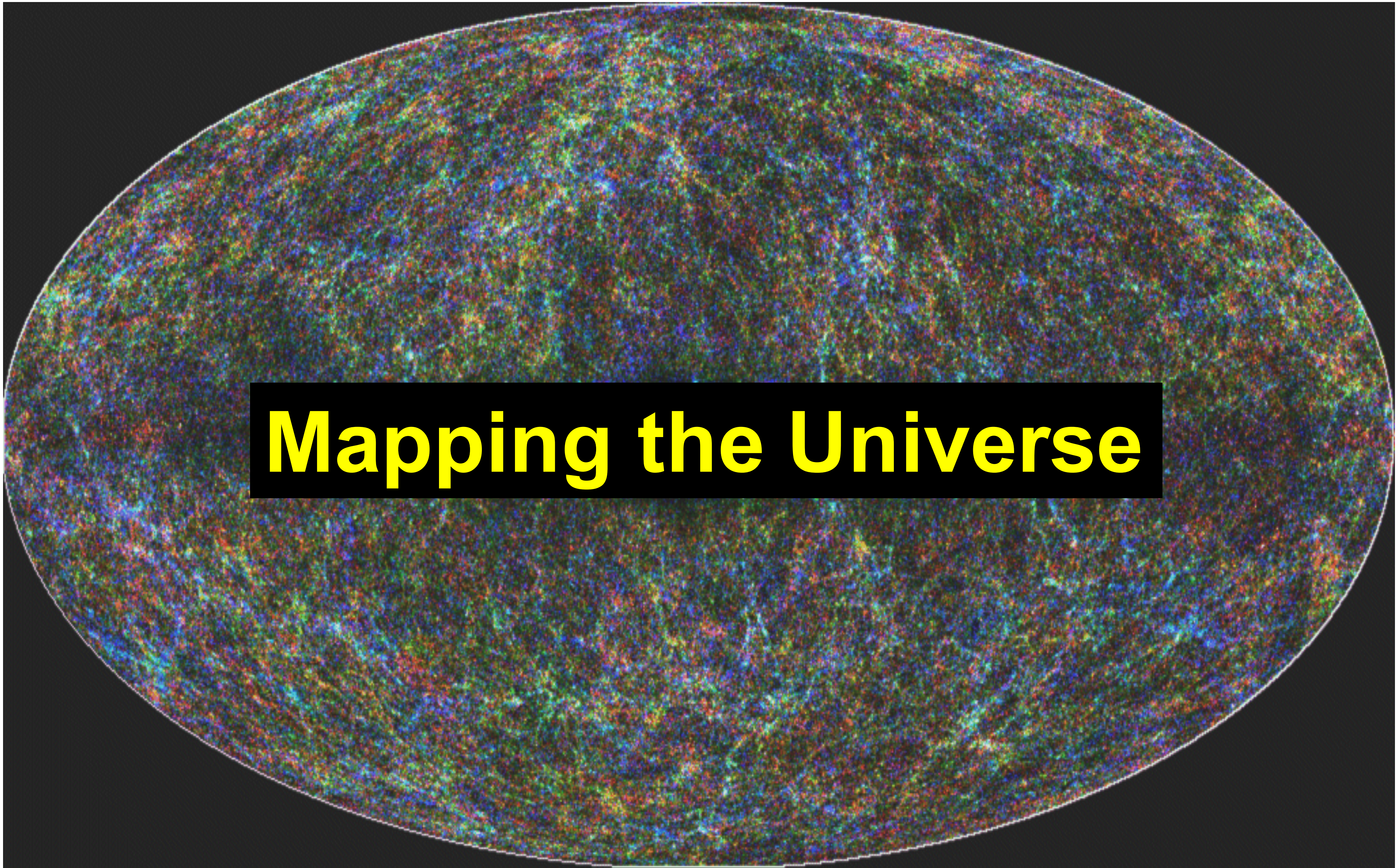
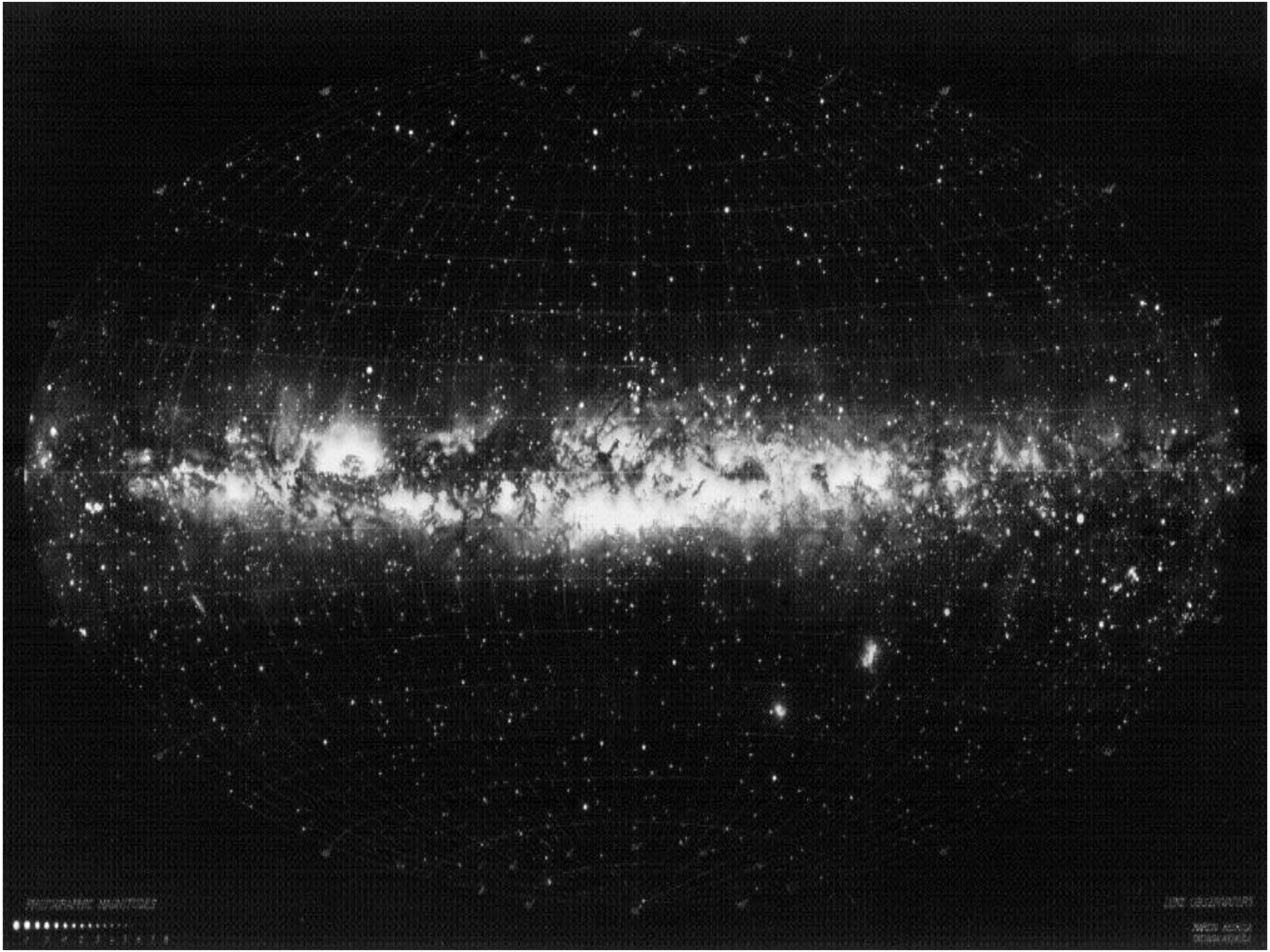


Mapping the Universe

John Peacock, University of Edinburgh

Portsmouth, 14 June 2010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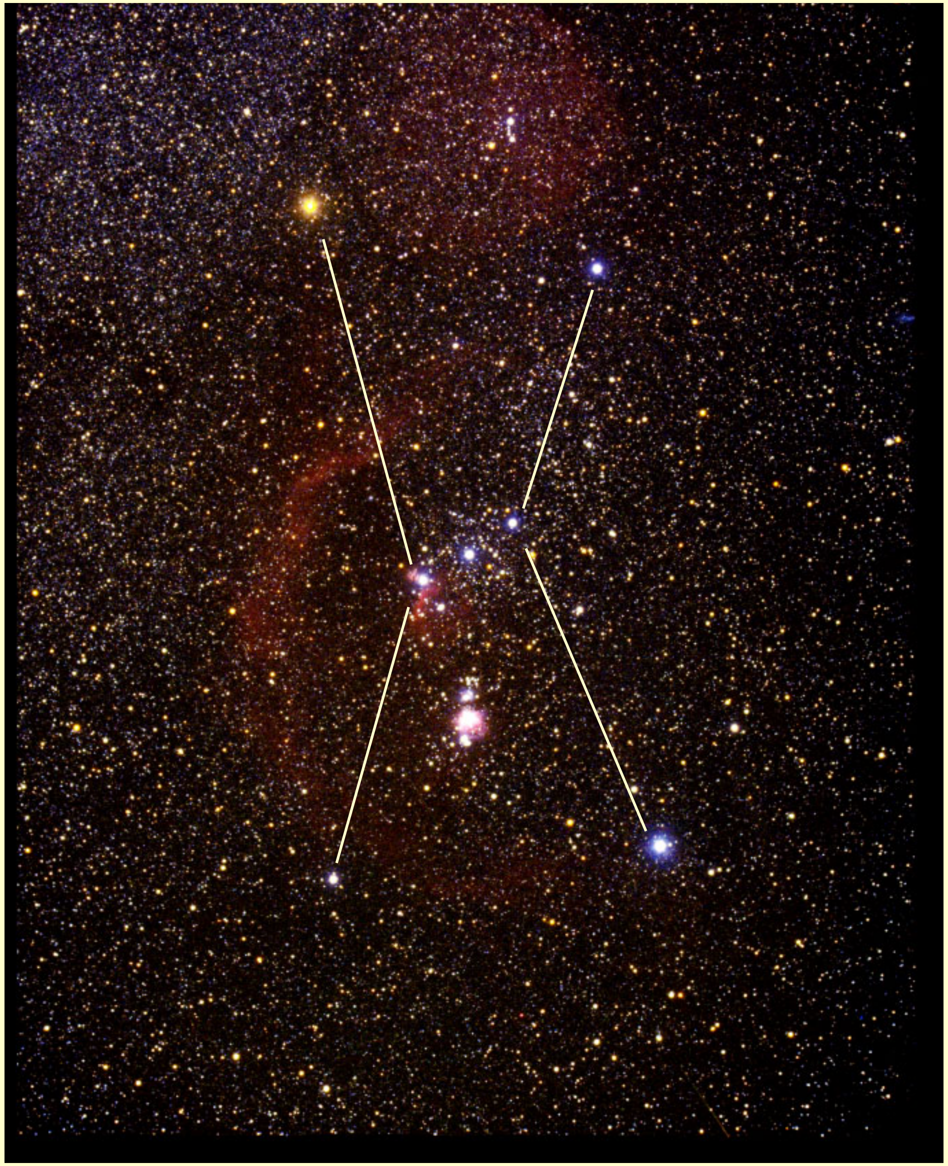
Bishop John Leslie (1578)

Nebulae

Orion

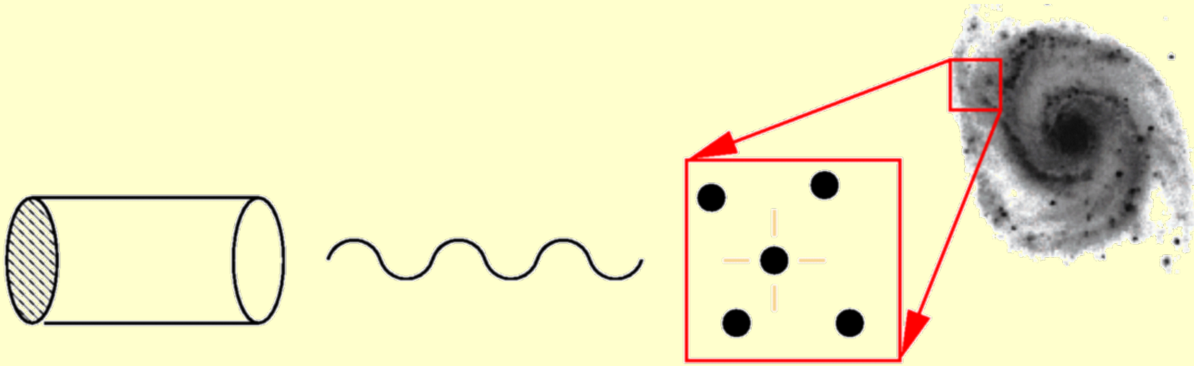


Andromeda

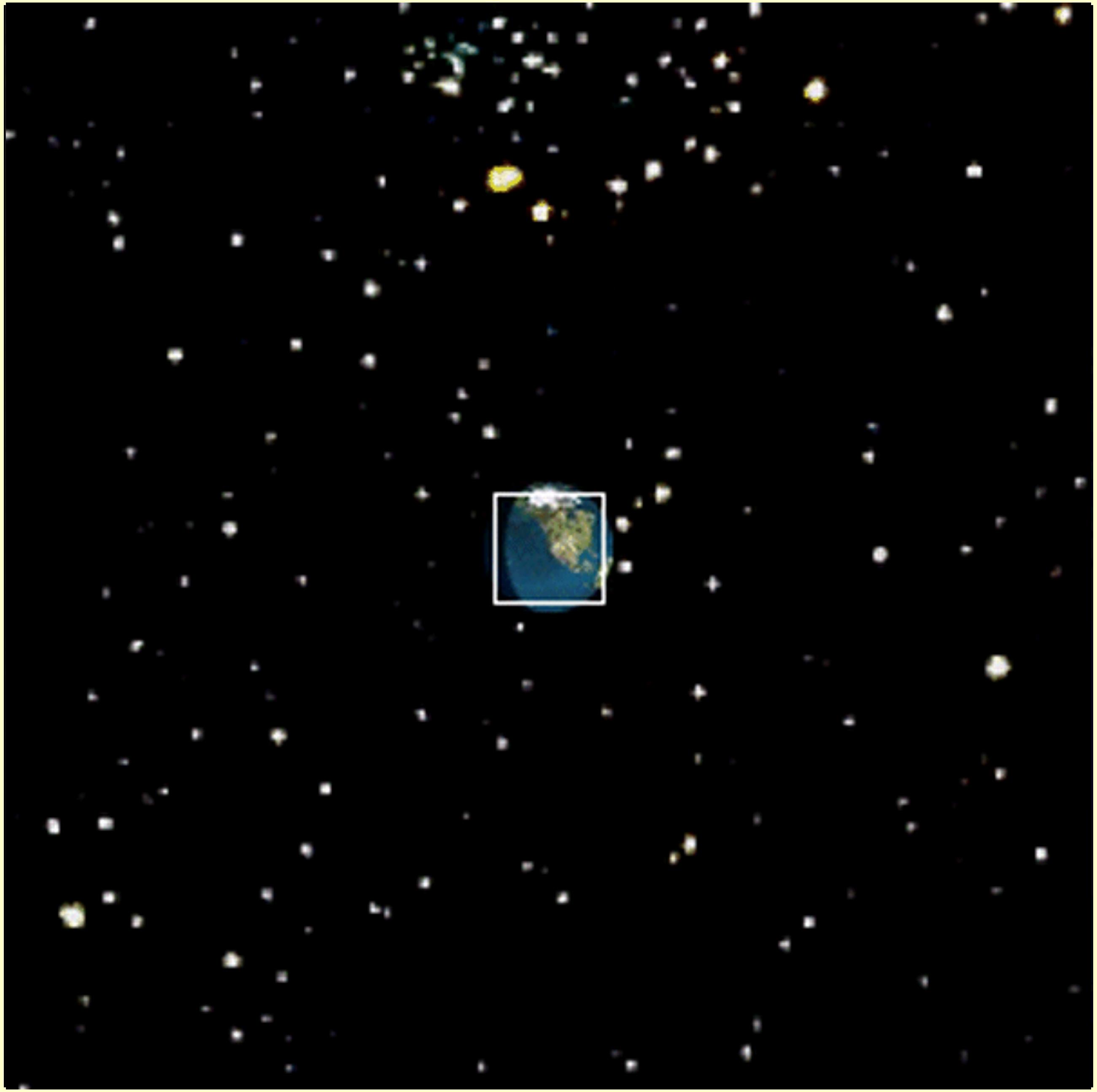
The Great Debate

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

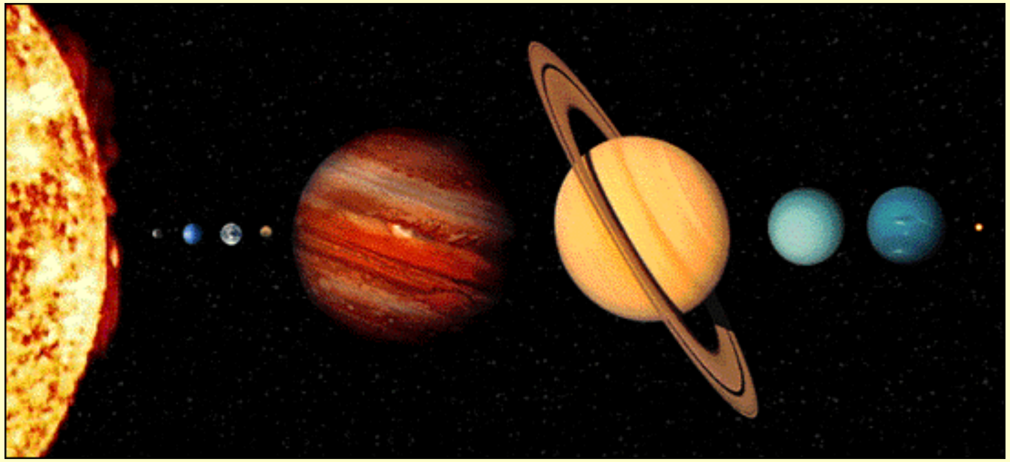
1924: Hubble solves the problem by finding Cepheid variable stars in M31



1 galaxy = 100 billion stars



Cosmic distances

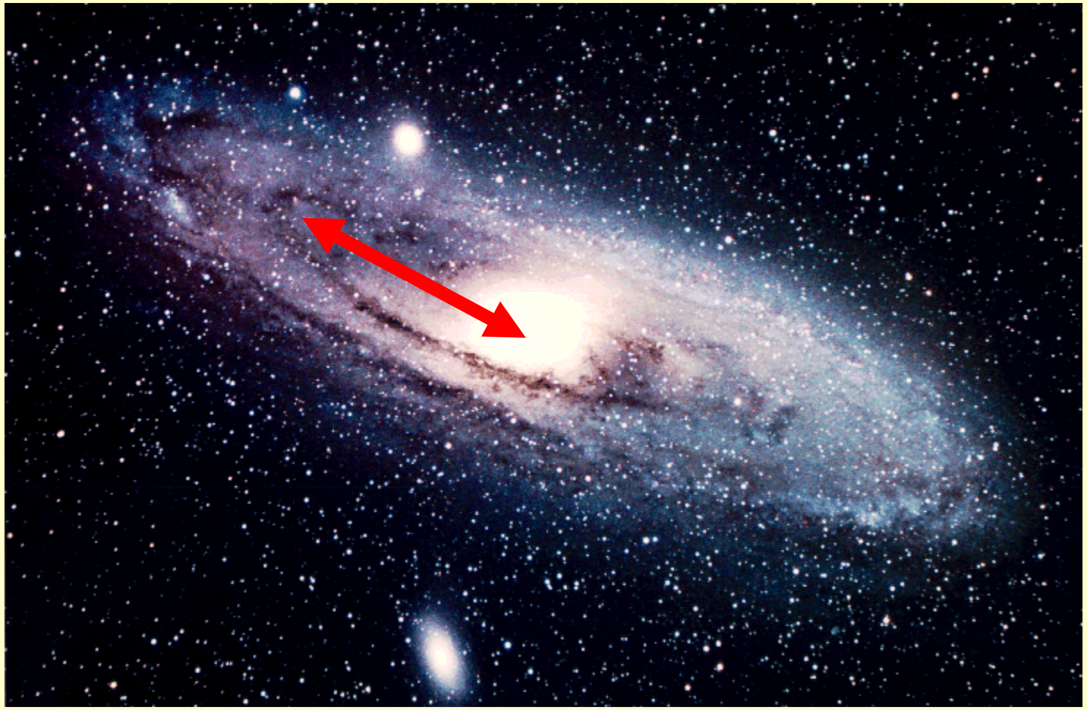


Earth - Sun = 150 million km
= 8 light minutes

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 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

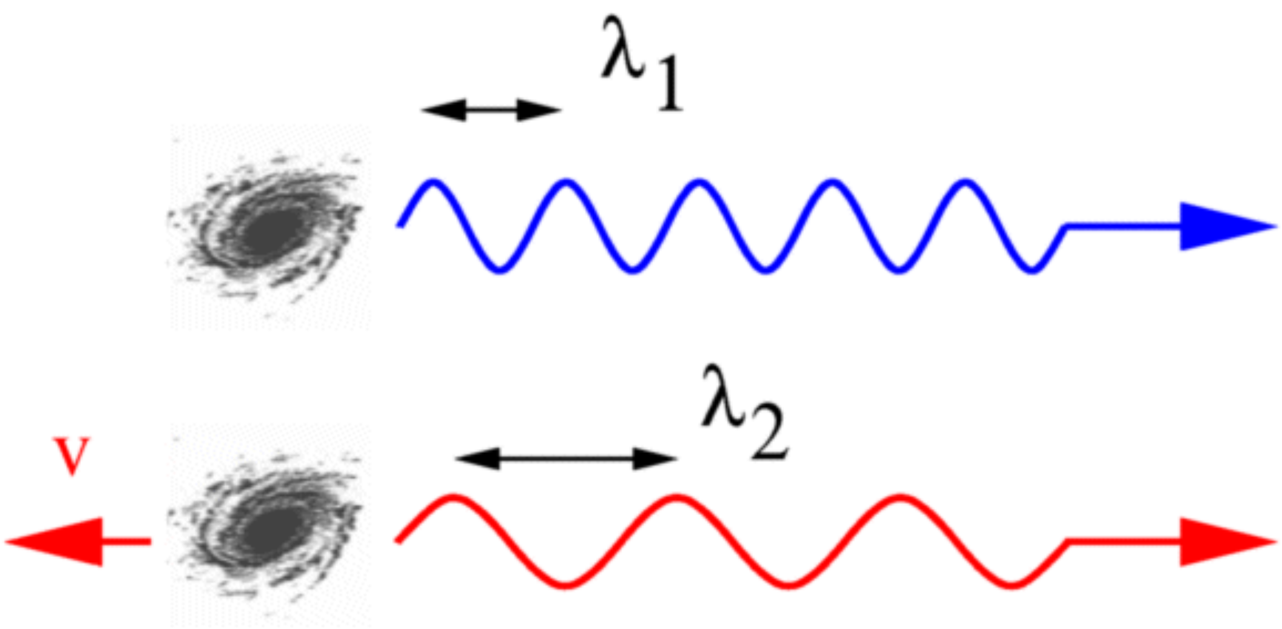
Reaches magnitude 28+

- about 1 billion times fainter than the human eye

100 billion galaxies over the whole sky

The expanding universe

1912 - 1920s: Slipher finds most galaxies are redshifted

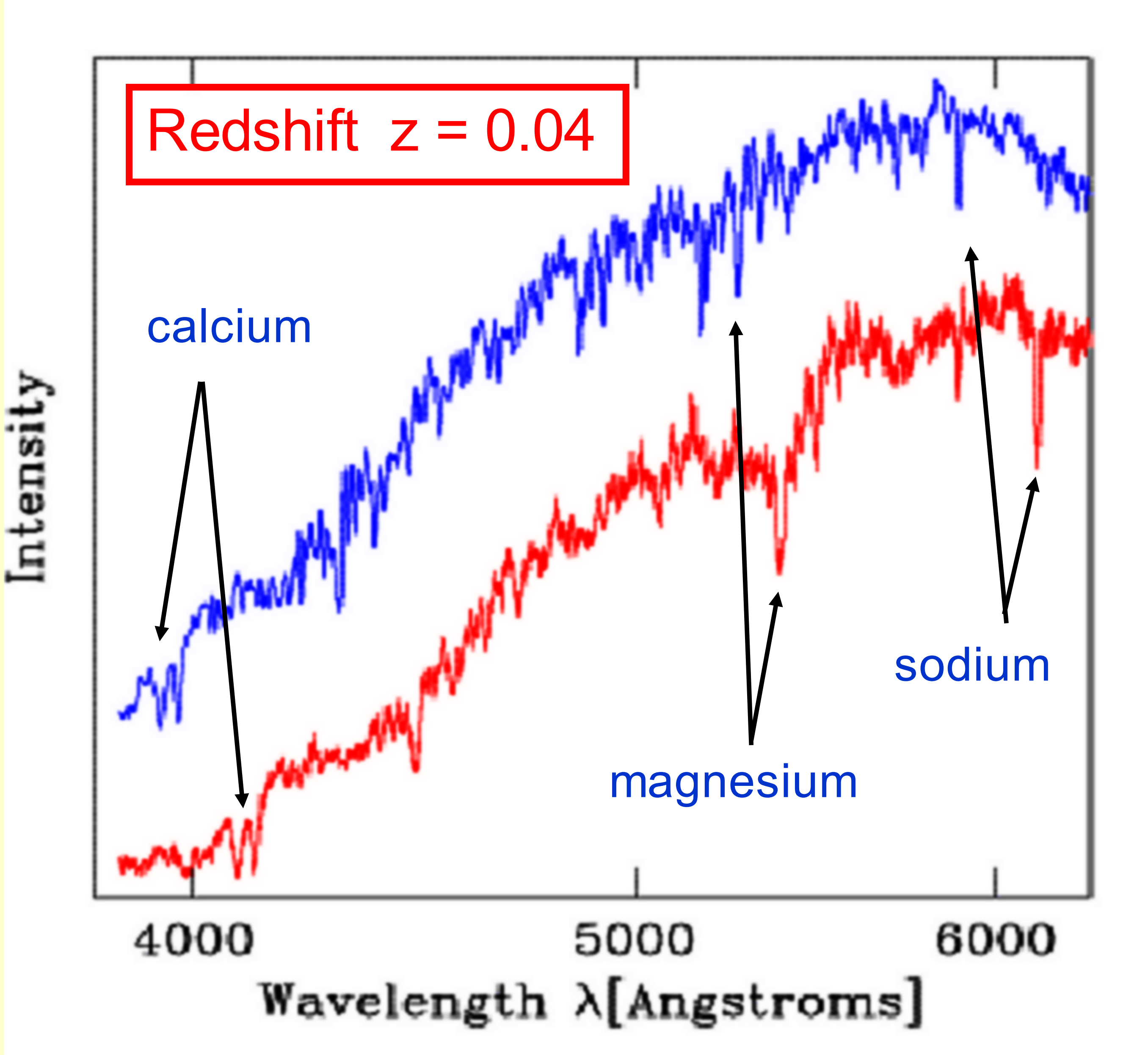


Vesto Slipher (1875 - 1969)

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

The Doppler (red)shift

Measuring redshifts



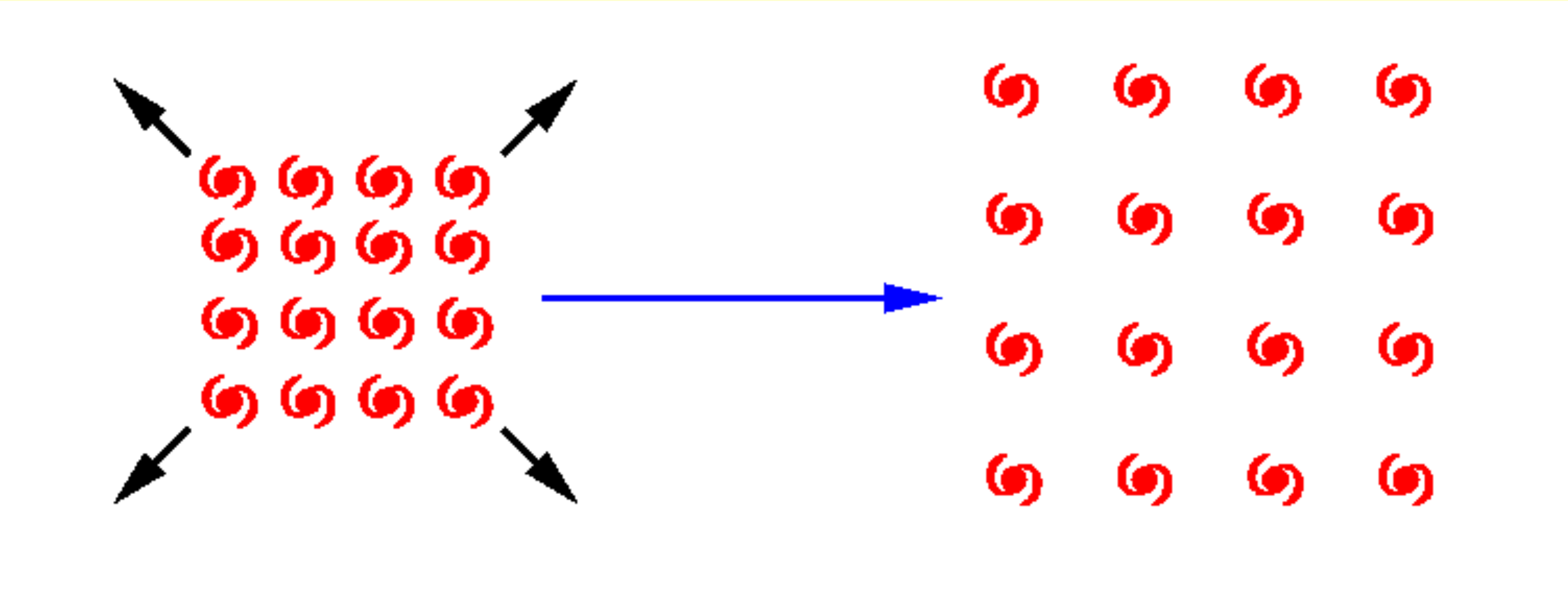
Spectroscopy:

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

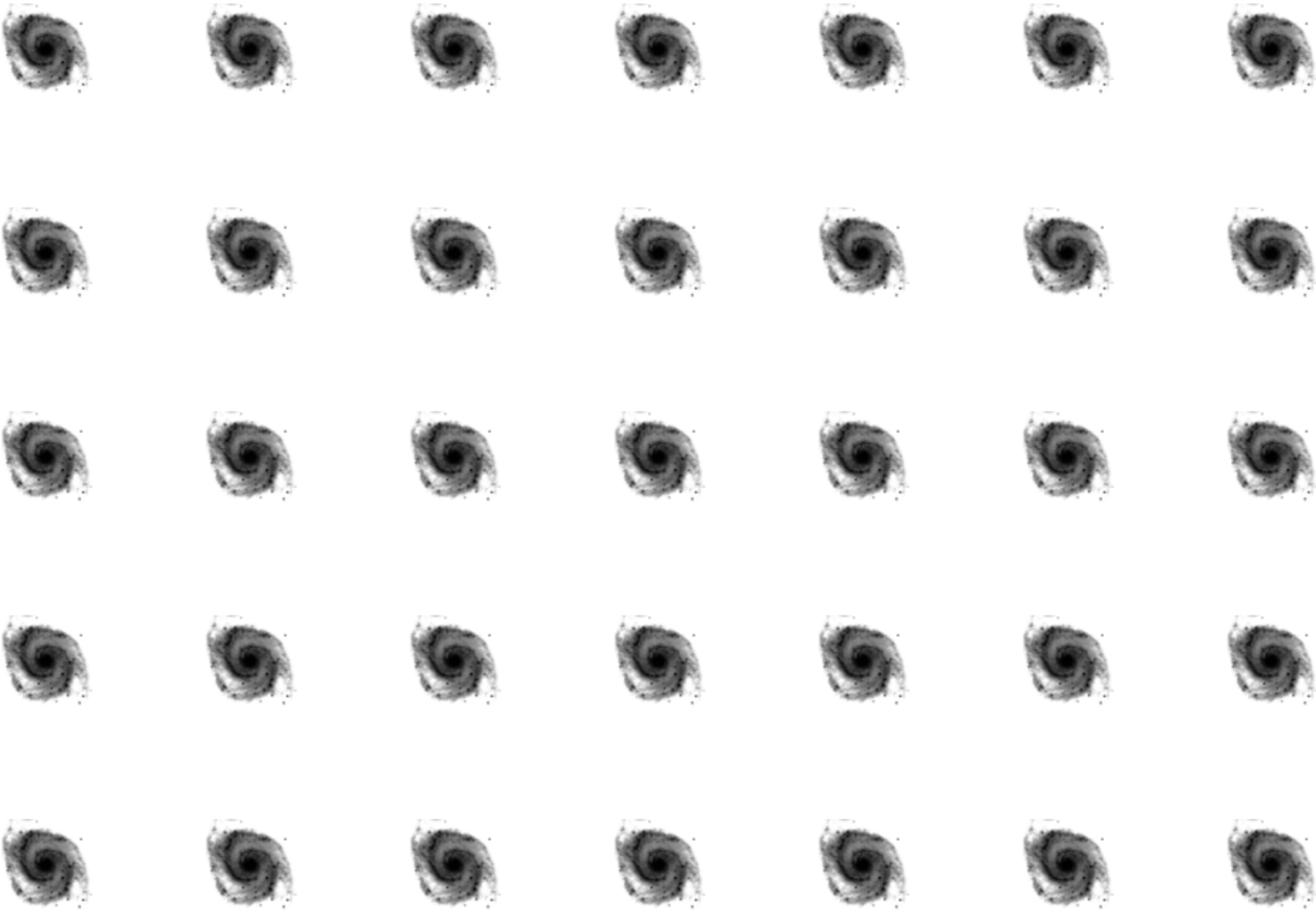
Hubble's Law

$$V = cz = Hd \quad (H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \pm 10\%)$$

Recession velocity proportional to distance



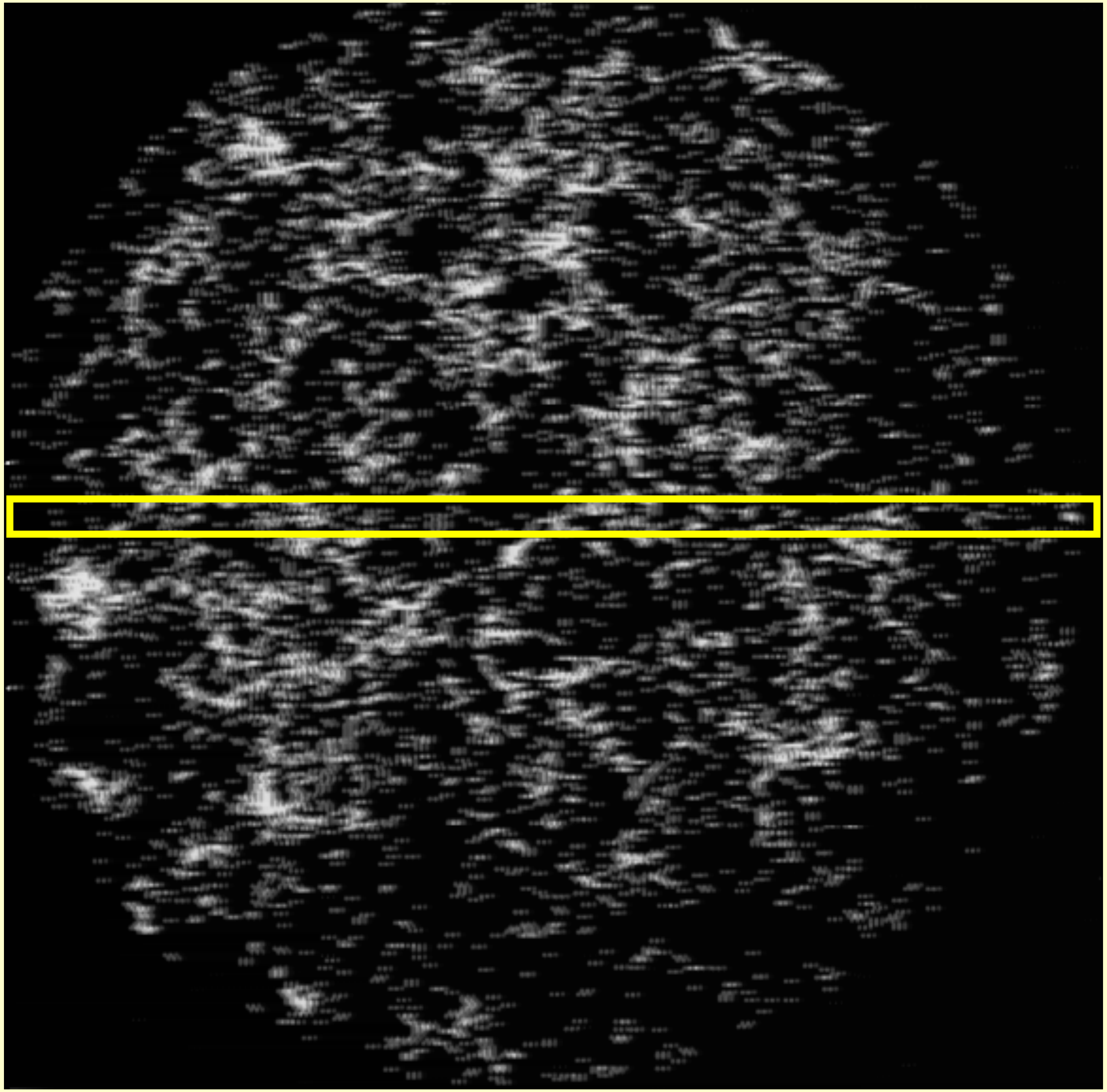
- Get Hubble's law if the galaxy distribution expands uniformly
- No outside to the expansion



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

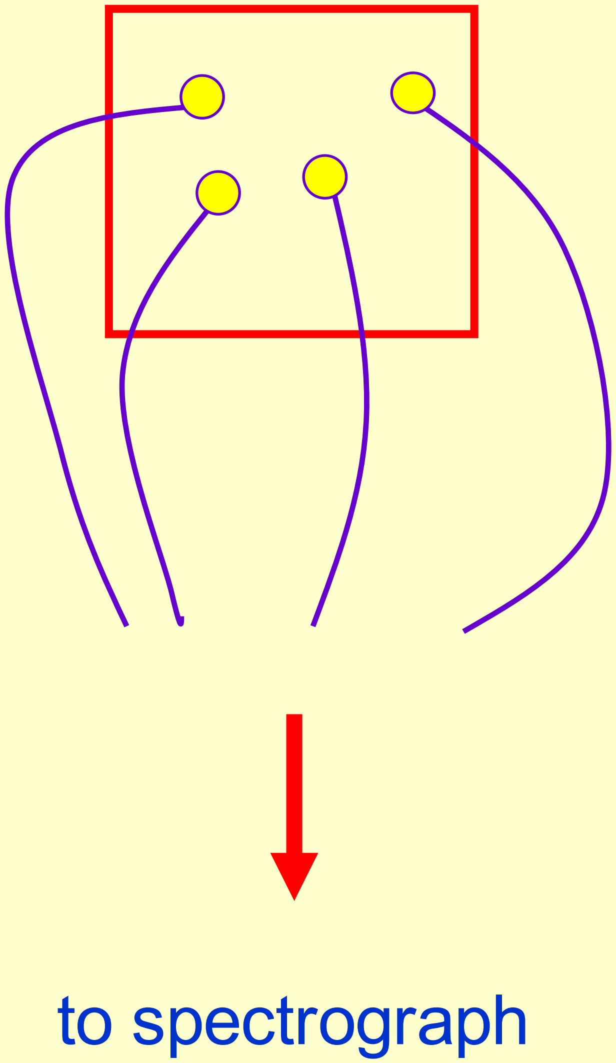
The 2dF Galaxy Redshift Survey

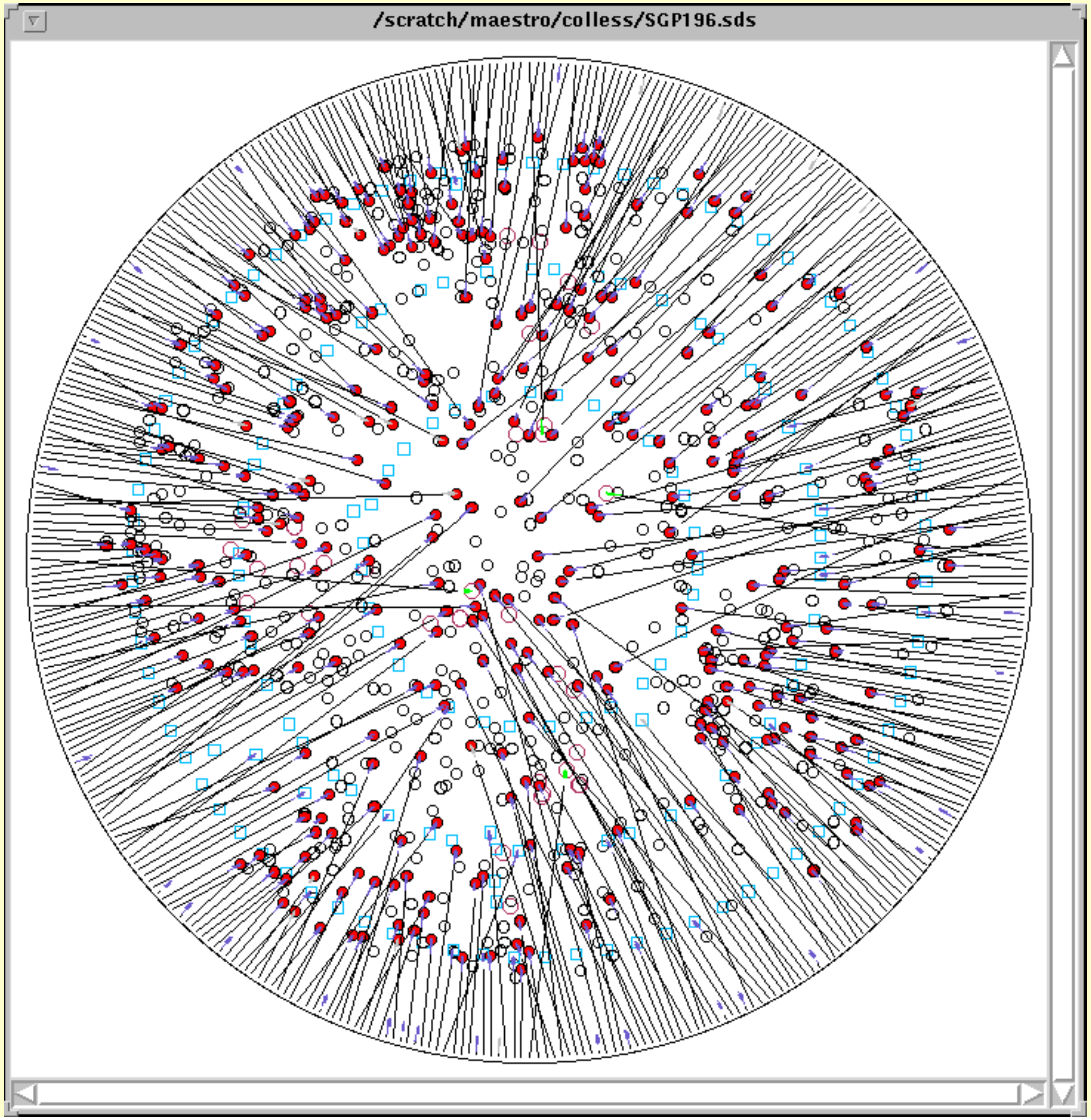
A UK / Australian project to map the positions of 250,000 galaxies: ten times the largest previous survey

The Anglo-Australian Telescope

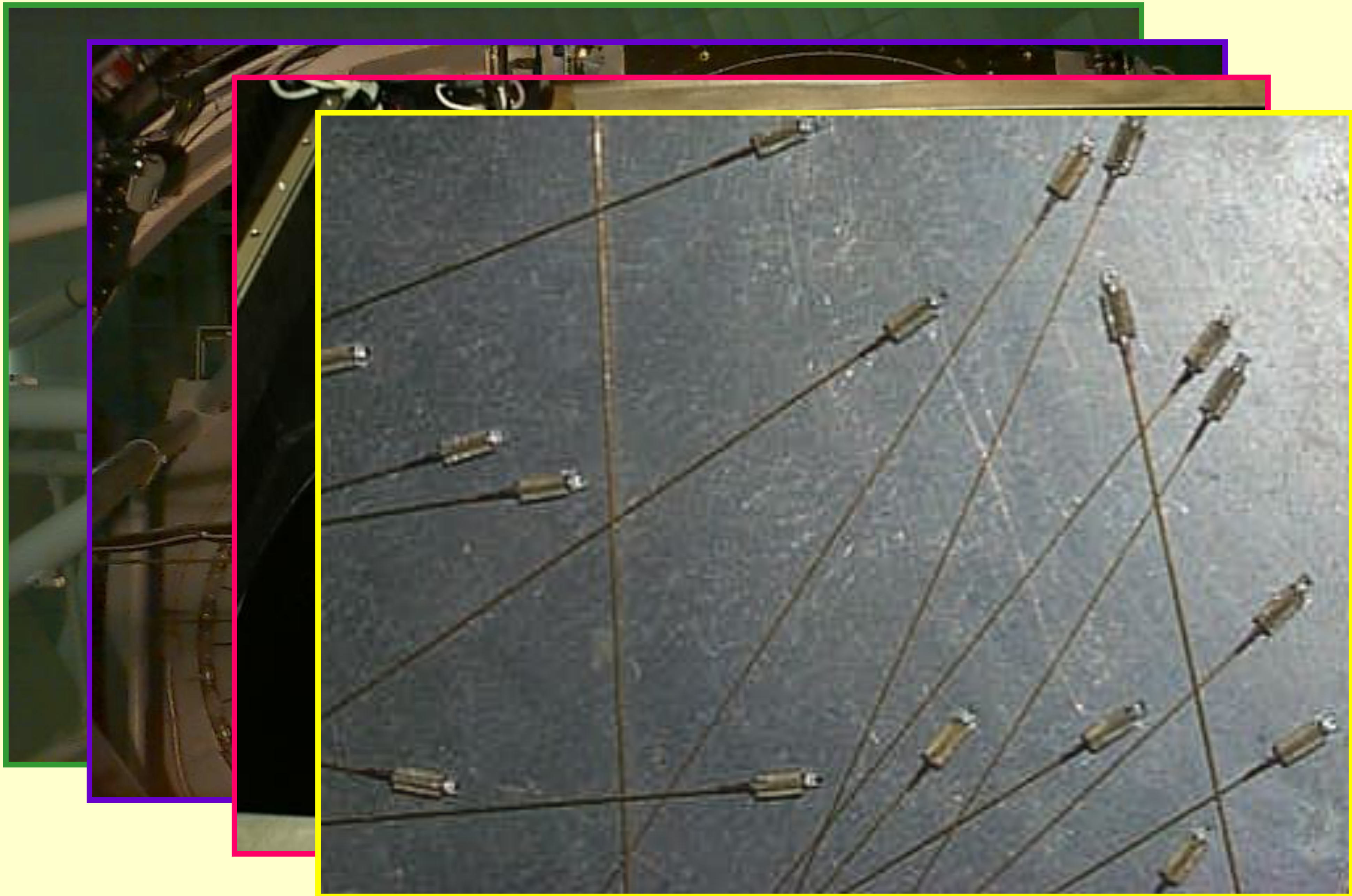
3.9m primary mirror

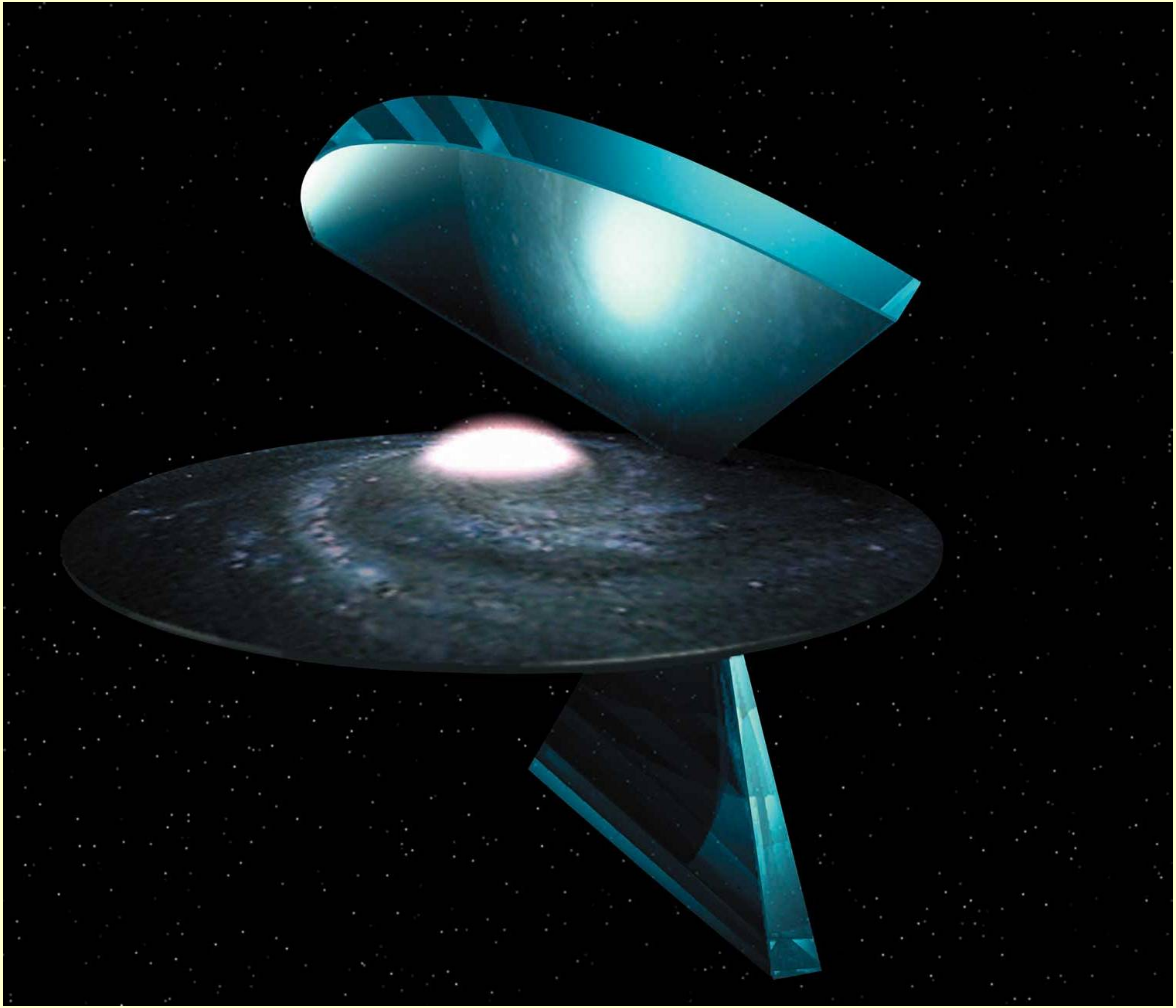
Going faster with fibre optics



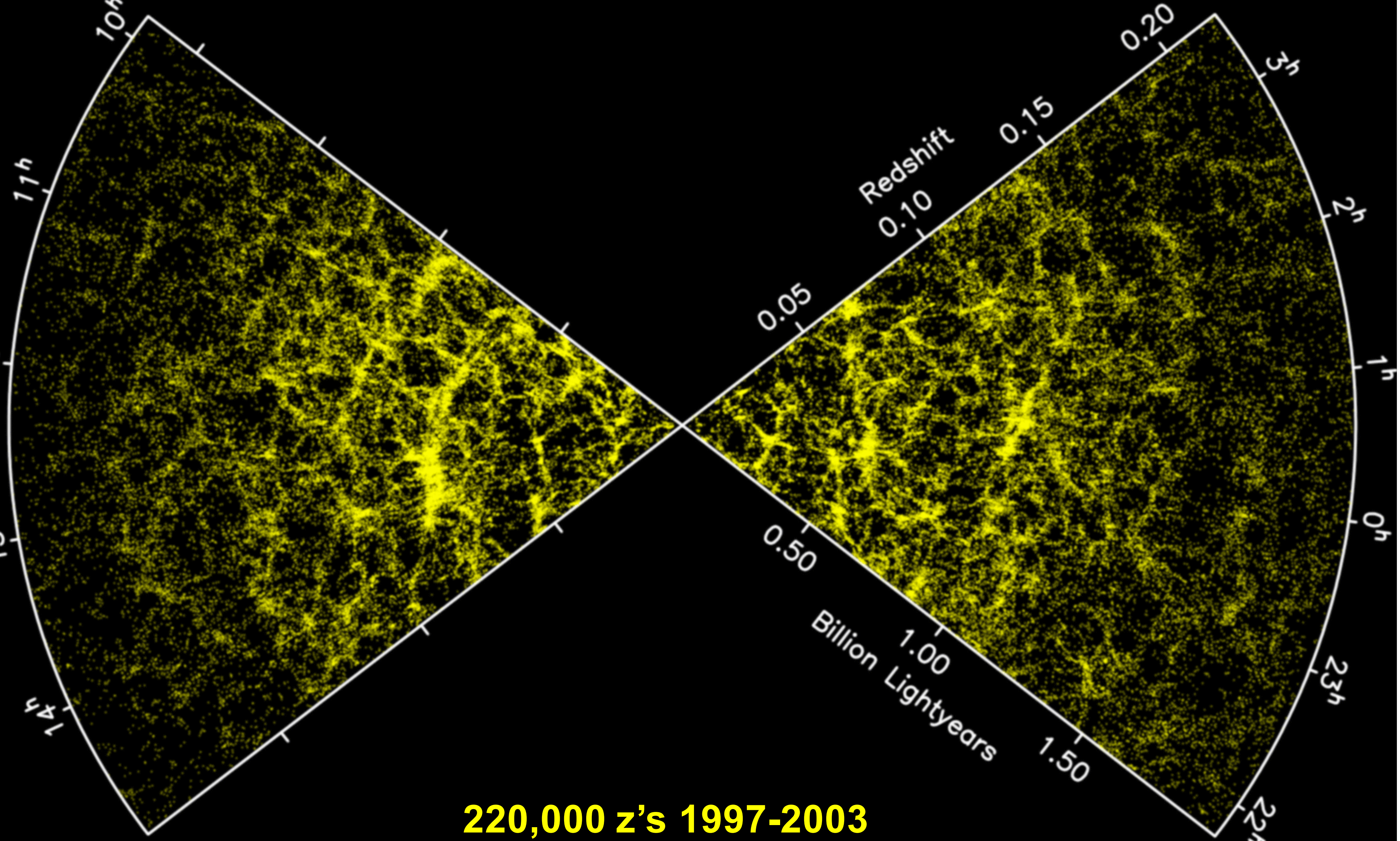


2dF on the AAT

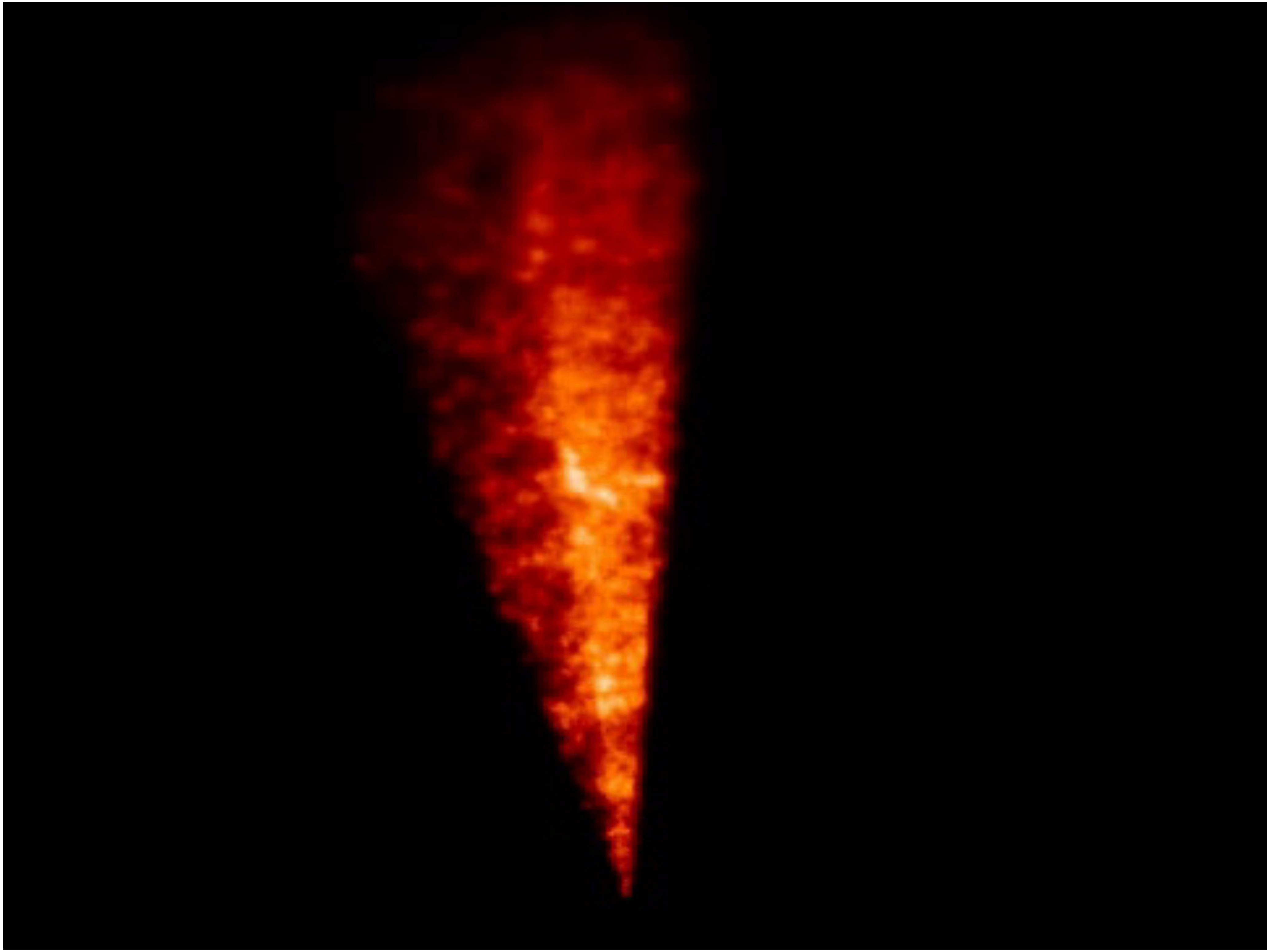


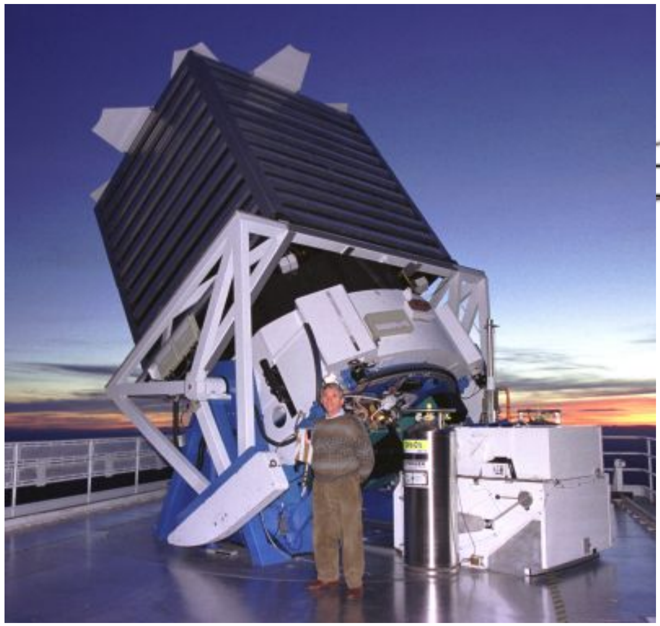


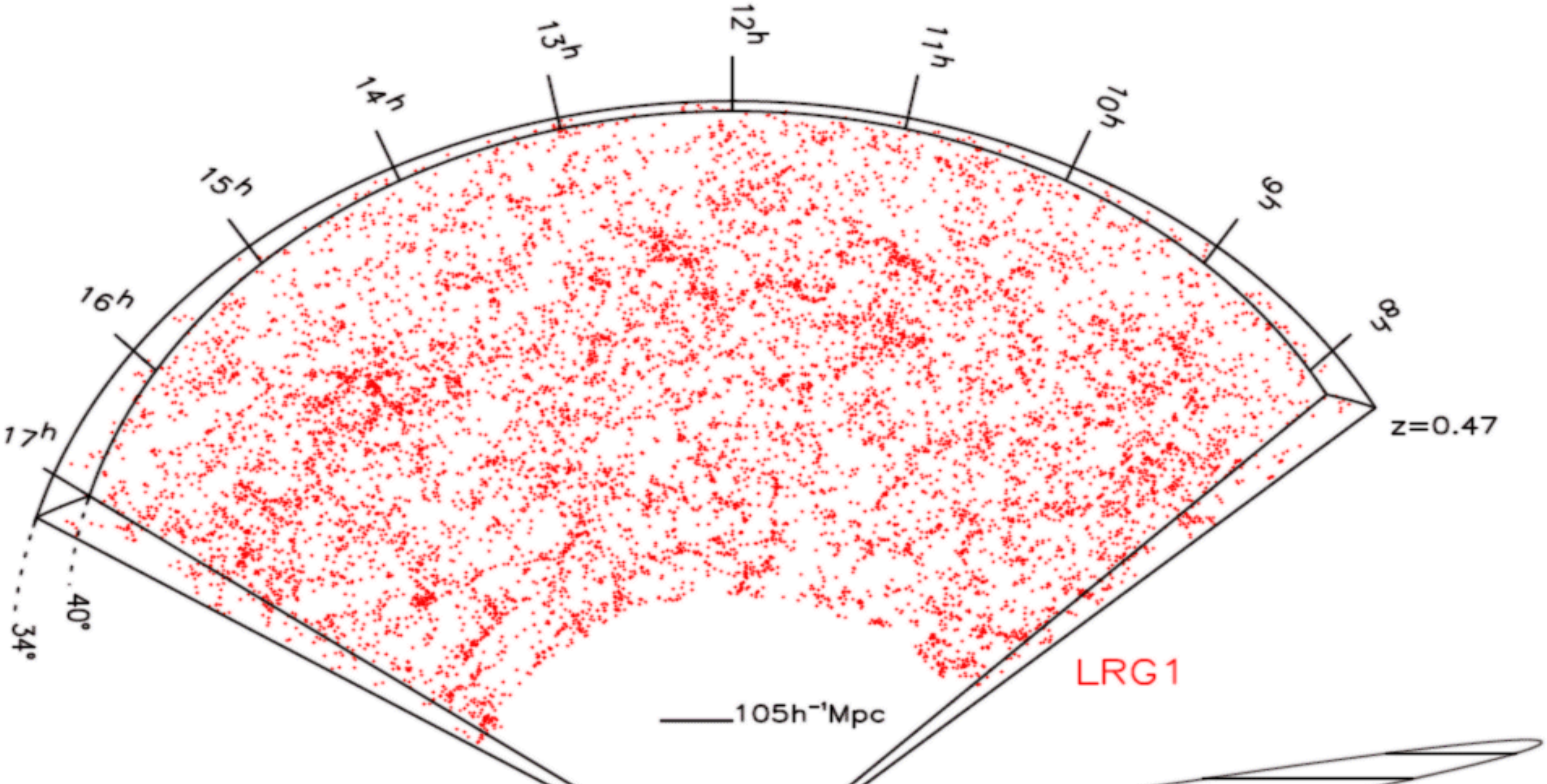
The 2dF Galaxy Redshift Survey

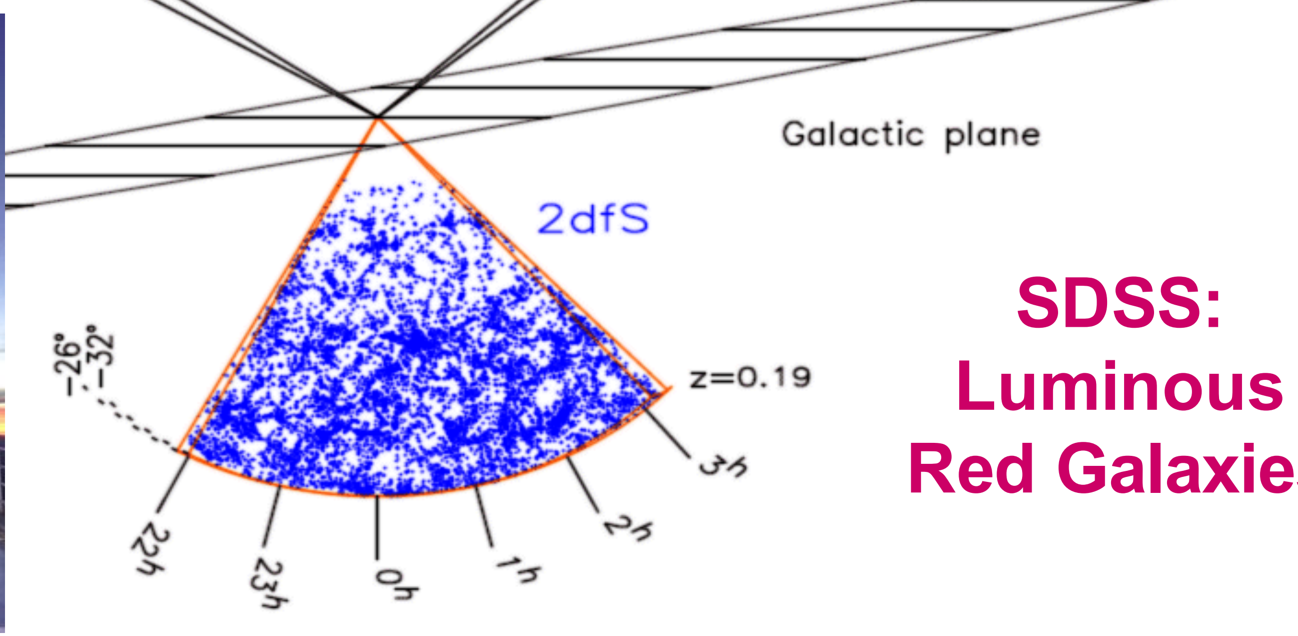


220,000 z's 1997-2003



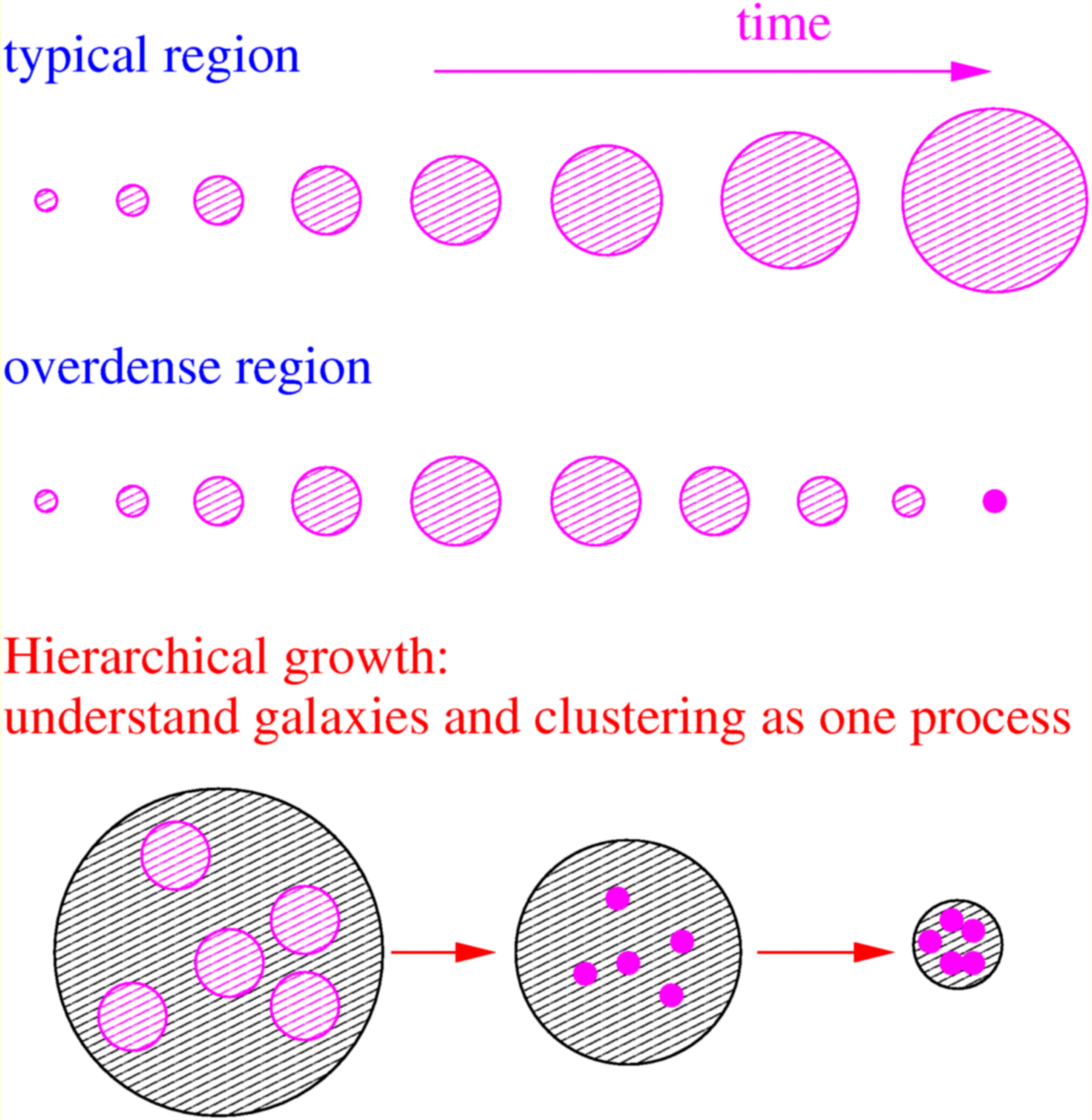






SDSS: Luminous Red Galaxies

Why do galaxies, clusters, and superclusters exist?

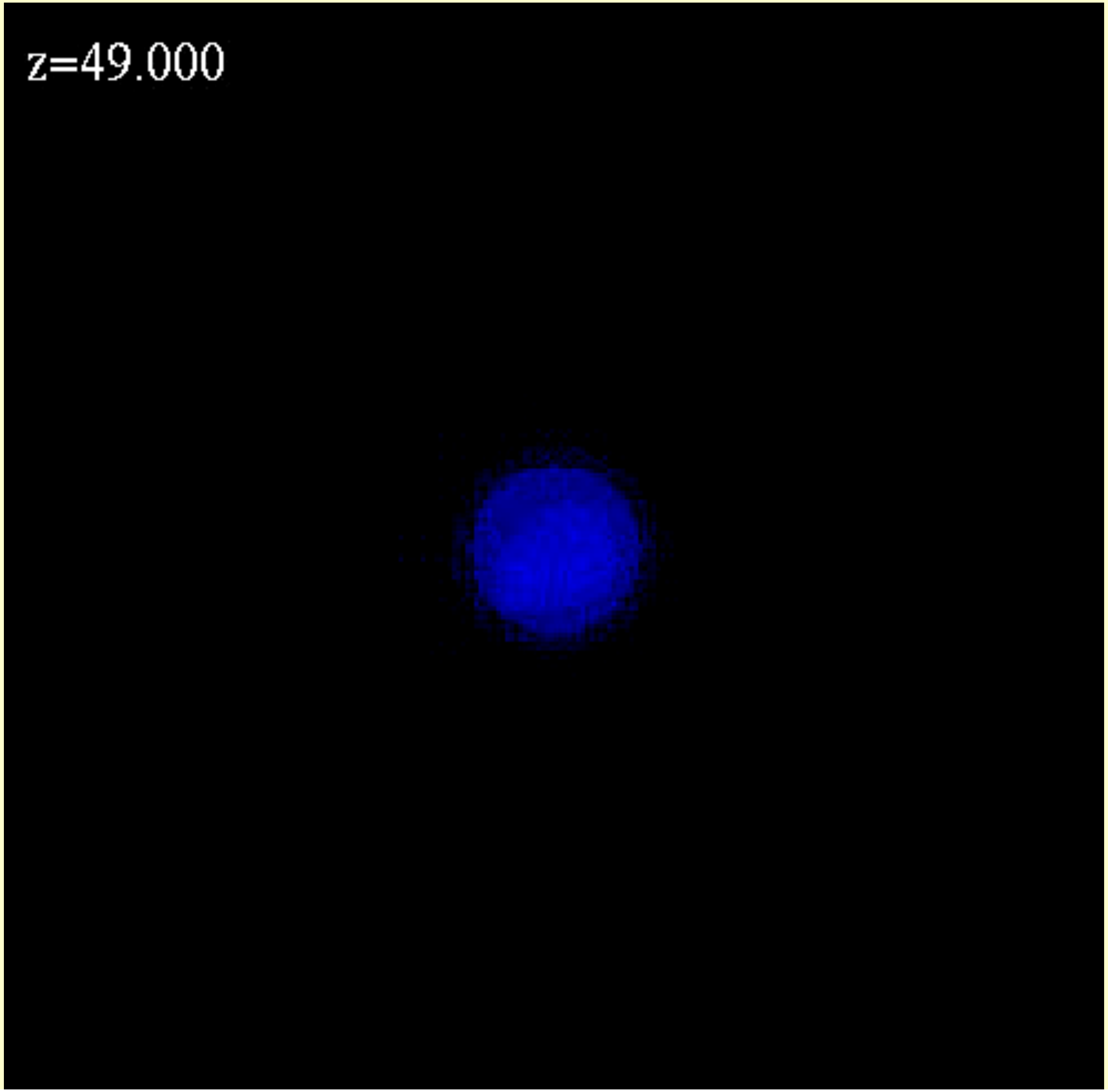


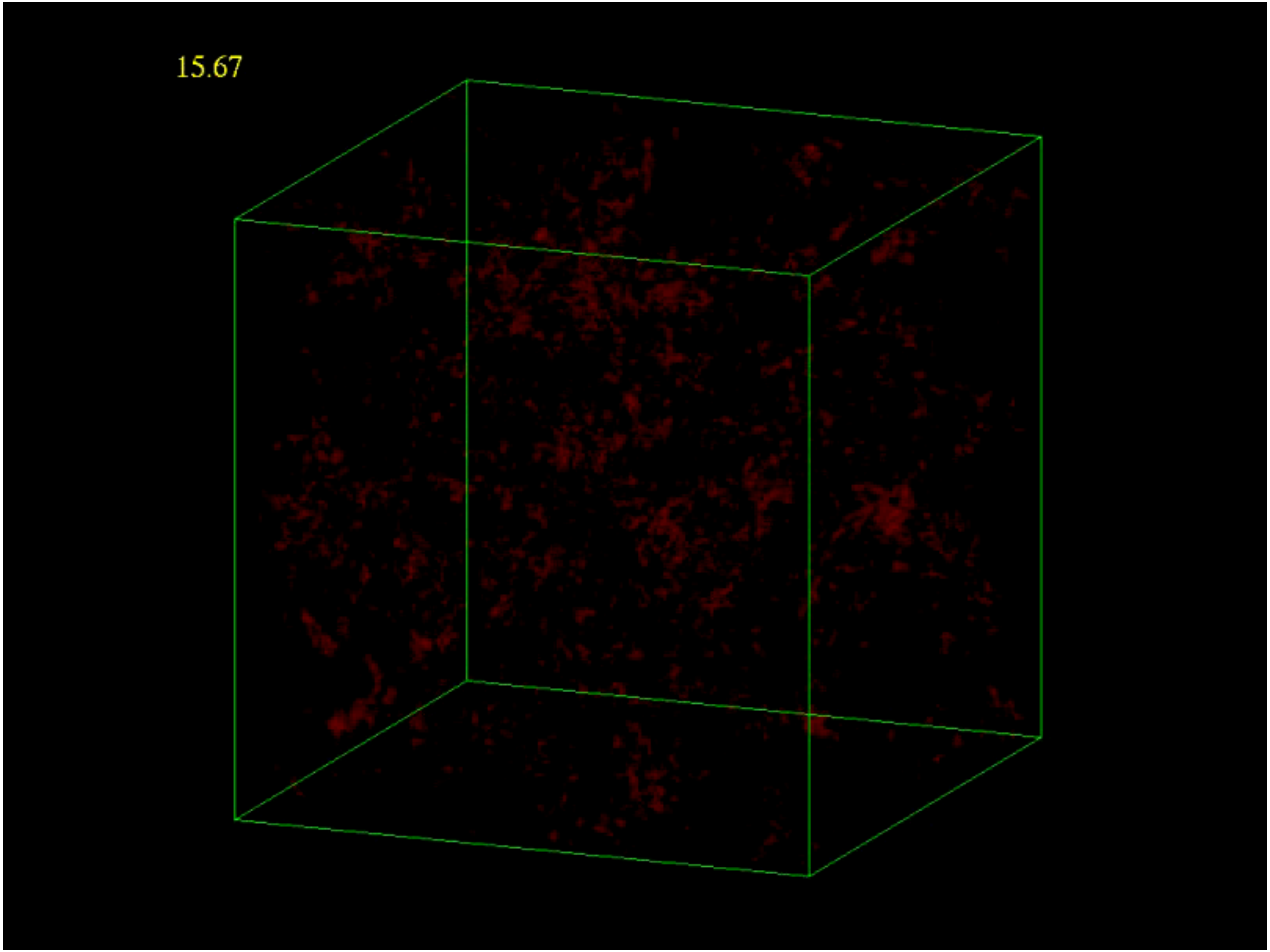
Gravitational instability:

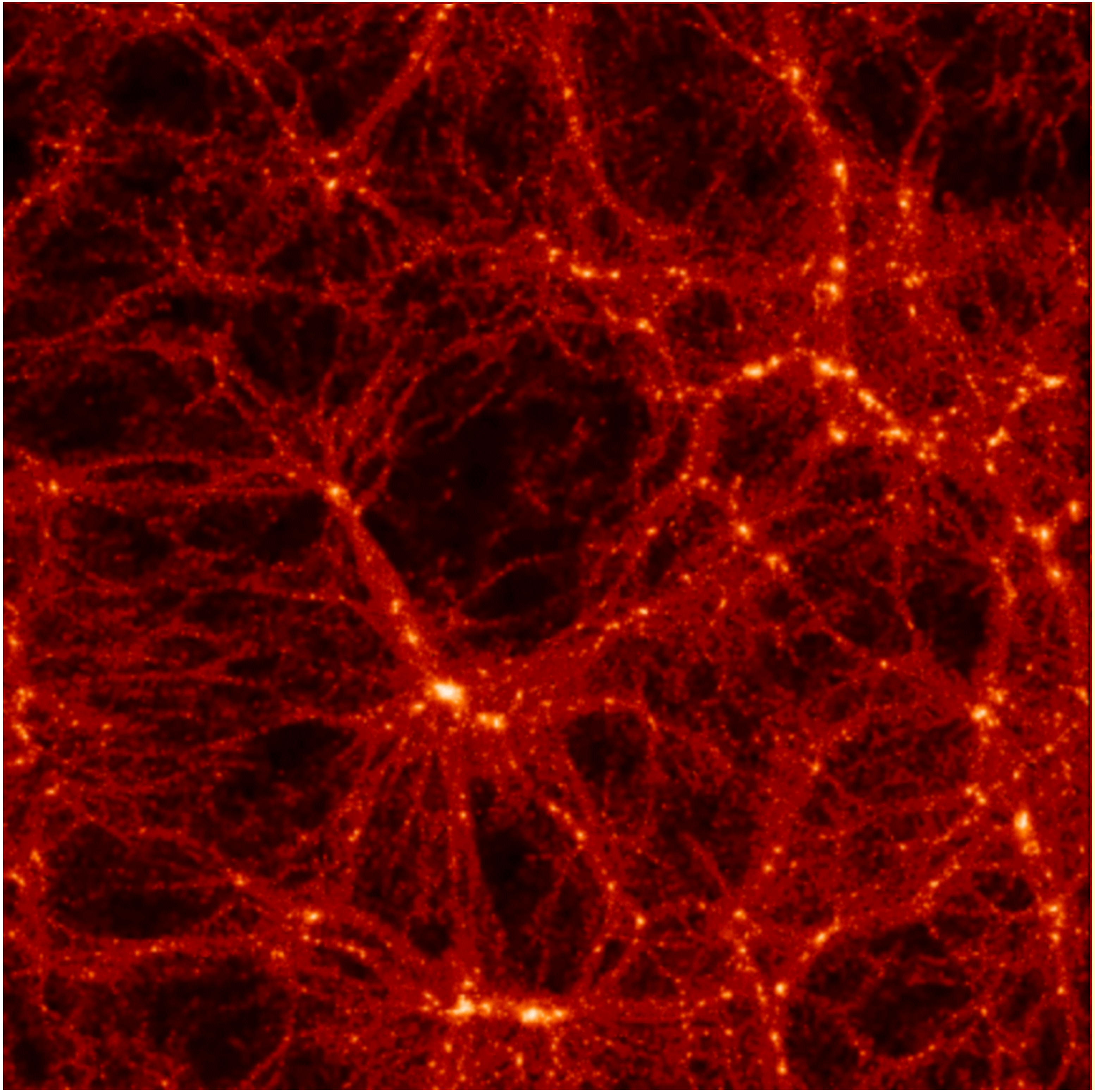
hierarchical collapse generates ever larger structures

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




15.67



Forming superclusters (comoving view)

redshift z=3

(1/4 present size)

redshift z=1

(1/2 present size)

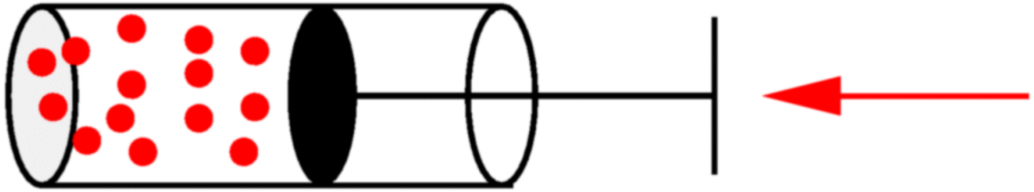
Redshift z=0

(today)

But can we see this evolution happening in the real universe?

The Hot Big Bang

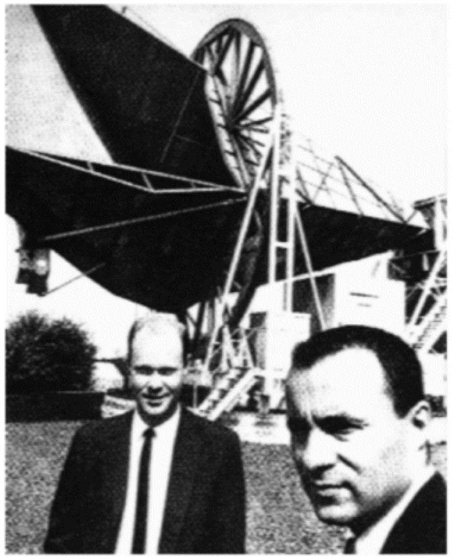
The universe was hot in the past



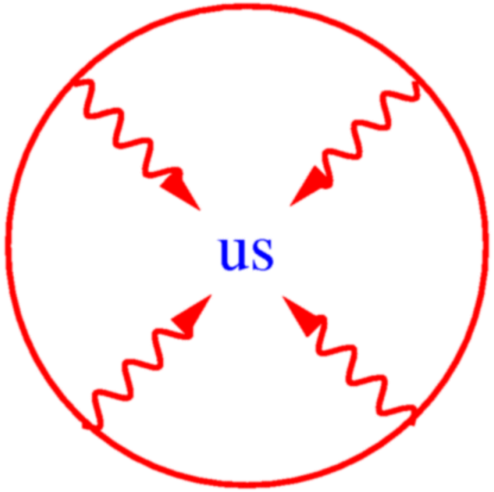
100,000 years: 1000 degrees — ionized plasma

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 $\boxed{\text{2.7 degrees}}$ above absolute zero

COBE Microwave Sky

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

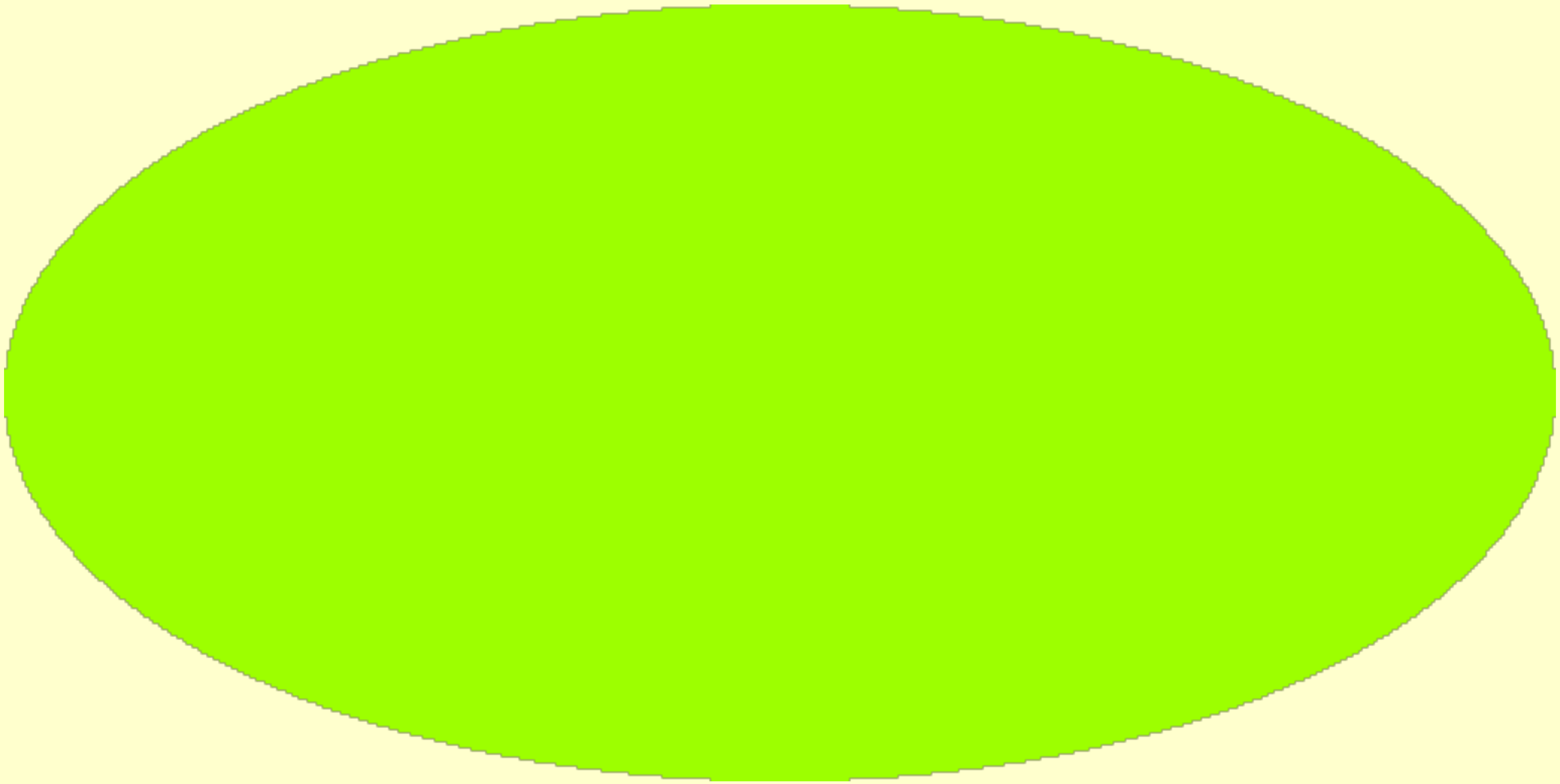


Image courtesy COBE homepage.

COBE Microwave sky: 1,000 X stretch

- The sky temperature with range from 2.724 - 2.732 Kelvin
    - blue is 2.724 K and red is 2.732 K

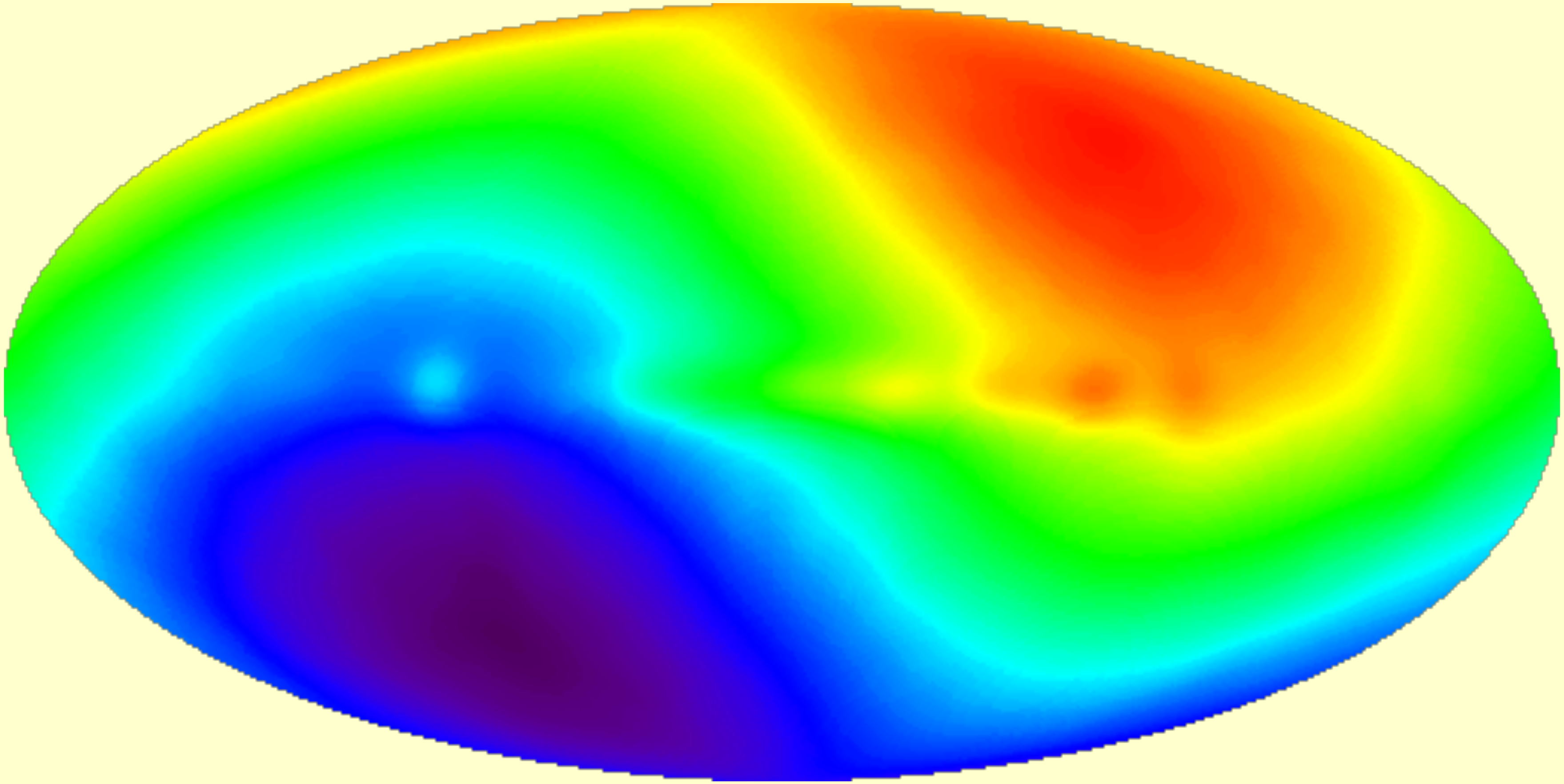


Image courtesy COBE homepage.

COBE microwave sky: 25,000 X stretch

The sky temperature ranging from 2.7279 to 2.7281 Kelvin

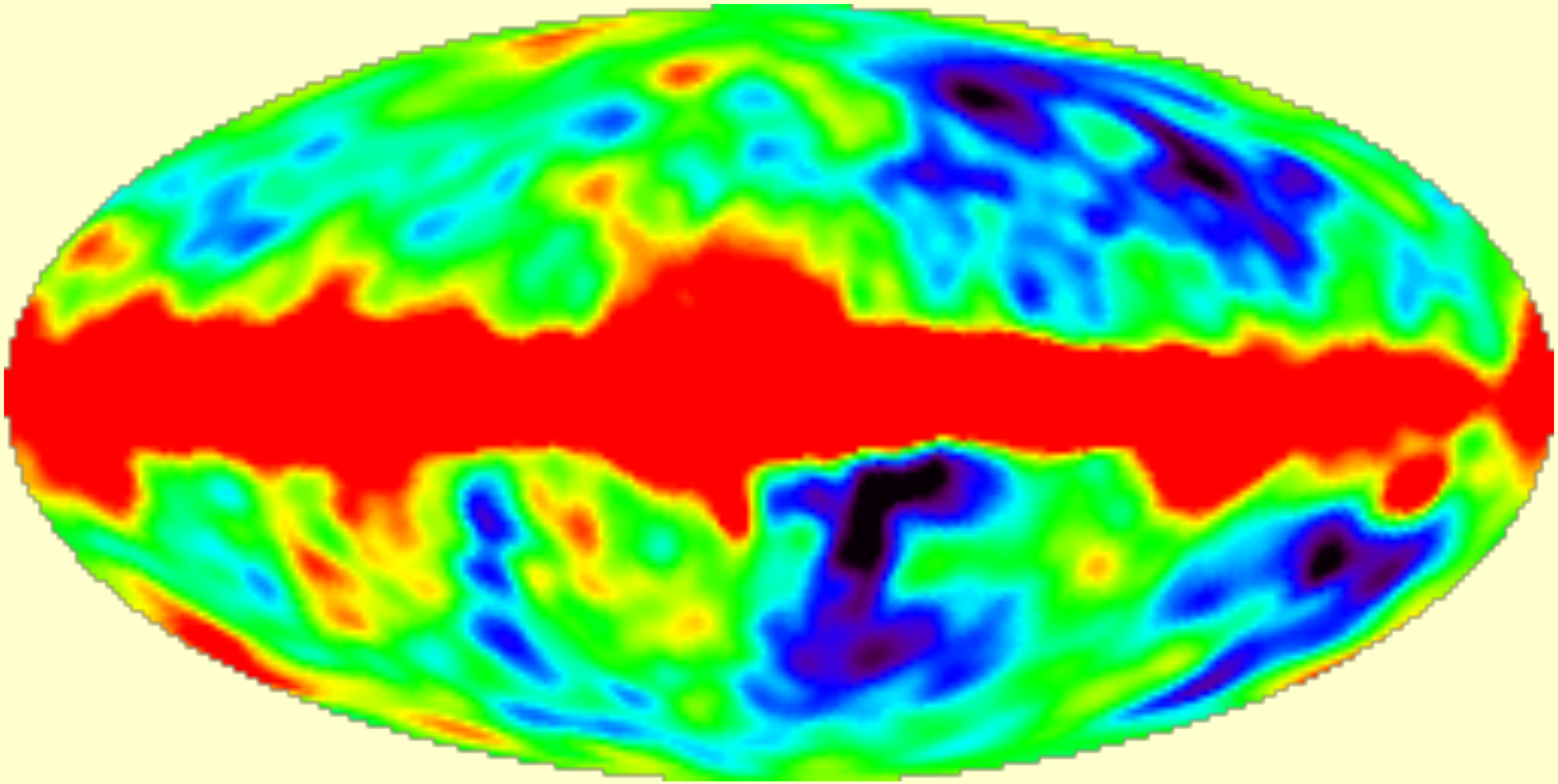
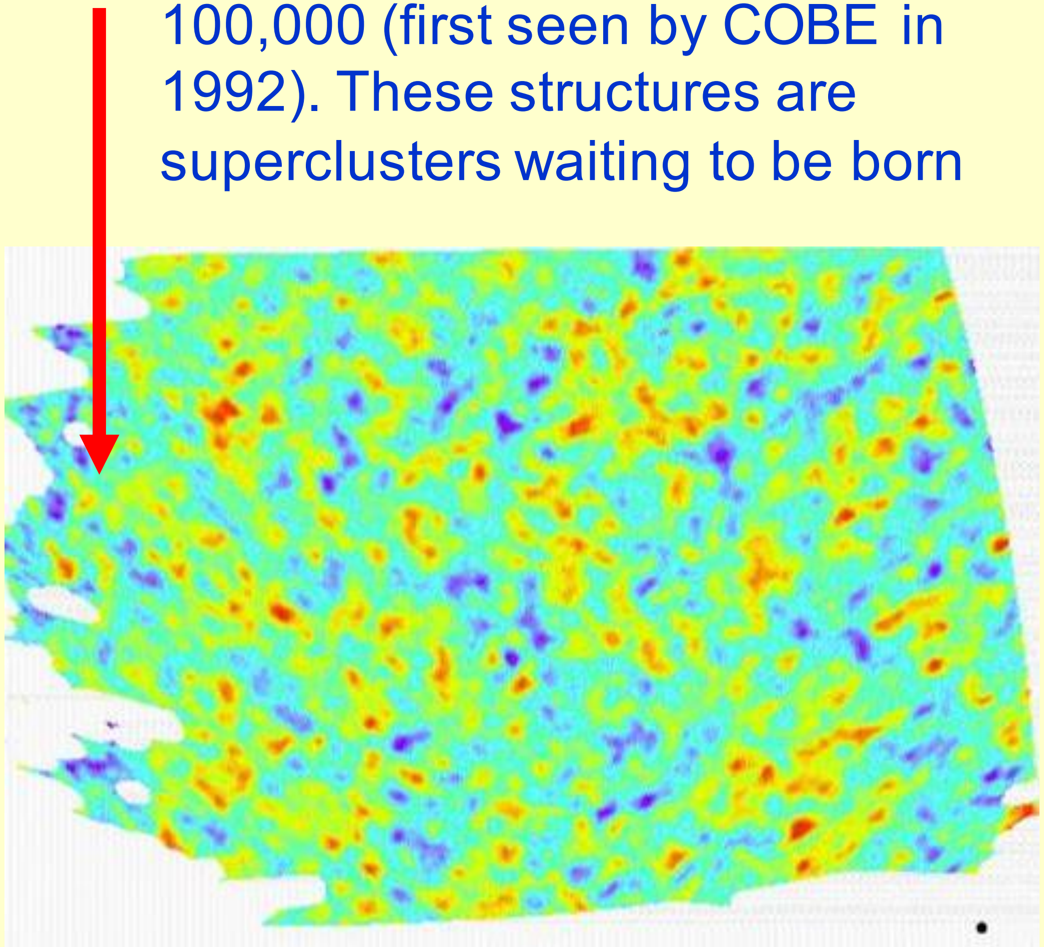
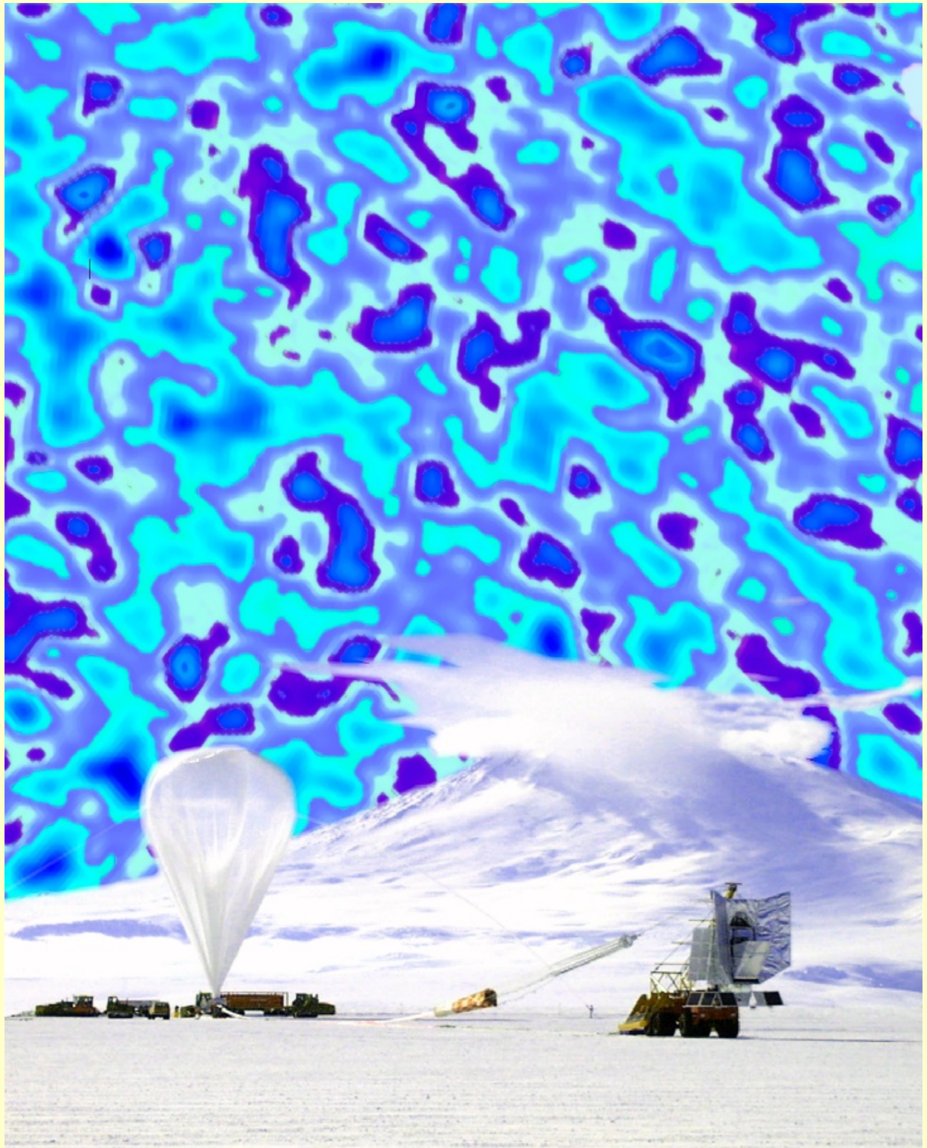


Image courtesy COBE homepage.

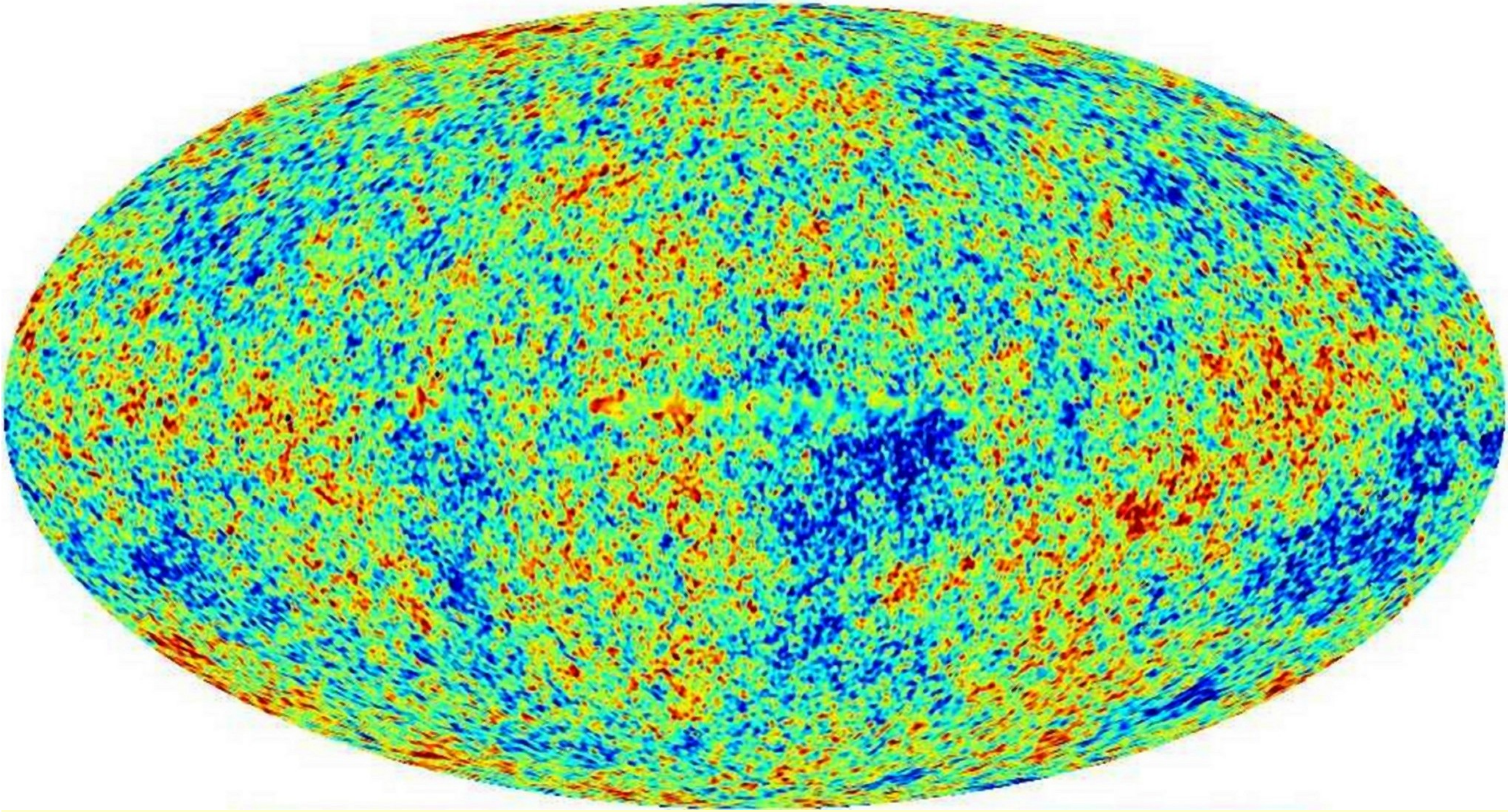
Observing prehistoric structure

30 degree patch of microwave sky from Boomerang shows intensity fluctuations of 1 part in 100,000 (first seen by COBE in 1992). These structures are superclusters waiting to be born

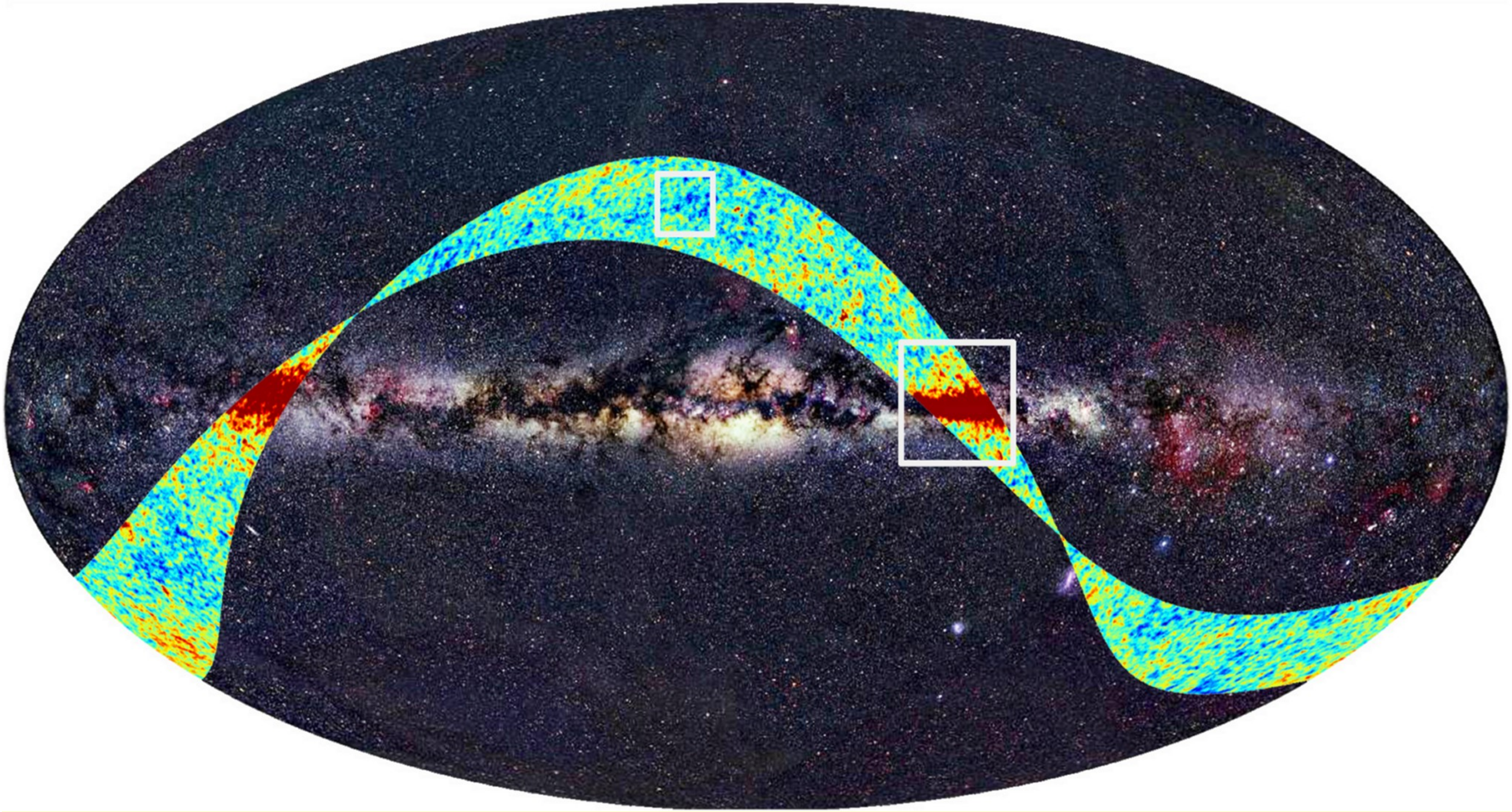




WMAP 2003: the full picture



2009 – 2012: Planck

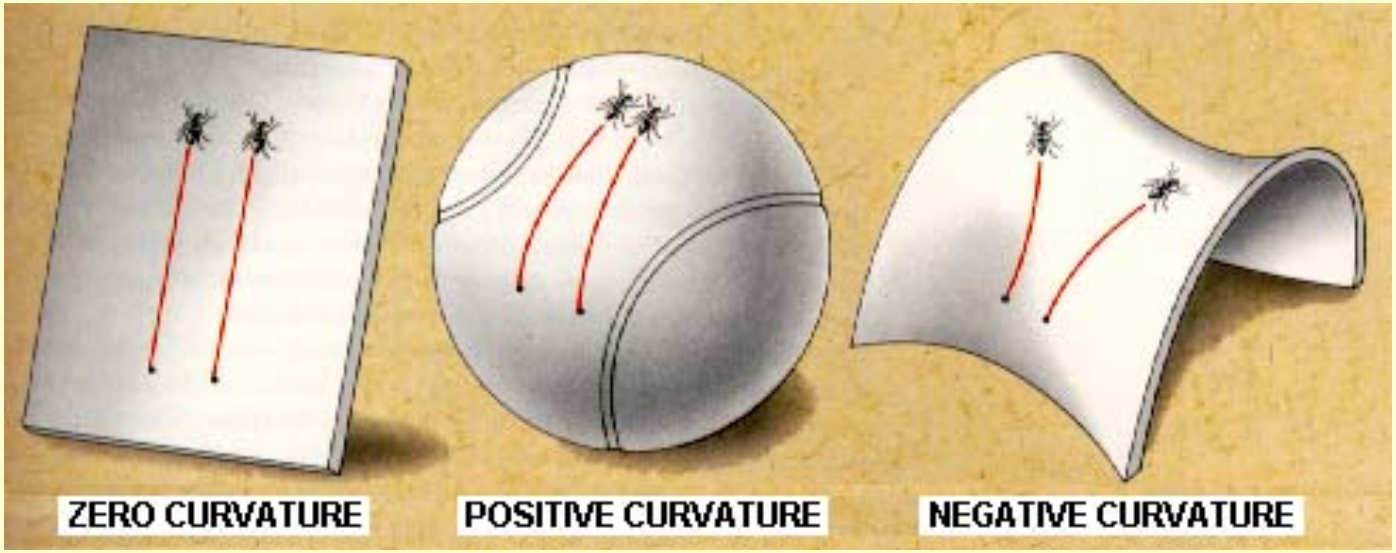


Even better, these pictures tell us what the universe is made of

The expanding curved universe

Matter curves space:

(no outside to expansion)

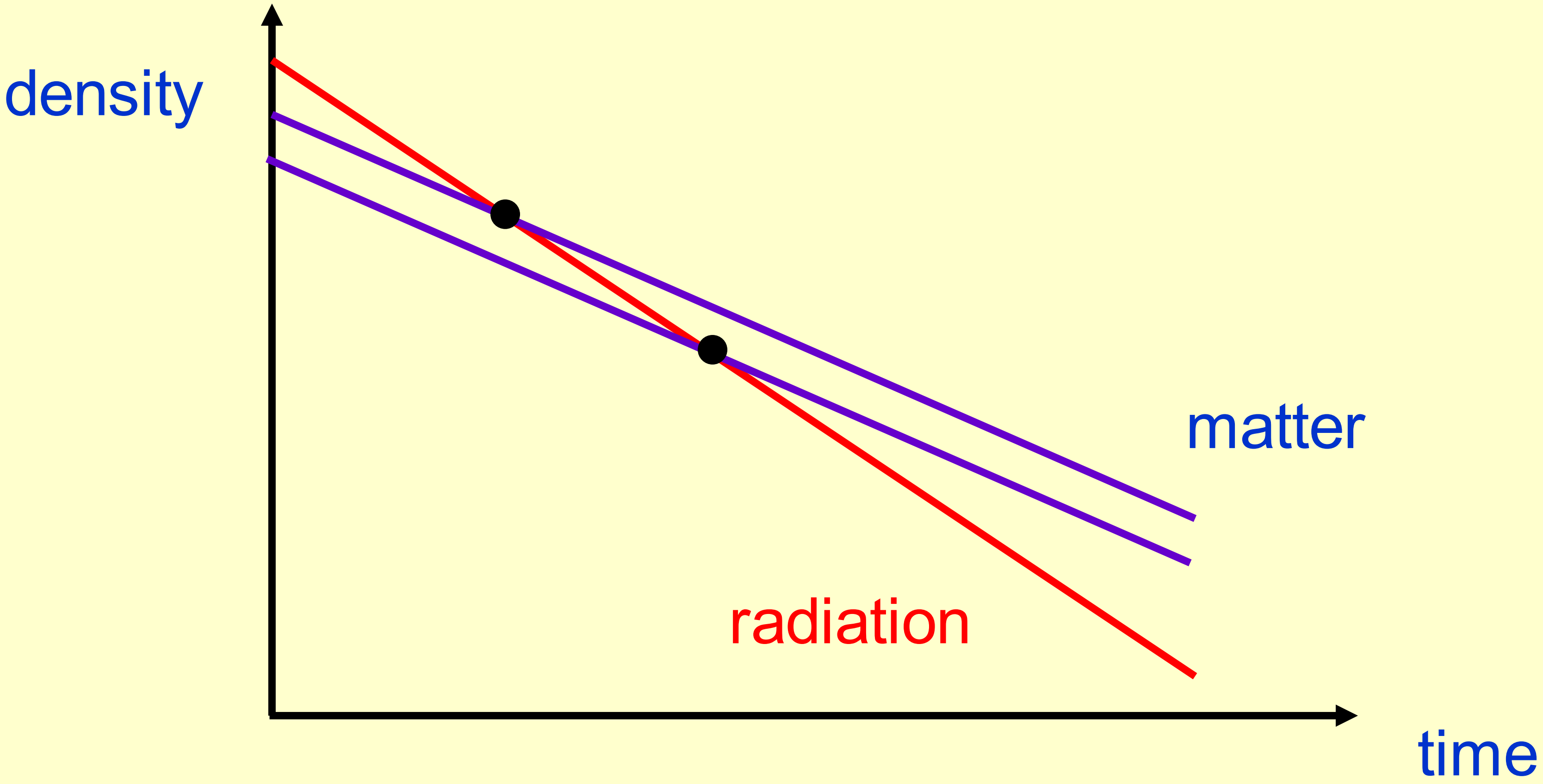


flat (infinite) closed (finite) open (infinite)

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

‘density parameter’: Ω = (density) / (critical density)

Weighing the universe - I



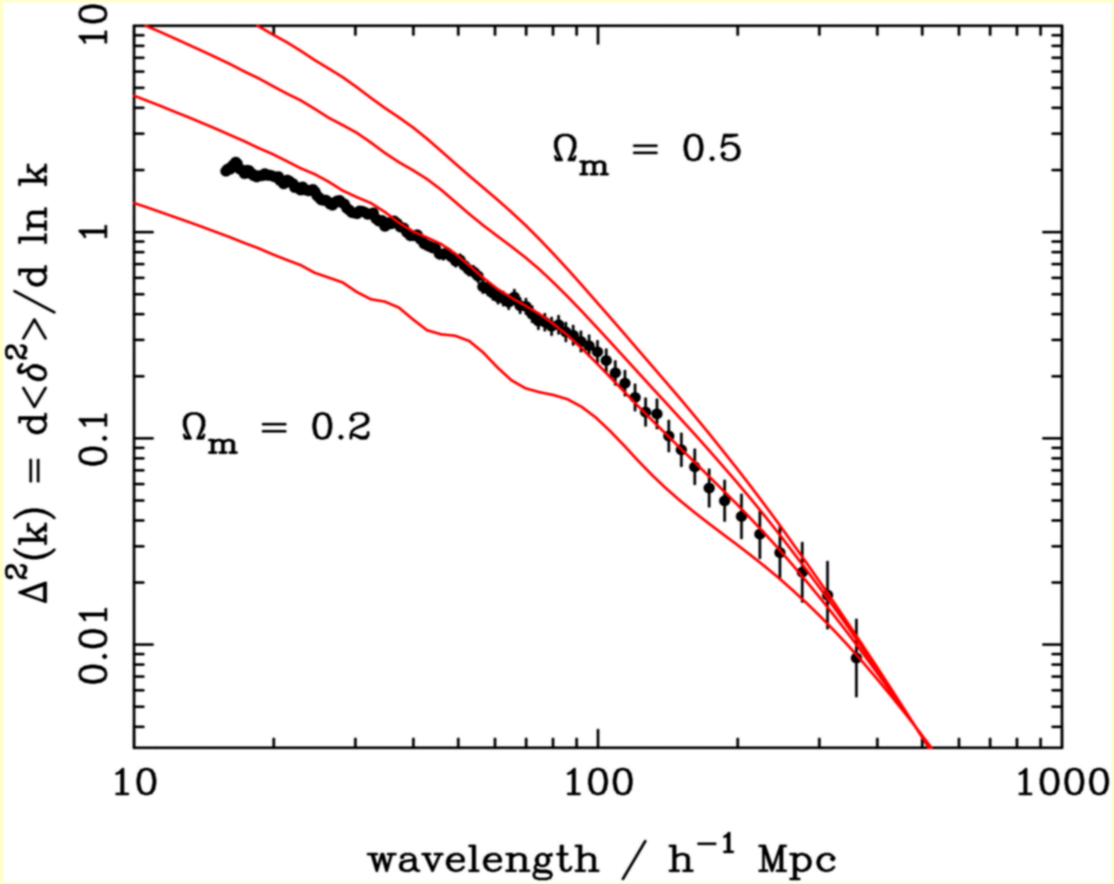
Now: background radiation ‘weighs’ 1 / 3000 of matter

t < 100,000 years (depending on matter density):

radiation weighs more - affects growth of structure

Weighing the universe - II

fractional variation in number density of galaxies



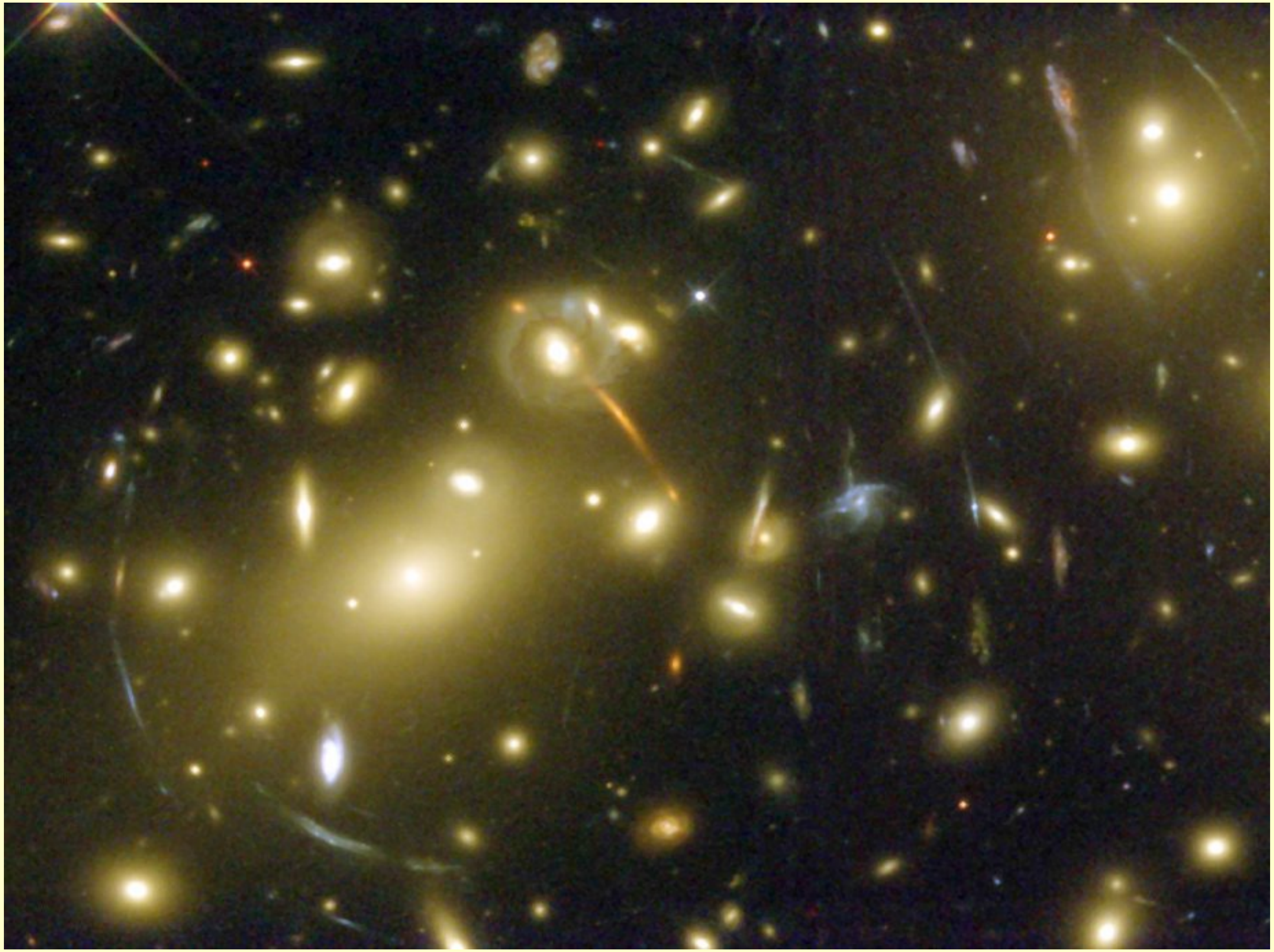
length-scale

Density of the universe is 'written on the sky': **Ω = 0.25**

This is 10 x the density of normal material:

So 'Dark matter' dominates the universe?

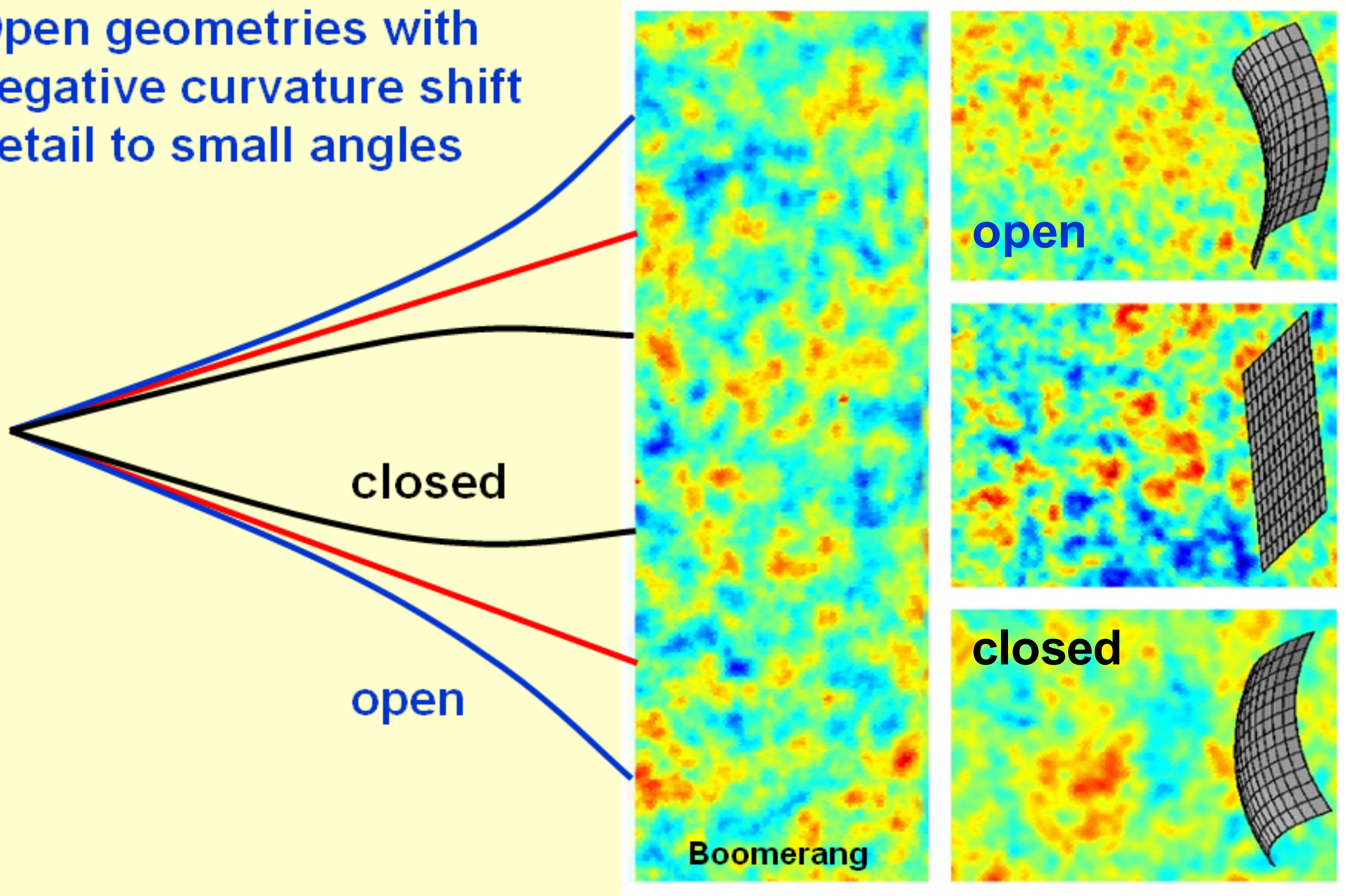
Dark Matter via gravitational lensing



Lensing measures total mass ~ 5 x (stars + gas)

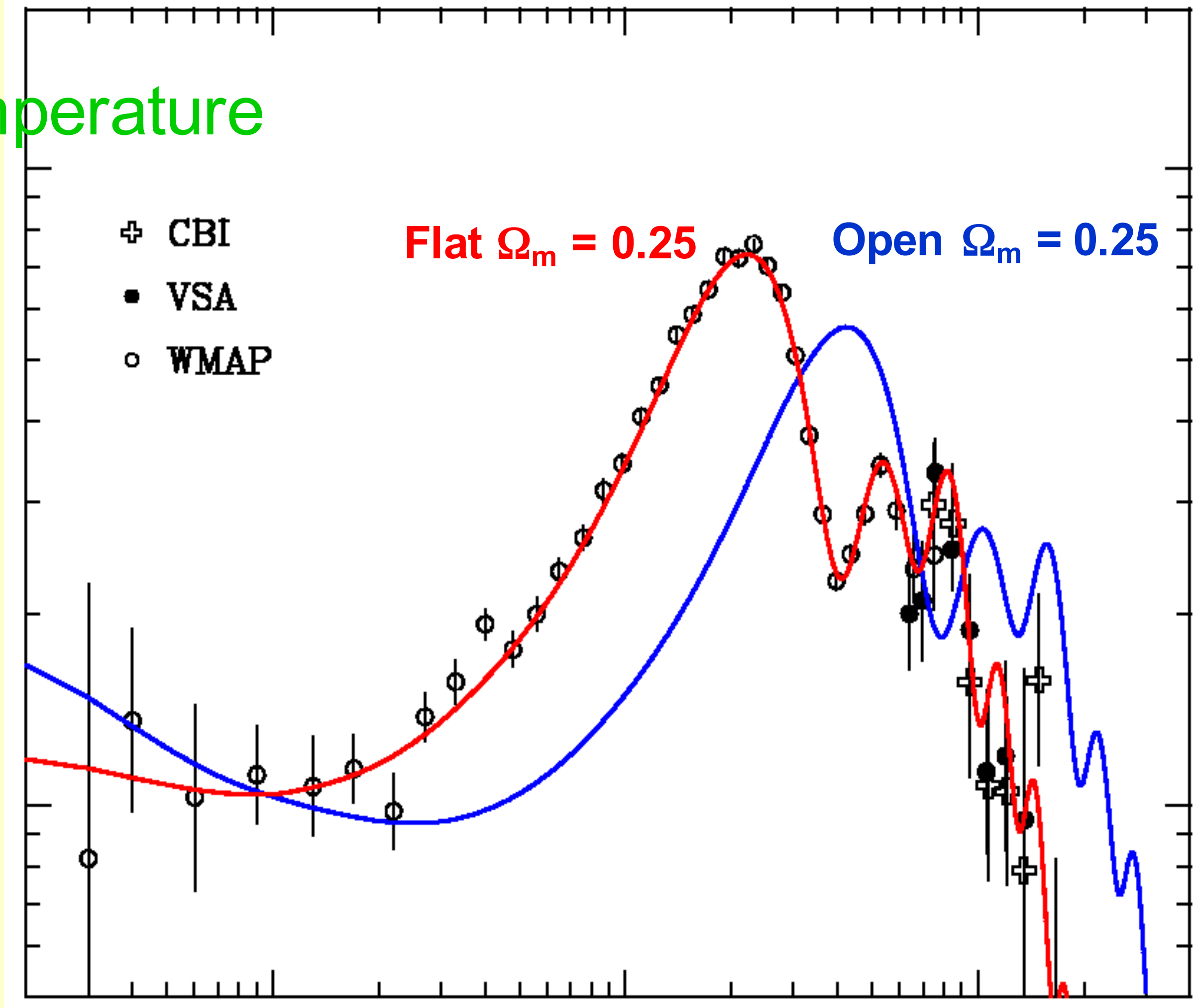
CMB and cosmic geometry

Open geometries with negative curvature shift detail to small angles



The amazing conclusion: a flat universe

Temperature



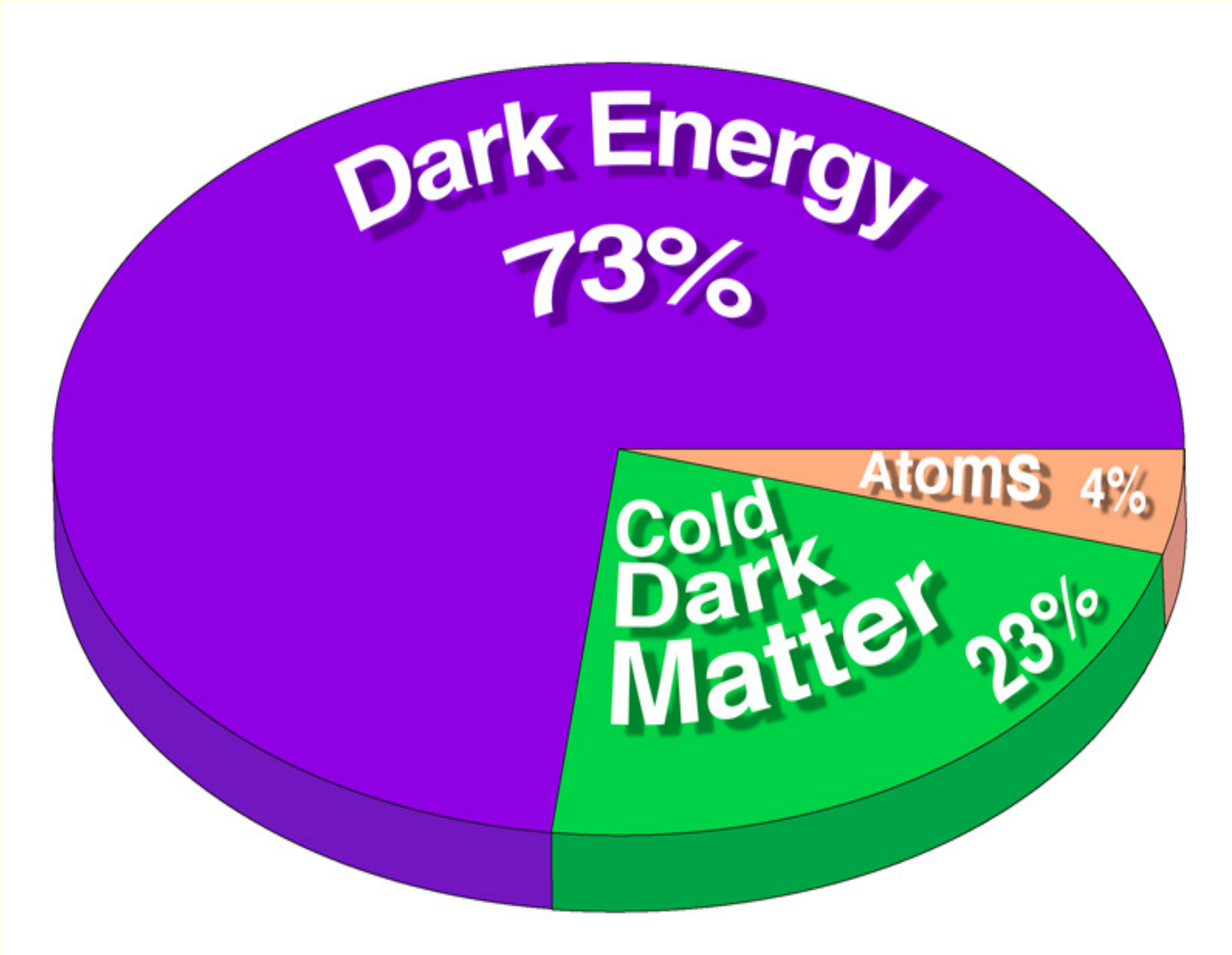
Large angles

small angles

Need an extra unclumped component that is 3 times as abundant as dark matter

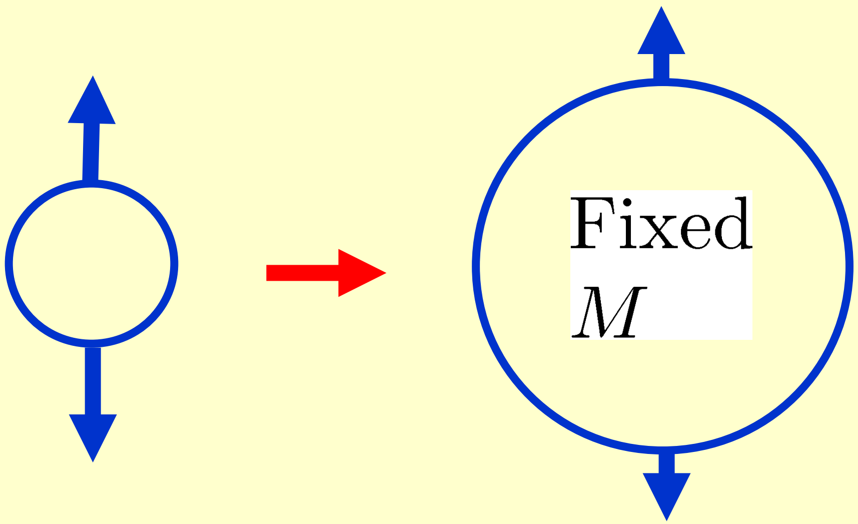
– call it vacuum energy or Dark Energy

The implausible universe



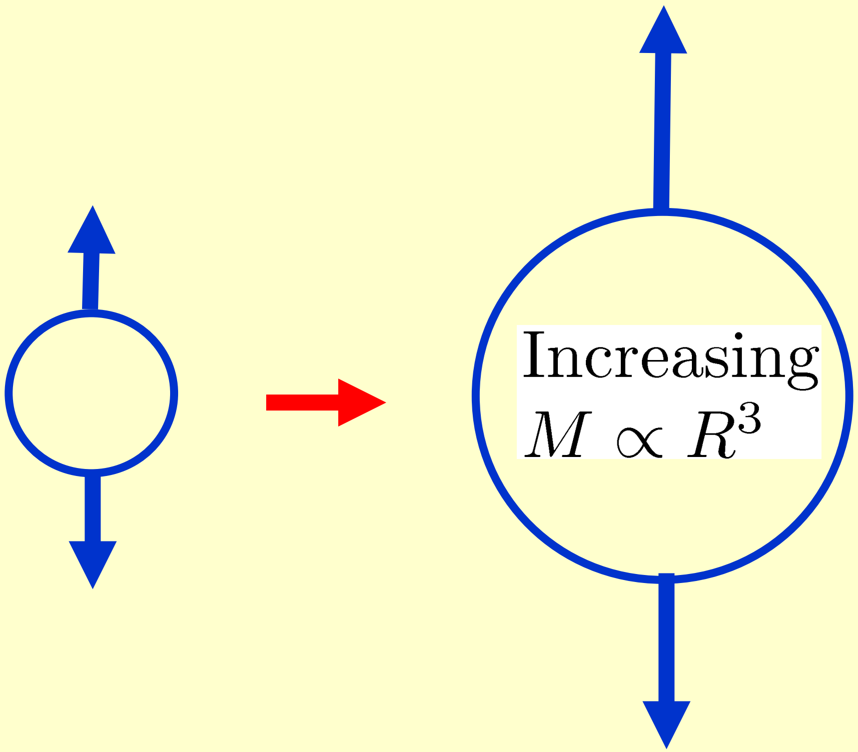
Vacuum energy has antigravity

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

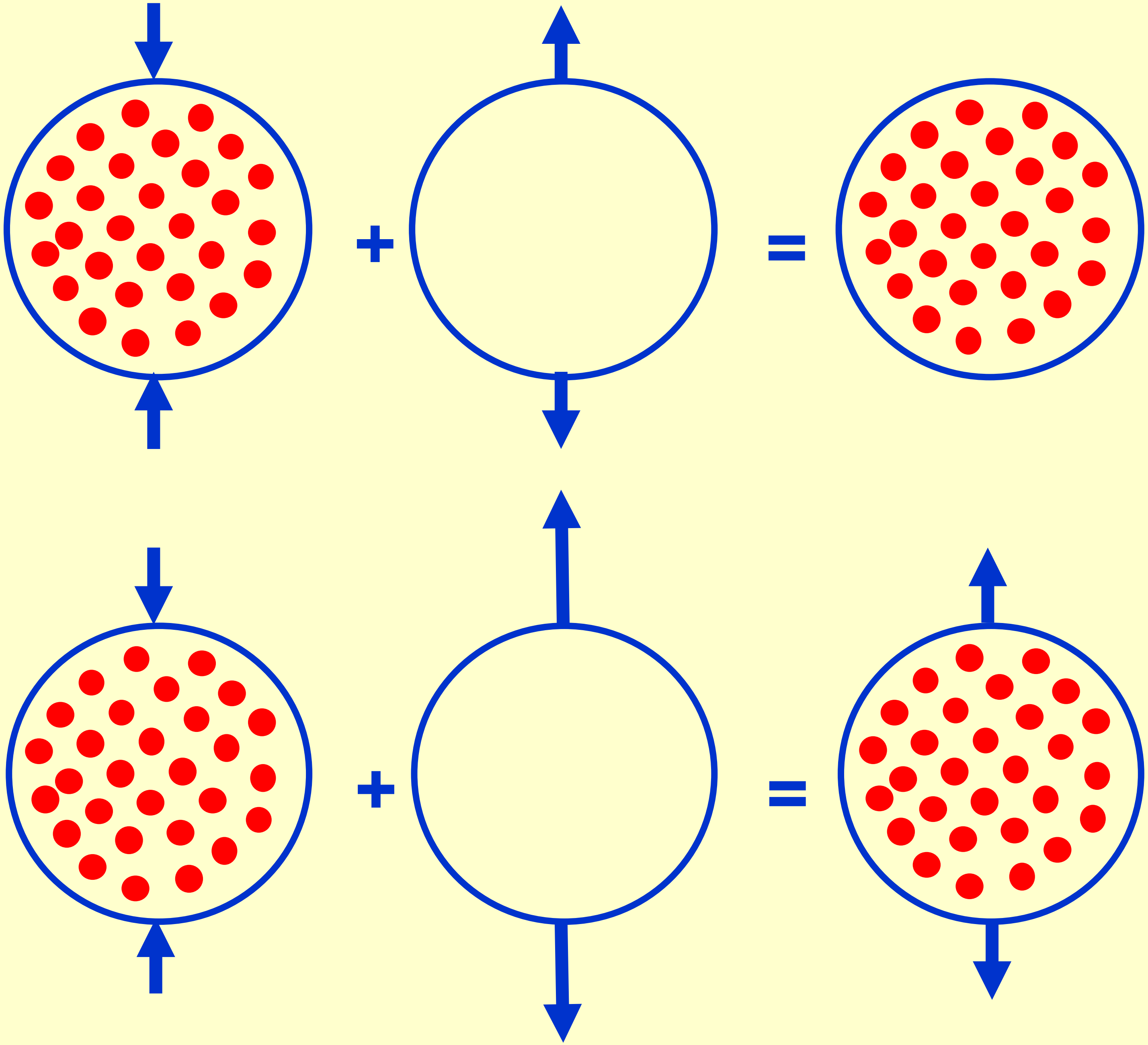


$$V = -GM/R \propto R^2$$

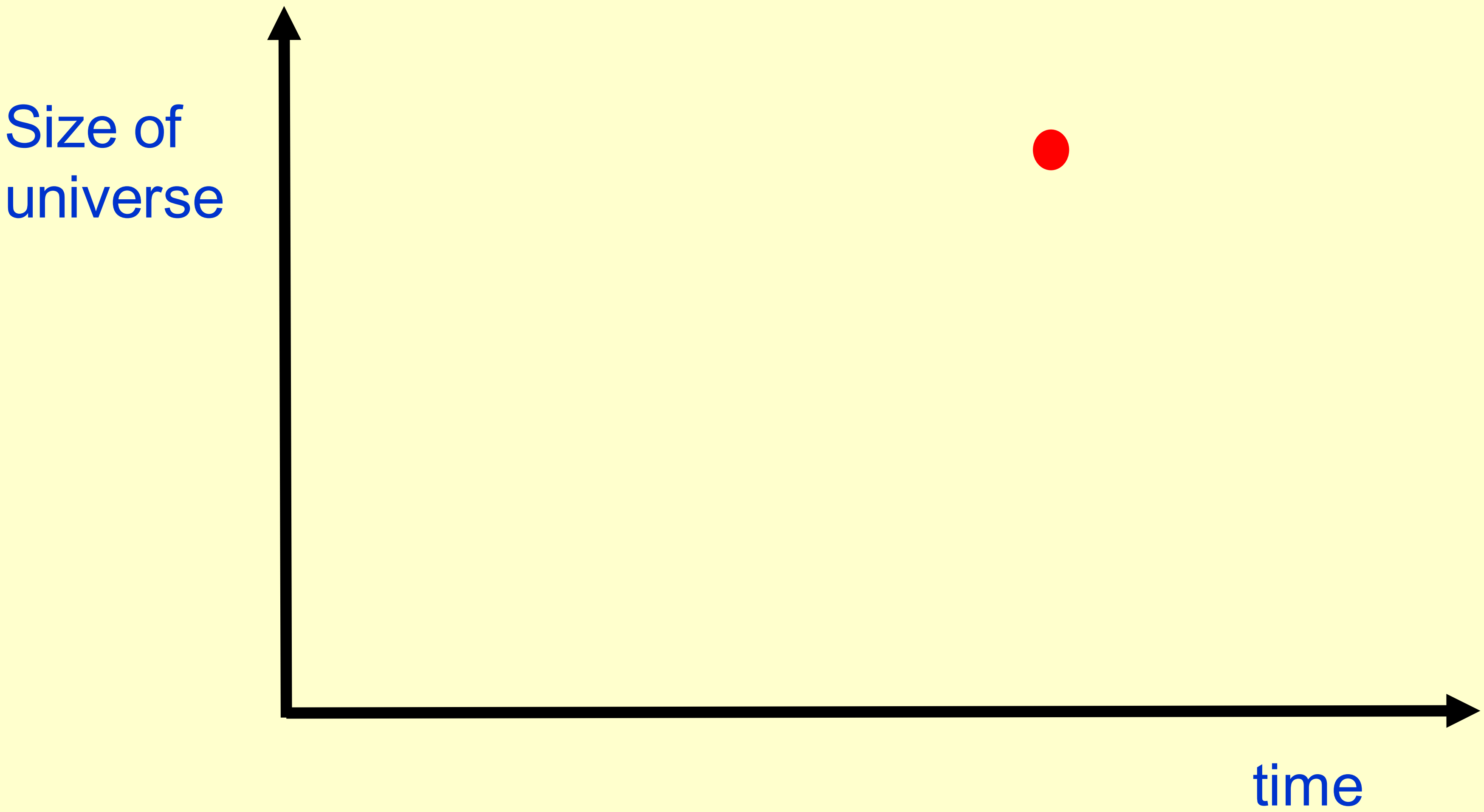
Vacuum energy: Einstein's missed chance

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

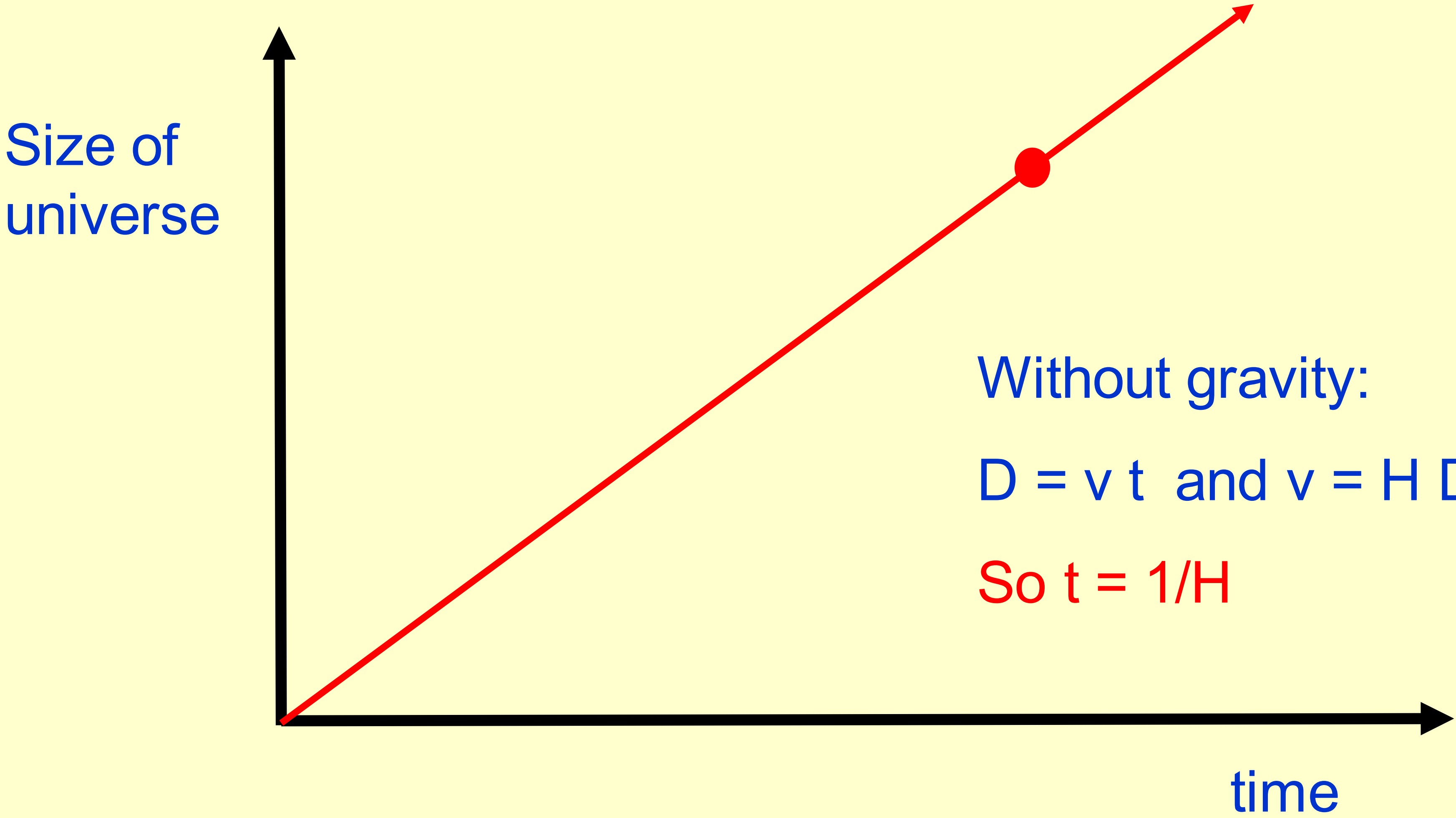
Now: **'Dark Energy'** can cause the expansion of the universe to accelerate



The Big Bang and cosmic acceleration



The Big Bang and cosmic acceleration



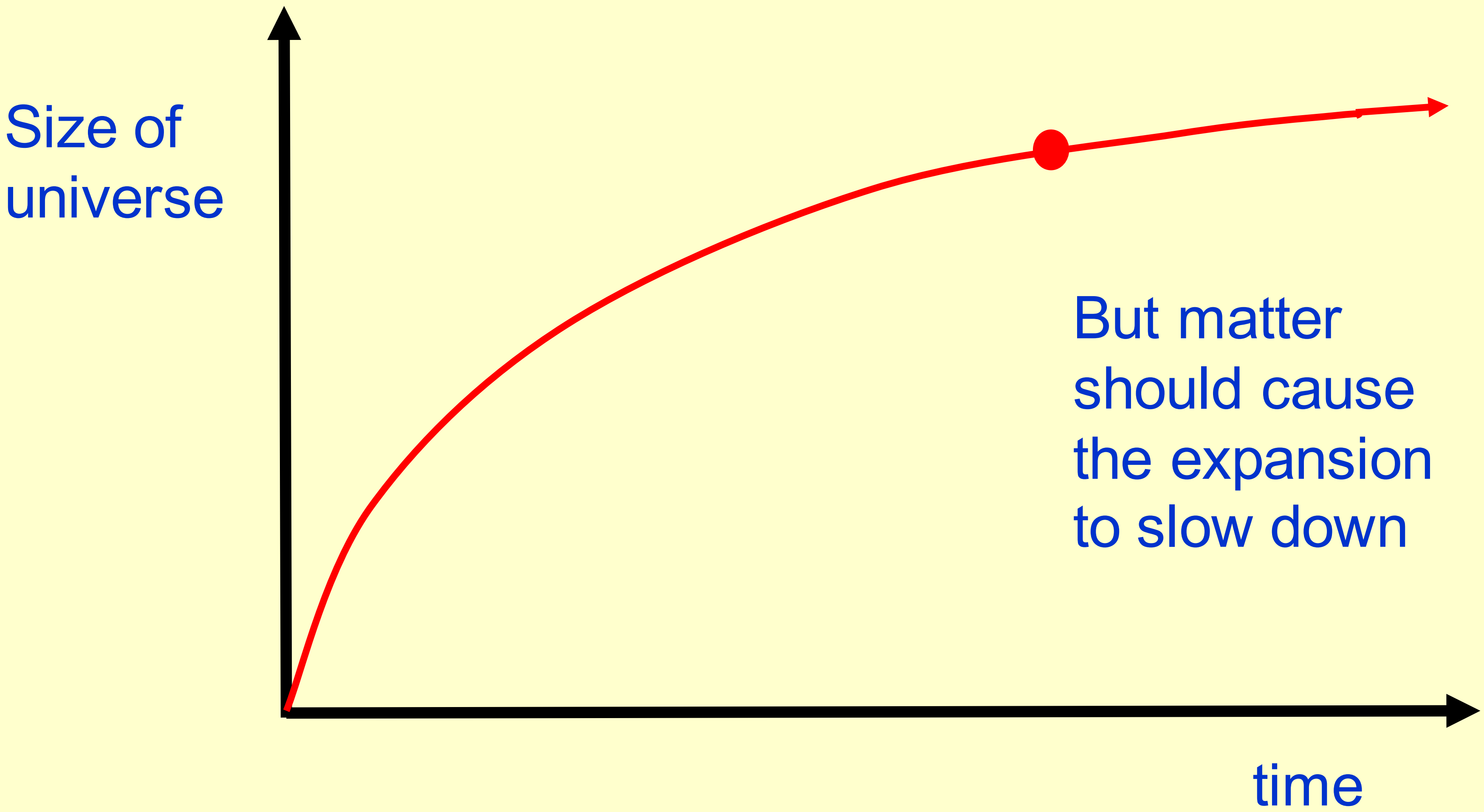
Without gravity:

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

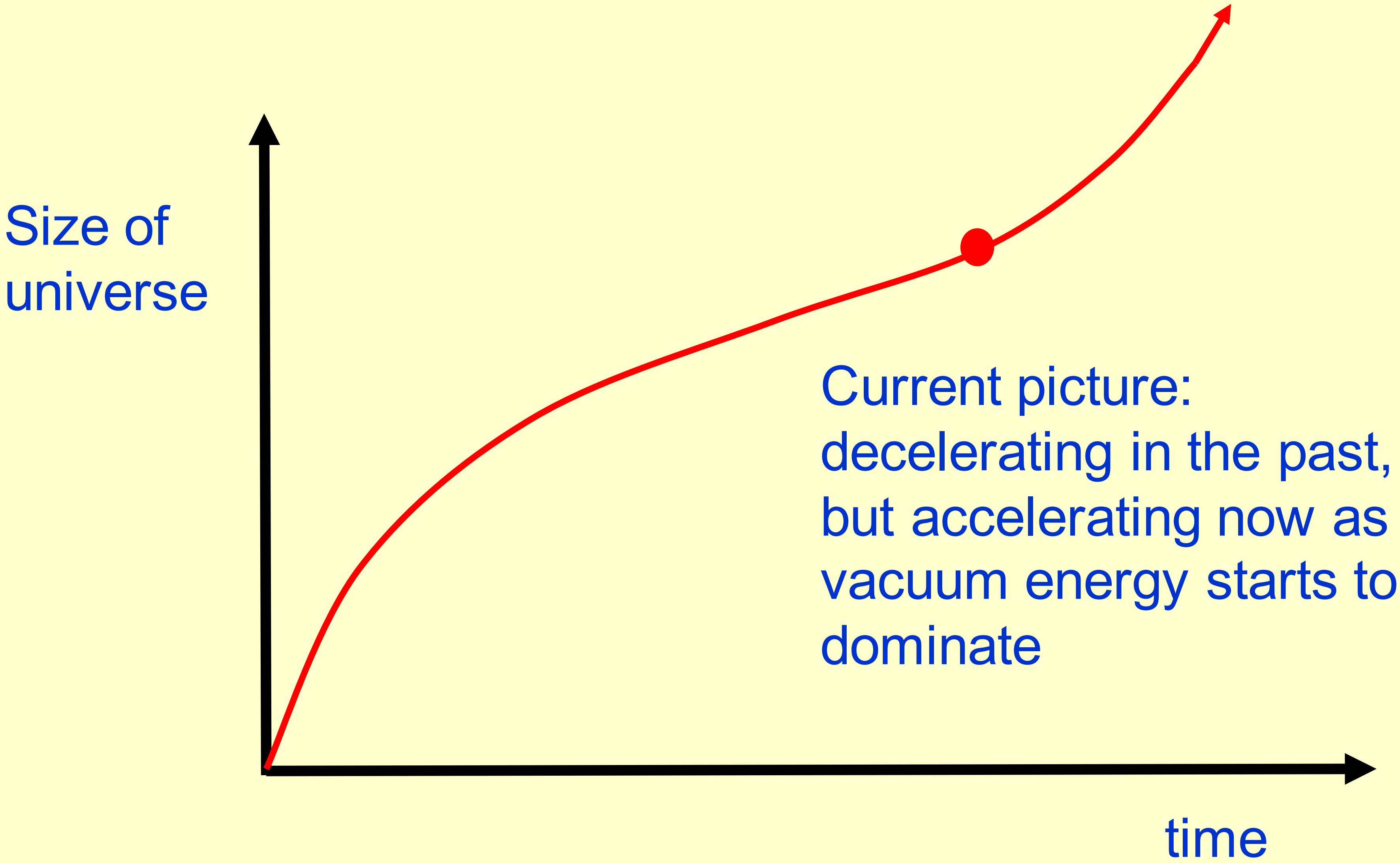
So $t = 1/H$

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

The Big Bang and cosmic acceleration

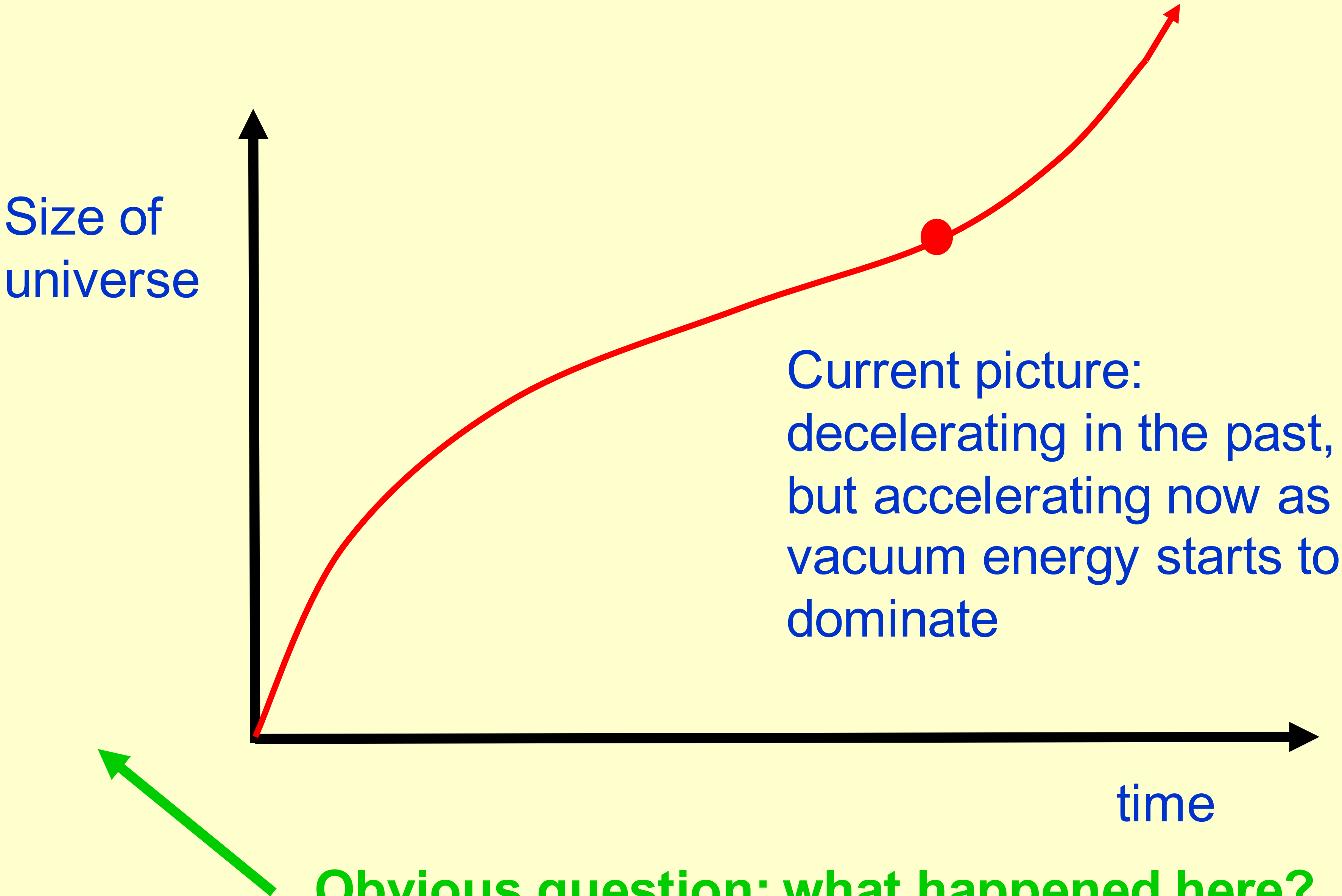


The Big Bang and cosmic acceleration



Current picture: decelerating in the past, but accelerating now as vacuum energy starts to dominate

The Big Bang and cosmic acceleration



Obvious question: what happened here?

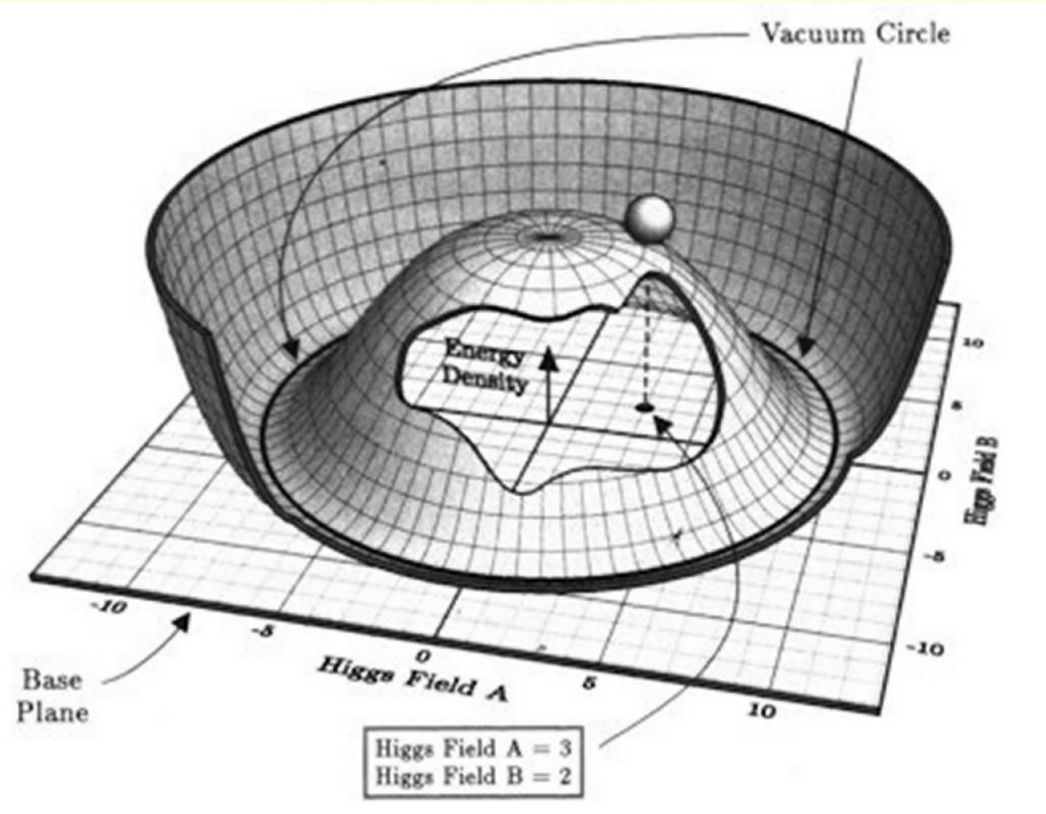
So everything is explained, except:

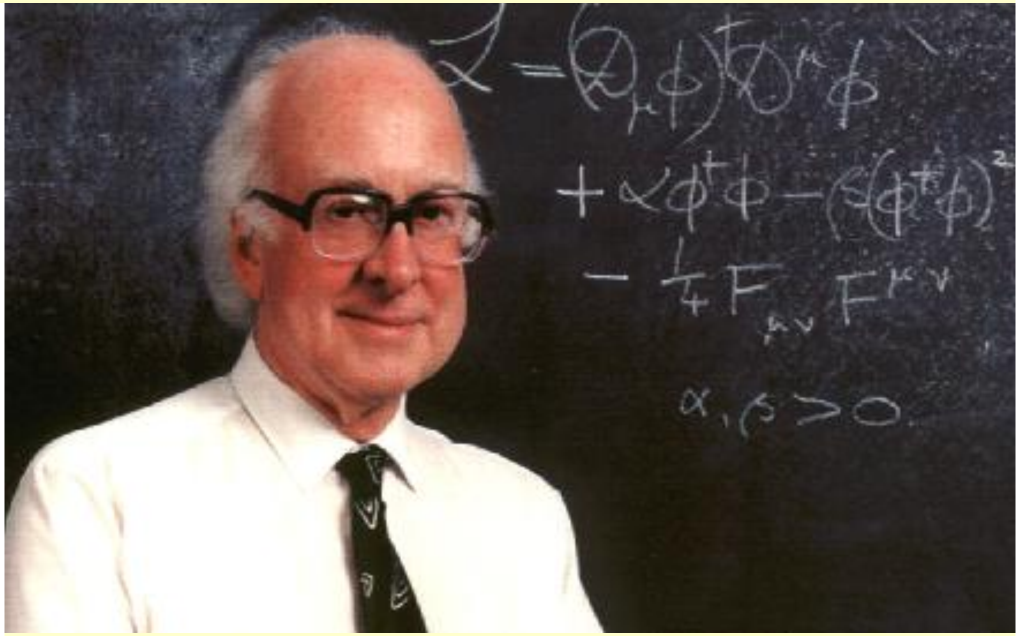
(1) What happened before the big bang?

(2) How can empty space have weight?

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

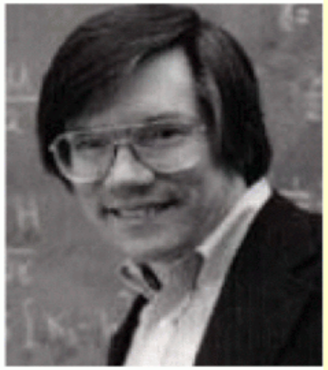
Peter Higgs (1963): explaining masses of elementary particles needs vacuum energy





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



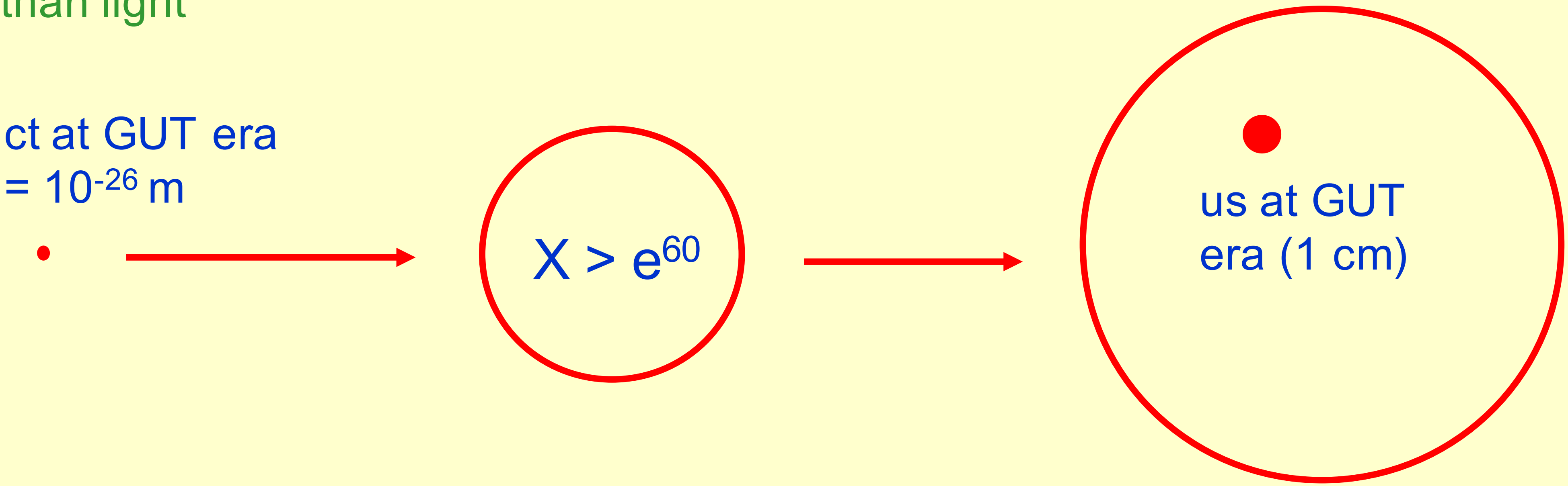
Alan Guth (1947 -)

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

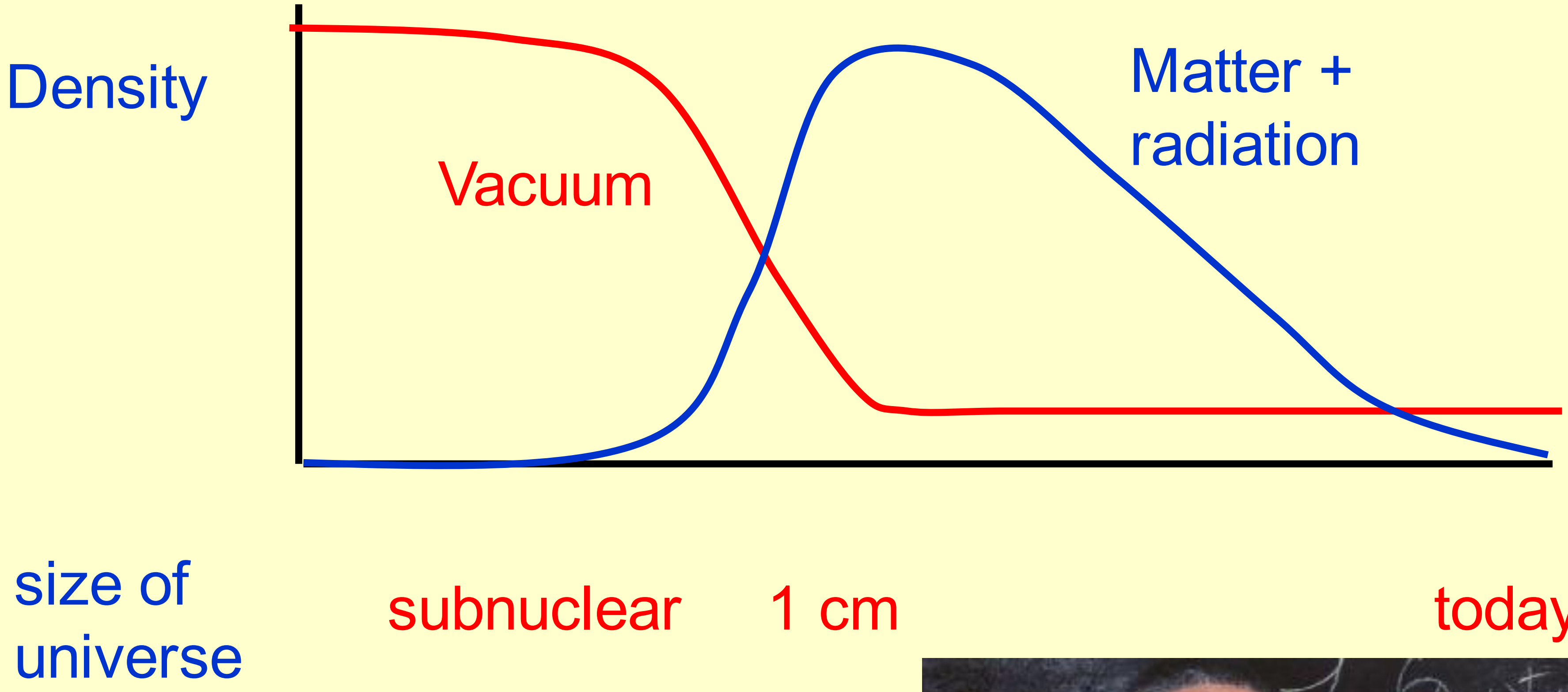
What if the vacuum density was much higher in the past?

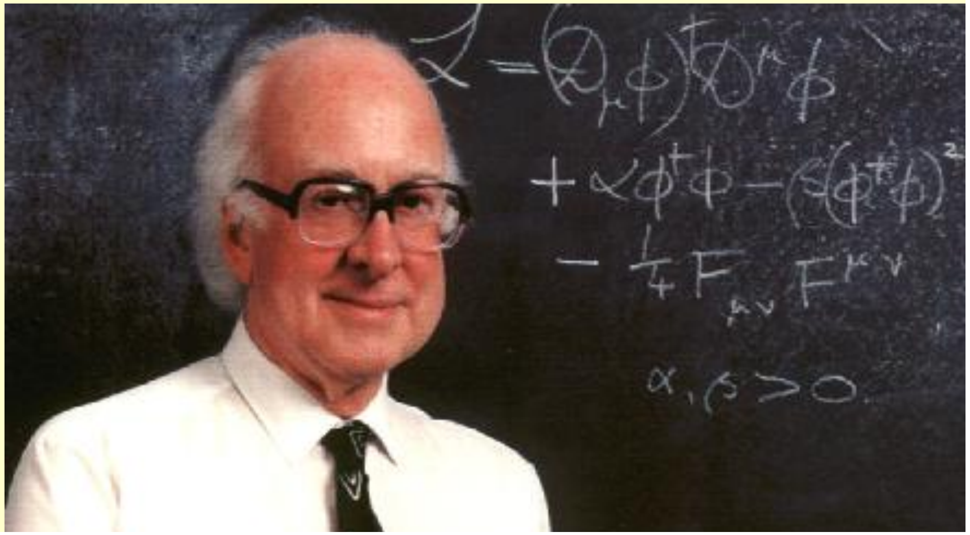
Needs 10^{80} kg m^{-3} to dominate at the ‘Grand Unification’ era of particle physics (10^{-26} today)

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



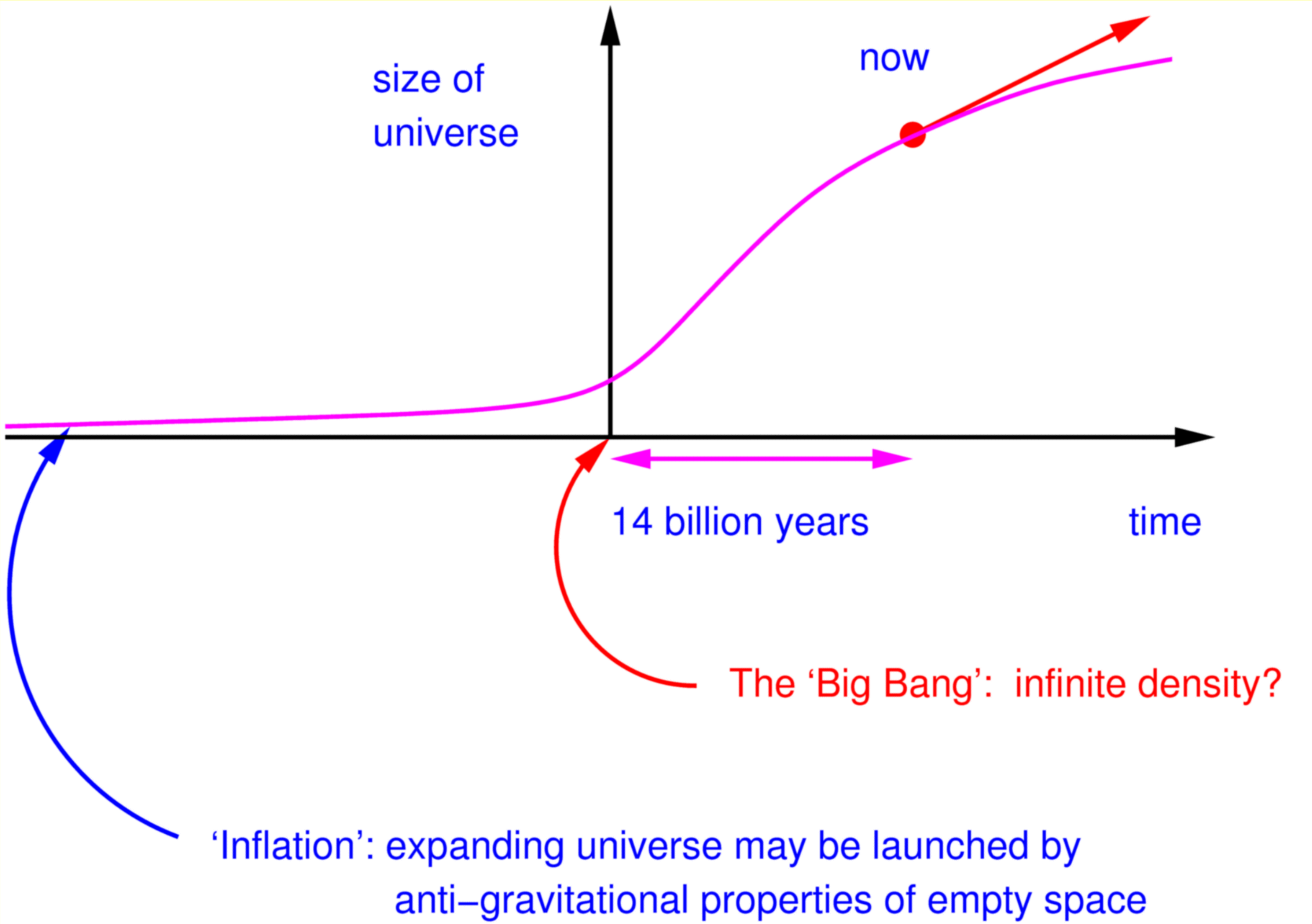
Inflation (1981): The History of the vacuum?





variable vacuum from something like the 'Higgs field' in particle physics

History of the expansion



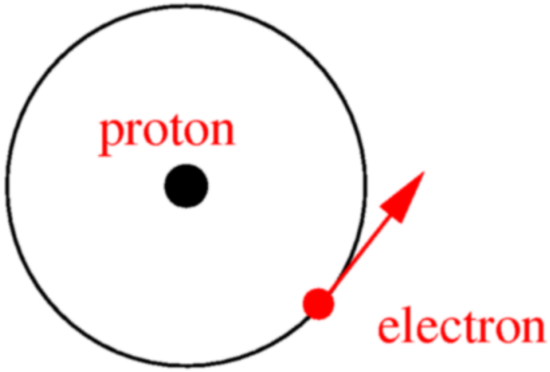
Physics of the subatomic realm: The uncertainty principle (1927)

$$\boxed{\Delta(mv)\,\Delta(x) \gtrsim \hbar}$$

Precise knowledge of both position and speed is impossible

Werner Heisenberg (1901 - 1976)

Sizes of atoms



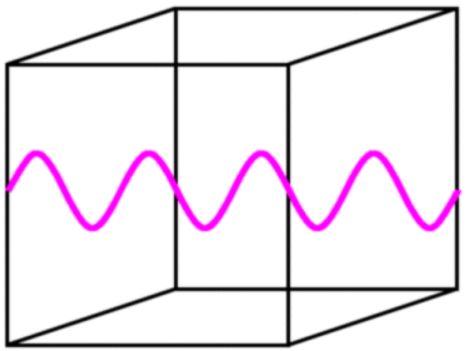
Uncertainty in speed of electron

= speed of light

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

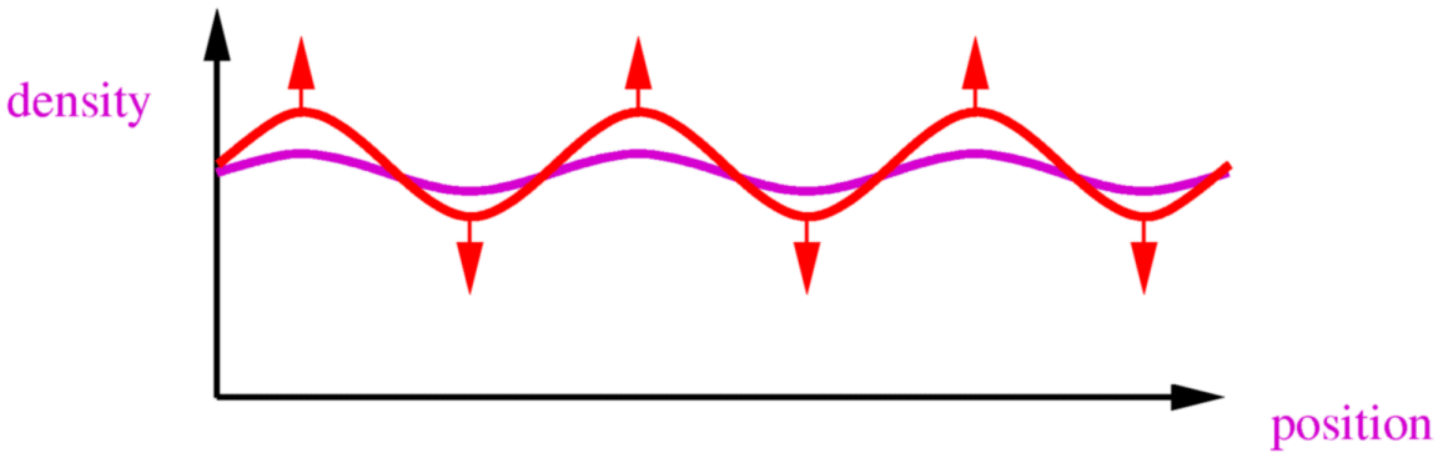
Quantum fluctuations and cosmic structure

The presently visible universe was once of subatomic size



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

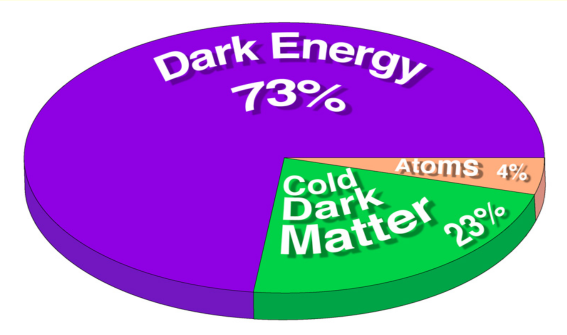
These are then amplified by gravity to make structure



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

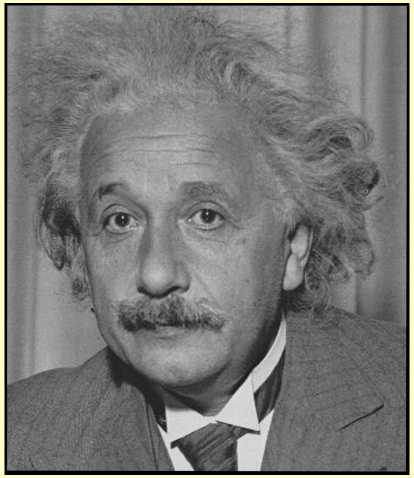
Is that everything?

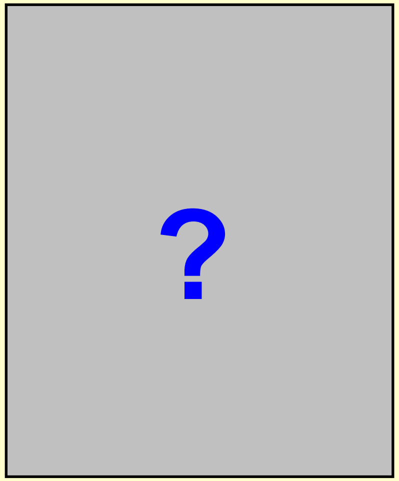
Maybe our theory of gravity is wrong



Dark energy: all current measurements relate to the accelerating expansion rate, assuming this comes from Einstein's 1915 General Relativity

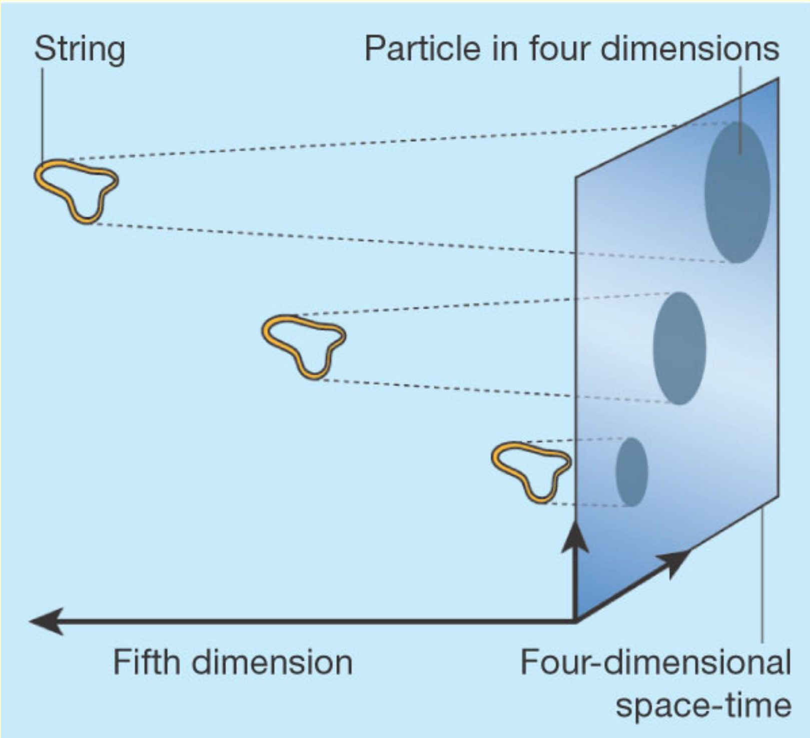
H^2(time) proportional to density of (matter plus dark energy)

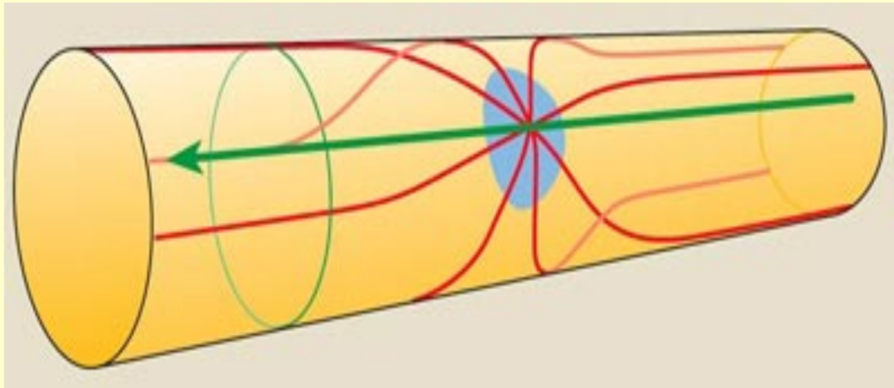




Example: extra dimensions

Are there more dimensions than we see? Speculation since the 1920s, revived via string theory





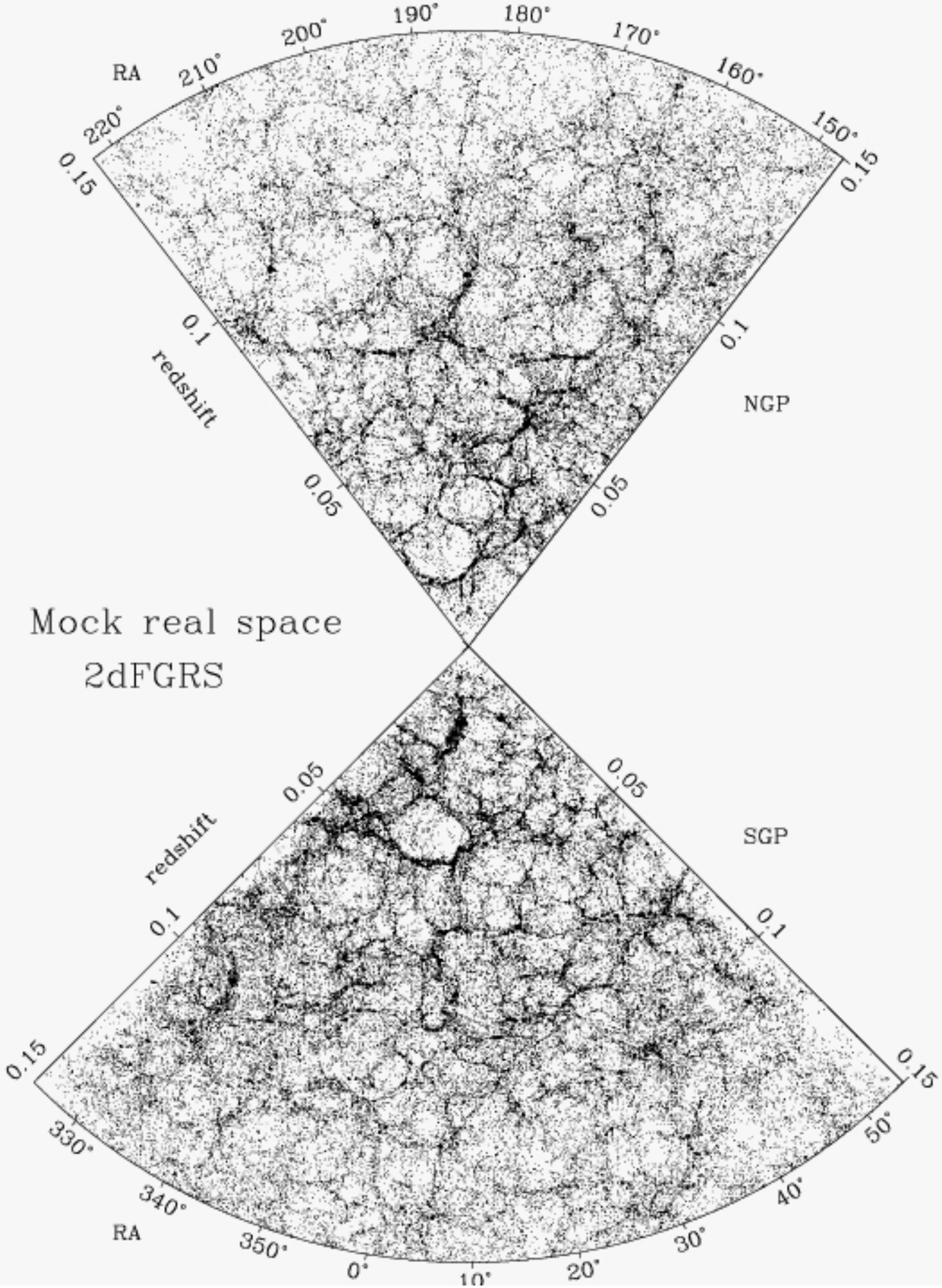
'Leakage' of gravity into 5th dimension changes strength with scale

How can we tell?

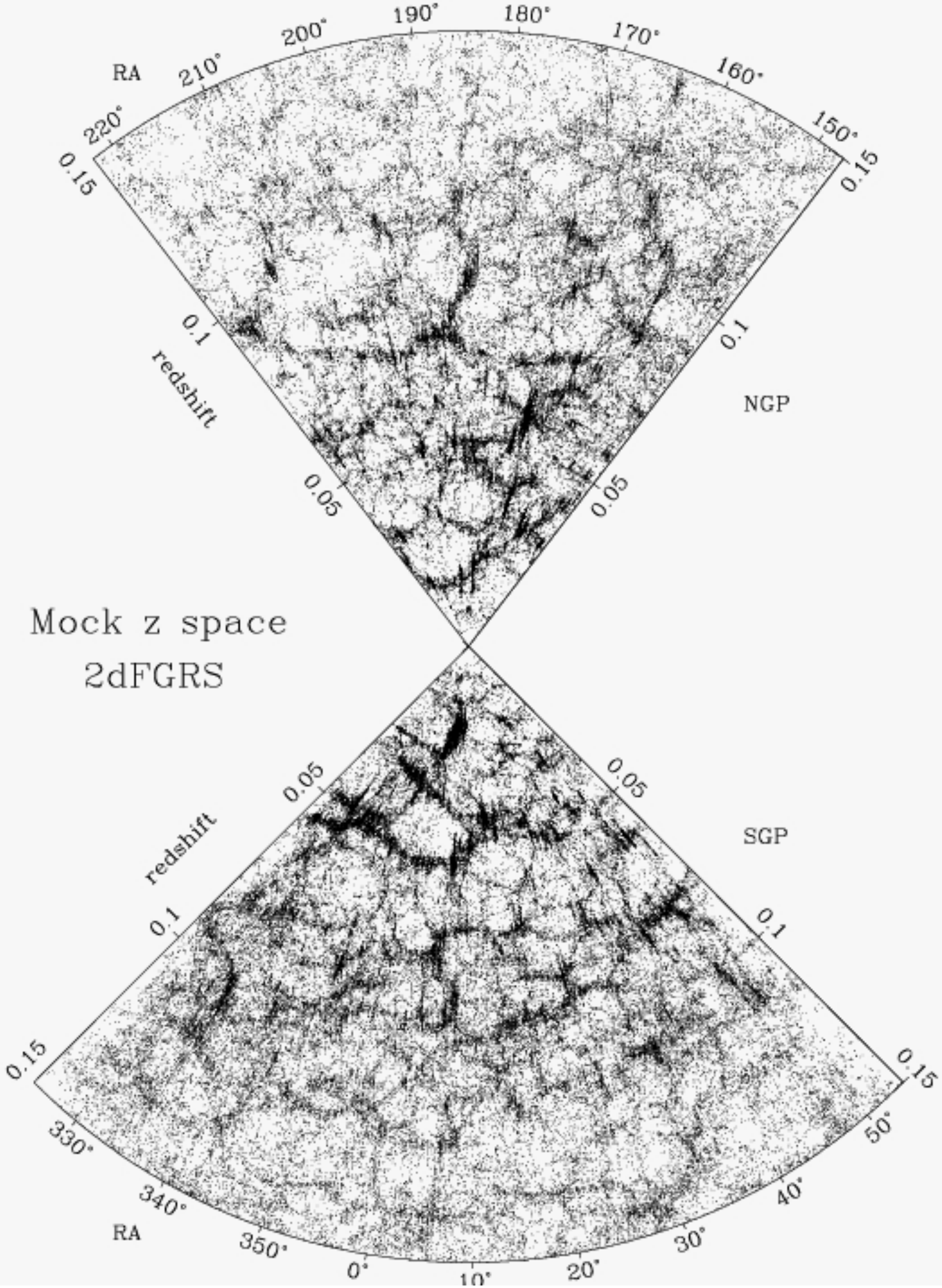
Measure gravity on intermediate scales, using the ‘peculiar velocities’ (deviations from uniform expansion) associated with structure formation

Peculiar velocities distort clustering

real space: where galaxies actually are in 3D



‘redshift space’:
assuming D = v / H
gives the wrong
distance



VIPERS

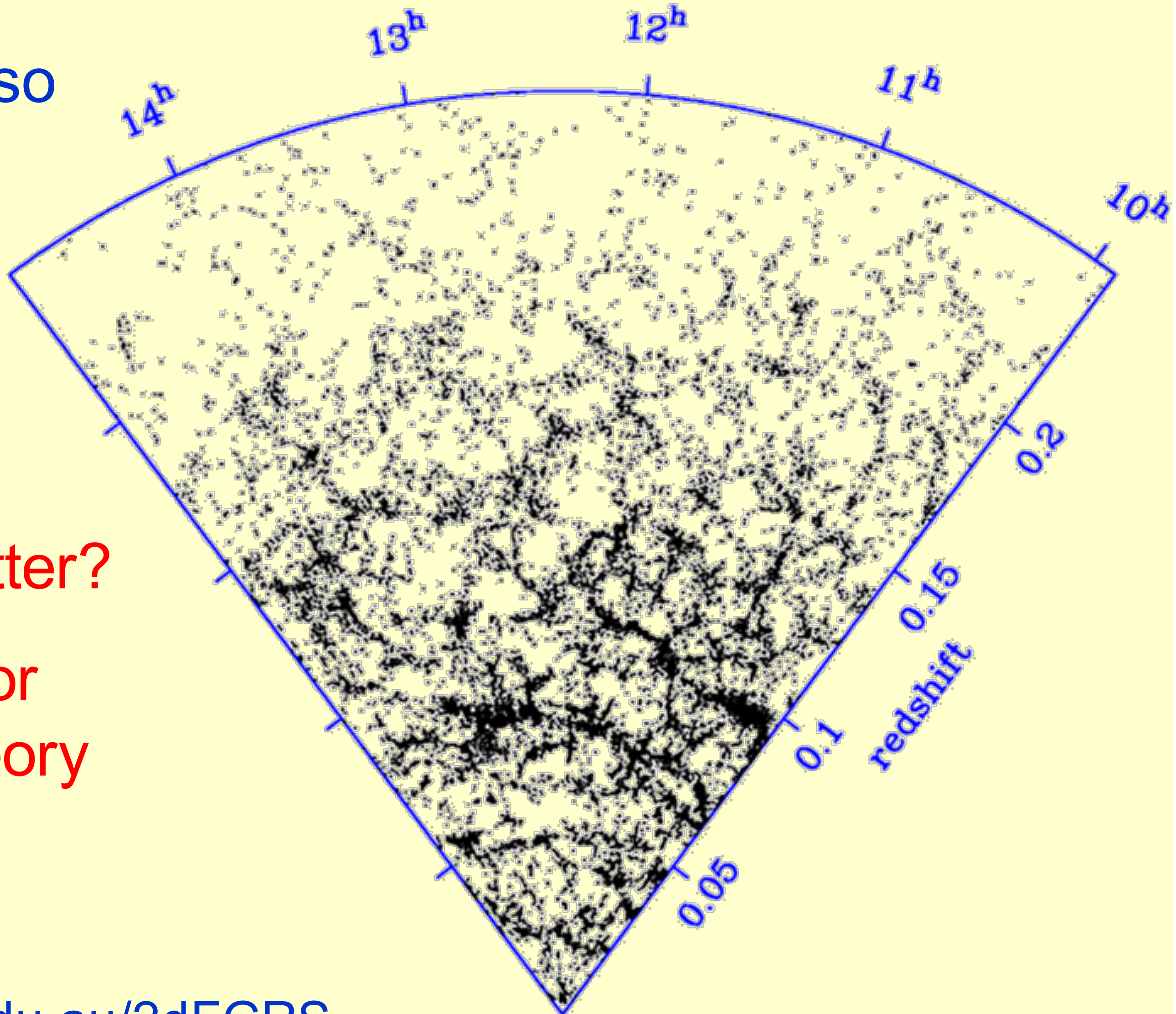
VImos Public Extragalactic Redshift Survey

Planning to test gravity by measuring redshift distortions using 100,000 galaxies

Observations at the Very Large Telescope in Chile

The outlook for cosmology

Huge progress, but also big questions:



• Did inflation really happen?

• What is the dark matter?

• Is dark energy real, or do we need a new theory of gravity?

See http://www.mso.anu.edu.au/2dFGRS

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