A universe, the Universe, or Multiverse

U. A. Yajnik

Indian Institute of Technology, Bombay

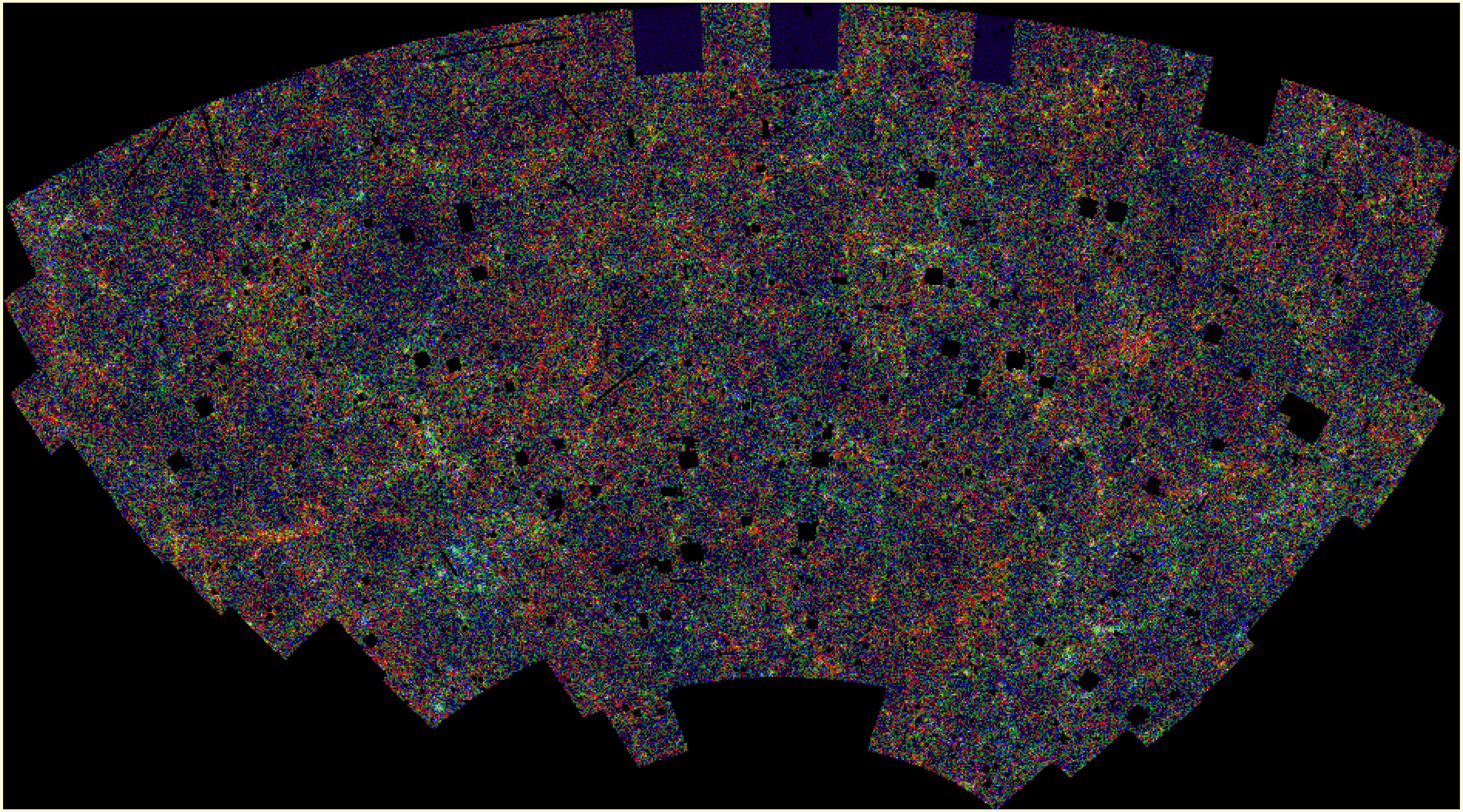
Punjab University Chandigarh April 1, 2015

Outline

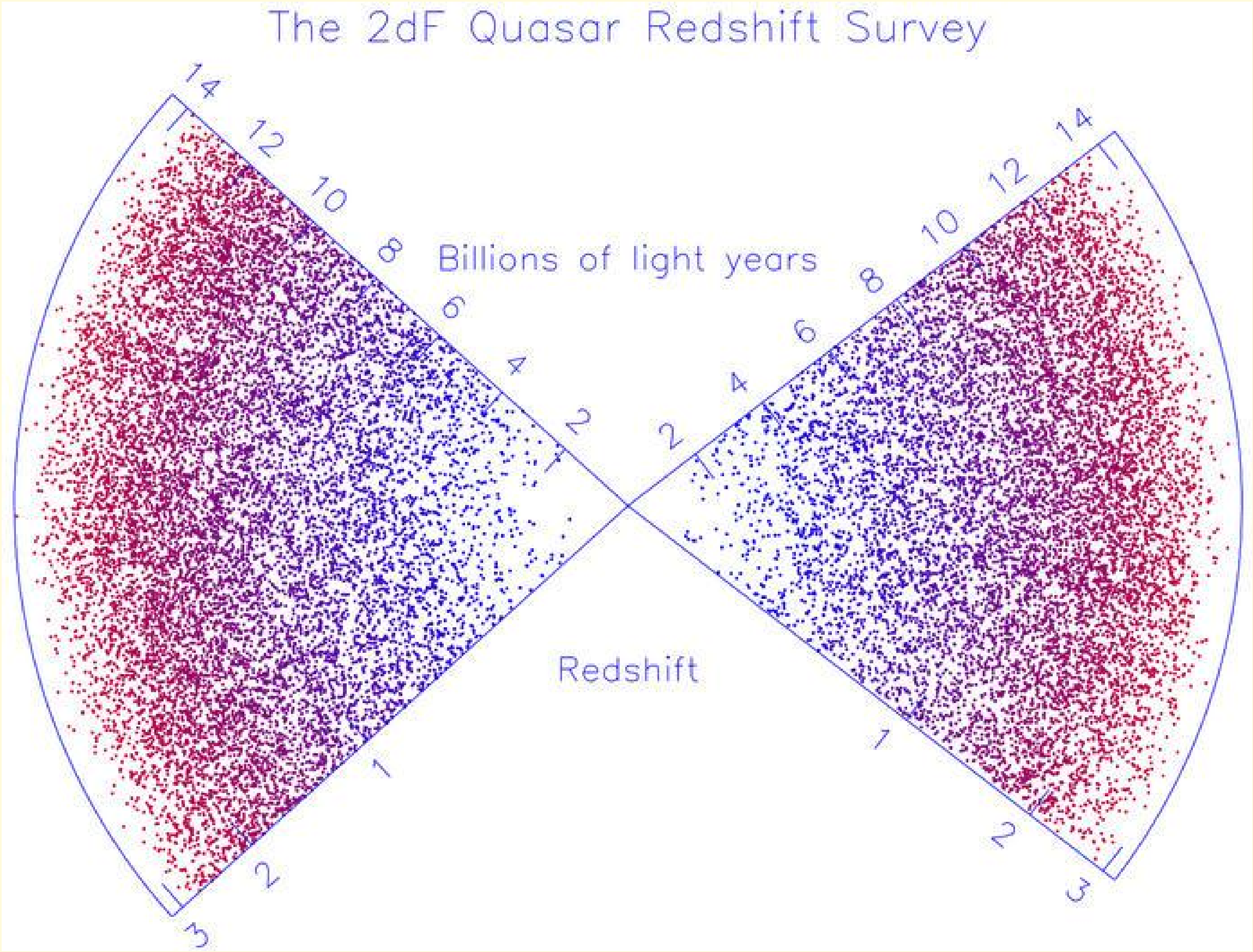
- The observed Universe
- What is Dark Matter?
- What is Dark Energy?
- Cosmic Microwave Background Radiation (CMBR)
- The big open questions

The Universe, observed

2degree Field Galaxy survey



2dF survey of quasars



The 2dF Quasar Redshift Survey
Billions of light years
Redshift
14
12
10
8
6
4
2
1
2
3

The Universe, observed

On the largest observable scales of distances, the Universe is homogeneous and isotorpic ...
this is actually also a great mystery.
Further, it is *v*ast in expanse, and well populated ...

→ About 100 to 300 billion stars per galaxy

→ About 100 to 200 billion galaxies already captured on our photographic plates

→ *As many stars in the Universe as there are specks of sand in all the beaches of the earth* – at the time of telling

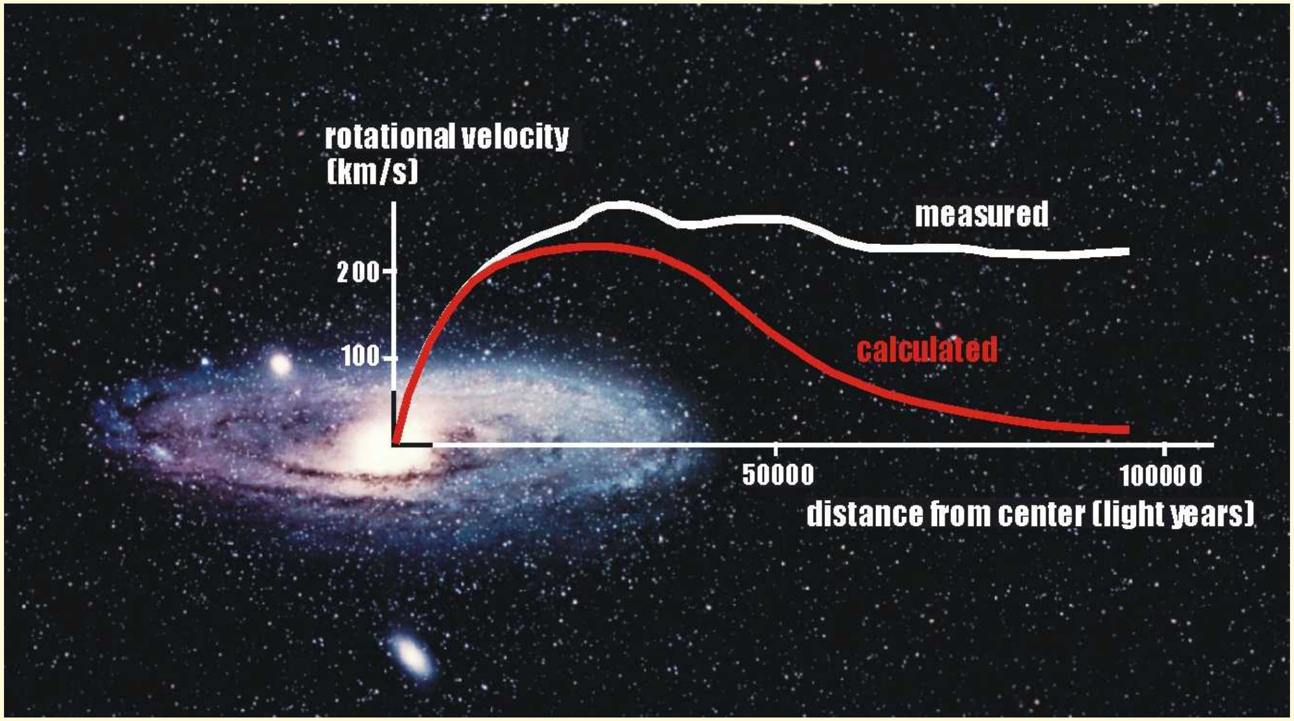
Dark Matter

Dark secrets of dark matter

A typical galaxy seen edgewise

Rotation curve for a galaxy

Doppler shift of the stars in the limb relative to average recession velocity of the galaxy gives "rotation curve"



A discreapnacy first observed by Zwicky (1934)

For a test particle (star!), at a distance R from the centre of the galaxy, velocity v is given by

$$\frac{v^2}{R} = G\frac{M(R)}{R^2}$$

So if most of the mass is concentrated within $R_{\max}$, then beyond $R_{\max}$,

$$v \propto \frac{1}{\sqrt{R}}$$

But ... the v vs. R curves continue to rise and become flat.

Persistent effect at all scales of distances

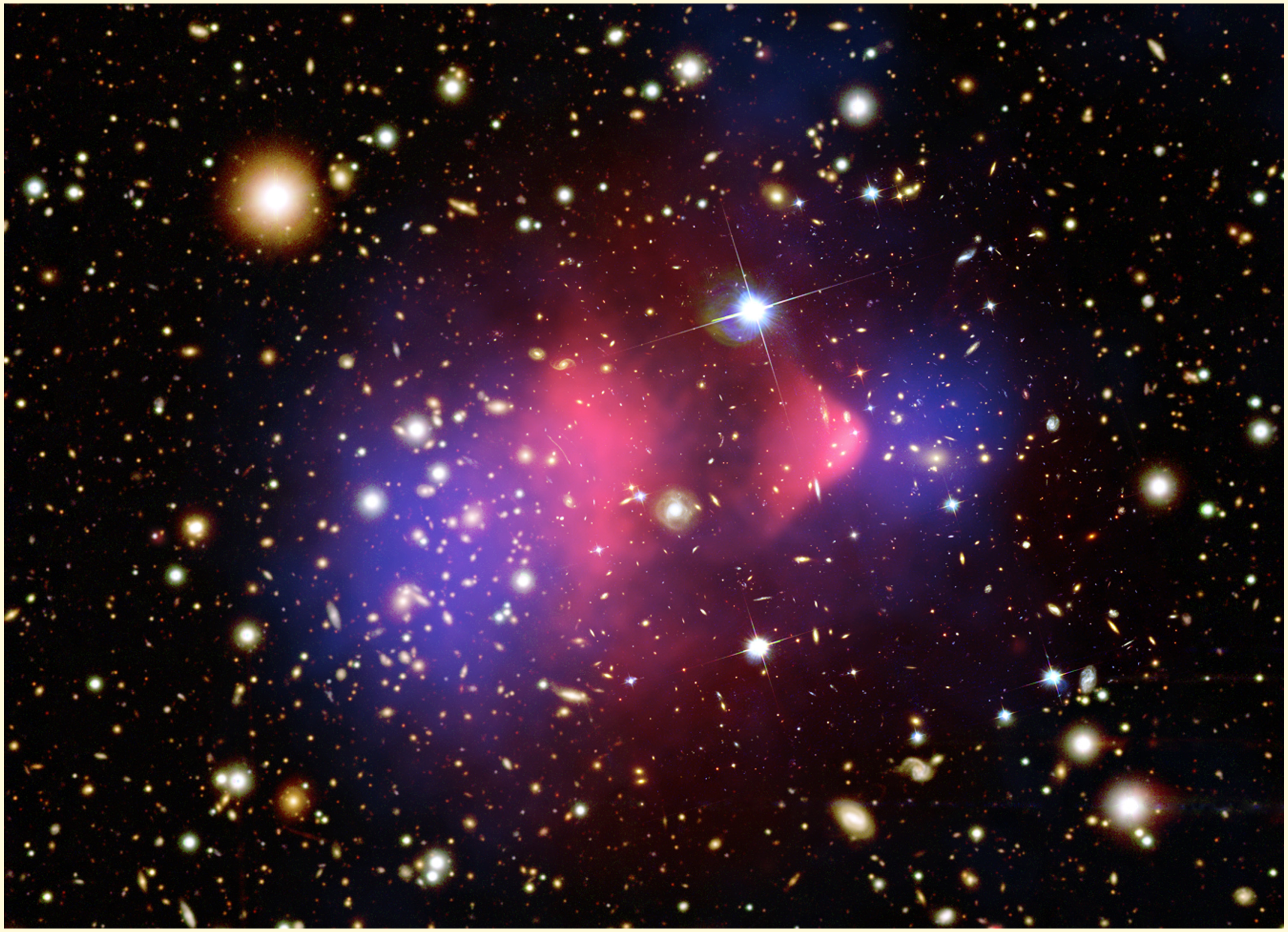
Some scientists insist it is time to modify Newton's gravity on galactic scale ...

$\rightarrow$ But the effect repeats at the scale of clusters of galaxies.

$\rightarrow$ And at the level of superclusters galaxies

$\rightarrow$ Further, ... there is smoking gun evidence as of year 2006

Galaxies caught in the act of colliding



The picture is composite of three different sources of data ...

... and with simulated color

→ Background of galaxies from Hubble Space Telescope

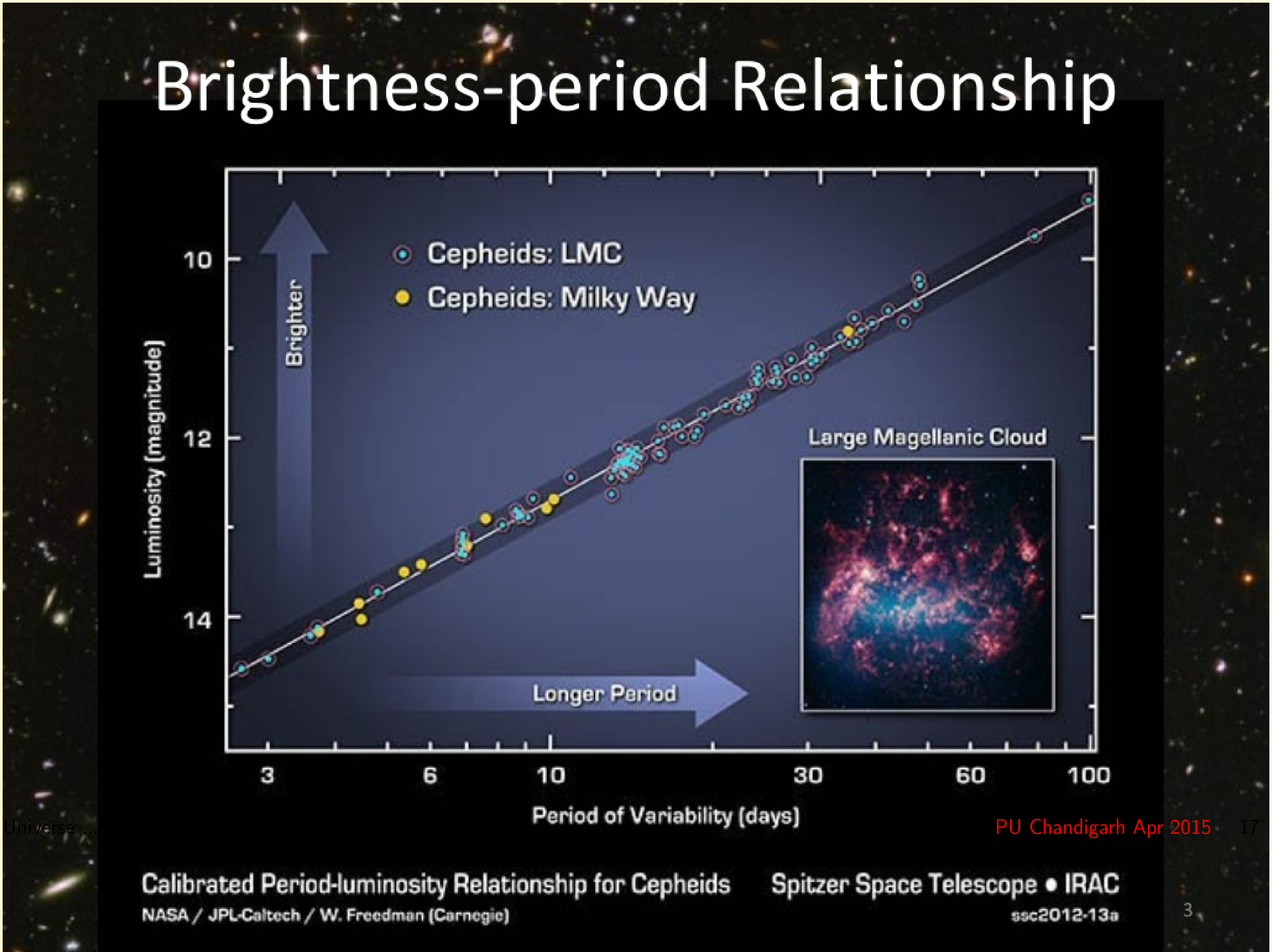
→ Red gas from X-ray observation satellites Chandra and XMM Newton

→ Blue gas (Dark Matter) from gravitational lensing ...

Dark Energy

- Begin in the 1920's ...
- New telescopes like Hale observatory and Mt. Palomar 200 in. telescope for the first time made galaxies visible in detail to human beings
- Henrietta Leavitt calibrates the Cepheid variables
- Hydrogen spectra of most of the 20+ galaxies showed a redshift rather than a blueshift.
- Edwin Hubble drew a line through the redshift vs. luminosity distance plot.

Brightness-period Relationship



Henrietta Leavitt

Hubble draws the line

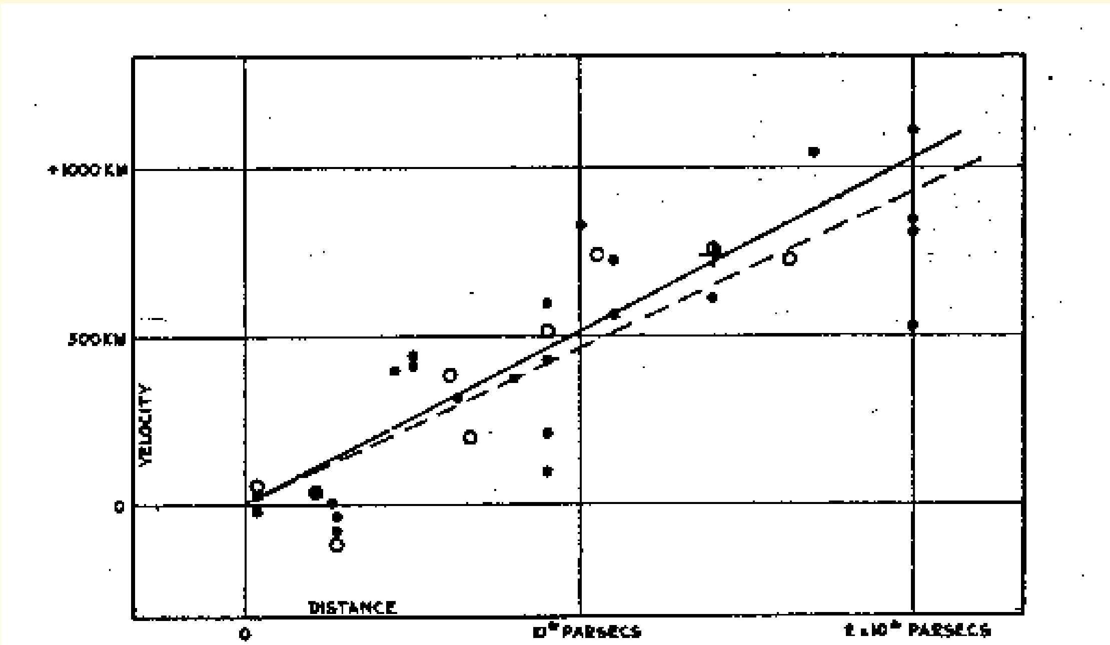
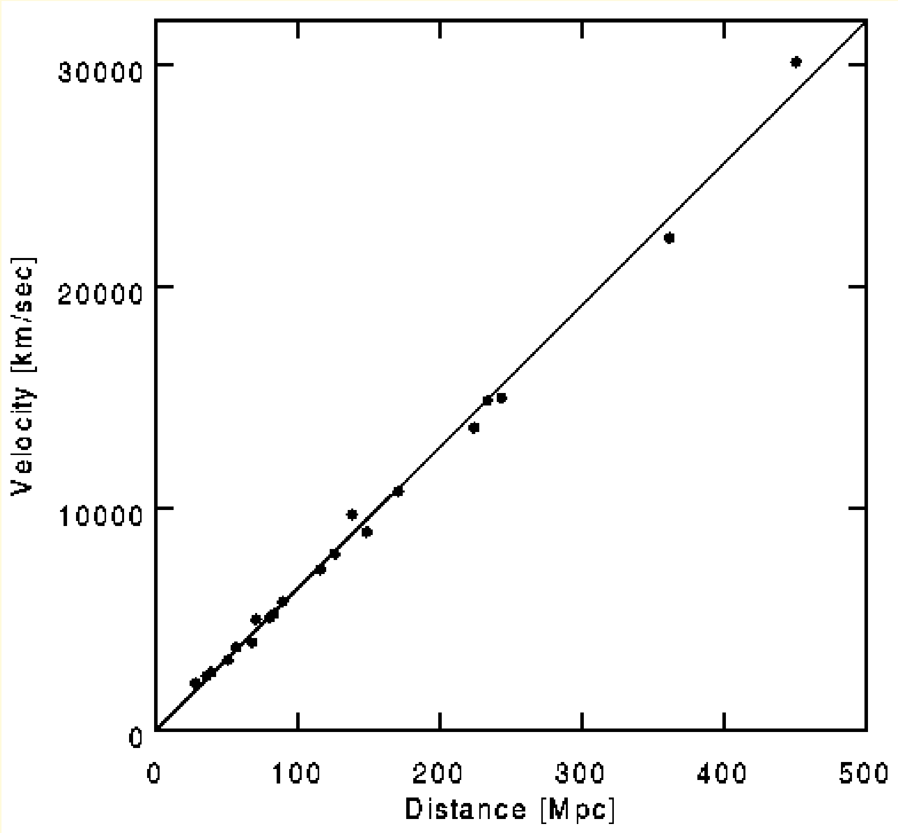
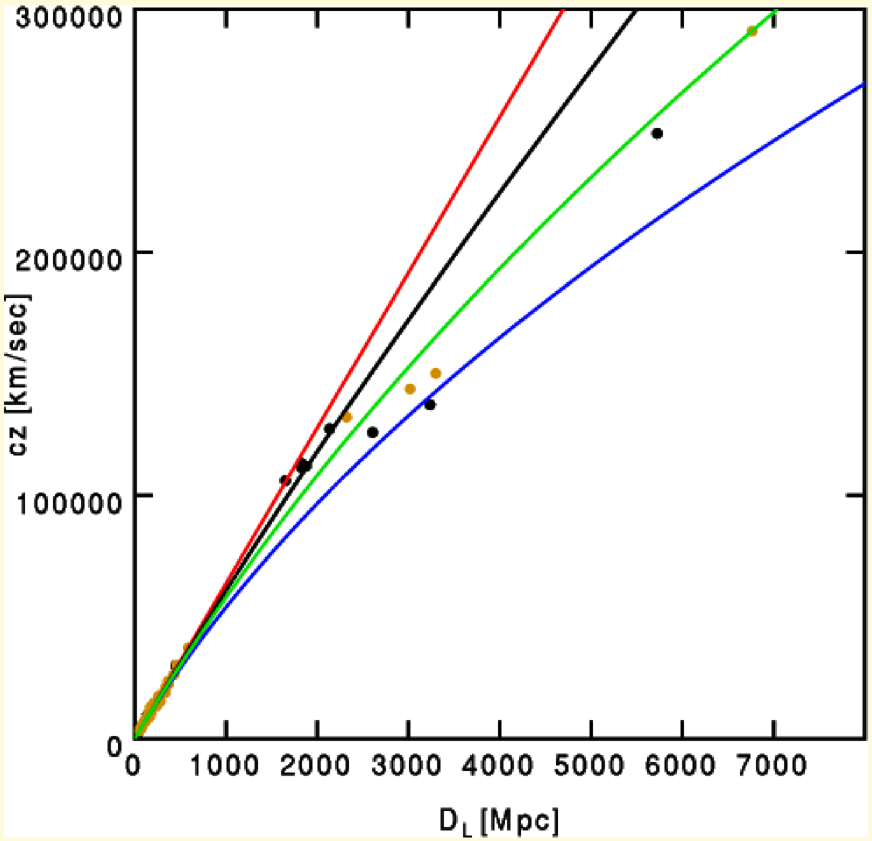


FIGURE 1

A Hubble Plot before Hubble Space Telescope



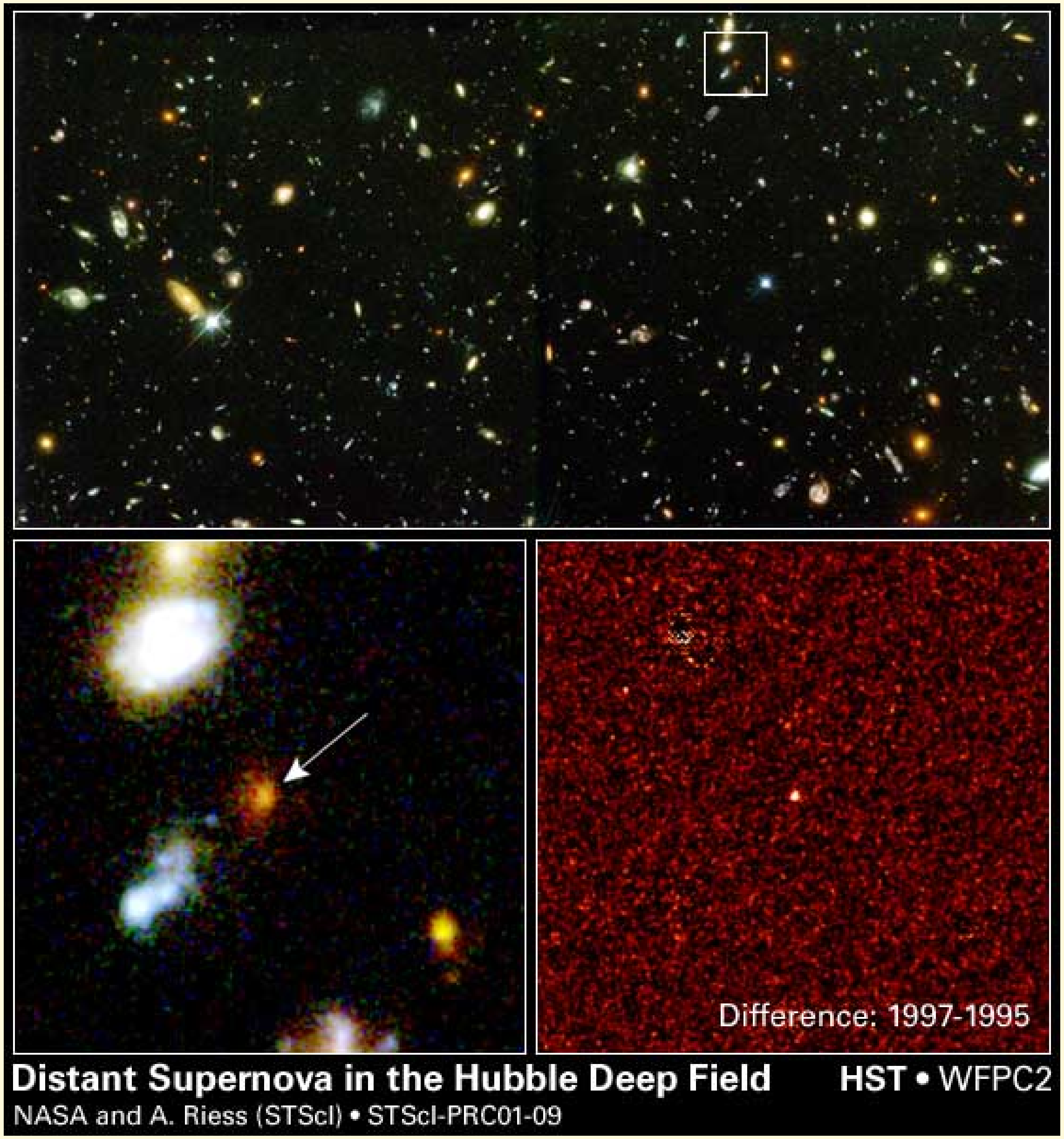
Modern Hubble plot – HST data included



- Expansion of the Universe has now been very well established
- But what is the rate of change of Hubble velocities?
- Is the expansion slowing down or speeding up?
- Gravity only attracts!
- So if the Big Bang pushed everything out for whatever reason, it should now start slowing down

Ground based telescopes could not distinguish the minute acceleration vs deceleration

By 1997 Hubble Space Telescope observed ... *a blast from the remote past*


Difference: 1997-1995
Distant Supernova in the Hubble Deep Field
HST • WFPC2
NASA and A. Riess (STScI) • STScI-PRC01-09

→ The bright spot glowed only for three weeks against the rest of the sky – digitally subtracted in lower right corner

→ This supernova had exploded 7 billion years ago – before the Sun began its life 4.5 b. years ago

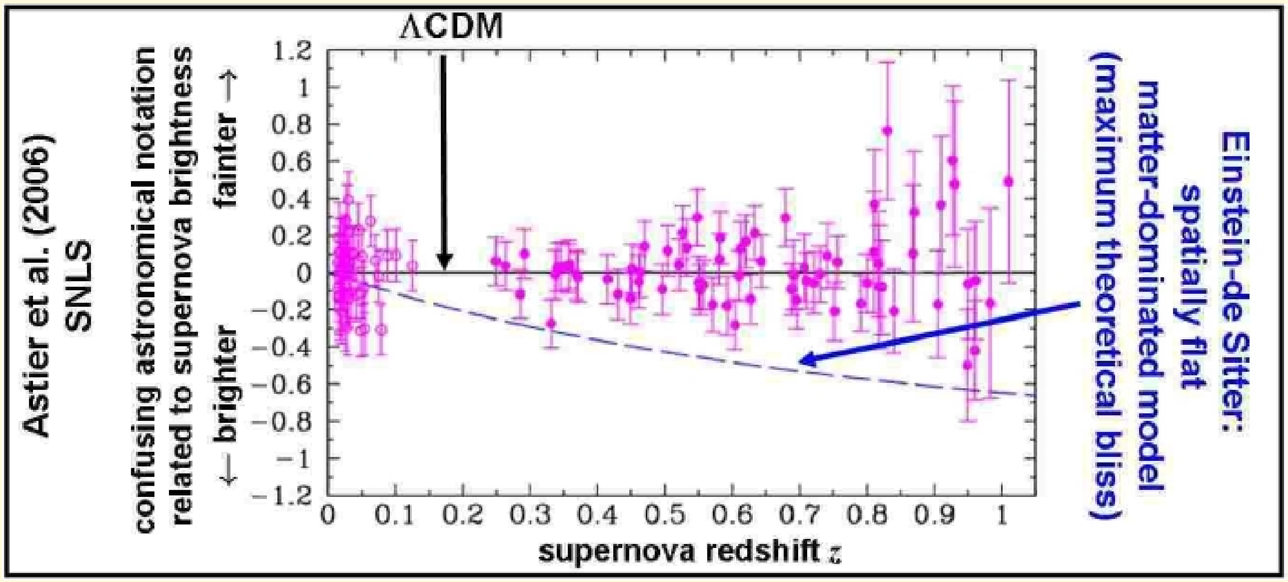
→ The explosion was captured in real time in Hubble Space Telescope

The next movie shows the reconstructed light curve of such a flare up.
The special form of the light curve characterises "Type Ia" supernova.
The total duration of the explosion is decides the absolute peak luminosity.

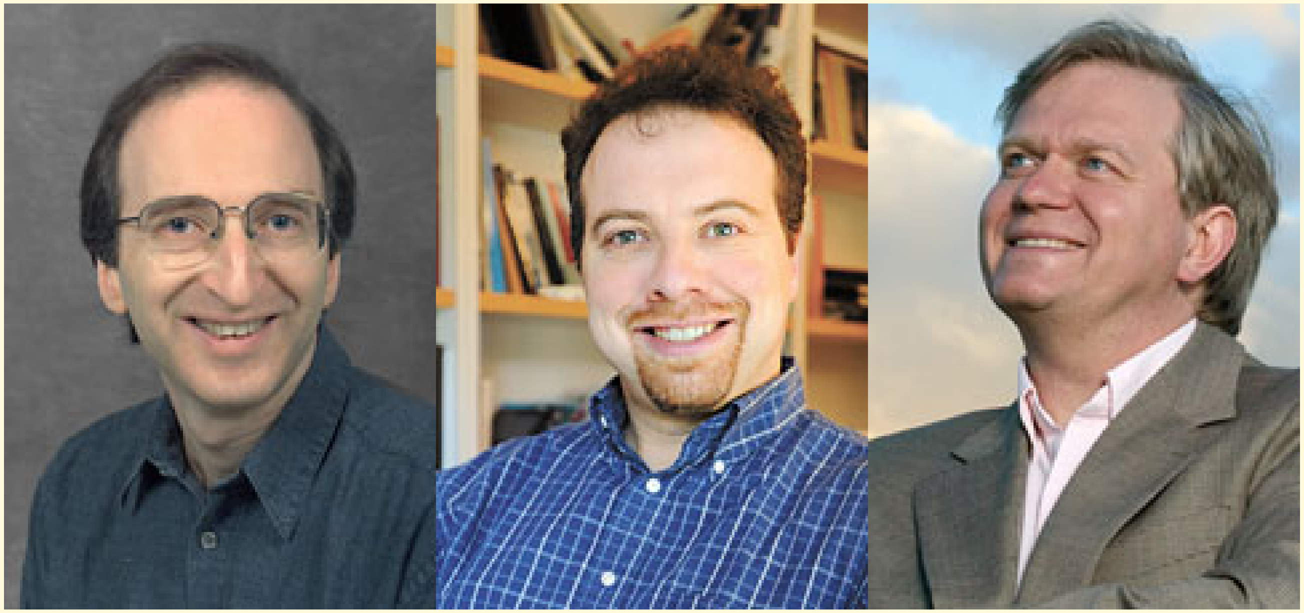
Perlmutter video

Accumulated data on such ancient supernovae

Show movie



Nobel 2011 for Perlmutter, Riess and Schmidt



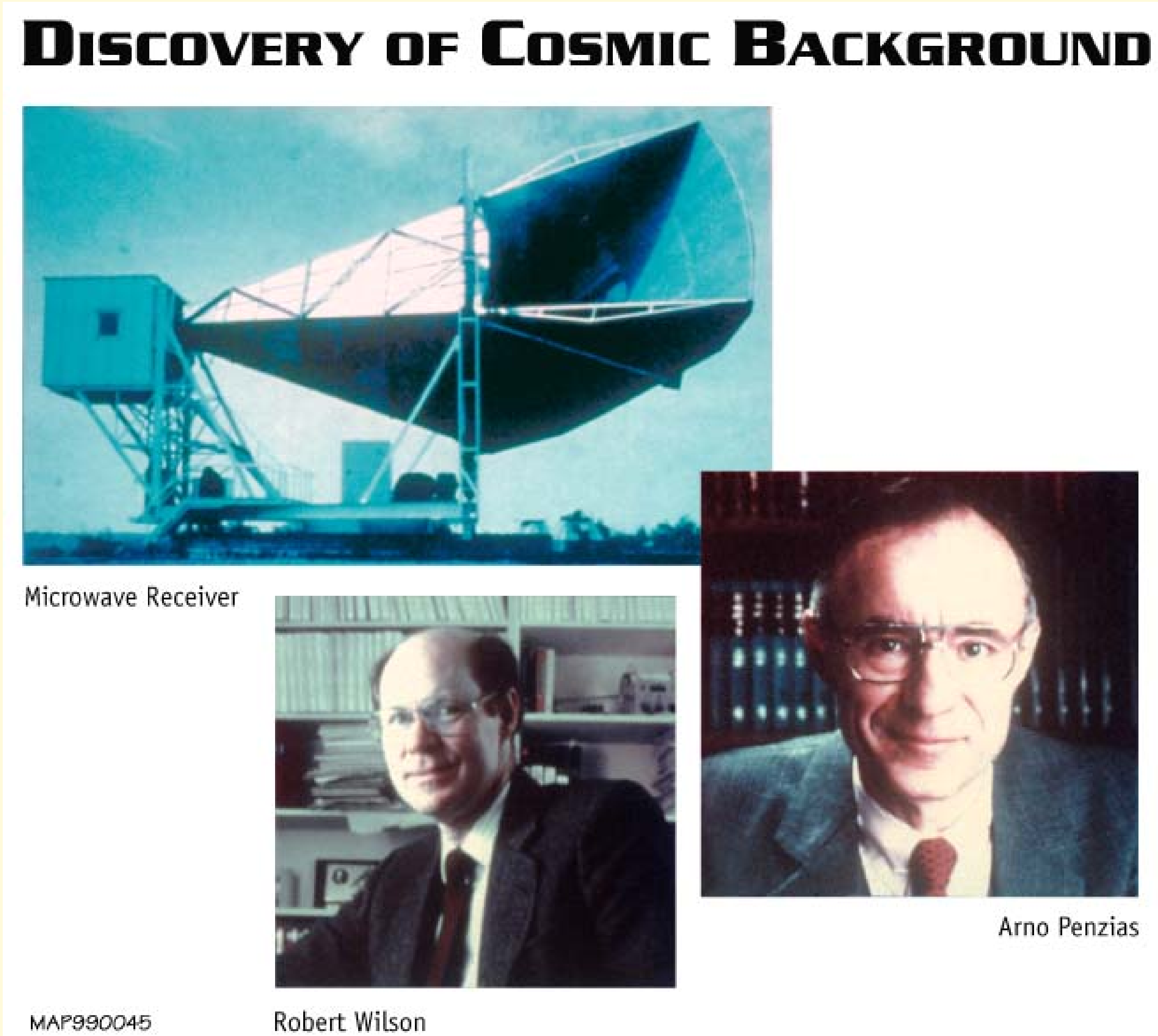
- The accumulated data of these ancient Type Ia supernovae strongly suggest that the Universe is accelerating rather than slowing down.

- Gravity usually only attracts, and slows down an expansion

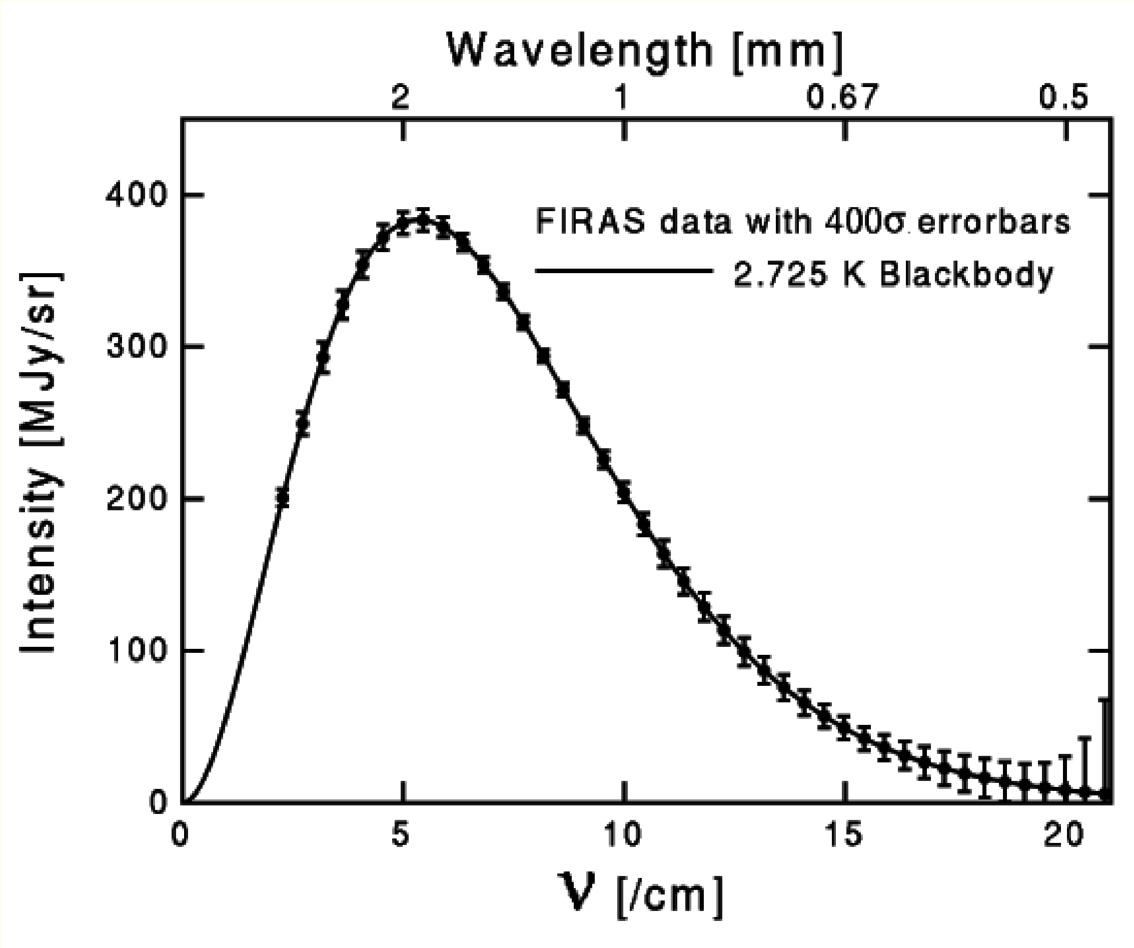
- This means that there is a very unusual form of matter-energy present in the Universe
- Special relativistic medium with *negative* pressure

All this is independently confirmed by ...

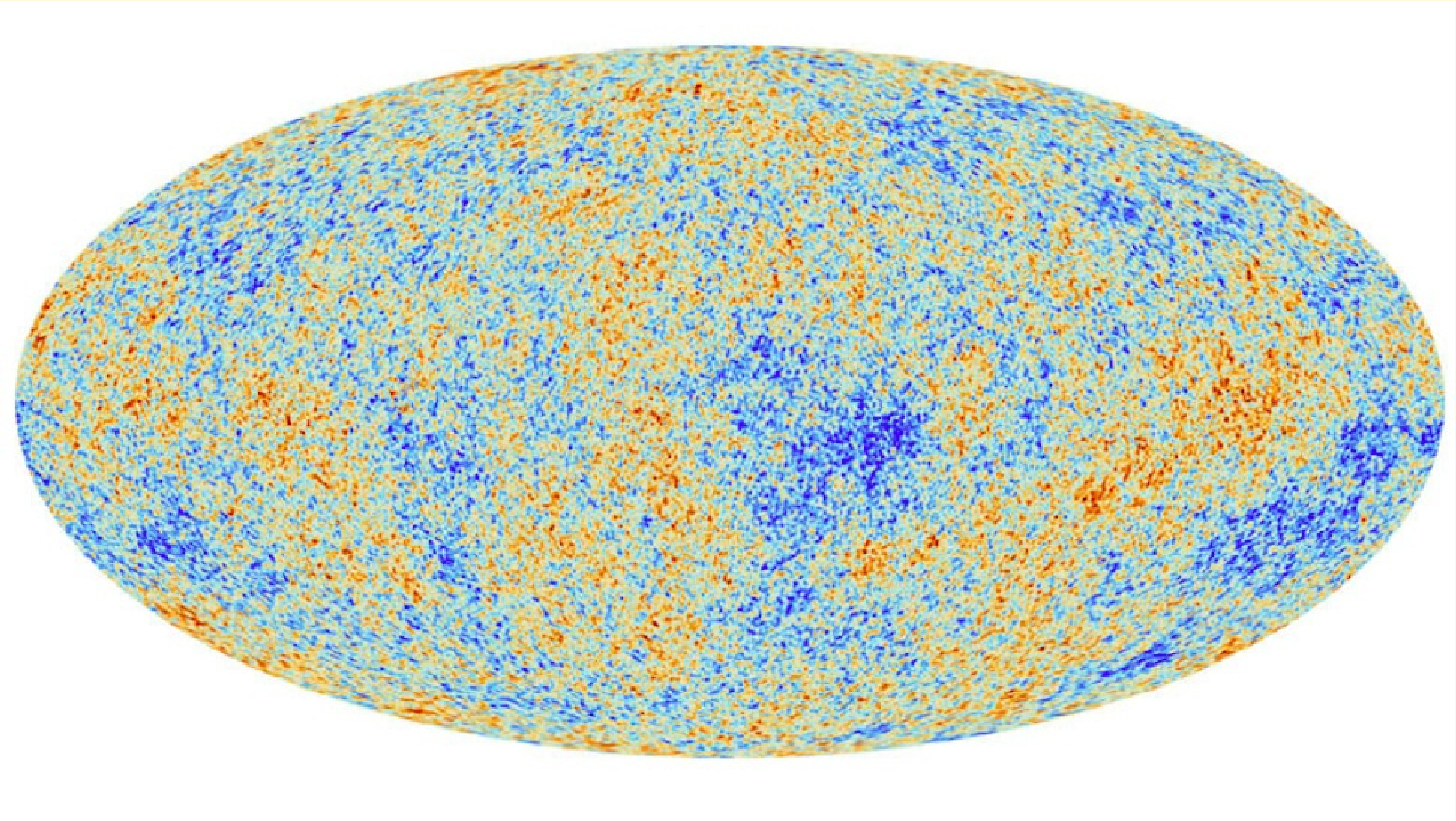
Cosmic Microwave Background Radiation CMBR


DISCOVERY OF COSMIC BACKGROUND
Microwave Receiver
Arno Penzias
MAP990045
Robert Wilson

COBE obtains a near perfect Planck spectrum of CMBR 1993



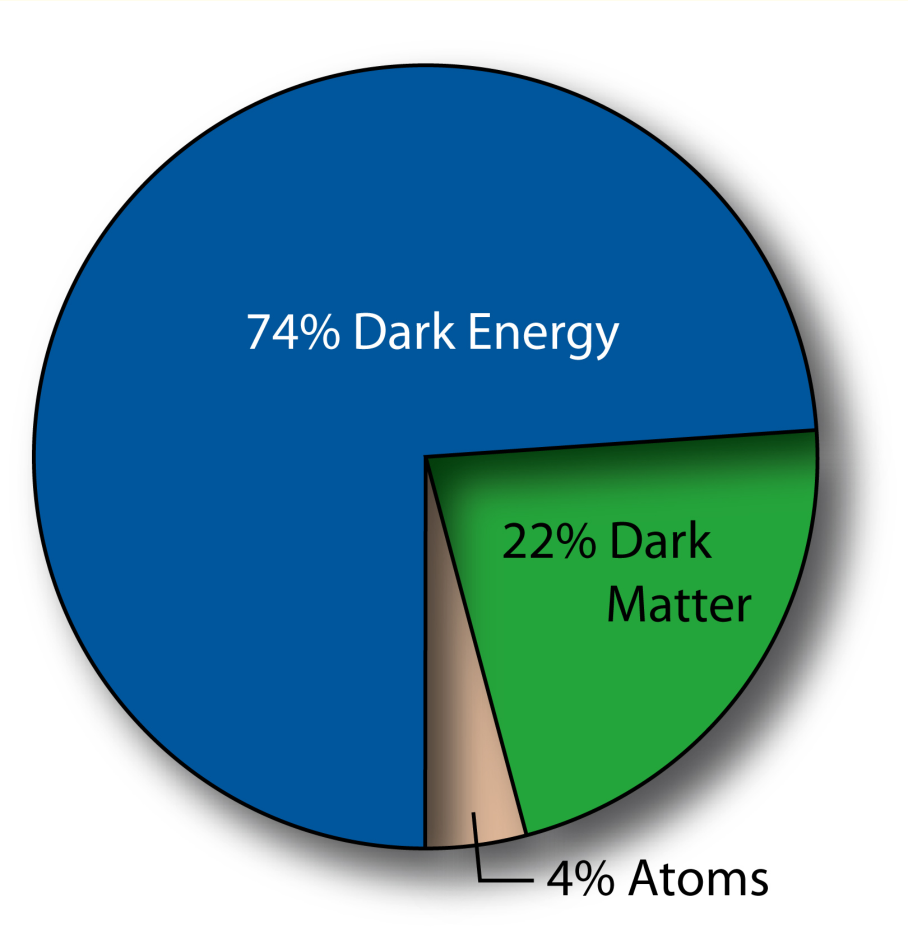
Planck satellite data as of 2013



These fluctuations are very charming blemishes ... 1 part per 10^5

- Exactly as required so that stars ... and us ... can be formed
- Their detailed study reveals that they exactly agree with accelerating Universe but not a descelerating one!
- The CMBR fluctuations confirm both Dark Matter and Dark energy

Cosmic accounting of constituents



The big open questions

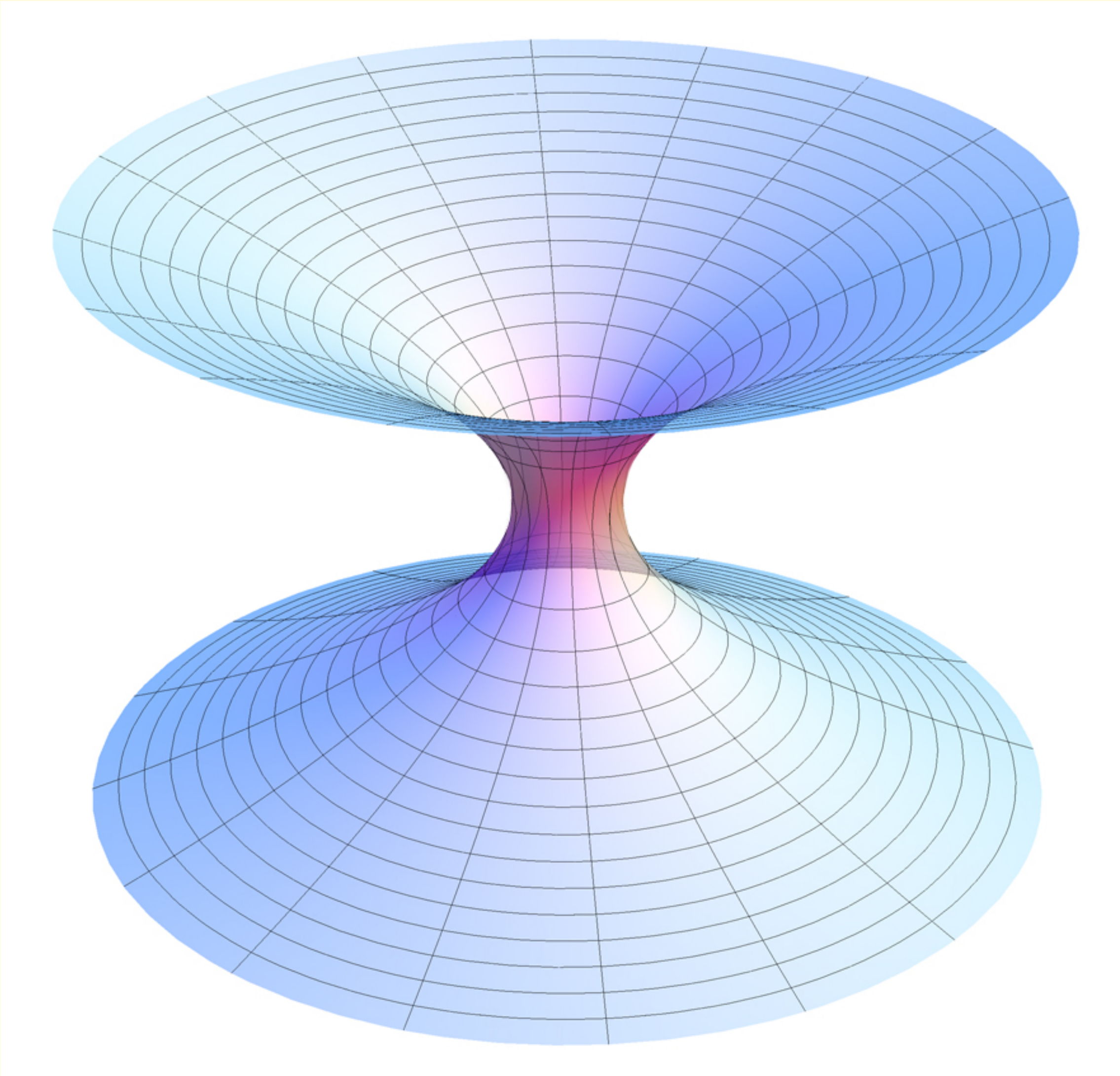
What was before the Big Bang?

Reply : It is meaningless to speak of "before"

How can the universe scrunch to zero size? And if it really had zero size how can it acquire non-zero size?

Reply : The "initial singularity" as well as growth out of it are necessary consequences of Einstein's equations. *Gravity can only attract*.

Reply part 2 : Some new physics should intervene. Simplest to think would be a wormhole.



Wormhole solution of Einstein's equations requires negative energy.

What about Quantum effects?

Reply : That was indeed our big hope. Unfortunately quantum version of Einstein's equations raises more problems. The theory requires too many constants to be adjusted by observation that we cannot predict anything new. Technically called *non-renormalisability*.

Reply part 2 : There is a fundamental problem with time in QM. It is impossible to interpret it when time component of the metric is itself a dynamical variable.

What new physics can intervene?

Seeking an elegant new principle

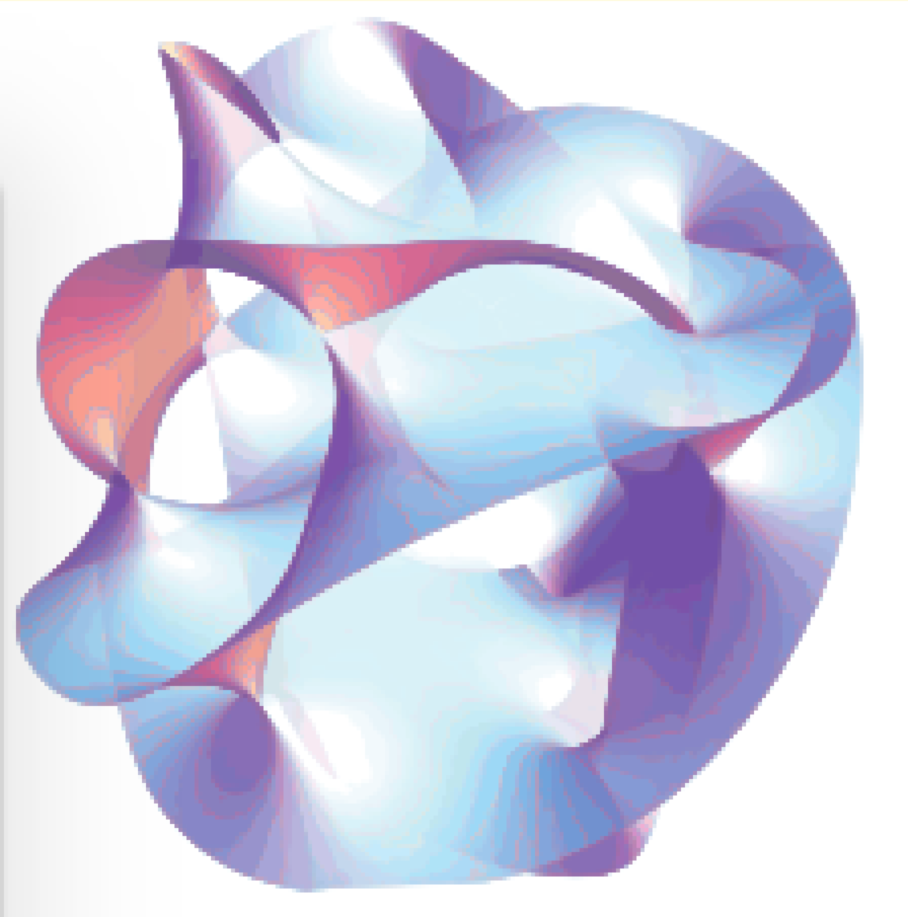
What new principles are available?

Reply : • Supersymmetry – interchangeability of bosons and fermions

- String theory – dynamics determined by geometry

Reply part 2: • Supersymmetry eases the problem of renormalisability – control over new constants induced by quantum effects.

- String theory does contain the graviton as a package.



The three laws of cosmology

Gravity = curved space-time

Scale-factor: The Universe appears to be homogeneous and isotropic

This is a remarkable fact, needing an explanation,

However, if accept this fact it becomes very easy to solve Einstein's equations for the Universe.

Law-I The metric (space-time measuring scales) can be described by the following generalisation of the usual Minkowski space-time interval

$$ds^2 = dt^2 - R(t)^2\{\frac{dr^2}{1+kr^2} + r^2 d\theta^2 + r^2 \sin^2 d\phi^2\}$$

$k = 0$ for flat Universe; $k = \pm 1$ for constant positive or negative curvature

$R(t)$ the Scale factor ... A. A. Friedmann

Law-II Equation of motion for the scale-factor: The dynamics of R is determined by the total energy density ρ

$$\left(\frac{1}{R}\frac{dR}{dt}\right)^2 + \frac{k}{R^2} = \frac{8\pi}{3}G\rho$$

Note : the combination $\dot{R(t)}/R(t)$ will be denoted $H(t)$. It signifies the expansion rate of the Universe in intrinsic length units. Its present value is the Hubble Constant H_0

Law-III Equation-of-state: We need to specify the relation satisfied by pressure and energy-density $p = p(\rho)$. Usually

$$p = w\rho$$

Examples :

1. Radiation dominated Universe : $p = \frac{1}{3}\rho \Rightarrow R(t) \propto t^{1/2}$
2. Matter dominated Universe : $p = 0 \Rightarrow R(t) \propto t^{2/3}$

3. Vacuum energy (Cosmological Constant dominated) : $p = -\rho \Rightarrow R(t) \propto e^{Ht}$

On second thoughts ...

.... add a Λ (Einstein 1924) in the law for $R(t)$ to avoid expanding / contracting Universe.

$$H(t)^2 + \frac{k}{R(t)^2} - \Lambda = \frac{8\pi G}{3}\rho(t)$$

✔ This introduces a new fundamental constant of nature, of dimensions $[L^{-2}]$,the Cosmological Constant

✔ If the $\Lambda$is transferred to the right hand side, it looks like a contribution to ρ, satisfying the unusual equation of state $p = -\rho$.

- ✘ By 1929 Hubble's Law was discovered and Einstein soon retracted the Λterm : He said in a letter to a colleague, "away with it if it is not required"

- ✘ However another report quotes him as orally admitting it to be the "biggest blunder" of his life to have introduced Λ term.

- ✘ The puzzle however persists – the whole of General Relativity was deduced by Einstein from theoretical arguments.

- ✘ But the arguments he used demand that this term should be also present – an exact zero value for it would be a great coincidence or a deep theoretical reason..

Summary

- Cosmology has grown into a precise science
- There seems to be 26% Dark Matter (pressureless, massive)
  - known from its gravitational tug on other matter and on light
- There seems to be 70% Dark Energy (space-filling, featureless vacuum energy)
  - known from accelerated expansion revealed by ancient supernovae
- There are parts per million ripples in an otherwise smooth Universe

– known from Cosmic Microwave Background Radiation (CMBR).

- These features require new forms of energy/matter
- And also perhaps new laws of Physics

Thank you !

the Universe awaits your participation!!

Typeset using FoilTeX