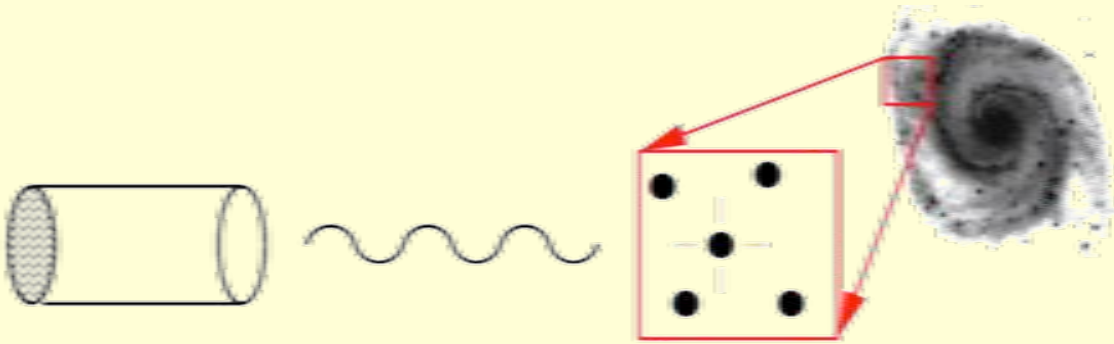
Andromeda



The Great Debate

Are these clouds of gas, or distant systems of stars?

1924: Hubble solves the problem by finding Cepheid variable stars in M31



1 galaxy = 100 billion stars

The Hubble Space Telescope

Whirlpool Galaxy · M51

Hubble Heritage

Barred Spiral Galaxy NGC 1300

Hubble Heritage

Galaxy ESO 510-G13

Hubble Heritage

Galaxies NGC 2207 and IC 2163

Hubble Heritage

The Hubble Deep Field

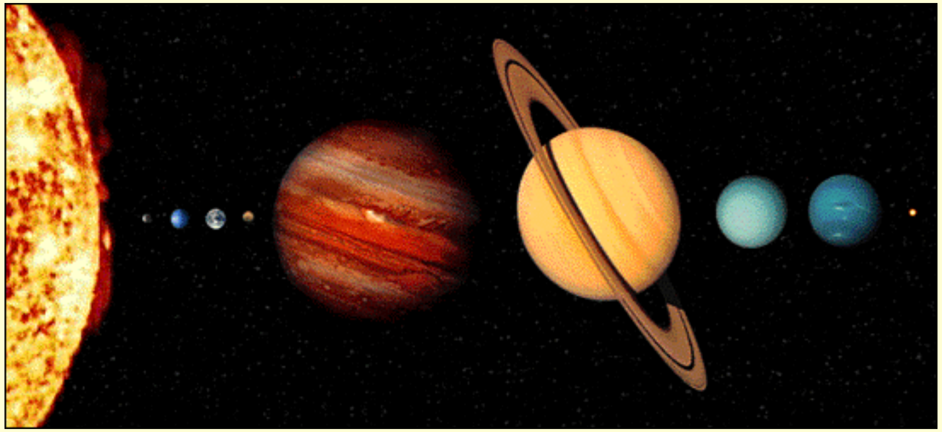
The deepest image of the sky - about 1% of the moon's apparent area

Reaches magnitude 28+

- about 1 billion times fainter than the human eye

100 billion galaxies over the whole sky

Cosmic distances



Earth - Sun = 150 million km
= 8 light minutes

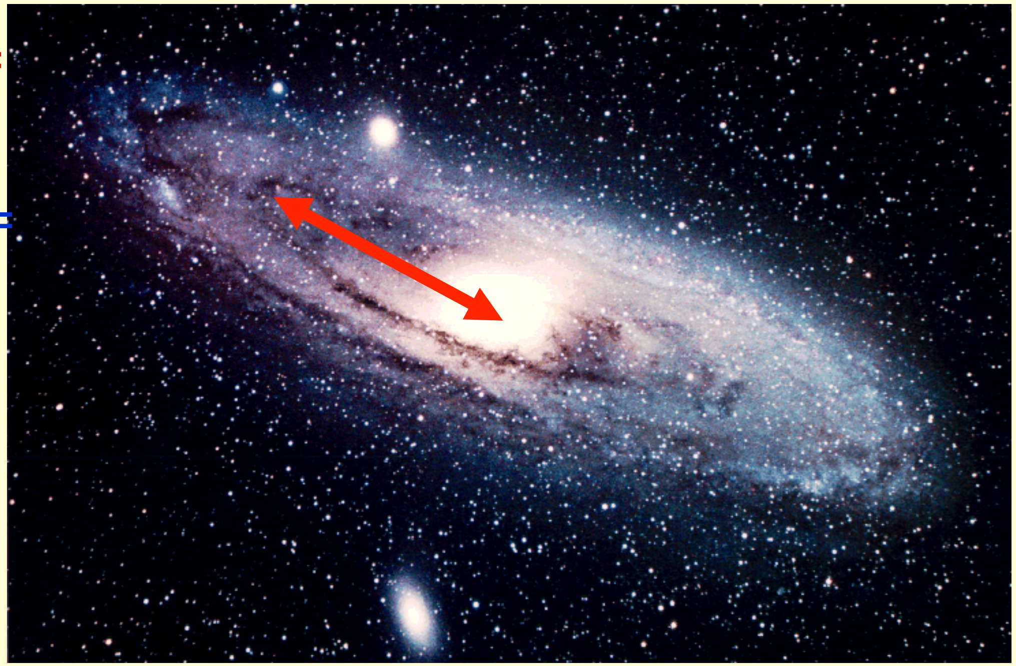
Next nearest star = 4 light years

Earth - centre of Milky Way =
26,000 light years

Next nearest galaxy (Andromeda) =
2.5 million light years

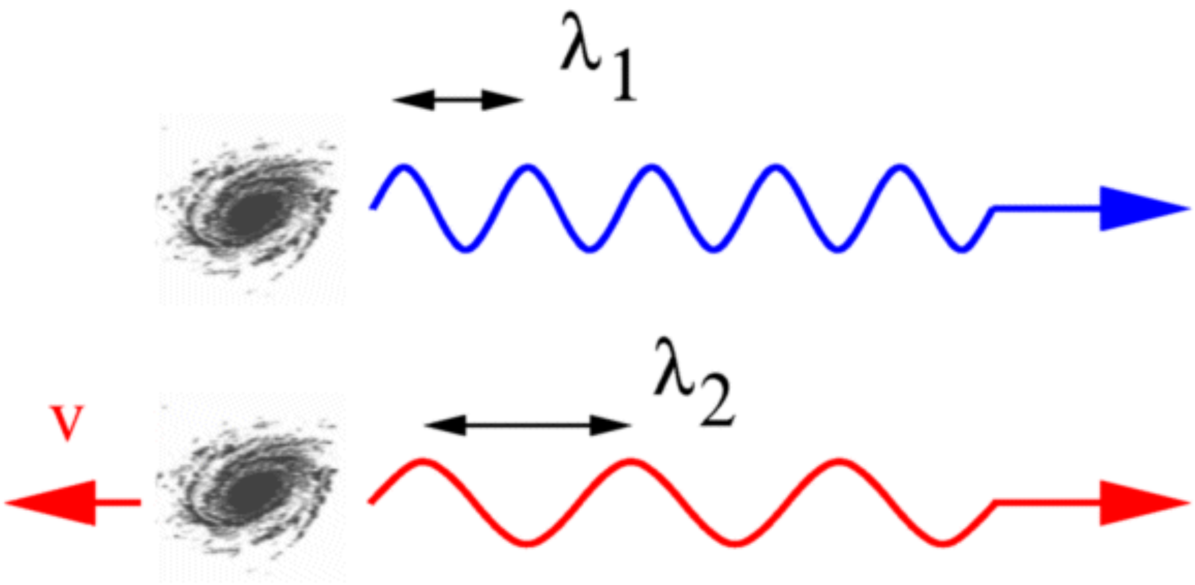
= 0.8 Mpc (Megaparsec)

1Mpc is typical inter-galaxy distance



The expanding universe

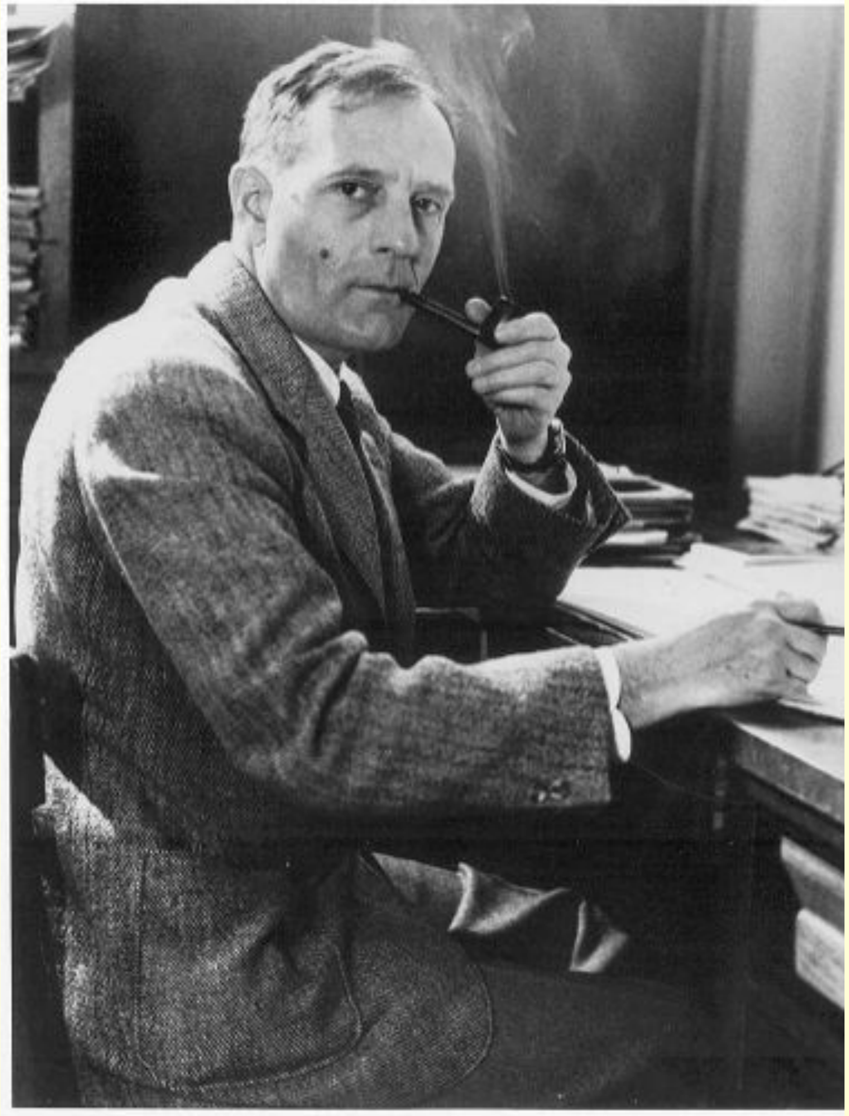
Motion of a light emitter stretches/compresses light waves

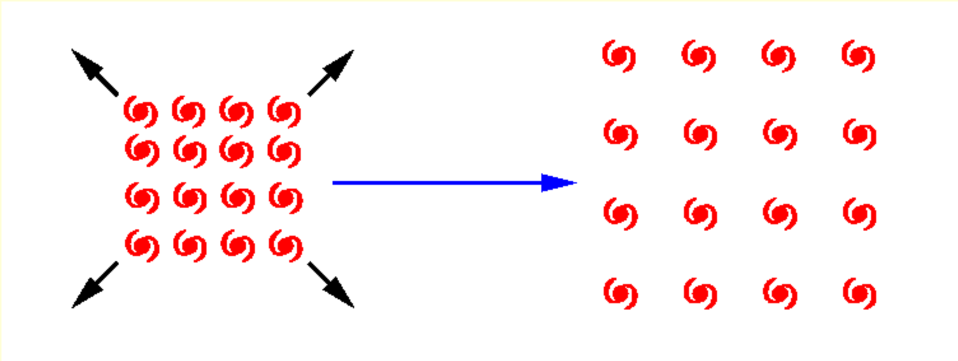


$$1 + z = \frac{\lambda_2}{\lambda_1} \simeq 1 + \frac{v}{c}$$

The Doppler (red)shift

The Hubble expansion



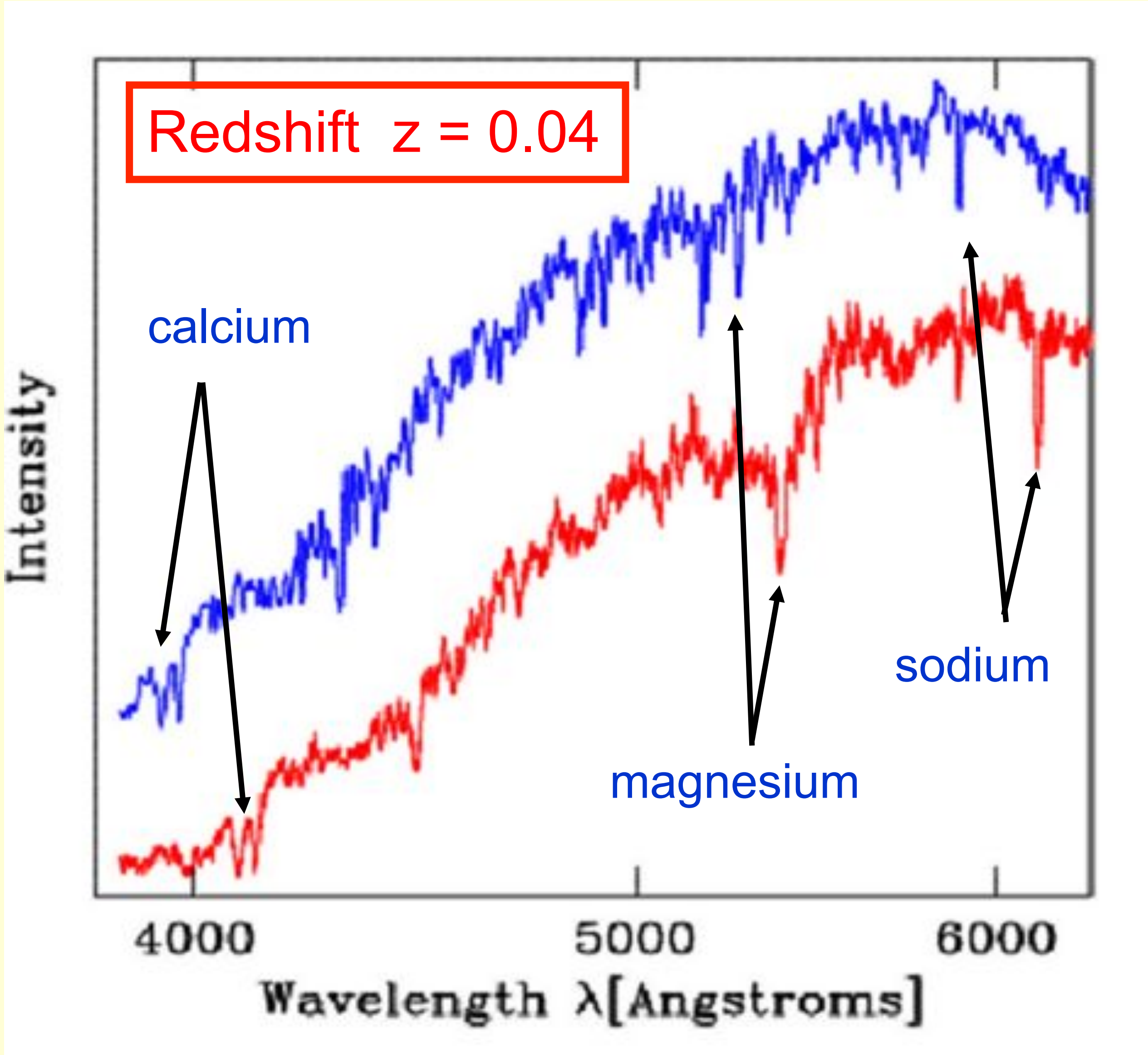


$$V = H\,D$$

"in 1929, Hubble discovered the expansion of the universe....."

How do we know?

Measuring redshifts

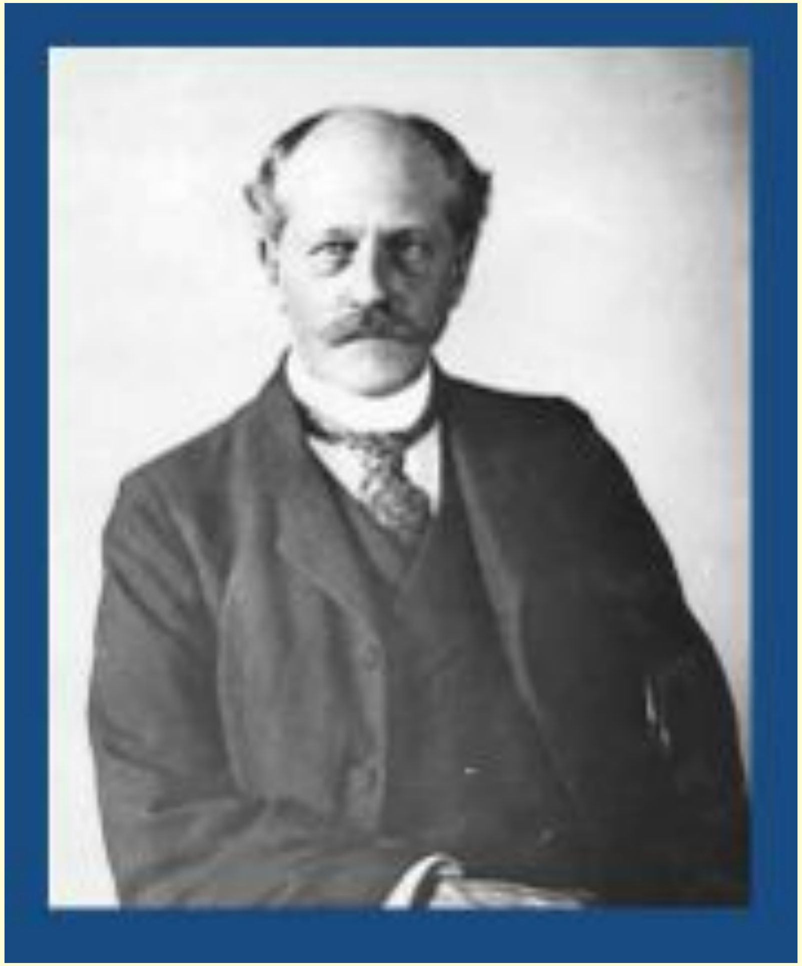


Spectroscopy:

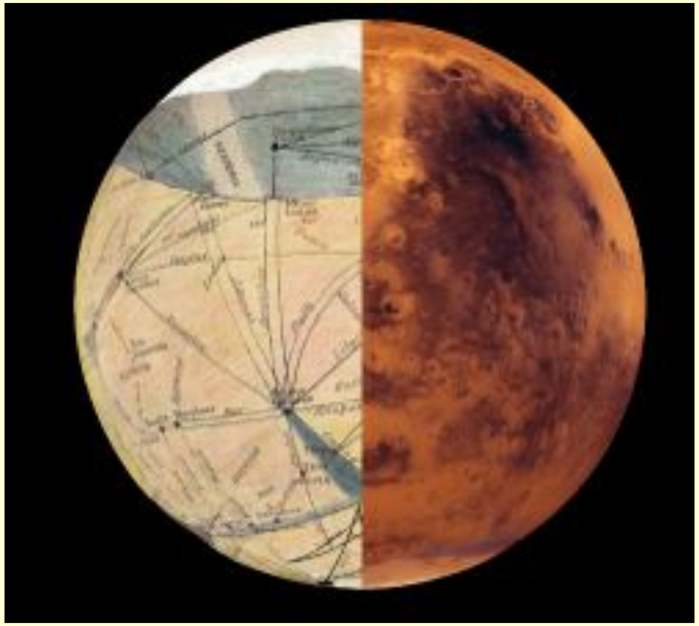
Dispersing the light from galaxies into different colours reveals signatures of atoms as seen on Earth

So Hubble was the first to measure redshifts using spectroscopy?

The Lowell Observatory, Arizona



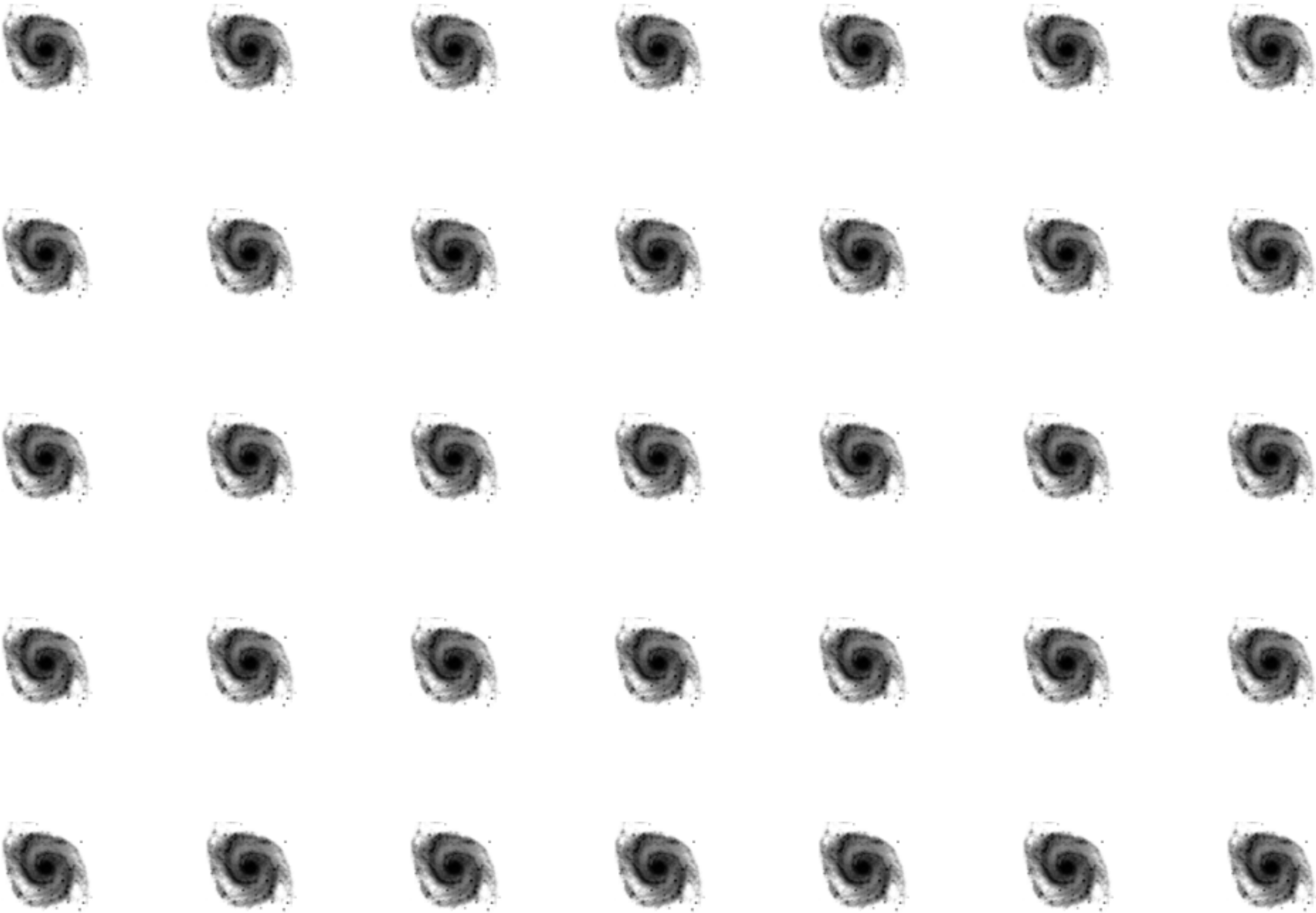
Percival Lowell (1855-1916)



Vesto Melvin Slipher (1875-1969)

- Measured first galaxy redshift on 17 September 1912 (actually a blueshift)

- By 1917, Slipher had spectra for 25 galaxies: 21 had redshifts



Conceptual difficulties with the expanding universe

- There is no ‘outside’ – not expanding into anything

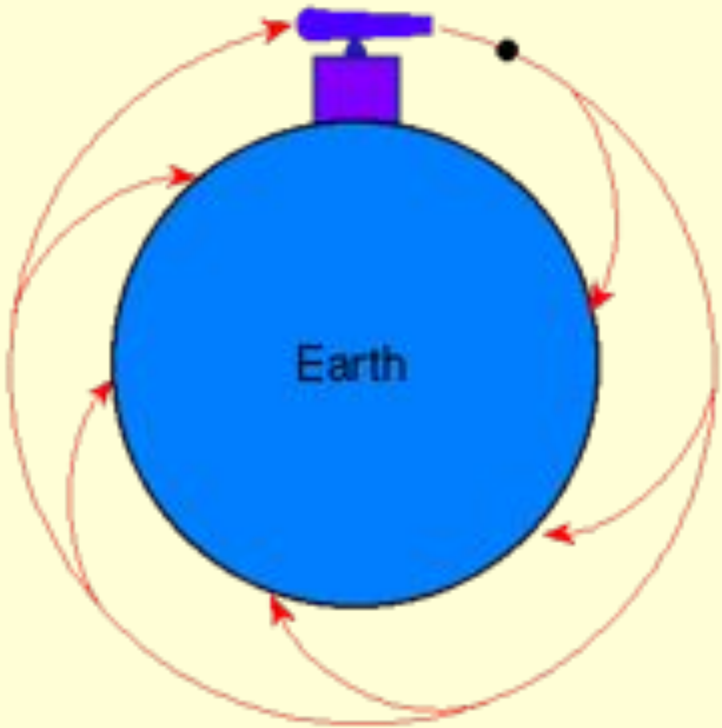
- We are not at the centre – there is no centre

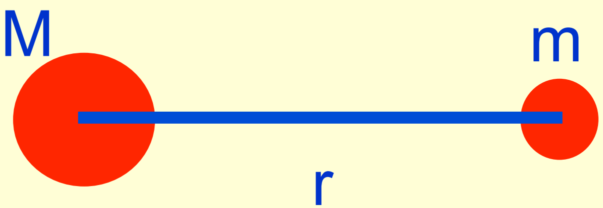
- Space is not ‘stretching’ locally – but there is more of it

Gravity makes (some) sense of the expansion

Newton & gravitation

Isaac Newton (1643-1727)



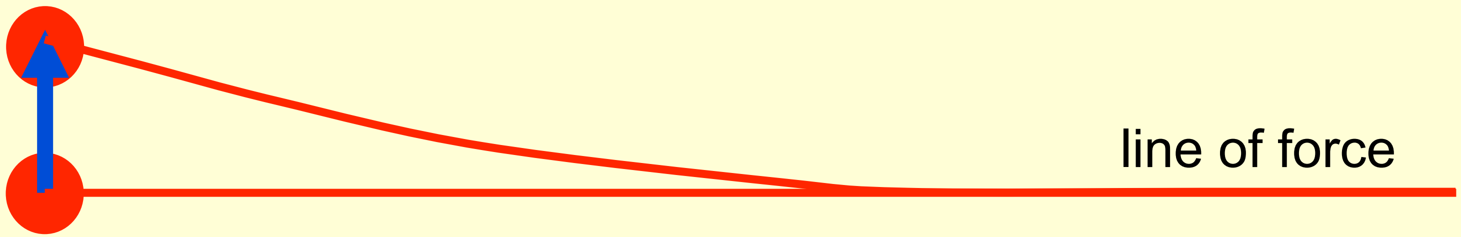


$$F = \frac{GMm}{r^2}$$

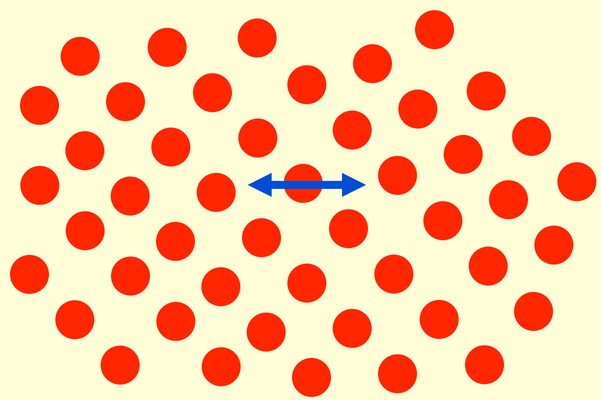
Inverse square law: double distance gives ¼ the attraction

Problems Newton couldn't solve

- Instantaneous action at a distance
  - Relativity says effects should move at c

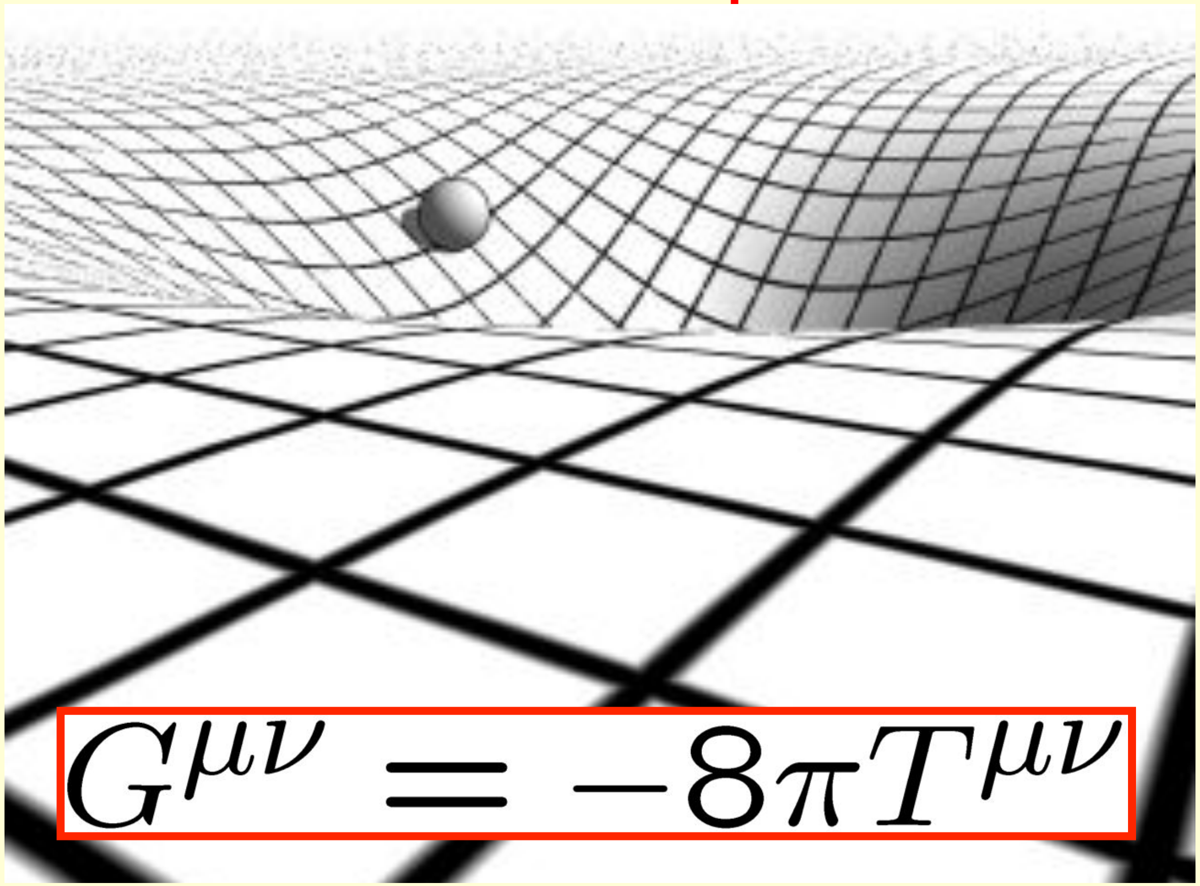


- An infinite distribution of mass
  - Which way do things move?



General Relativity (1915)

Matter bends space-time



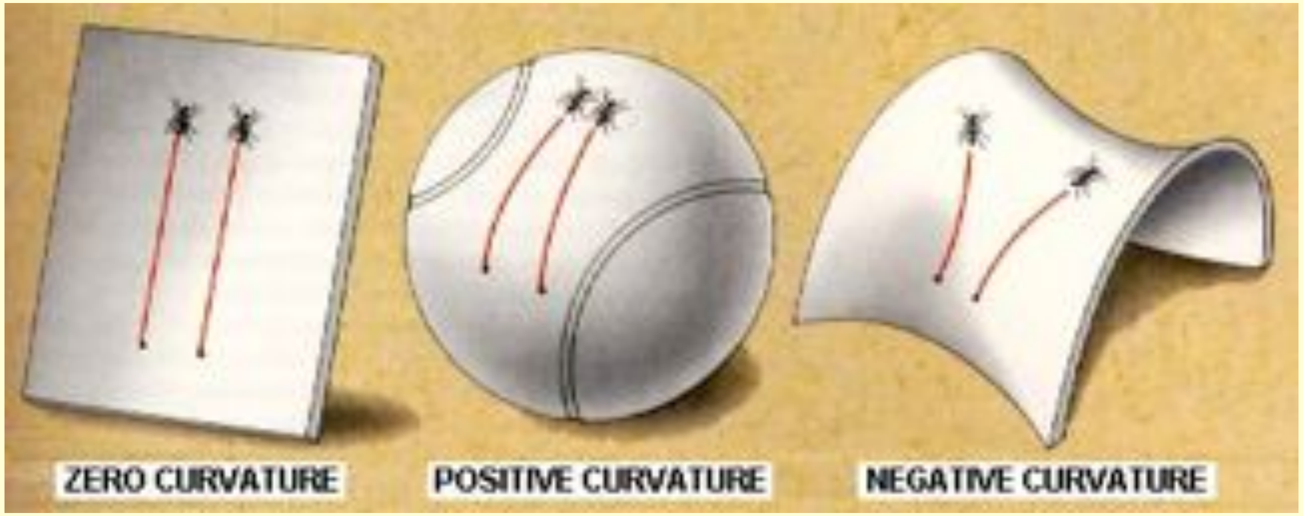
$$G^{\mu\nu} = -8\pi T^{\mu\nu}$$

Matter moves along paths in bent space-time

The expanding curved universe

Matter curves space:

(no outside to expansion)



flat (infinite) closed (finite) open (infinite)

'critical density' to turn open into closed: about 1 atom per m^3

'density parameter': Ω = (density) / (critical density)

So two big questions:

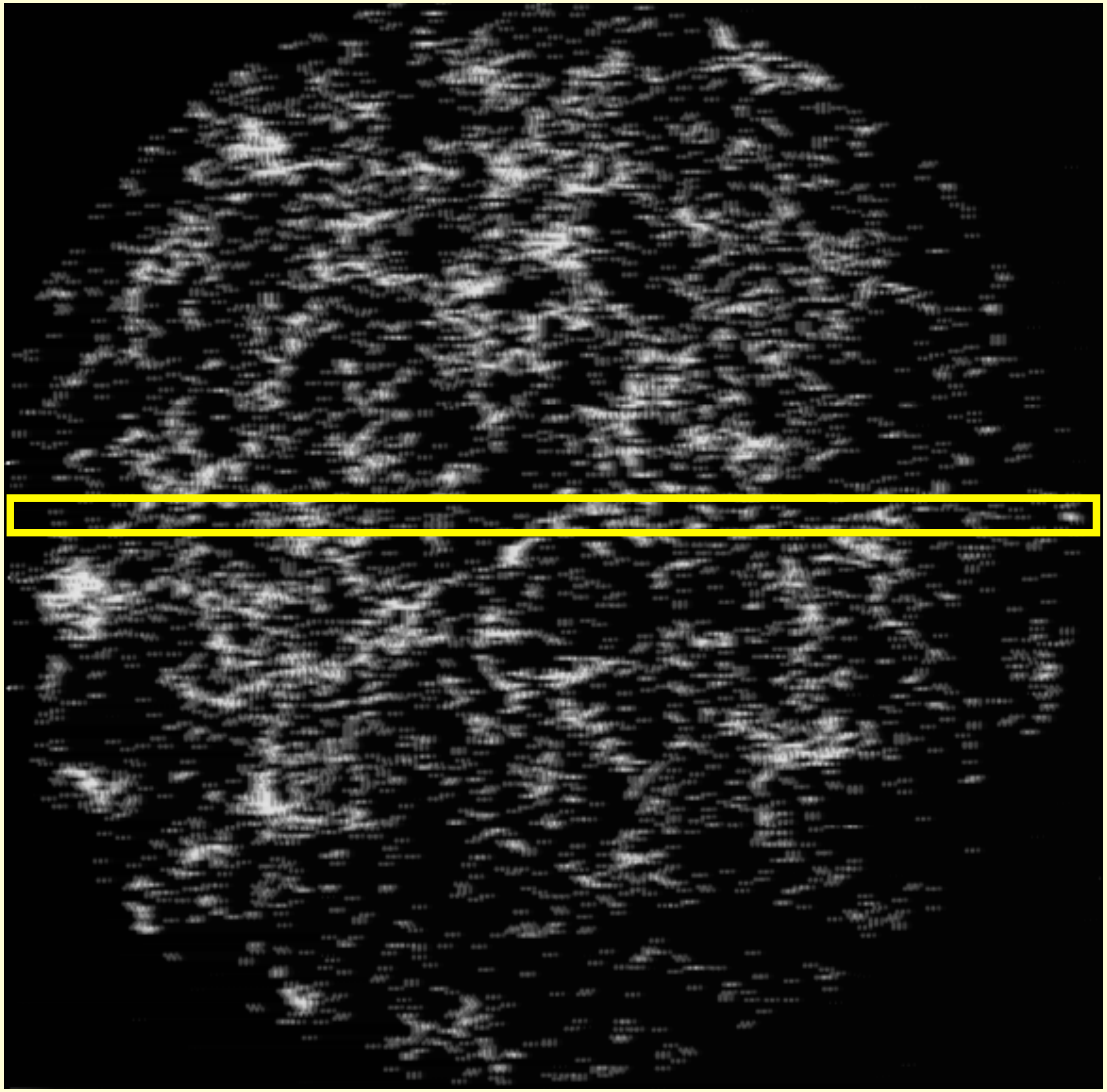
Why is the universe expanding?

What is its geometry (density)?

The expanding universe means that we can make a 3D map of the galaxies by measuring redshifts:

The 'Redshift Survey'

The distribution of the galaxies



1950s:

filamentary patterns in the sky distribution?

1980s:

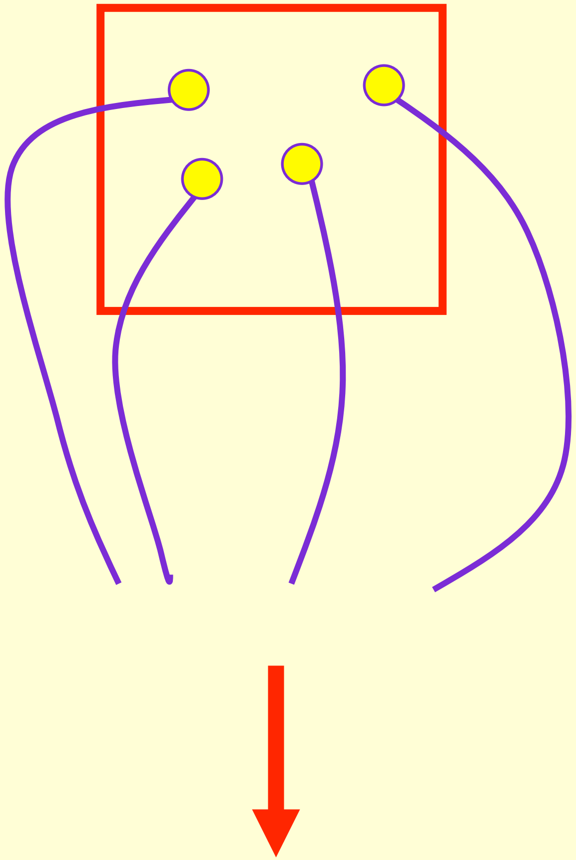
Take a strip and get redshifts

Inverting $v = Hd$ gives an approximate distance

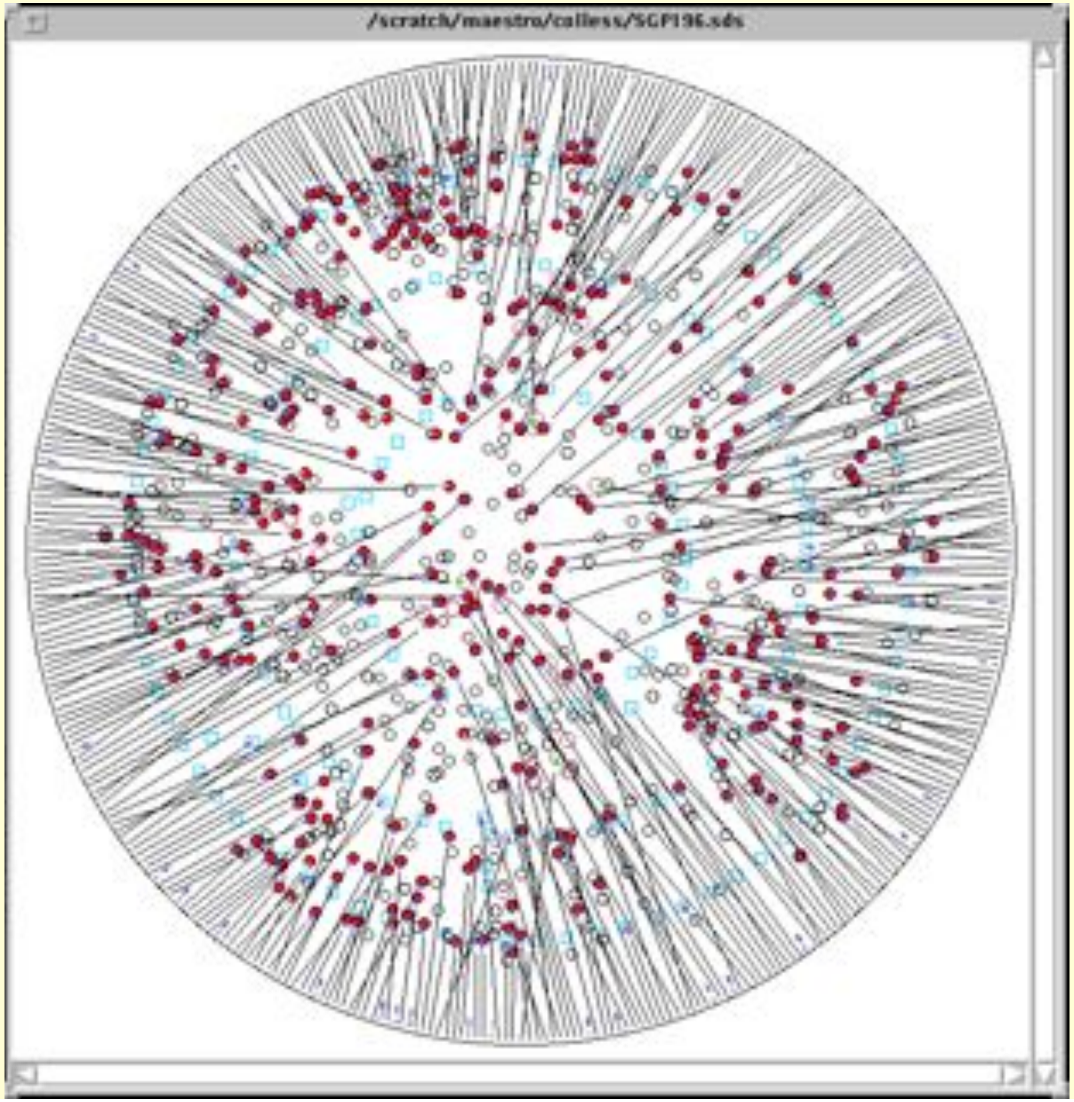
The Anglo-Australian Telescope

3.9m
primary
mirror

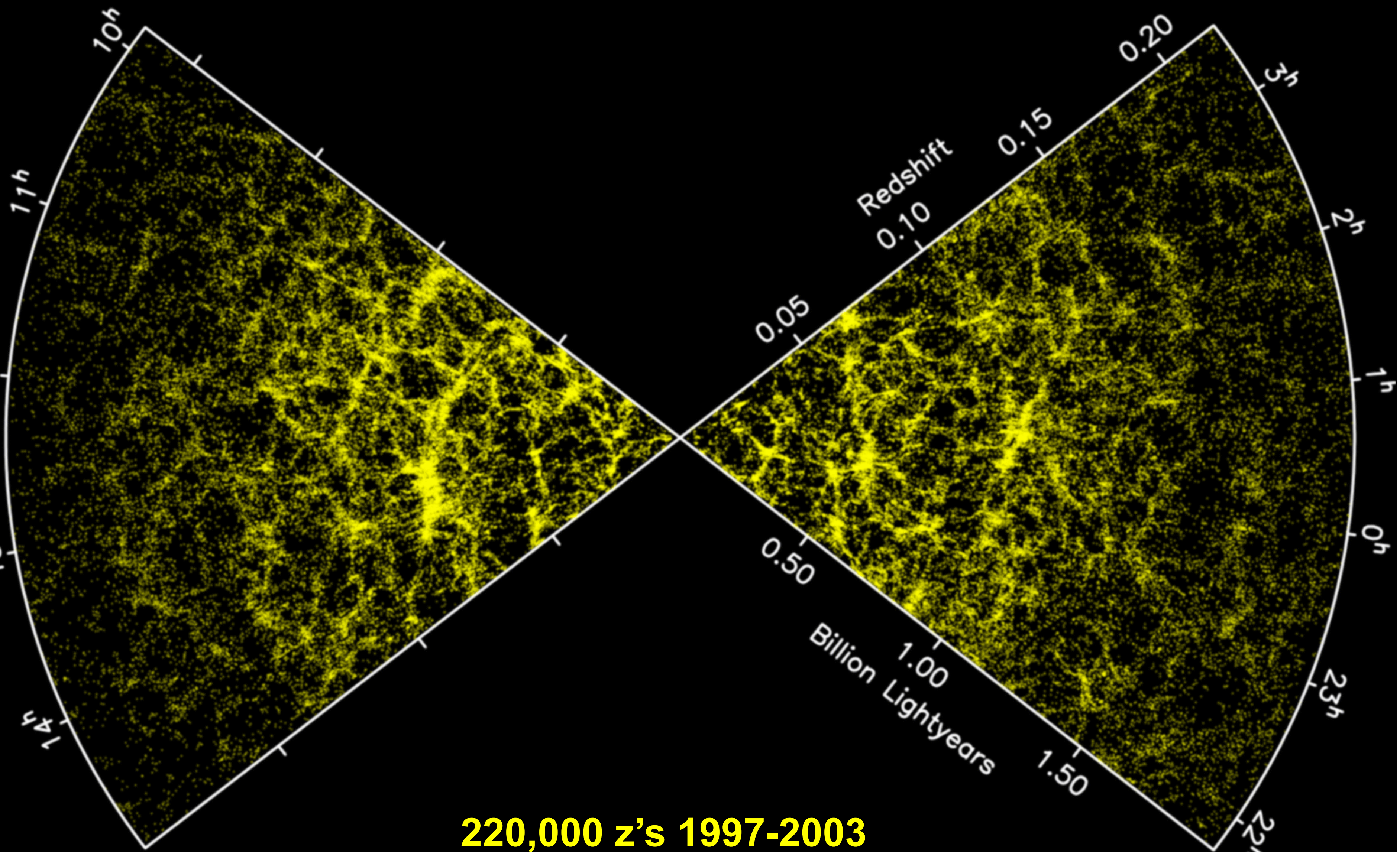
Going faster with fibre optics



to spectrograph



The 2dF Galaxy Redshift Survey

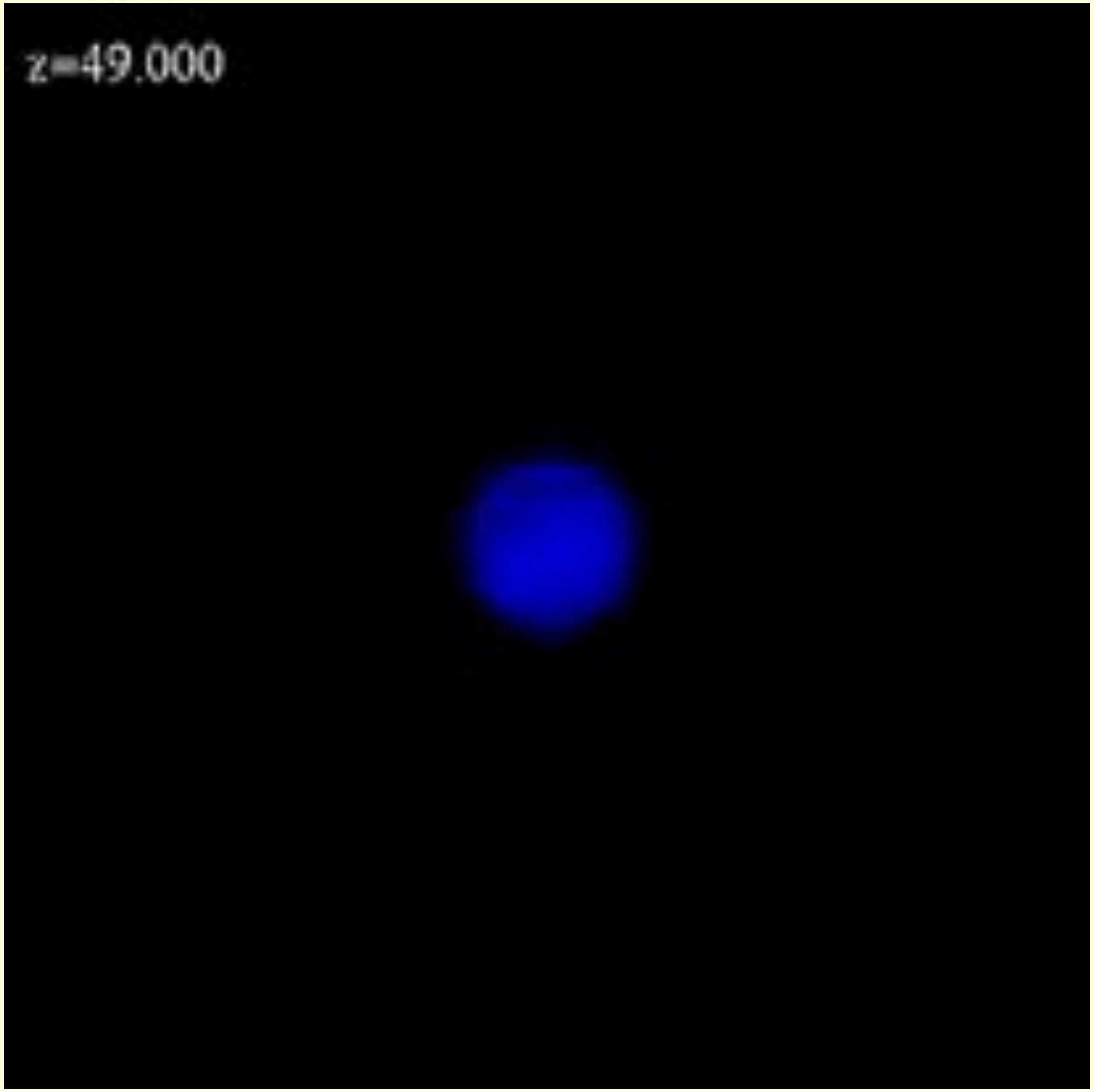


220,000 z's 1997-2003

Why do galaxies, clusters, and superclusters exist?

Simulating structure formation

Use a supercomputer to calculate the gravitational force between up to 10 billion imaginary particles of matter, starting with slight non-uniformity



So three big questions:

Why is the universe expanding?

What is its geometry (density)?

Why did it start out non-uniform?

The modern answer: because the vacuum has weight

– but surely a vacuum is nothing, by definition?

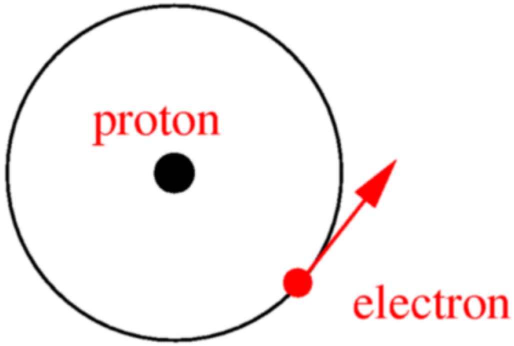
Physics of the subatomic realm: The uncertainty principle (1927)

$$\Delta(mv)\,\Delta(x) \gtrsim \hbar$$

Precise knowledge of both position and speed is impossible

Werner Heisenberg (1901 - 1976)

Sizes of atoms

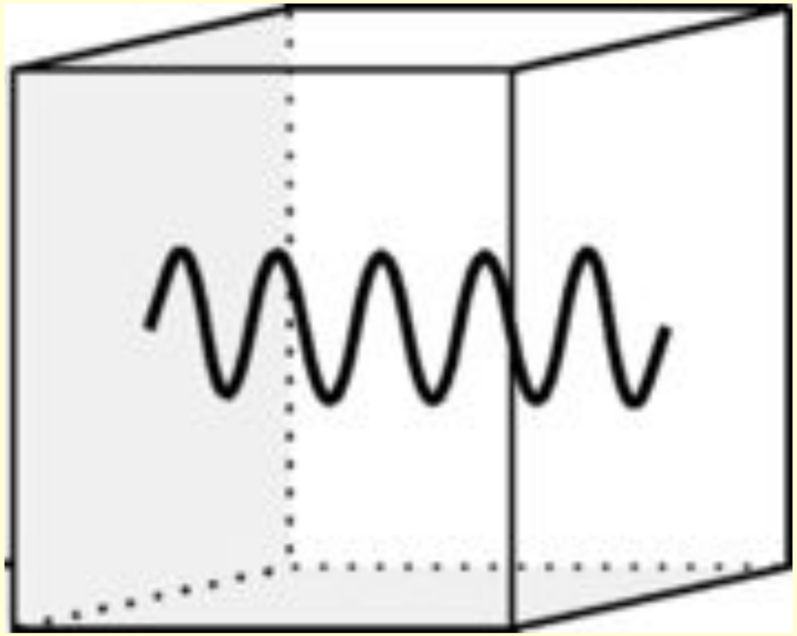


Uncertainty in speed of electron

= speed of light

if size of atom = 10^{-12} metres

The vacuum of fields: zero-point energy



Energy in electromagnetic wave mode of frequency ν

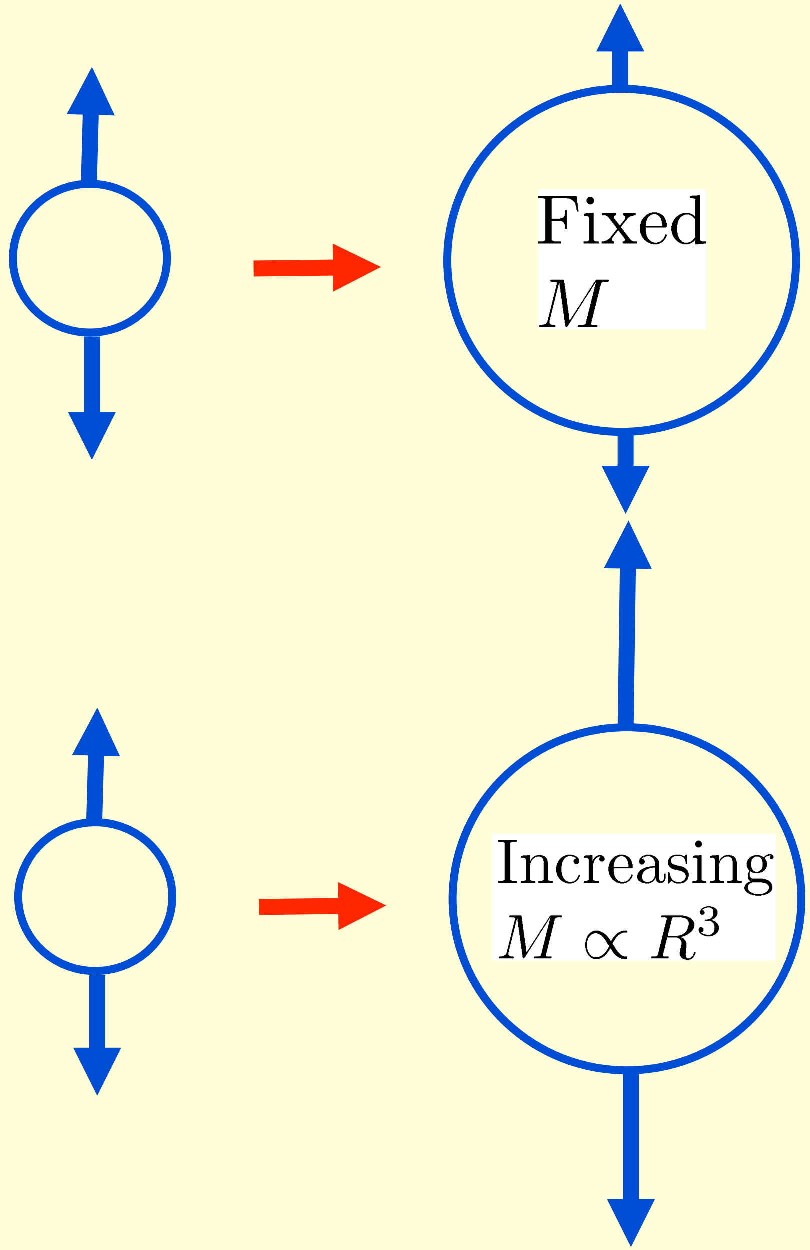
$= (n+1/2)\, h\nu$

n photons and zero-point energy (inevitable from uncertainty principle)

– not the only contribution to vacuum energy

Empty space has antigravity

Ordinary matter: expansion slows as it expands, since gravitational energy is less



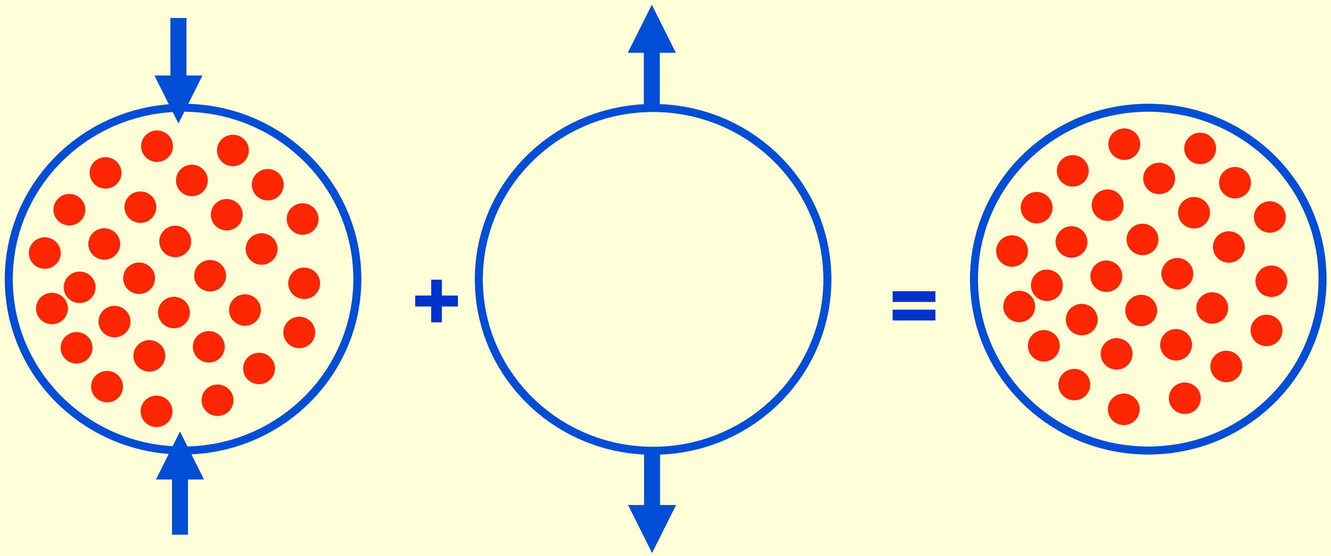
$V = -GM/R \propto 1/R$

A sphere of vacuum increases mass as it expands, so gravitational energy goes up

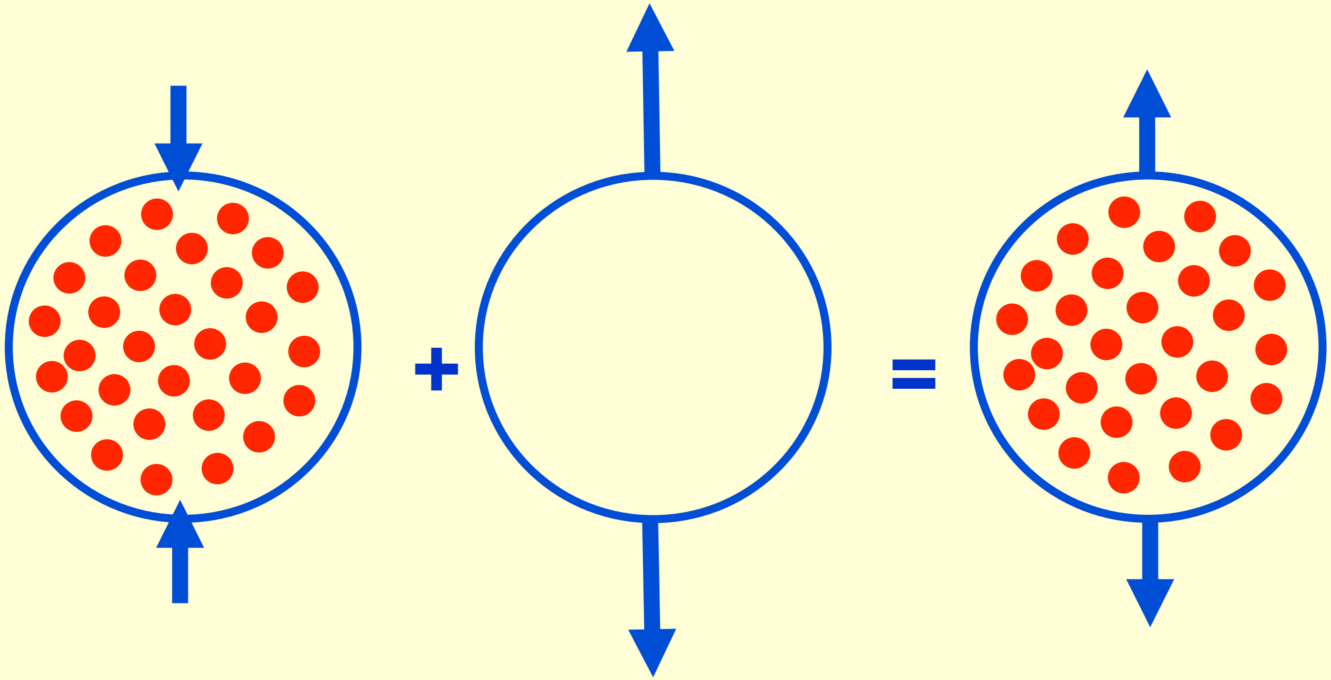
$V = -GM/R \propto R^2$

Vacuum energy: Einstein's missed chance

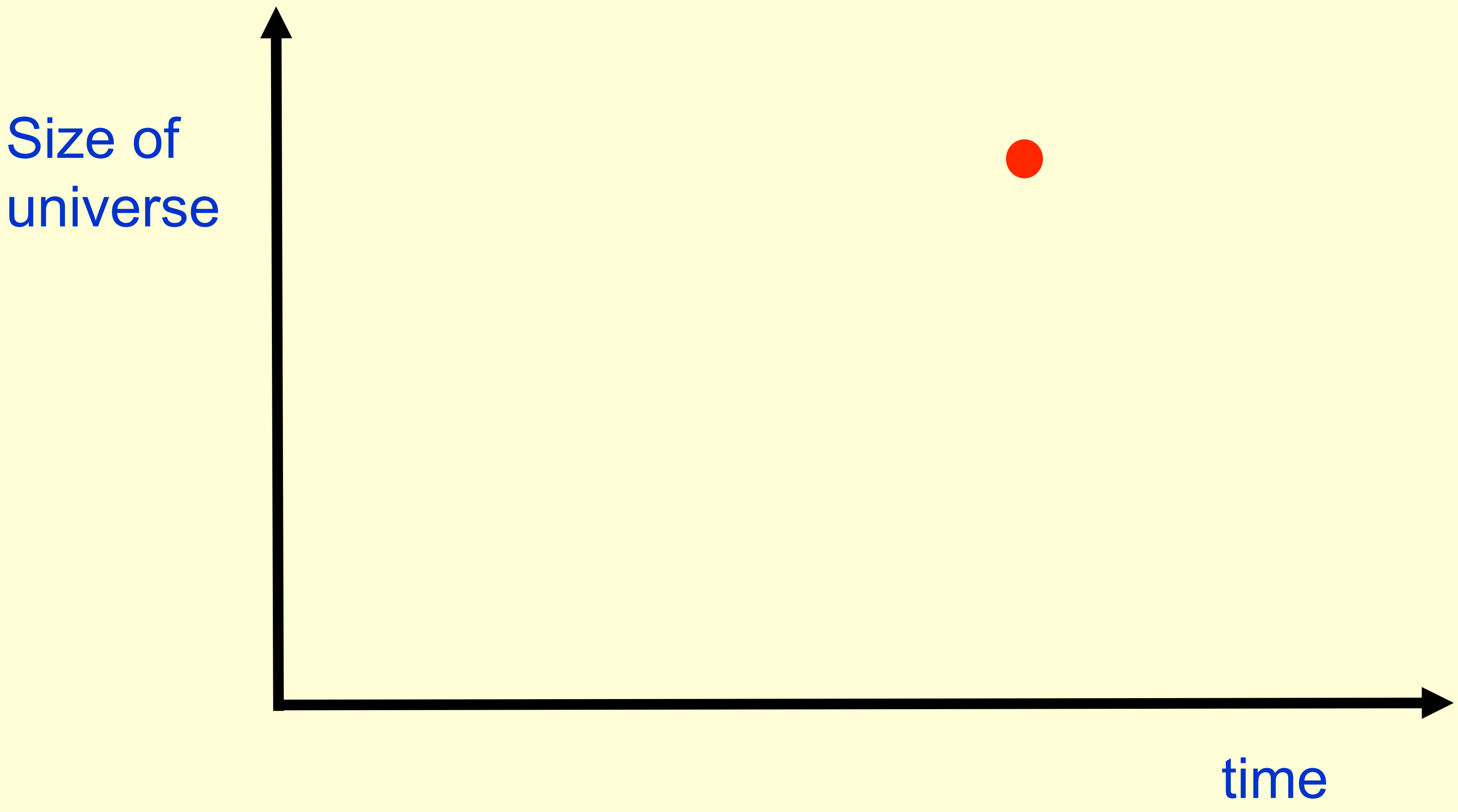
1917: Einstein's static universe balances gravity and repulsion from cosmological constant – abandoned after Hubble



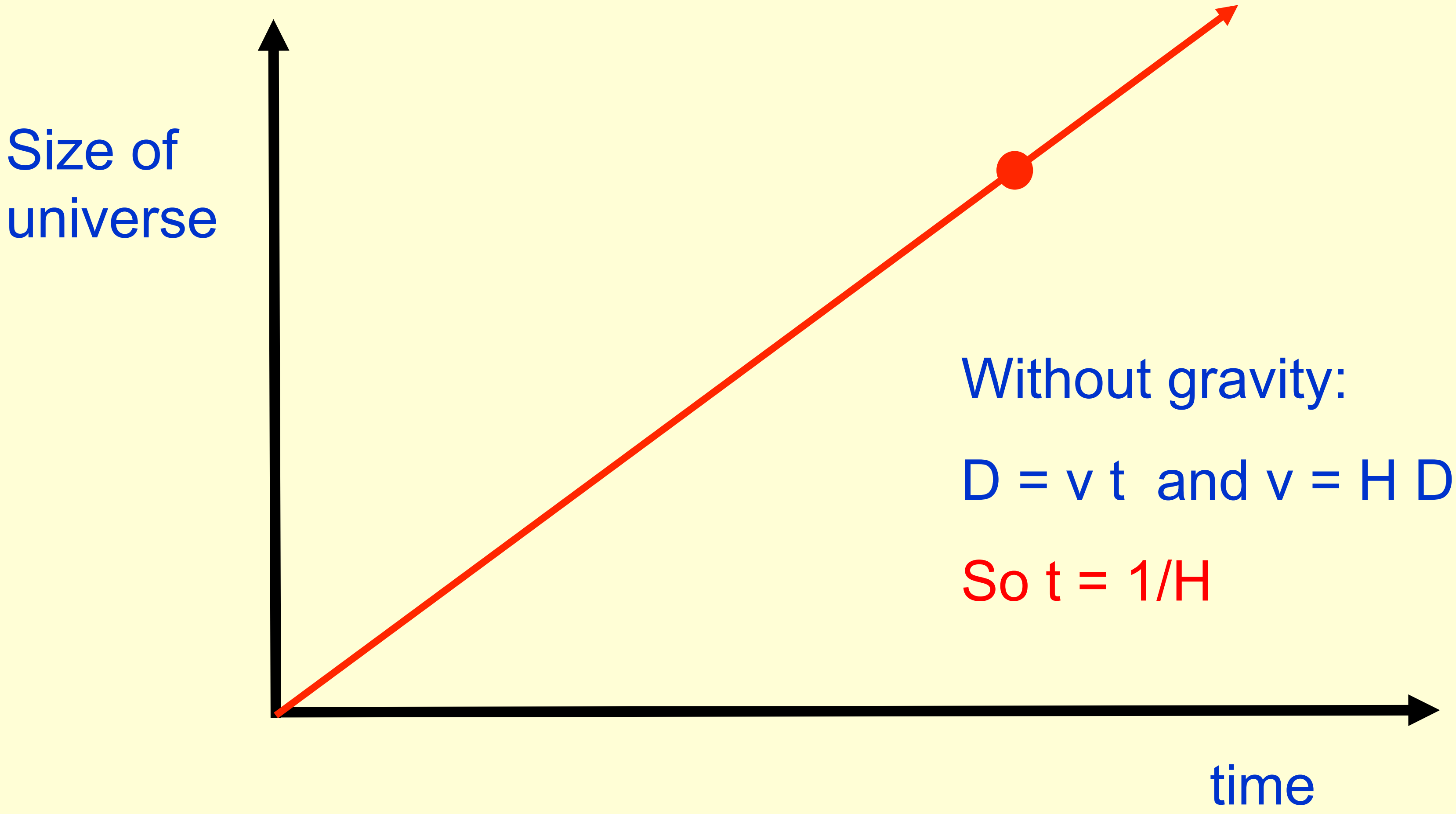
Now: **'Dark Energy'** can cause the expansion of the universe to accelerate



The Big Bang and cosmic acceleration



The Big Bang and cosmic acceleration



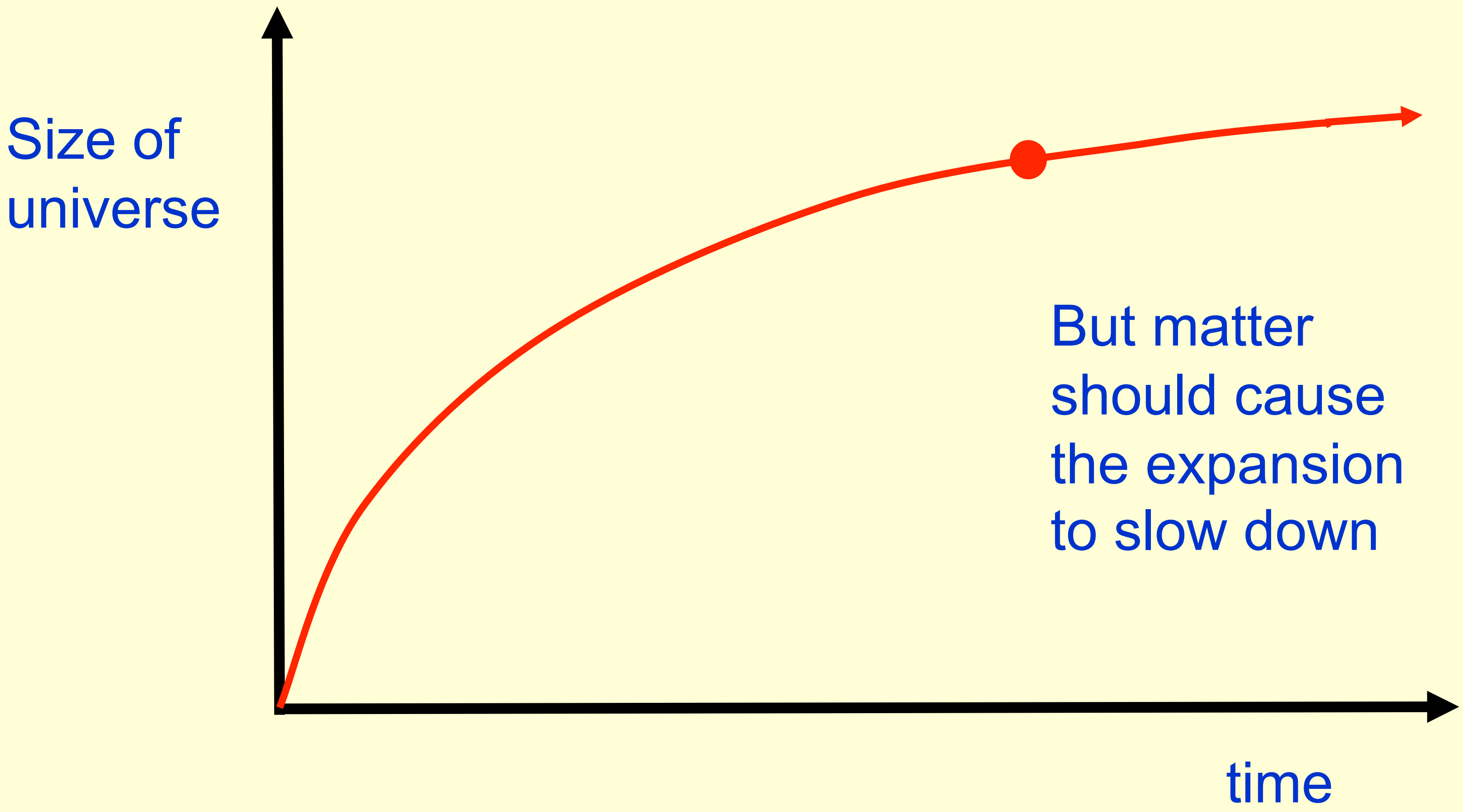
Without gravity:

$D = v\,t$ and $v = H\,D$

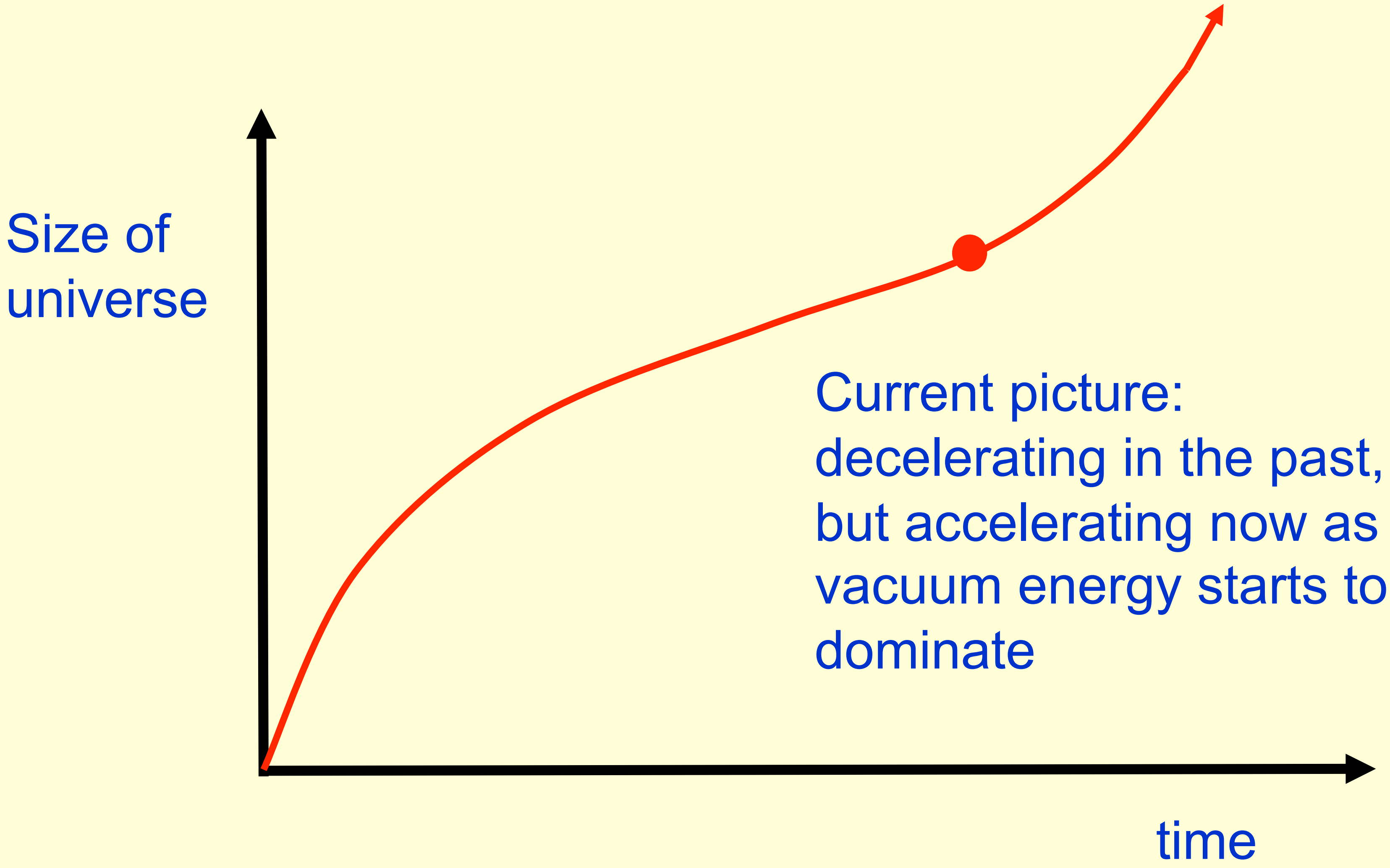
So $t = 1/H$

The Big Bang: zero size and infinite density 1/H = 14 billion years ago

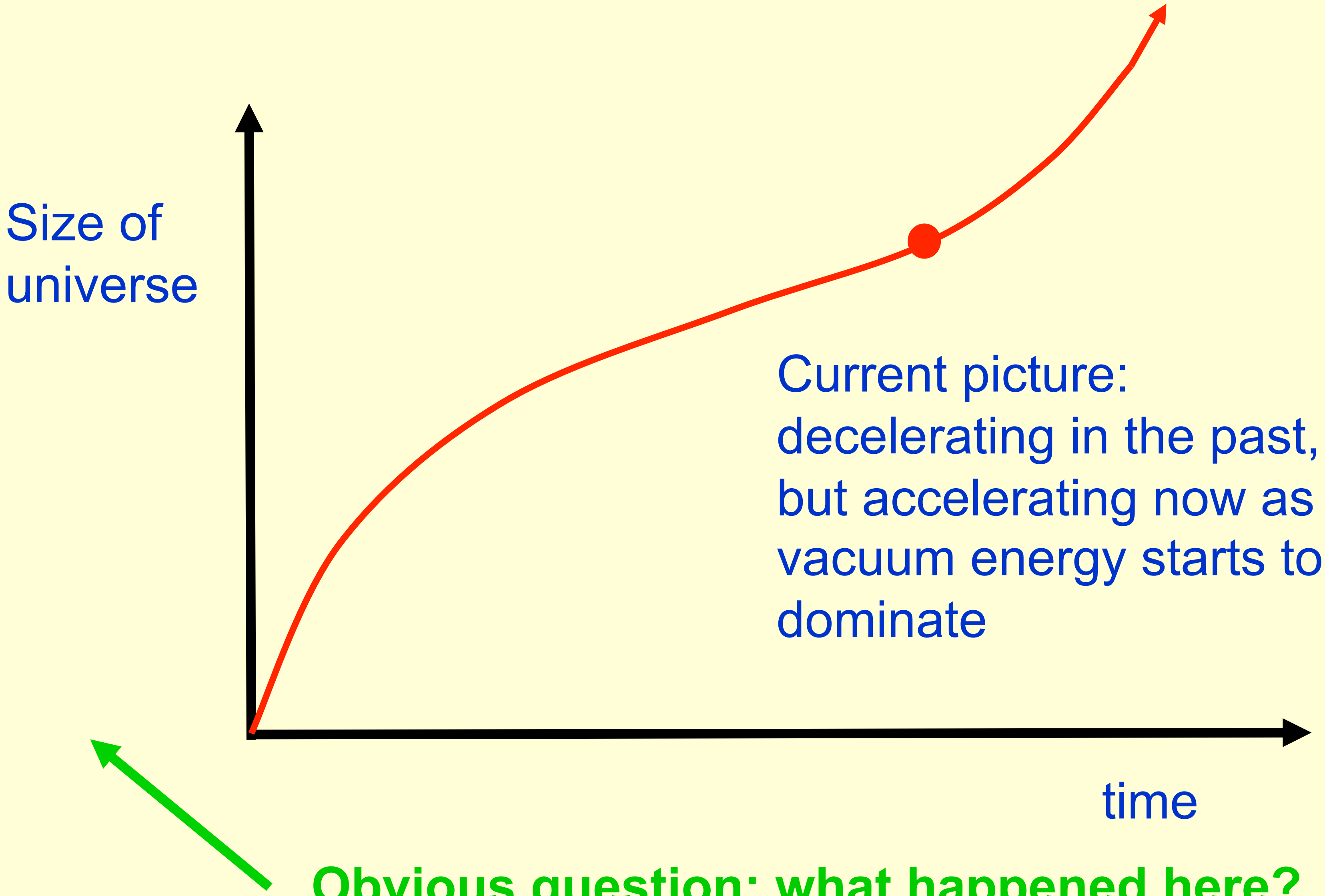
The Big Bang and cosmic acceleration



The Big Bang and cosmic acceleration



The Big Bang and cosmic acceleration

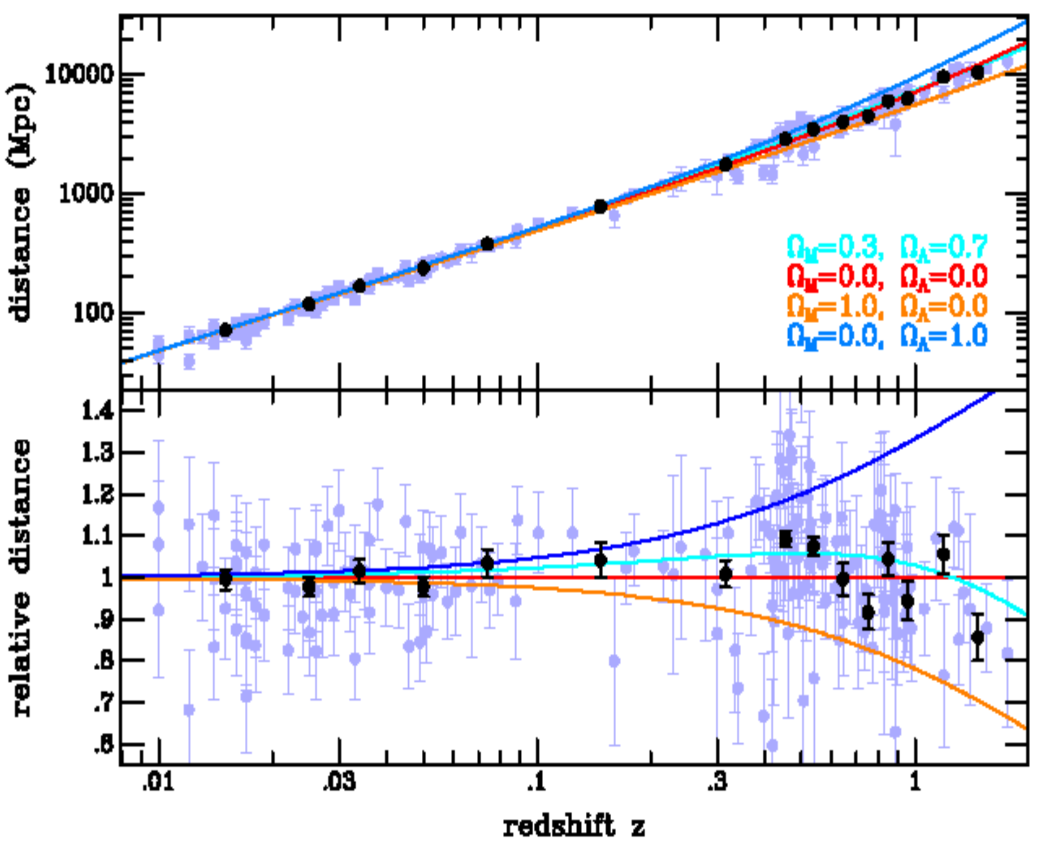


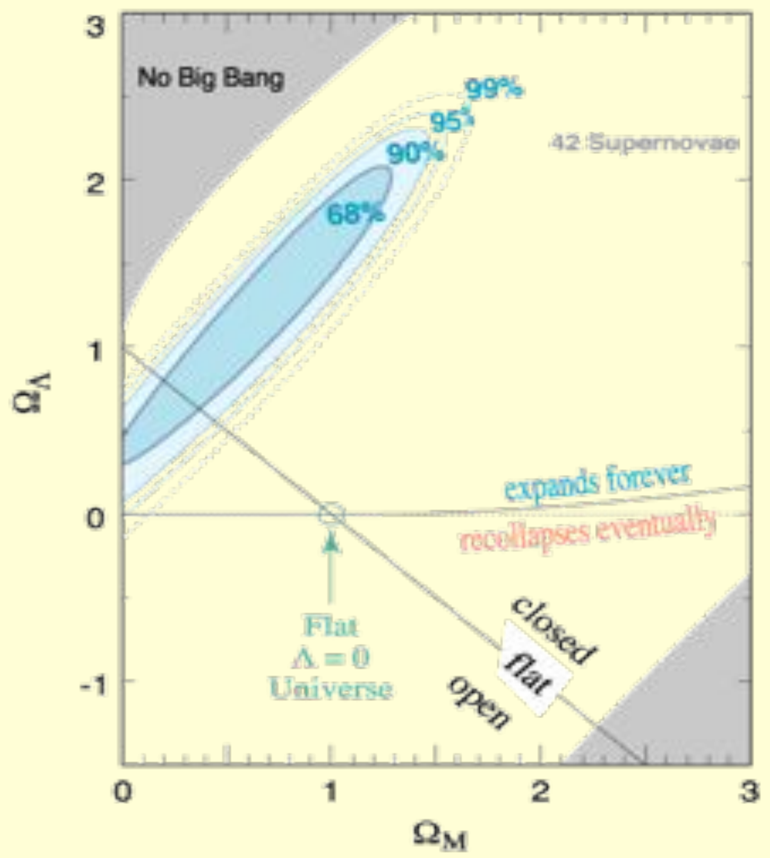
Obvious question: what happened here?

SNe Ia as standard candles
(1998; 2011 Nobel Prize)

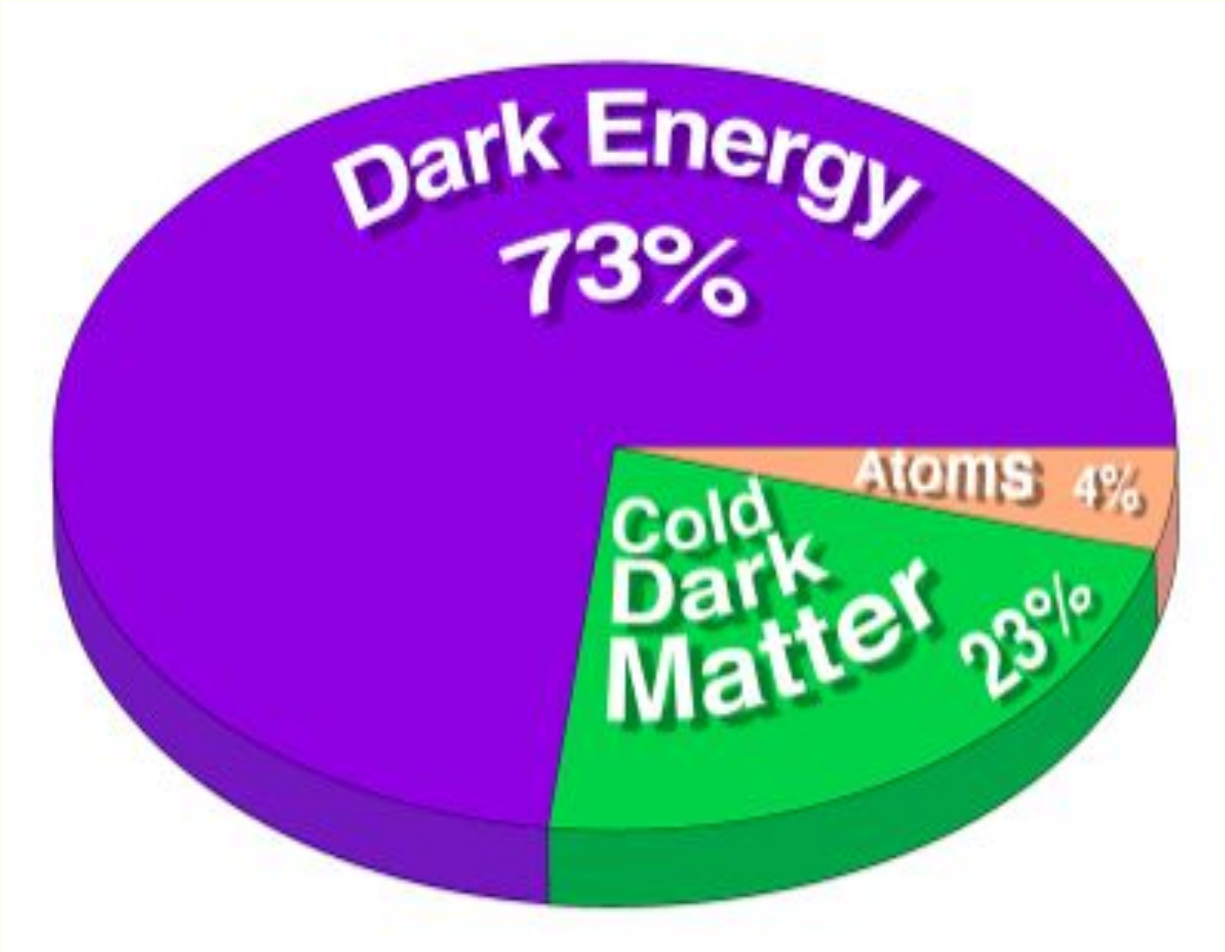
D-z relation at high z probes H in past

Curvature in D-z relation depends on both dark matter and dark energy





The implausible universe



Total density: Ω = 1 to +/- 1%: an infinite flat universe

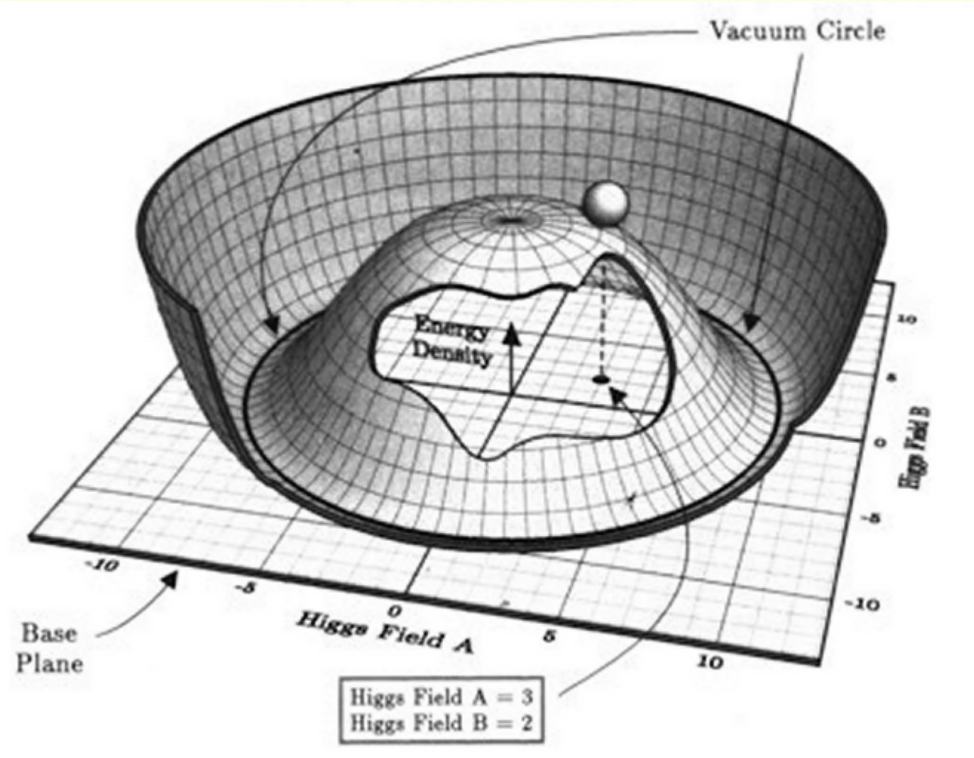
So everything is explained, except:

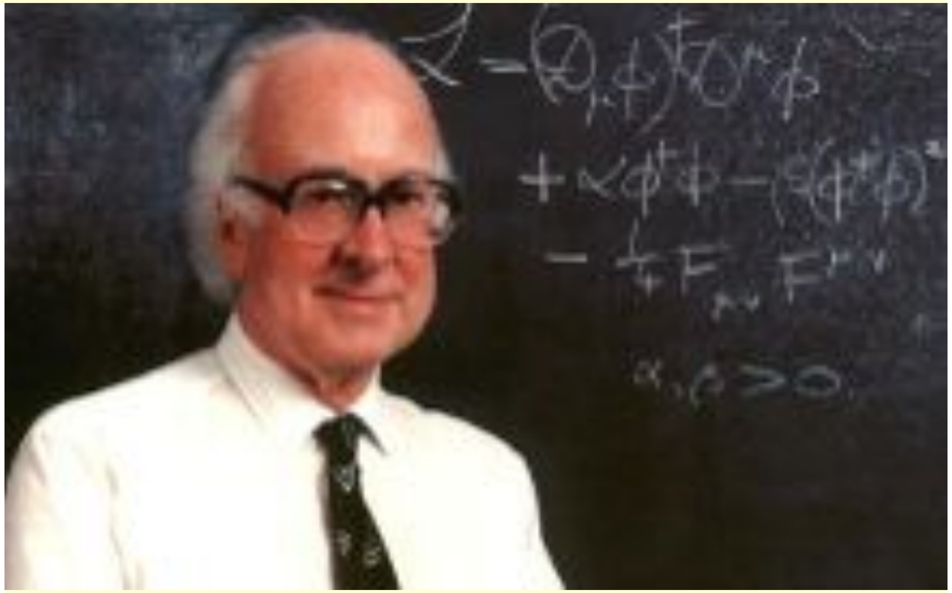
(1) What happened before the big bang?

(2) Can we predict the density of empty space?

(3) Where did the initial structure in the universe come from?

Peter Higgs (1963): explaining masses of elementary particles needs vacuum energy





Scalar field ϕ: like electric field but no direction. Has potential energy density V(ϕ) which fills all space

Higgs field is dynamical – can change with time

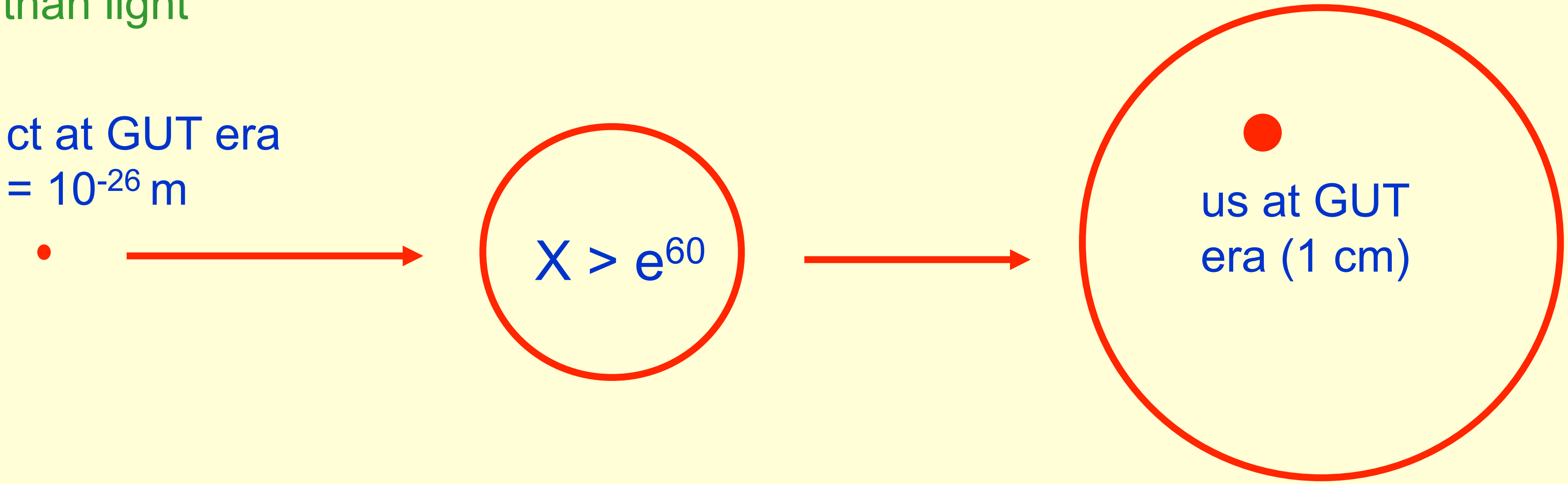
Alan Guth (1947 -)

The Inflationary universe
(1981: long before vacuum energy was proved to exist today)

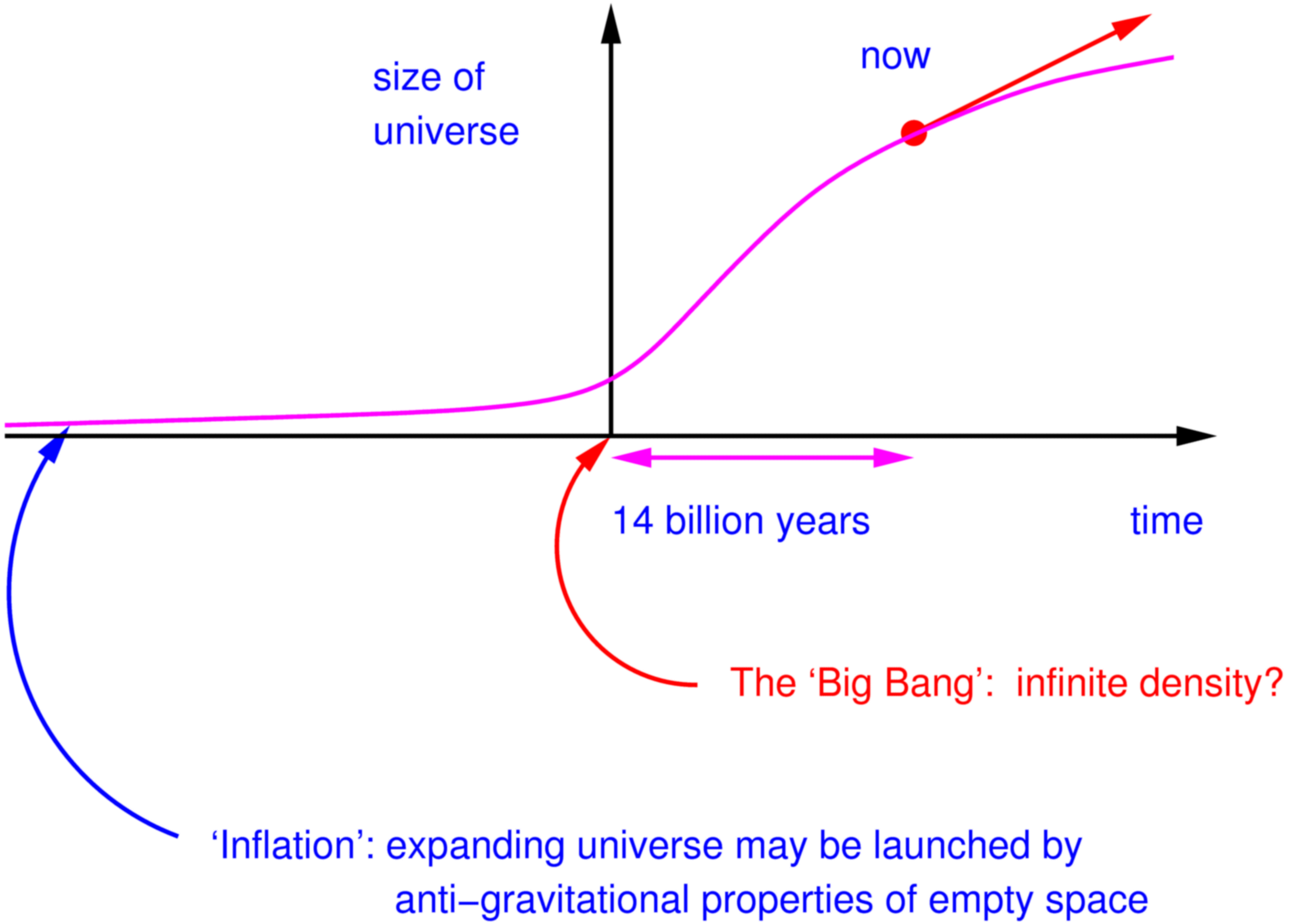
What if the vacuum density was much higher in the past?

Needs 10^{80} kg m^{-3} to dominate at the ‘Grand Unification’ era of particle physics – $E=10^{15}$ GeV = 10^{11} X LHC (density is 10^{-26} today)

Antigravity can blow a big bubble from a subatomic patch, growing faster than light

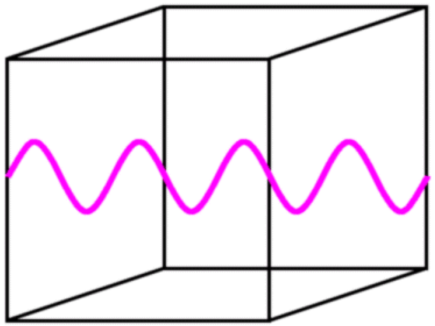


History of the expansion



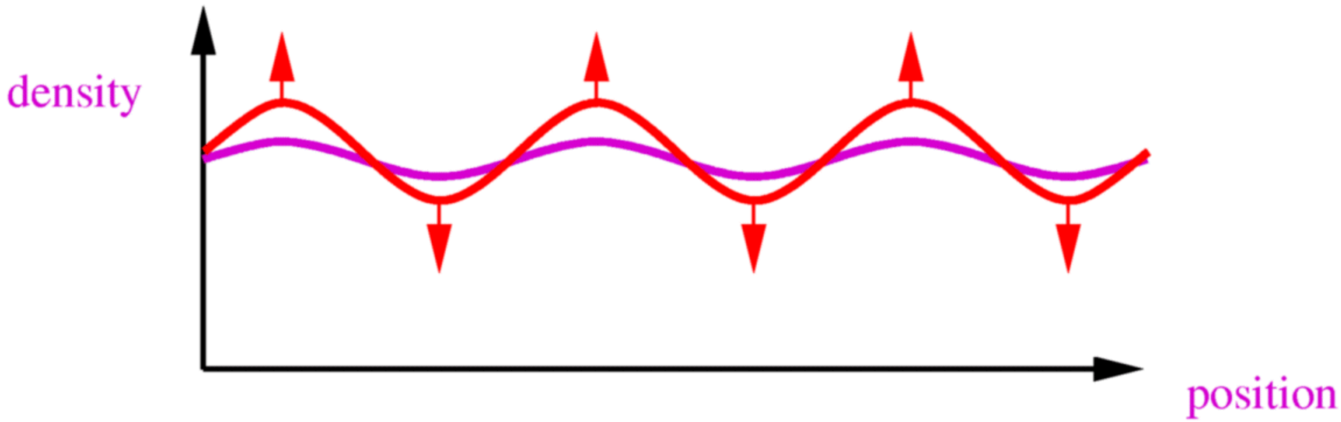
Quantum fluctuations and cosmic structure

The presently visible universe was once of subatomic size



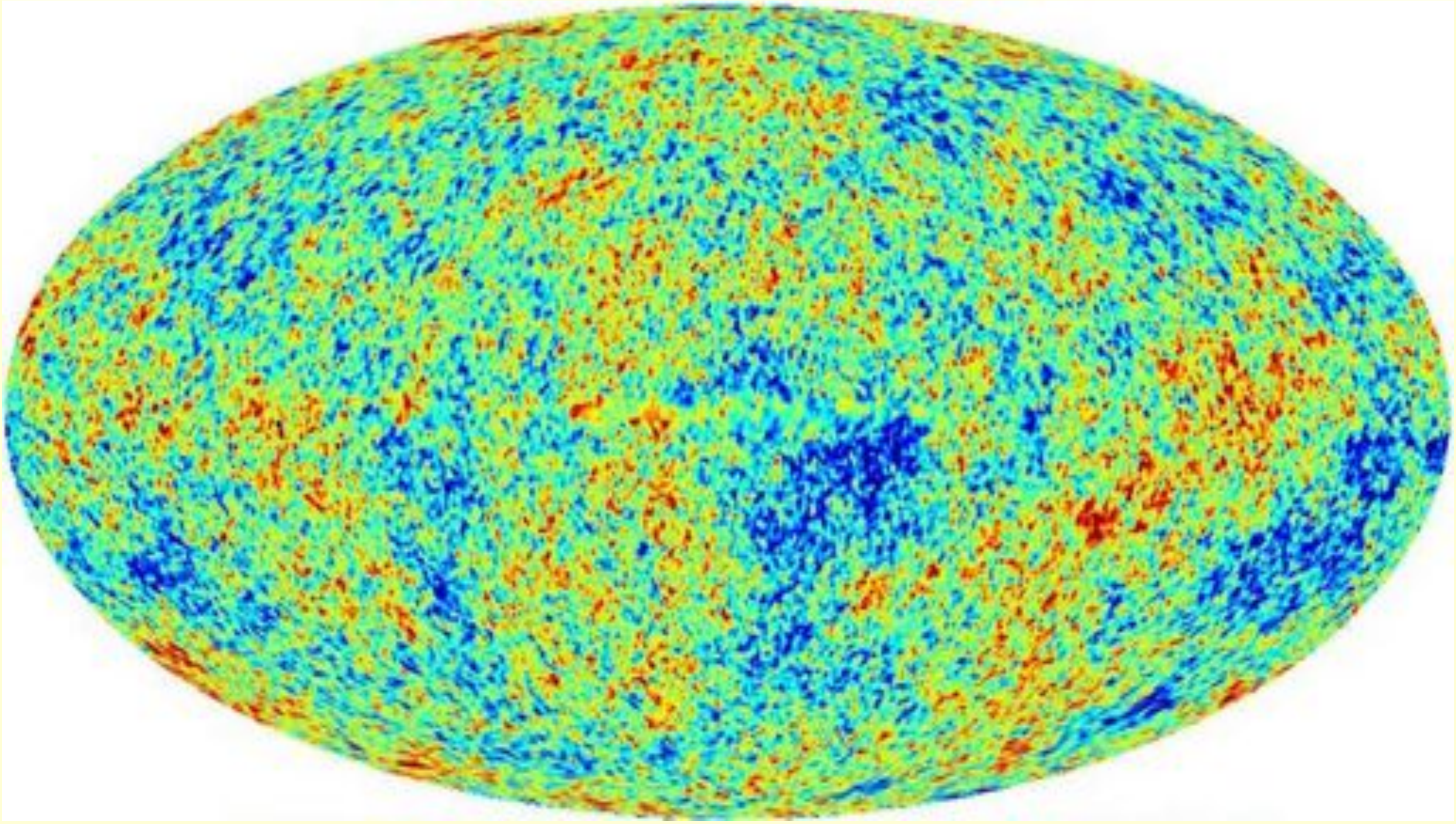
Quantum fluctuations
leave 'ripples' in the universe
when it is very small

These are then amplified by gravity to make structure



How can we test if inflation happened?

– pattern of structure can be predicted, especially in microwave background (redshifted radiation from when universe was in a plasma state at T = 3000 K)

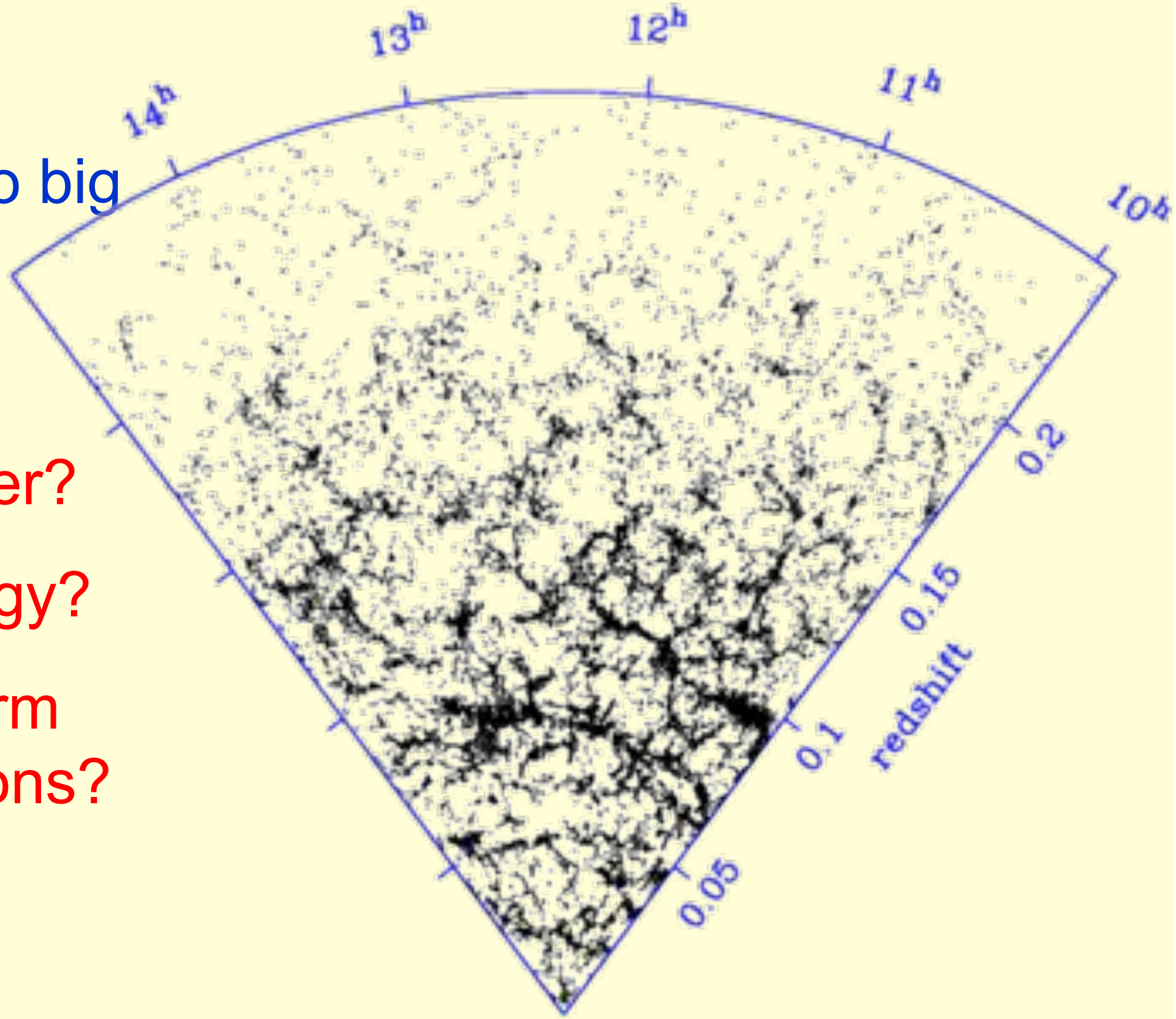


NASA's WMAP (2003)

ESA's PLANCK (2013)

The outlook for cosmology

Huge progress, but also big questions:



- What is the dark matter?
- What is the dark energy?
- Did structure really form from quantum fluctuations?

Suggested reading: Guth 'The inflationary universe' (Vintage)

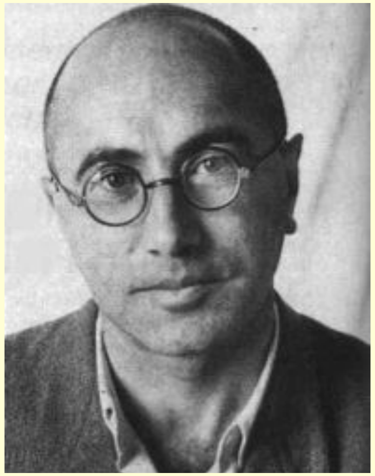
[redacted]

So scalar fields let us understand how the universe started expanding, how it became so big and nearly uniform, but with small fluctuations left to cause galaxies, stars and people

Is that everything?

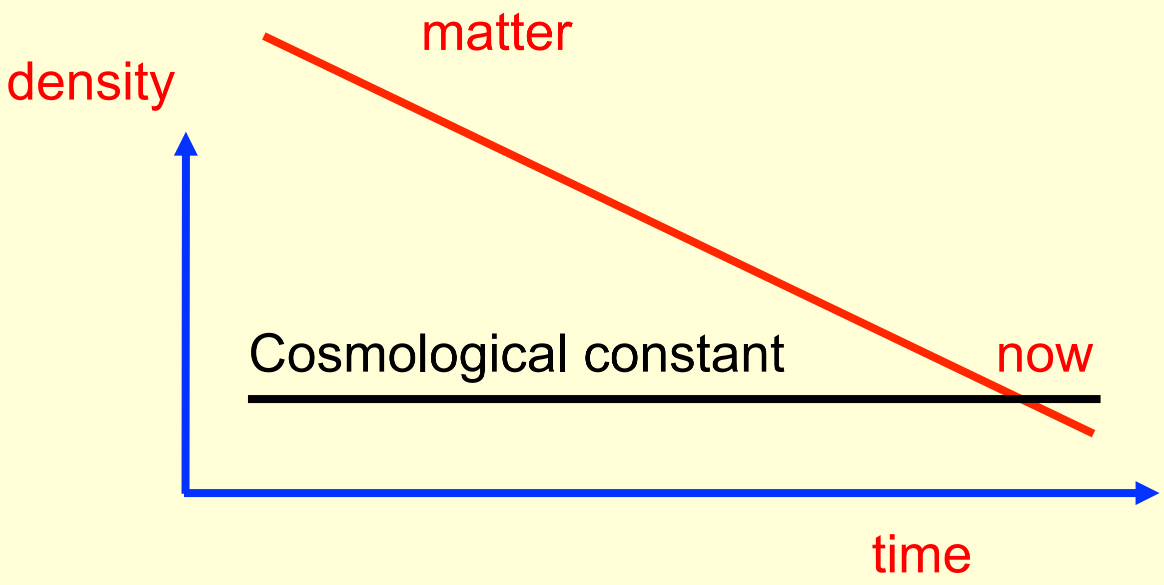
The dark-energy puzzles

$$\rho_{\text{vac}} = \sum_{0}^{E_{\text{max}}} \hbar\omega/2 \sim E_{\text{max}}^4$$



Zeldovich (1967): a cosmological constant vacuum density from zero-point energy.
But E_{max} is apparently 2.4 meV

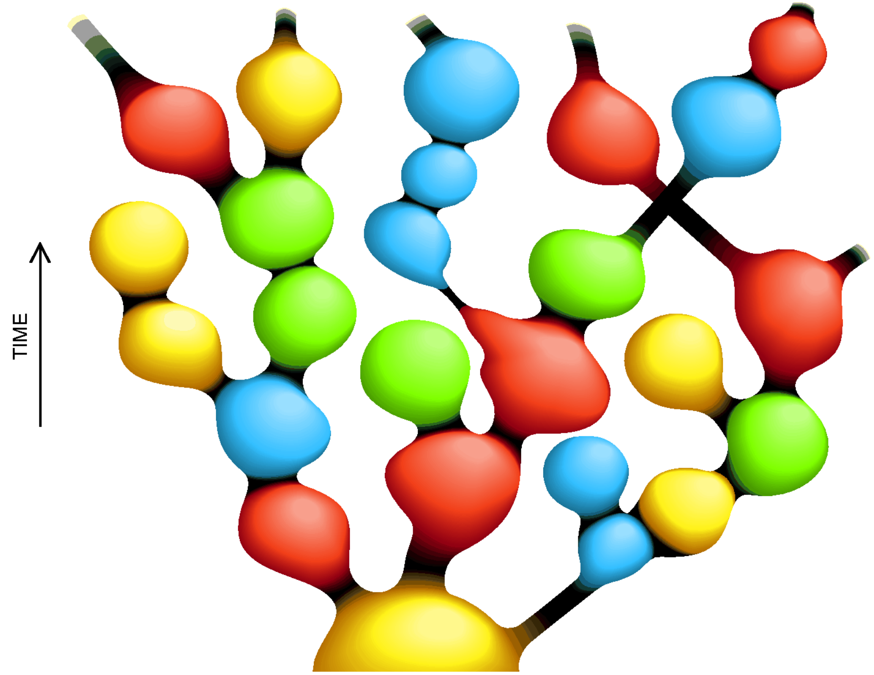
The 'why now' problem:



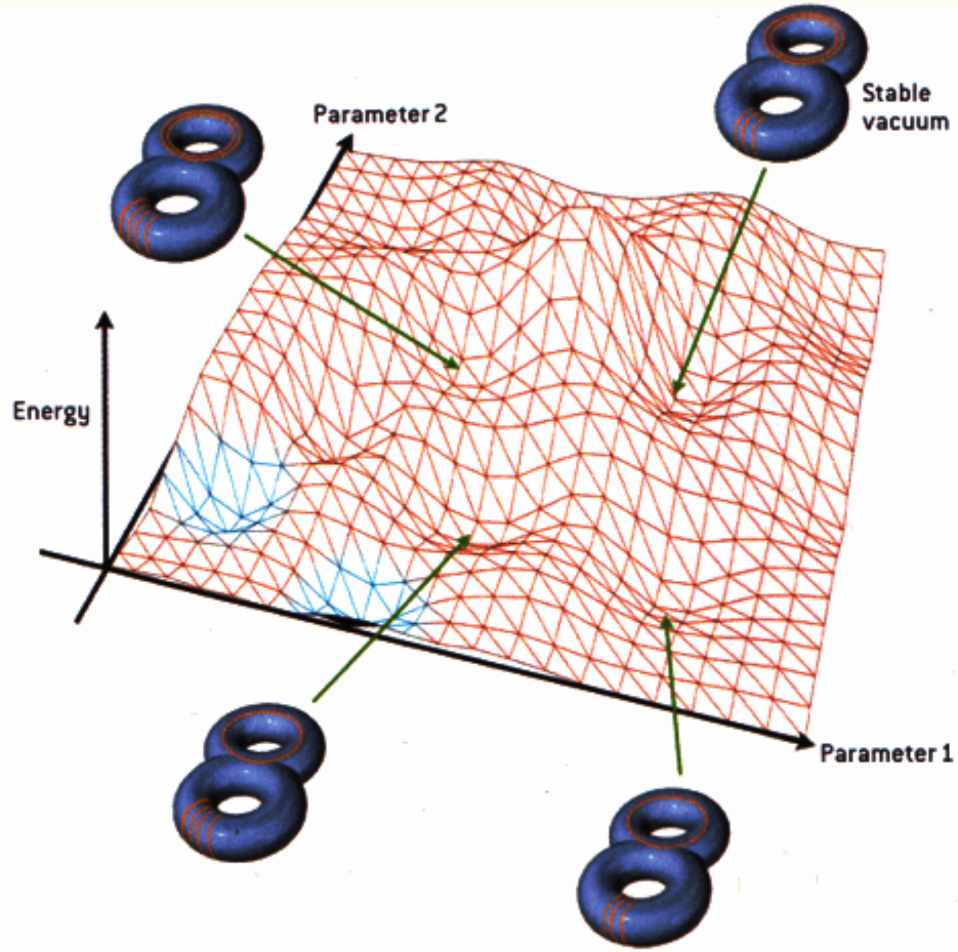
The answer to ‘why now’ must be anthropic

- One-universe anthropic
  - Life (structure) only after matter-radiation equality
  - Not controversial
  - k-essence would do
  - But need to solve classical Λ=0 problem

- Many-universe anthropic
  - Predates landscape, but requires new physics for variable Λ
  - Can we ‘detect’ the ensemble?
  - Sound logic (exoplanets)



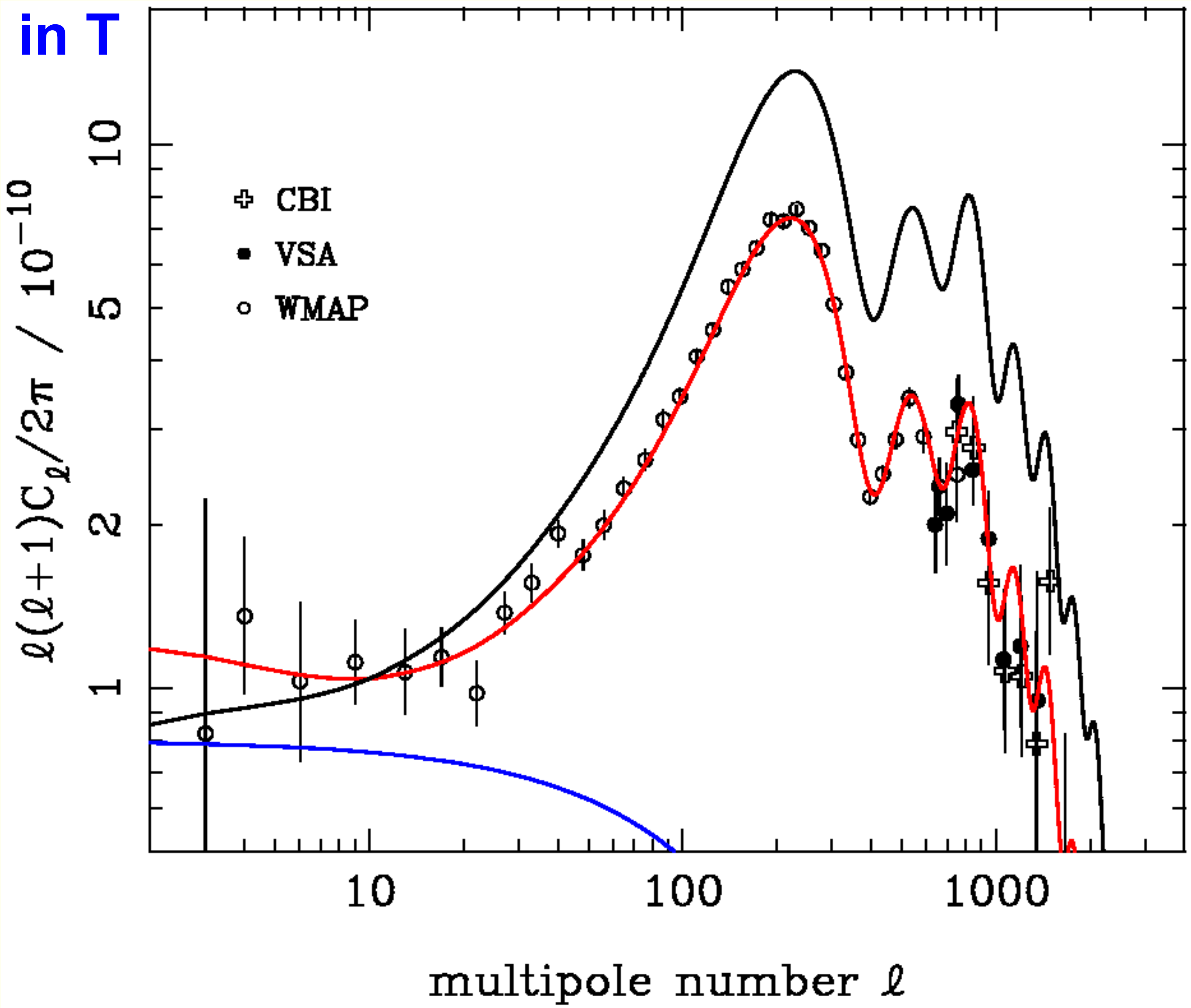
The landscape of string theory



10^{500} different vacuum states. Just what's needed for the anthropic ensemble?

CMB: signatures of inflation

variance in T



(1) Tilt:

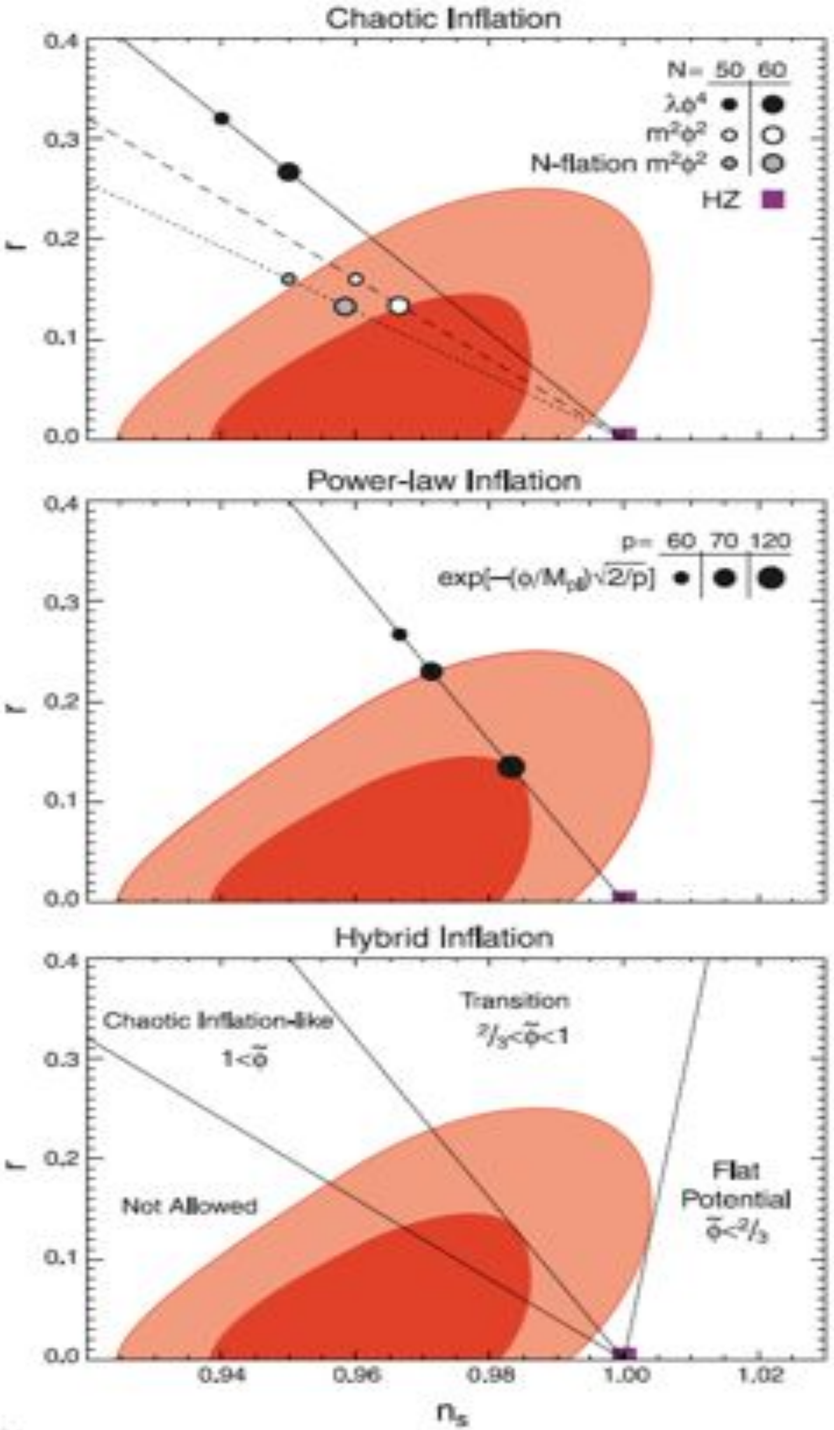
Degenerate with matter content

spectrum / (scale)$^{n-1}$ simple predictions: |n-1| ~ 1%

(2) Tensors:

Primordial gravity waves. Large scales only

now: r = T/S < 0.3
target: r = 10^{-3} – 10^{-5}

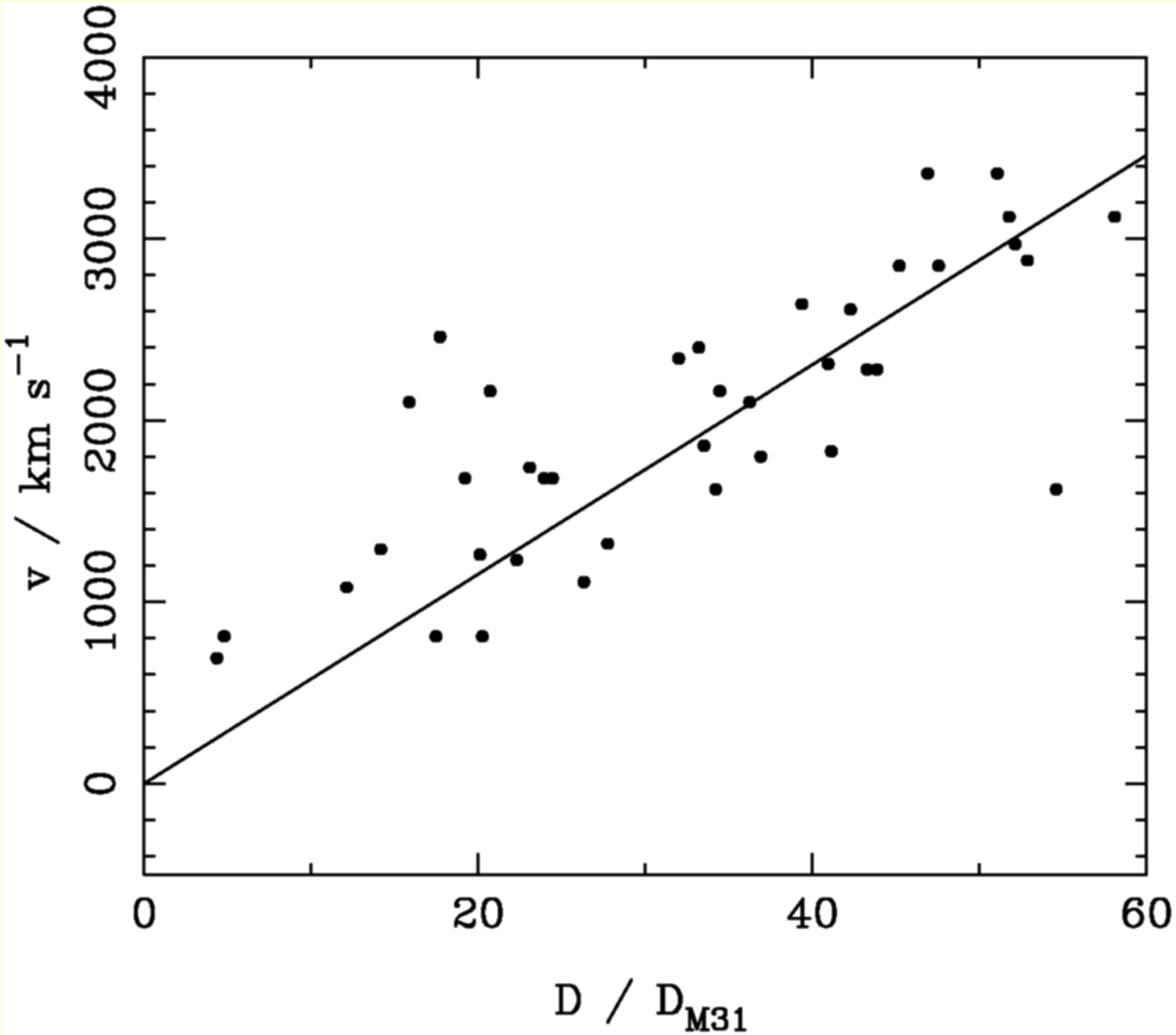


Constraints on inflation

(Komatsu et al. 2008)

Simple scale-invariant n=1 spectrum without relic gravity waves ruled out

Modern data: Supernove standard candles



Need data to 40-50 Mpc to establish a linear relation

2dF on the AAT

The 1929 distance-redshift relation

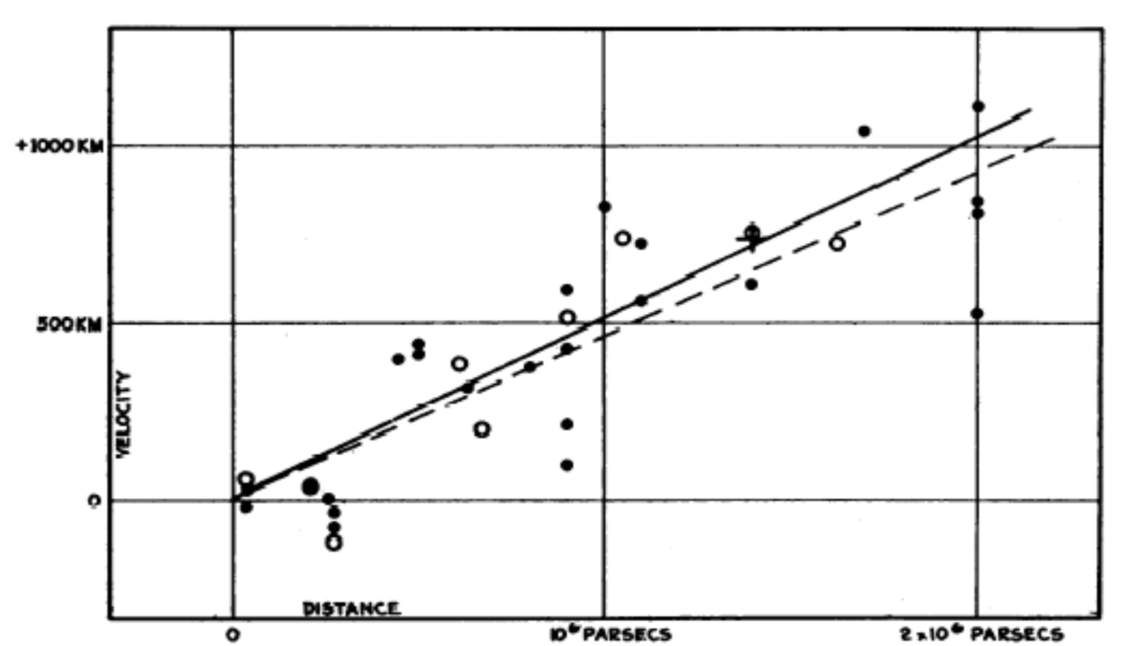


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Linear relation with $V = H D$

- D from apparent brightness of Cepheids
- $H = 513$ km s^{-1} Mpc^{-1} (used Shapley calibration that actually applied to pop II W Virginis variables)
- Who measured the V's?

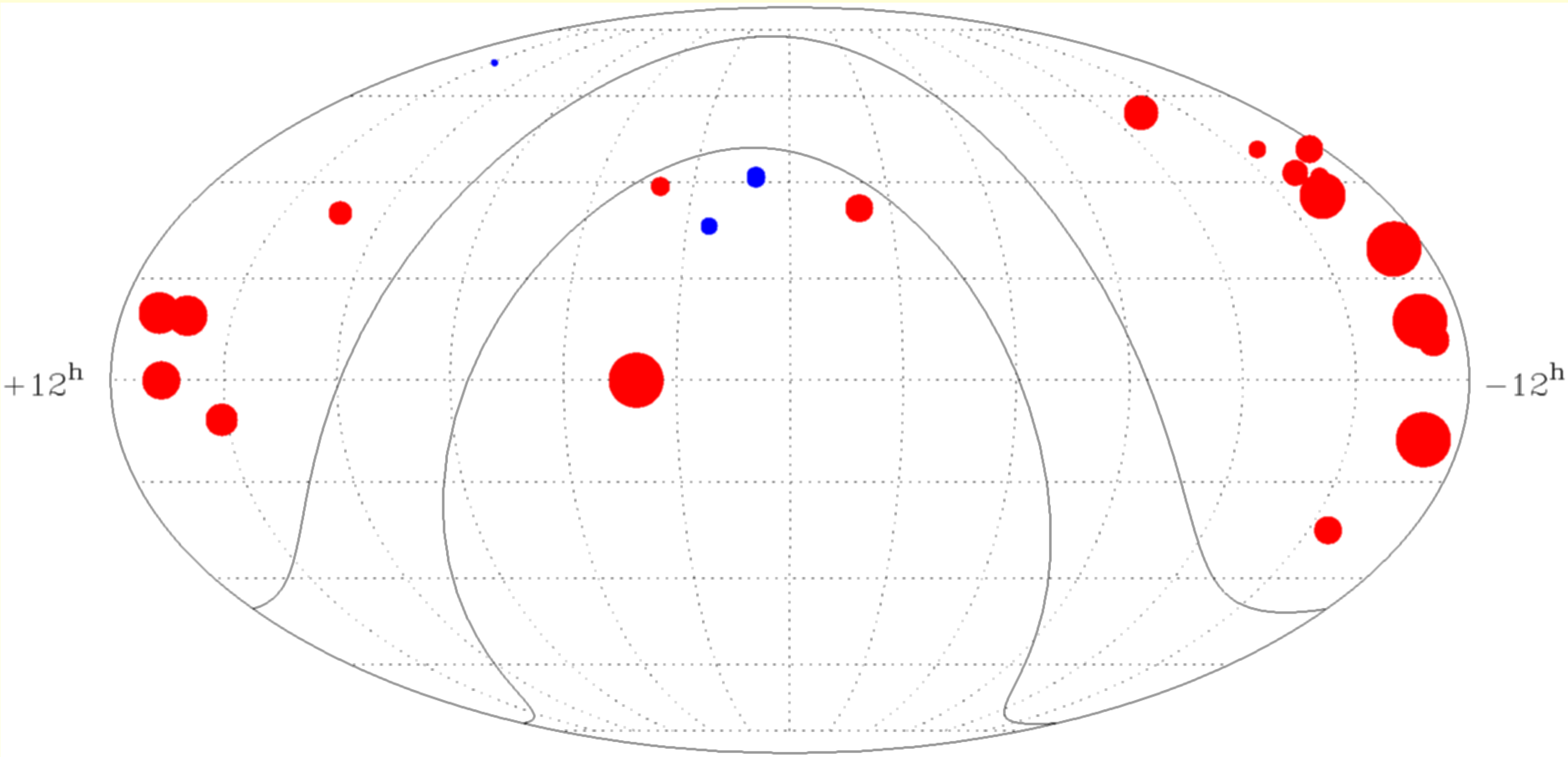
Slipher biography

V.M. Slipher was born on November 11, 1875 on a farm in Mulberry, Indiana.

He was educated first at a high school in Frankfort, Indiana and later at the University of Indiana at Bloomington. Here, he received a bachelors degree in mechanics and astronomy in 1901, a masters degree in 1903, and a PhD in 1909.

He began work at Lowell Observatory in August of 1901.

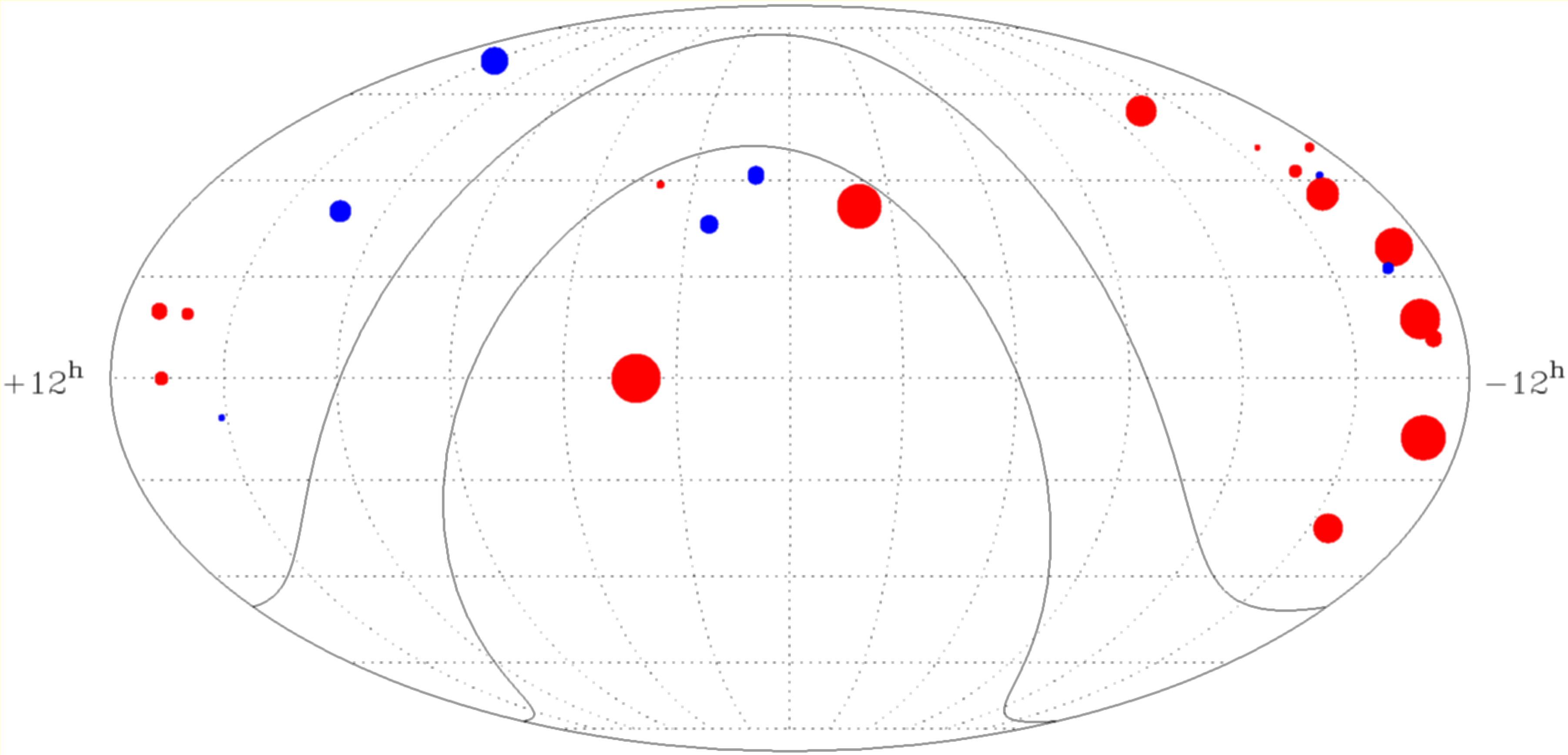
Slipher's 1917 data



-300 to +1100 km s^{-1}

The mean of the velocities with regard to sign is positive, implying the nebulæ are receding with a velocity of nearly 500 km. This might suggest that the spiral nebulæ are scattering but their distribution on the sky is not in accord with this since they are inclined to cluster.

Slipher's 1917 data: dipole corrected



V_{sun} = 700 km s^{-1} towards 22^h -22^o

Reduces <V> from 502 to 143 with rms 400

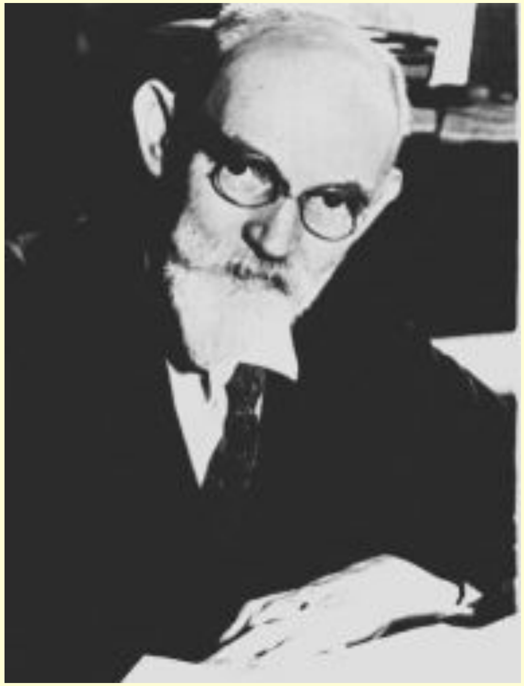
An imaginative leap

> We may in like manner determine our motion relative to the spiral nebulæ, when sufficient material becomes available. A preliminary solution of the material at present available indicates that we are moving in the direction of right-ascension 22 hours and declination —22° with a velocity of about 700 km. While the number of nebulæ is small and their distribution poor this result may still be considered as indicating that we have some such drift through space. For us to have such motion and the stars not show it means that our whole stellar system moves and carries us with it. It has for a long time been suggested that the spiral nebulæ are stellar systems seen at great distances. This is the so-called "island universe" theory, which regards our stellar system and the Milky Way as a great spiral nebula which we see from within. This theory, it seems to me, gains favor in the present observations.

(1) They move; (2) So do we; (3) We are a set of stars

) nebulae are galaxies (7 years before Hubble)

Theorists on the march



Willem de Sitter
(1872-1934)

1917: vacuum dominated relativistic cosmology

Arthur Stanley Eddington
(1882-1944)

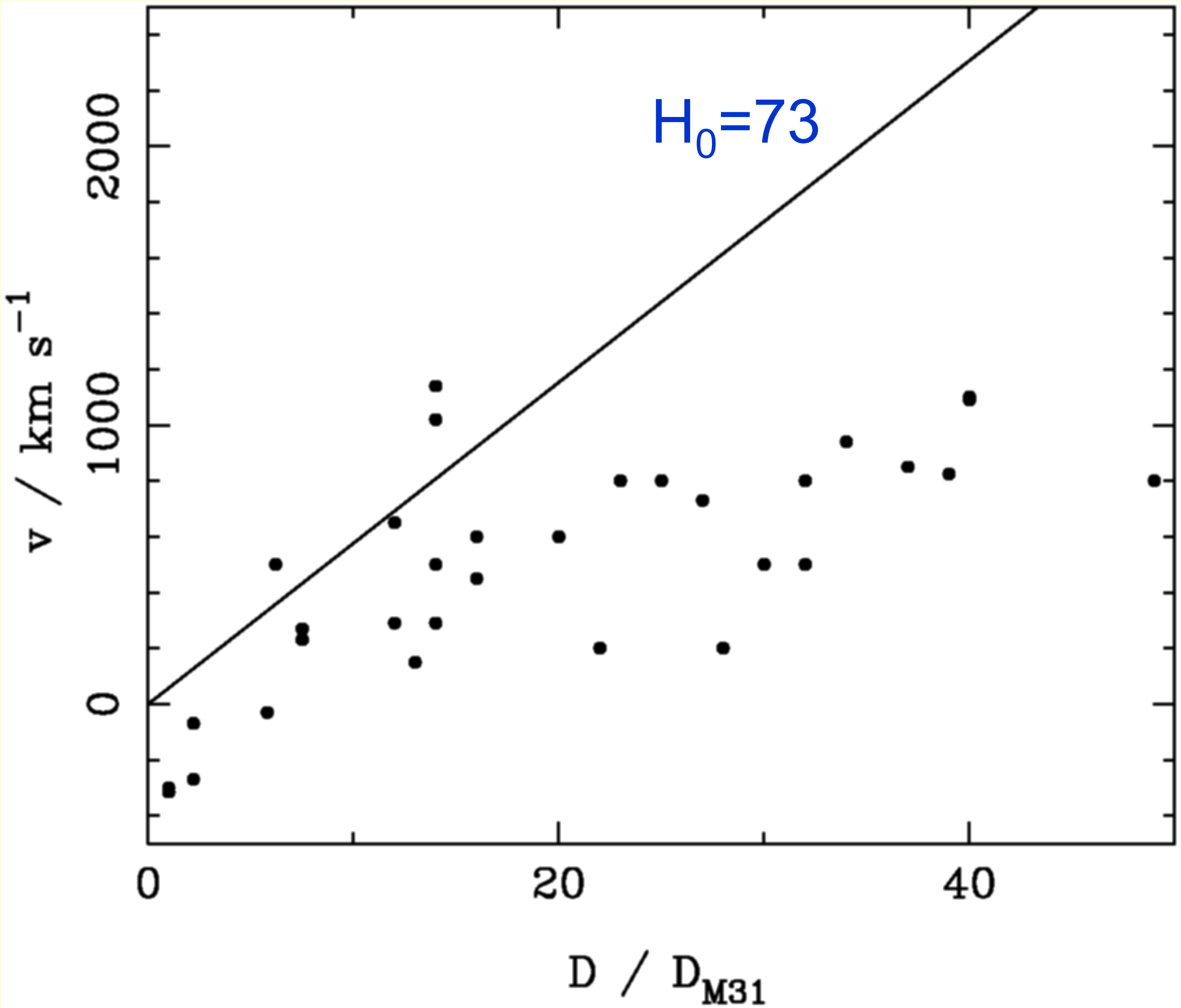
Hermann Weyl
(1885-1955)

1923: expect linear D-z relation

Expansion?

- Not the initial interpretation (this came later: Lemaitre 1927; Robertson 1928, and took into the 1930s to be clarified)
- Just expected distant clocks to run slow - like gravitational time dilation
- Attempts to “measure the curvature of spacetime via the de Sitter effect”. All looking for a linear effect
  - Silberstein 1924
  - Lundmark 1924
  - Wirtz 1924
  - Robertson 1928

Lundmark (1924)

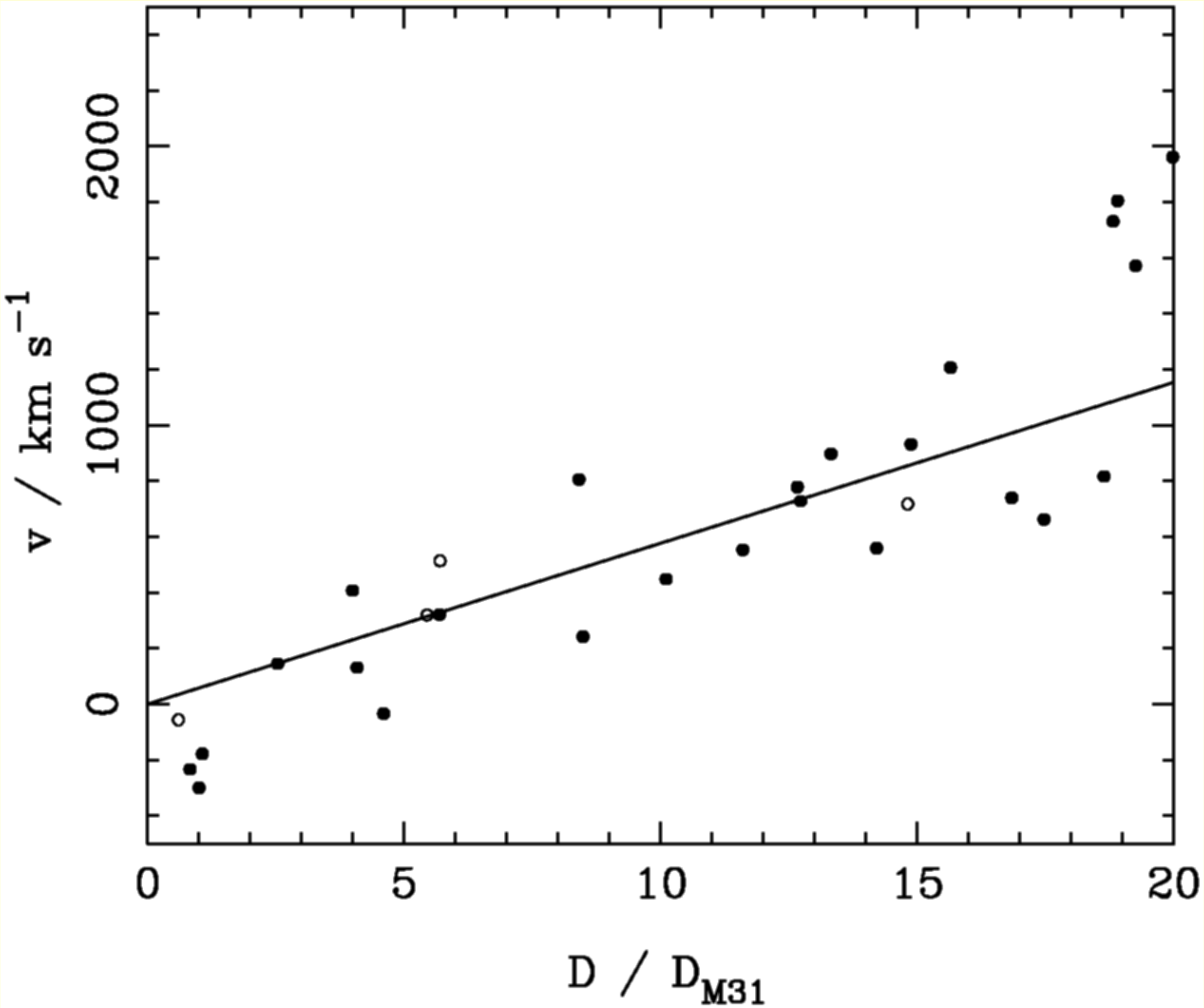


Distances in M31 units from magnitudes and/or diameters (standard candle approach)

− but notes Novae in M31 imply distance about 500 kpc

38/44 redshifted

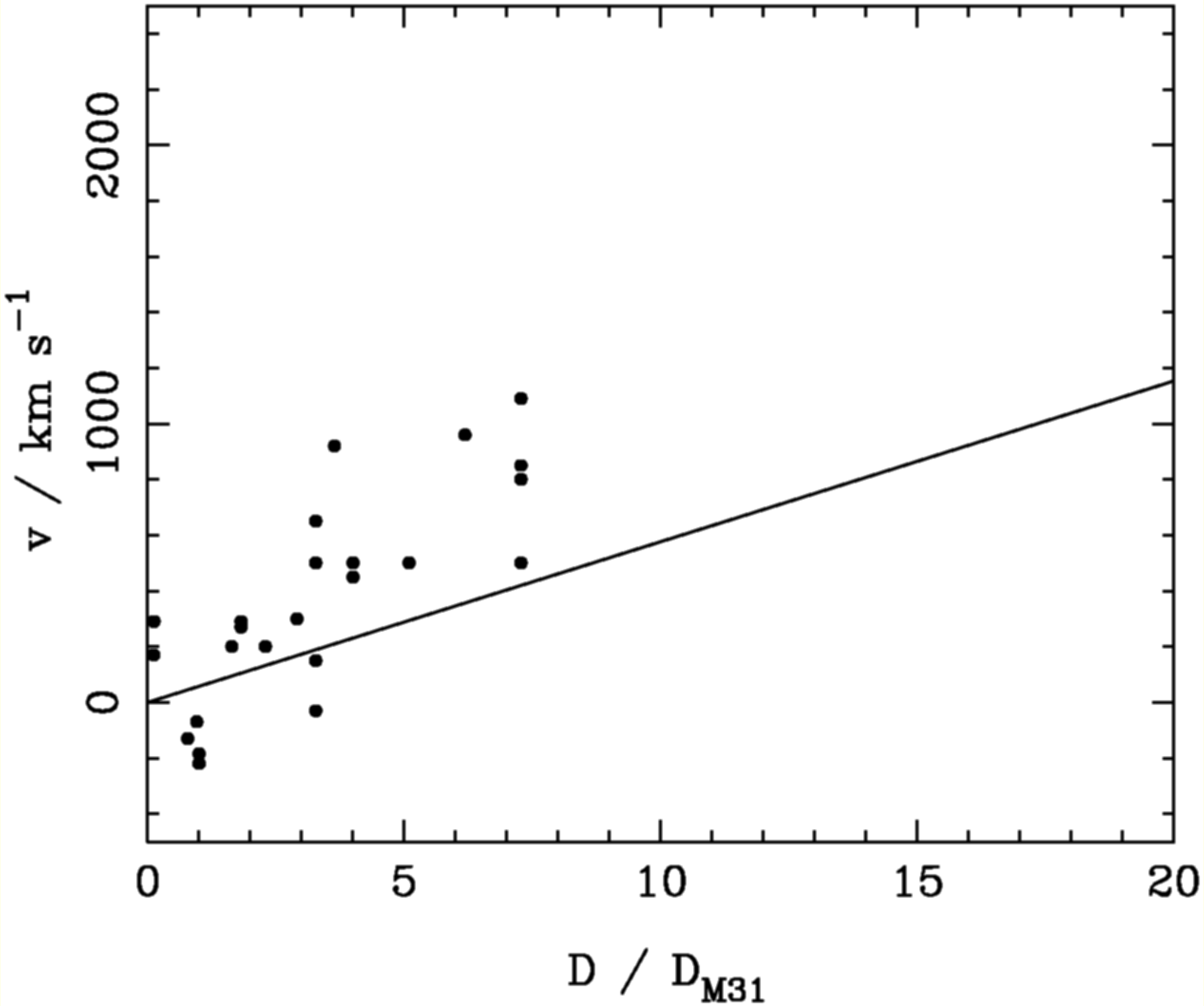
Modern data: HST Cepheid variable standard candles



Local region to 15 Mpc is 'quieter' than average:

Really need data beyond 20 Mpc to prove linear expansion

Hubble's data



Not deep enough

Distances too low in addition to mis-calibration

Hubble plotted data corrected for best solar motion assuming a linear D-z:

$$v = HD + \mathbf{v}_{\odot} \cdot \hat{\mathbf{r}}$$

Hubble not even first

Robertson (1928):

”Comparing the data given by Hubble (1926) concerning the value of r for the spiral nebulae with that of Slipher concerning the corresponding radial velocities, we arrive at a rough verification of the linear relation and a value of R = 2 £ 10^{27} cm”

In modern terms, correct figure for effective curvature radius is

R =1.27 £ 10^{28} cm

Hubble's interpretation

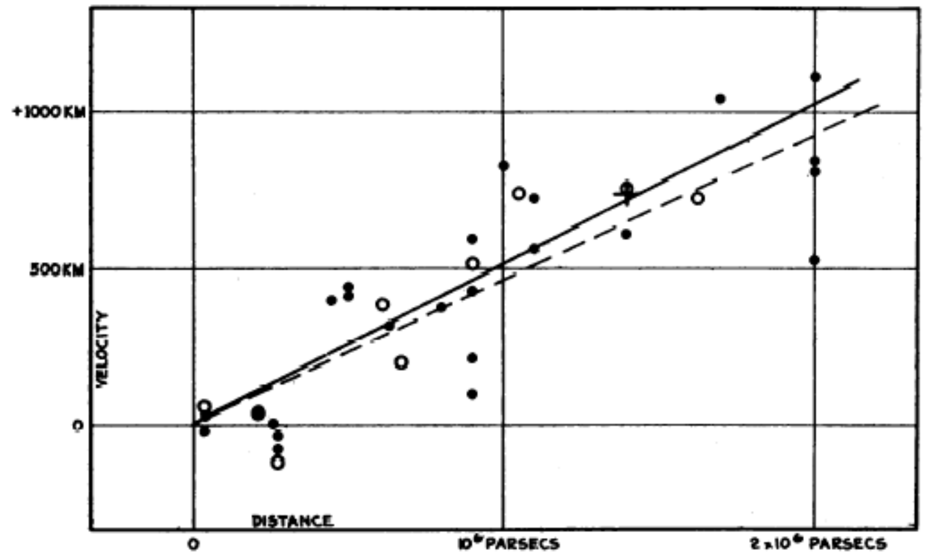


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

"...the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space."

Even to his death in 1953, never publicly endorsed a Doppler interpretation

In short

- Data at the time of Hubble's "discovery" were not deep enough to reveal true expansion
- Hubble's distances were wrong (twice)
- Establishment of Hubble as a hero came from subsequent publicity from theorists like Eddington, who knew that z=r/R had to be right
- Slipher's velocities were right, and he used them with correct physical insight to reach just the justified conclusions a decade before any competition:
  - The non-uniform cosmological velocity field
  - The peculiar motion of the Milky Way
  - Hence other galaxies as moving stellar systems

The Clark 24-inch refractor

$20,000 in 1896 (~$1M in modern terms)

World's largest refractor at time 36 inch

1913: Redshift (not) of M31

LOWELL OBSERVATORY

BULLETIN No. 58

VOL. II — No. 8

THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

1912,	September	17,	Velocity,	—284 km.
	November	15–16,	"	296
	December	3–4,	"	308
	December	29–30–31,	"	—301
		Mean velocity,		—300 km.

Multi-night photo integration (6 hrs+)

The magnitude of this velocity, which is the greatest hitherto observed, raises the question whether the velocity-like displacement might not be due to some other cause, but I believe we have at the present no other interpretation for it. Hence we may conclude that the Andromeda Nebula is approaching the solar system with a velocity of about 300 kilometers per second.

Confident

1917

NEBULÆ.

By V. M. SLIPHER, Ph.D.

(Read April 13, 1917.)

In addition to the planets and comets of our solar system and the countless stars of our stellar system there appear on the sky many cloud-like masses—the nebulæ. These for a long time have been generally regarded as presenting an early stage in the evolution of the stars and of our solar system, and they have been carefully studied and something like 10,000 of them catalogued.

Proc. Amer. Phil. Soc., 56, 403 (1917)

21/25 redshifted

TABLE I.

Radial Velocities of Twenty-five Spiral Nebulæ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

1914: Galaxies rotate

LOWELL OBSERVATORY

BULLETIN No. 62

VOL. II — No. 12

THE DETECTION OF NEBULAR ROTATION

A spectrogram of the Virgo Nebula, N. G. C. 4594, made a year ago showed the nebular lines to be inclined. A second plate was immediately undertaken but failed, through exasperating circumstances, of a sufficient exposure—although it verified as far as it went, the inclination; and I resolved to withhold any announcement until a second satisfactory plate might be obtained. This observation is now available and fully confirms those of a year ago. The inclination of the lines which is analogous to that produced by the diurnal rotation of a planet, is unmistakable and leads one directly to the conclusion that the nebula is rotating about an axis.

1915: A public triumph

SPECTROGRAPHIC OBSERVATIONS OF NEBULAE.

By V. M. Slipher.

During the last two years the spectrographic work at Flagstaff has been devoted largely to nebulae. While the observations were chiefly concerned with the spiral nebulae they also include planetary and extended nebulae and globular star clusters.

Nebular spectra may be broadly divided into two general types (1) bright-line and (2) dark-line. The so-called gaseous nebulae are of the first type; the spiral nebulae of the second type.

In the table is a list of the spiral nebulae observed. As far as possible their velocities are given, although in many cases they are only rough provisional values.

N.G.C.	Velocity	
221	— 300 km	These nebulae are on the south side of the Milky Way.
224 †	— 300	
598	—	
1023	+ 200 roughly	
1068	+ 1100	
7331	+ 300 roughly	
3031	+ small	These are on the north side of the Milky Way
3115	+ 400 roughly	
3627	+ 500	
4565	+ 1000	
4594	+ 1100	
4736	+ 200 roughly	
4826	+ small	
5194	± small	
5866	+ 600	

As far as the data go, the average velocity is 400 km.

August 1914 AAS:

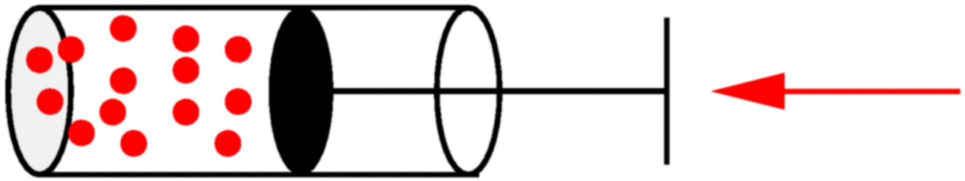
11/15 redshifted

Standing ovation

Popular Astronomy, 23, 21 (1915)

The Hot Big Bang

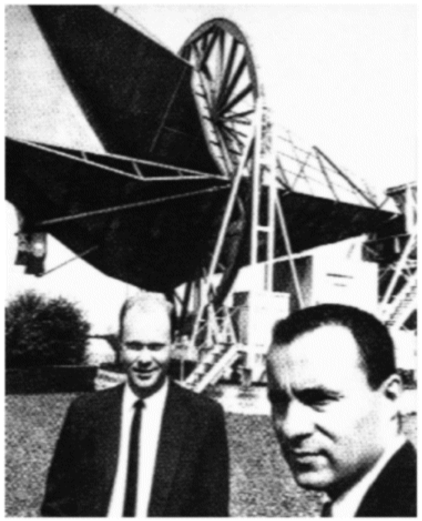
The universe was hot in the past



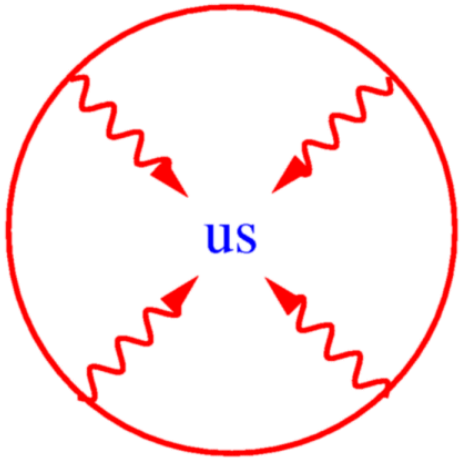
100,000 years: 1000 degrees — ionized plasma

3 minutes: 10^{10} degrees — nuclear reactions

See this in the microwave background



Robert Wilson & Arno Penzias
with Bell Labs antenna (1965)



Last scattering at 1000 degrees

redshifted to **2.7 degrees** above absolute zero

Observing fluctuations from the early universe:

Furthest back we can see is the microwave background ($z = 1100$)

The Microwave Sky from NASA's COBE COsmic Background Explorer (1992)

- The sky temperature with range from 0 - 4 Kelvin
- Microwave background is very uniform at nearly 2.73 Kelvin

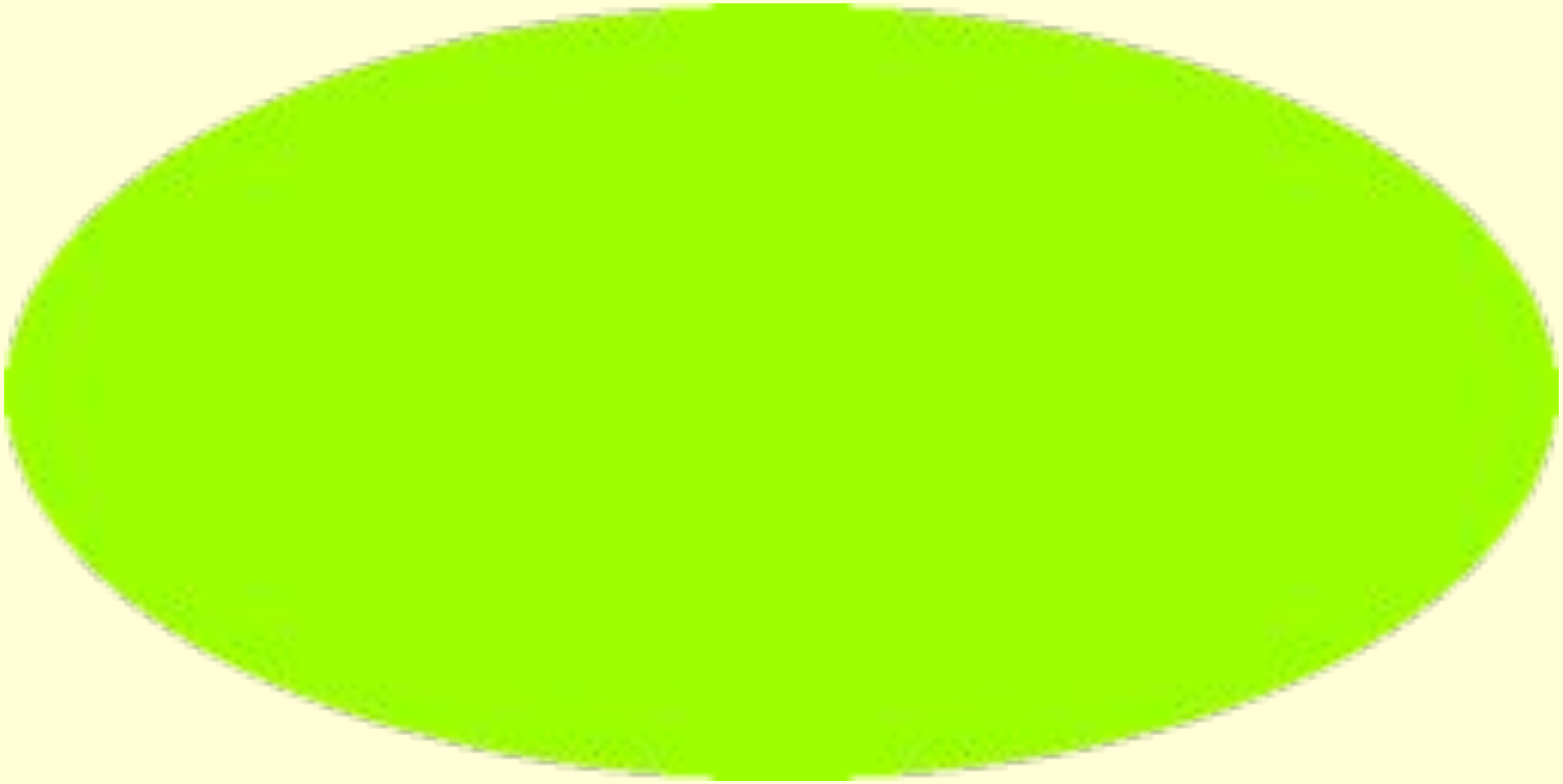


Image courtesy COBE homepage.

COBE microwave sky: 25,000 X stretch

The sky temperature ranging from 2.7279 to 2.7281 Kelvin

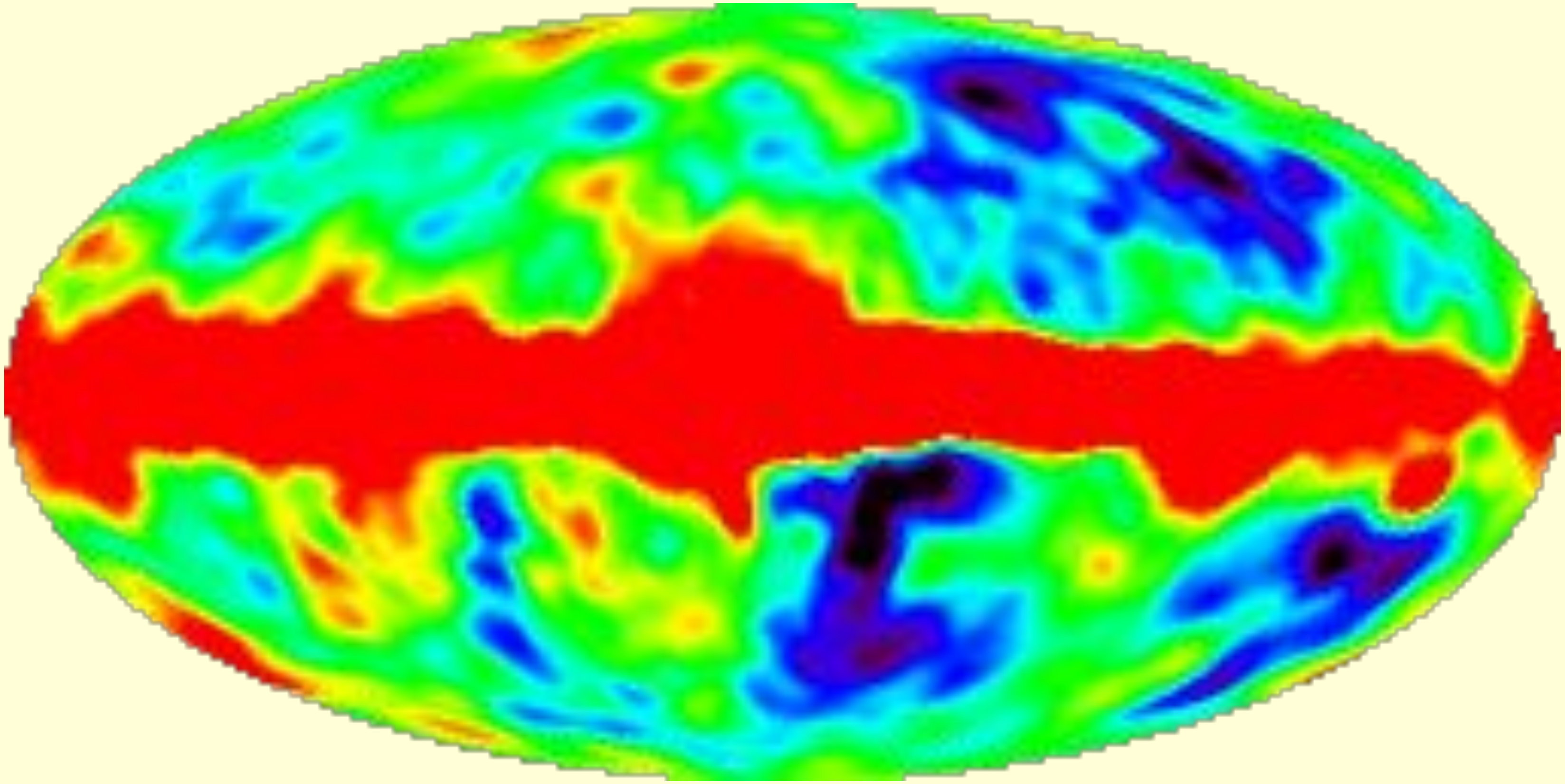
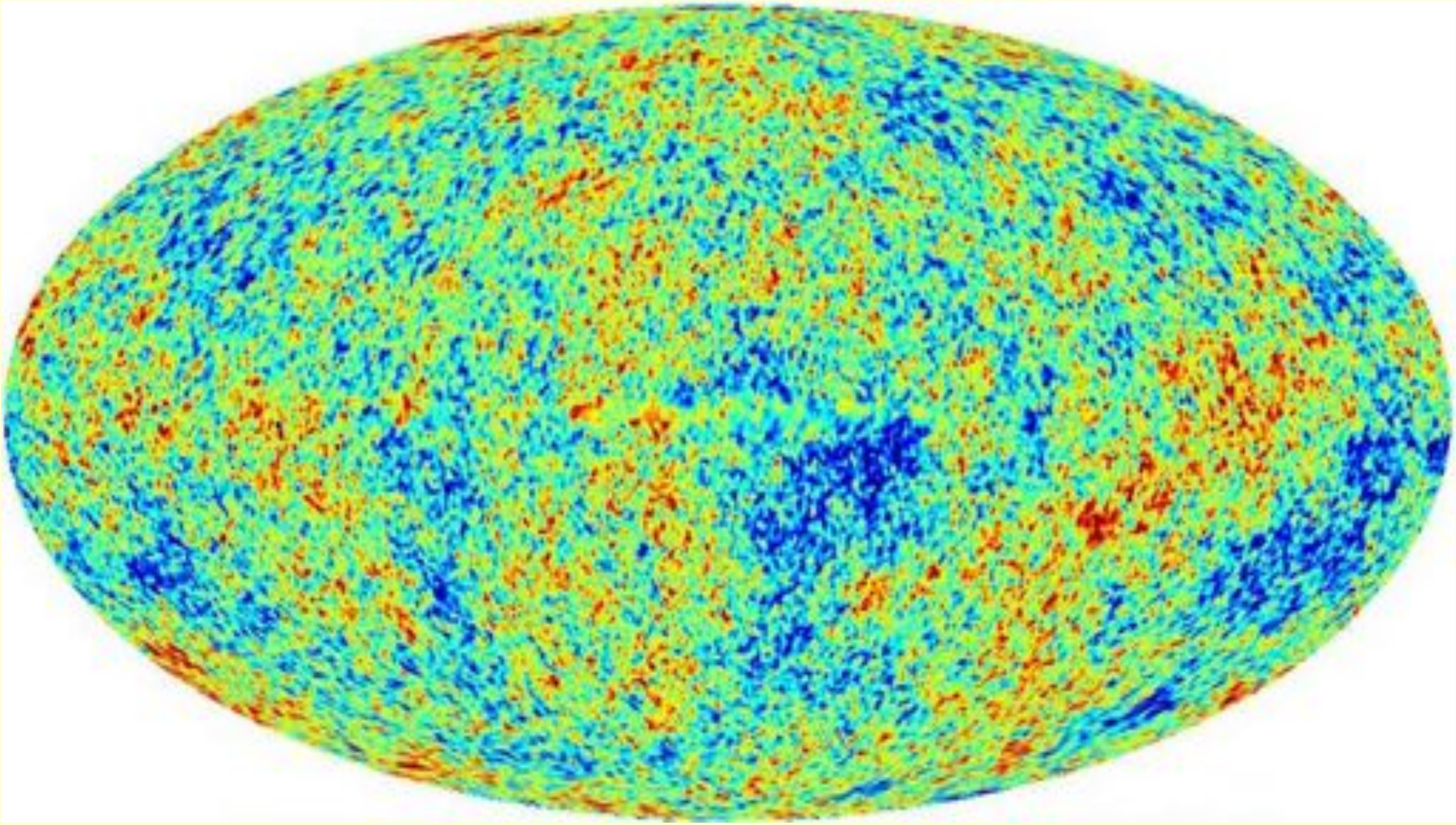


Image courtesy COBE homepage.

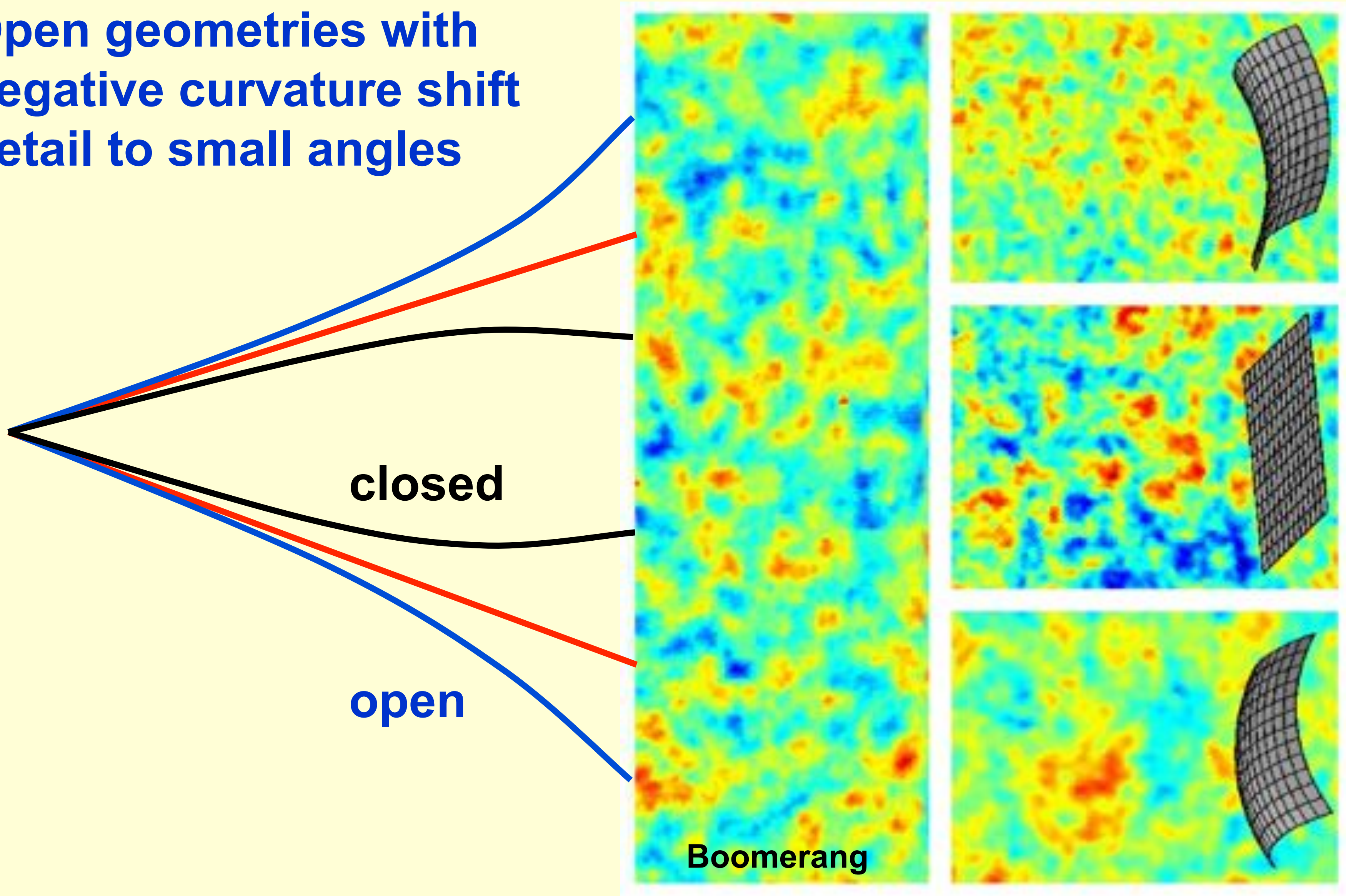
WMAP 2003: The full picture
(Milky Way subtracted)

Superclusters waiting to be born

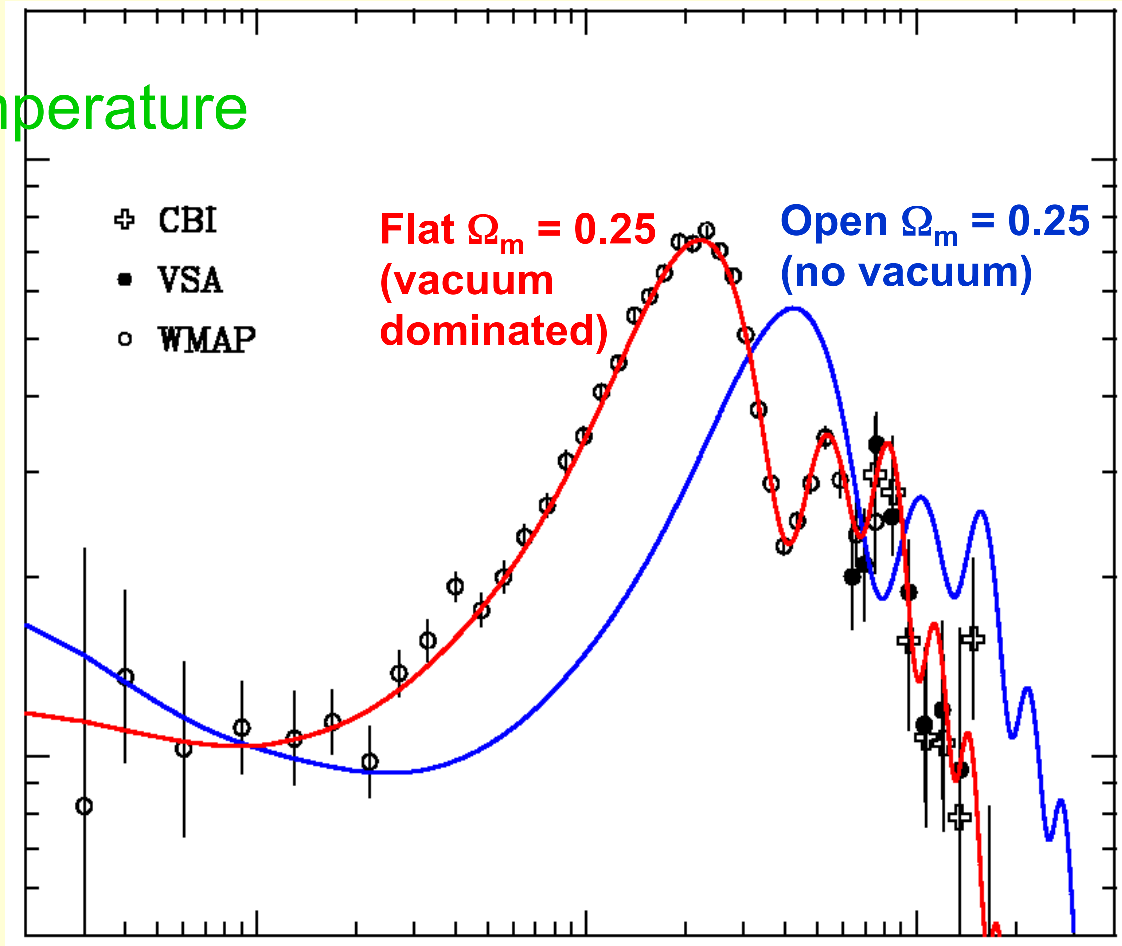


CMB and cosmic geometry

Open geometries with negative curvature shift detail to small angles



The amazing conclusion: a flat universe



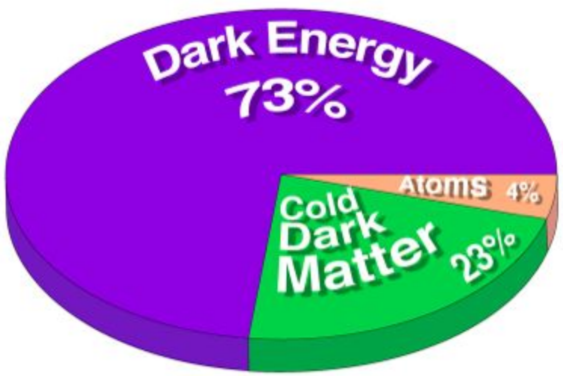
Need a vacuum-dominated universe:

Ω_{matter} = 0.25

Ω_{vacuum} = 0.75

Einstein was right in the end

The cosmic puzzle



Why so many constituents
at similar level?

Vacuum energy:
why now?