Dark Matter, Dark Energy and supersymmetry

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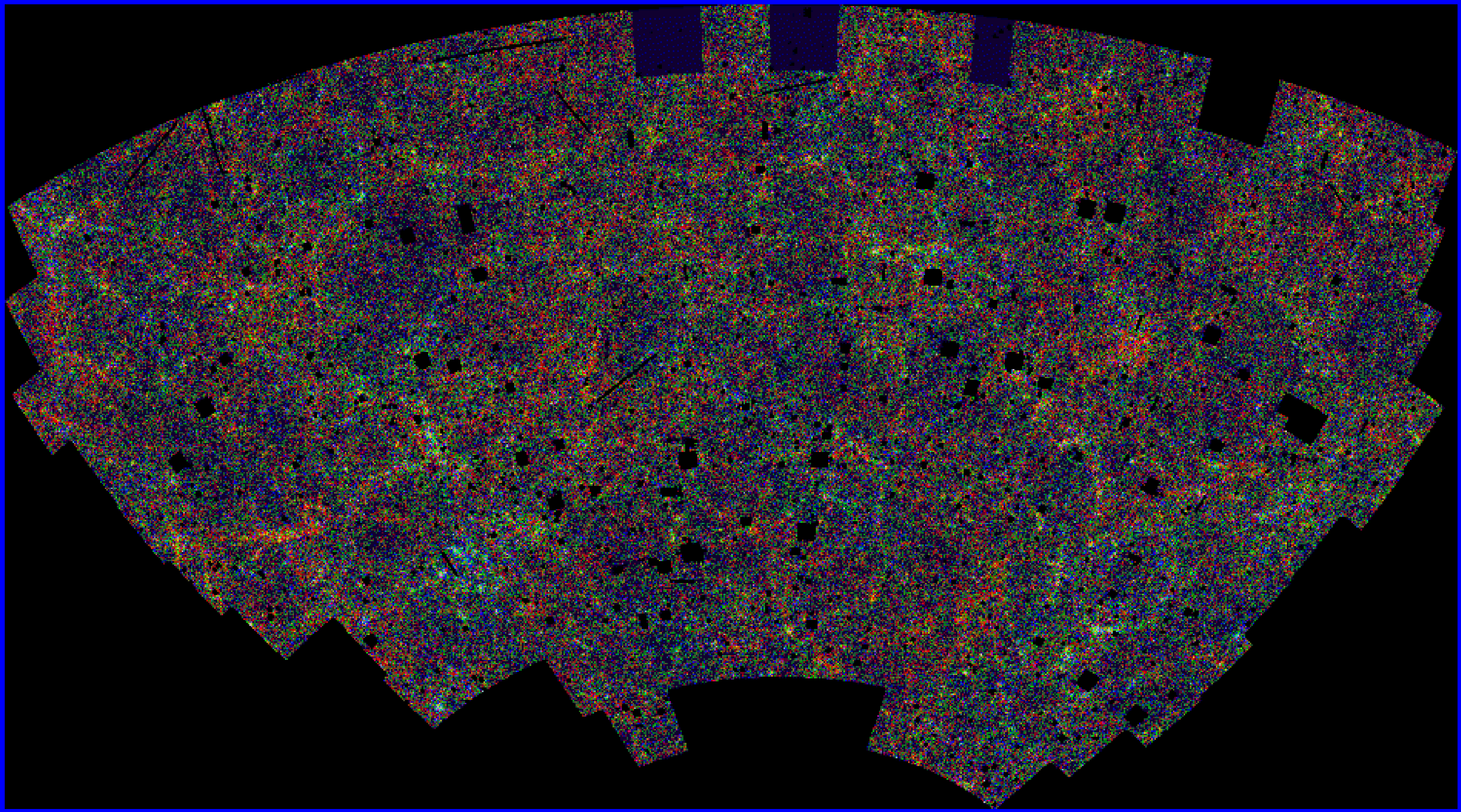
Indian Physics Association, Navyug College, Surat, January 25, 2011

Outline

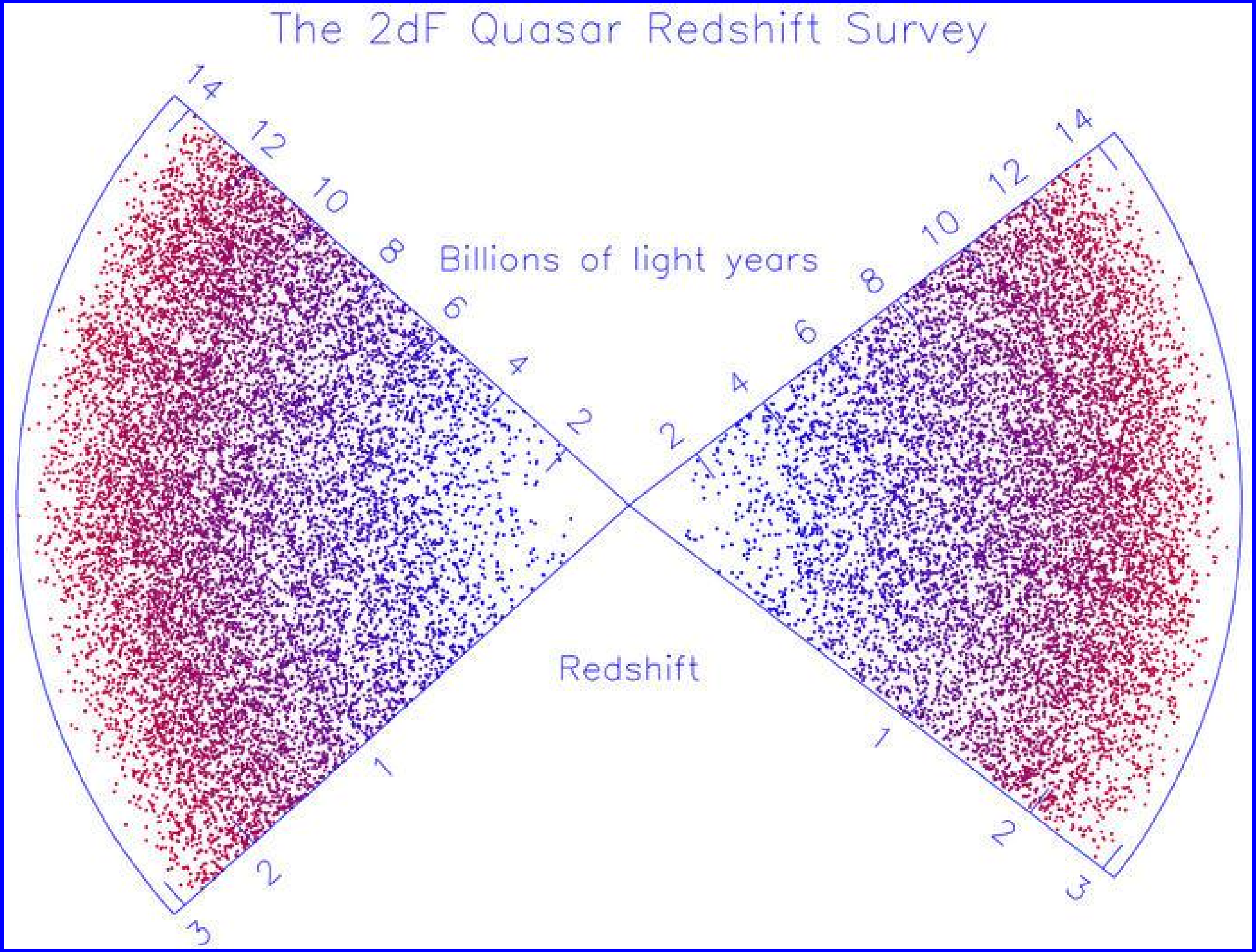
- Why Dark Matter?
- Why Dark Energy?
- The Three Laws of Cosmology
- WMAP confirms DM and DE
- Supersymmetry
  - ⋆ Lightest supersymmetric particle (LSP)
  - ⋆ (Almost) vanishing vacuum energy

The Universe observed

Distribution of galaxies (2-degree-Field survey)



Quasar distribution



Dark Matter

"Rotation curves" of galaxies

Zwicky (1934)

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

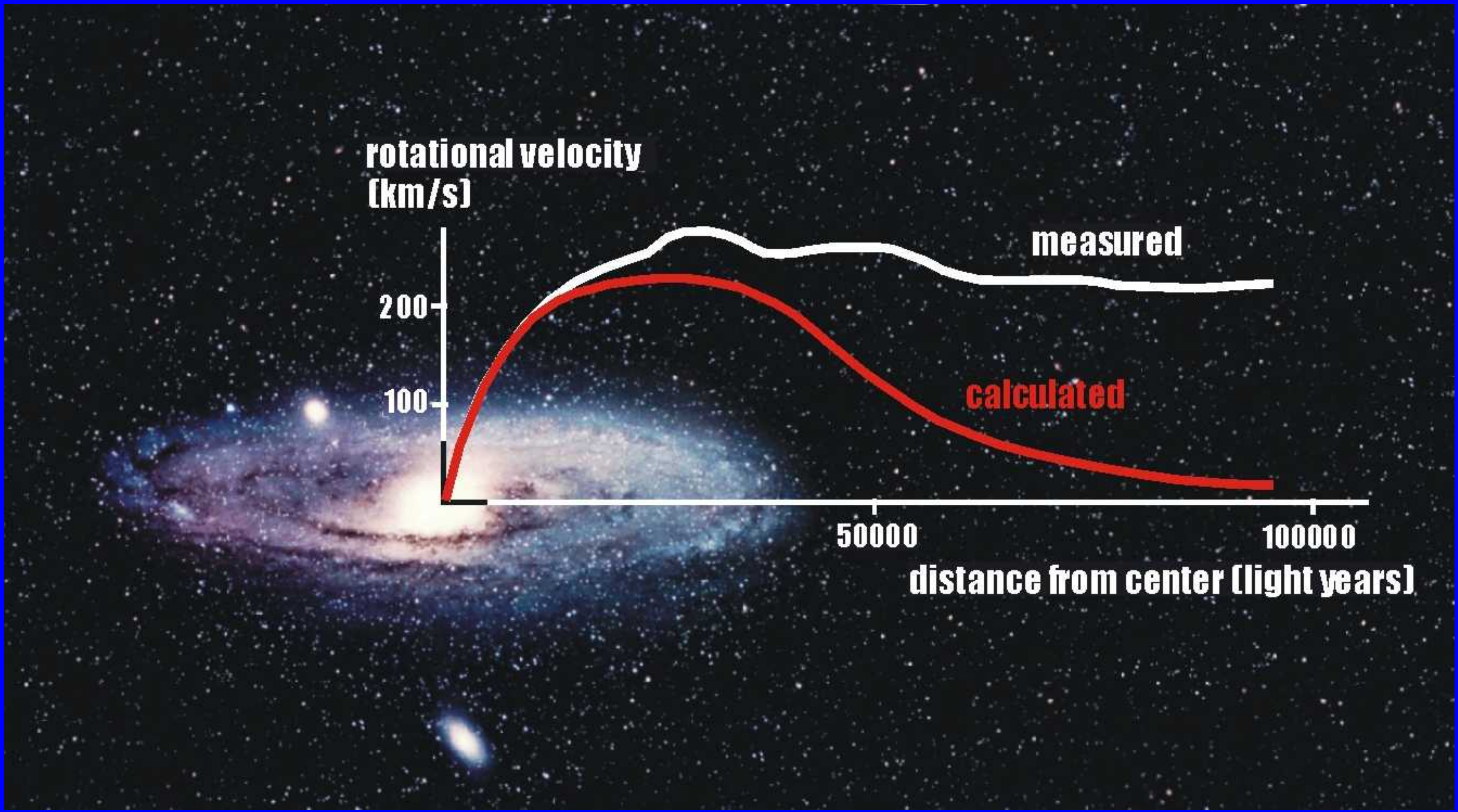
$$\frac{v^2}{R} = G\frac{M(R)}{R^2}$$

So if most of the mass is concentrated within R_{max}, then $v \propto 1/\sqrt{R}$ beyond R_{max}.

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

Galaxy edge on

Measured curve - example



Persistent effect at all scales

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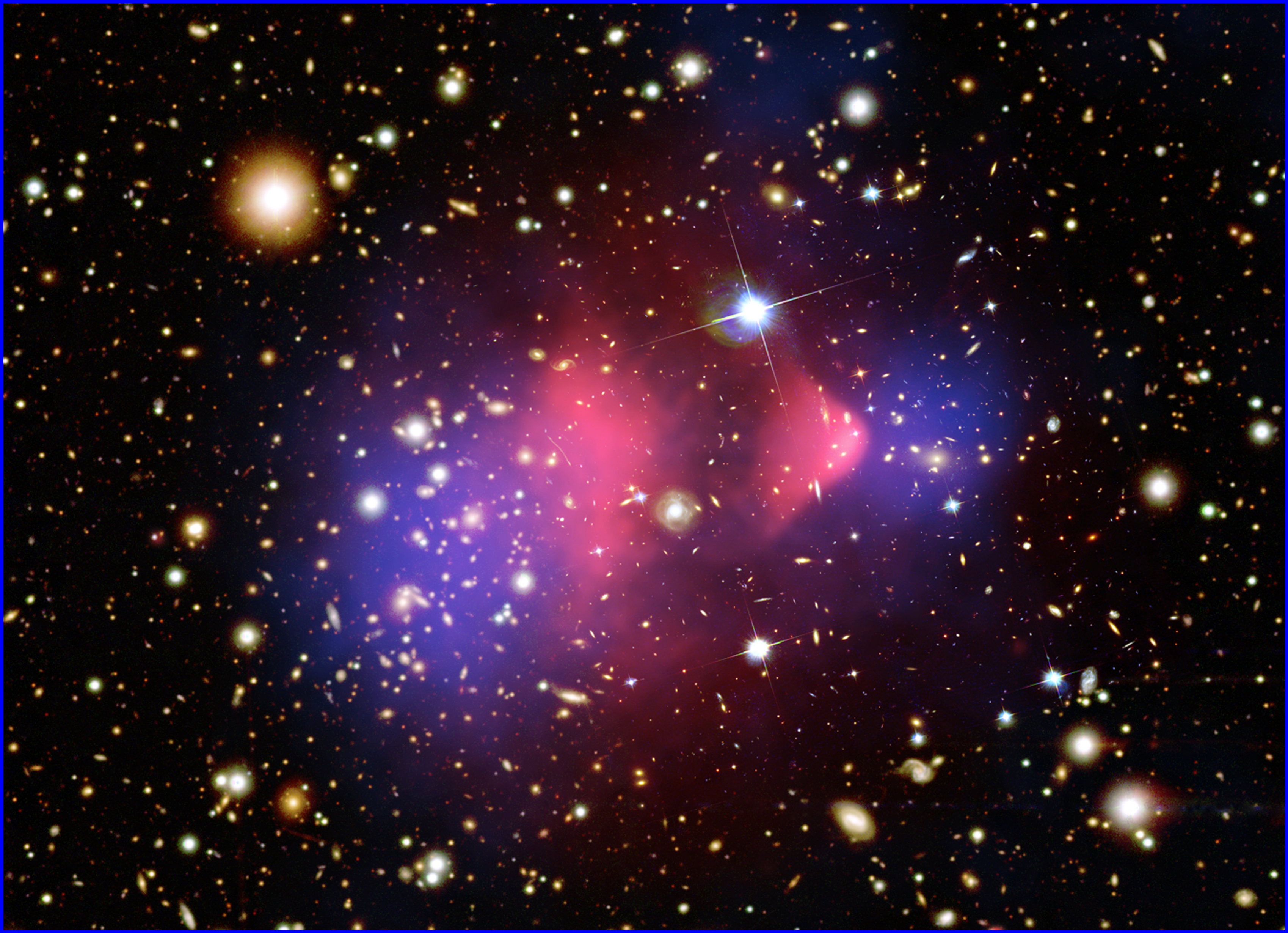
And at superclusters level. ... Further, ...

More spectacular evidence – “bullet cluster”



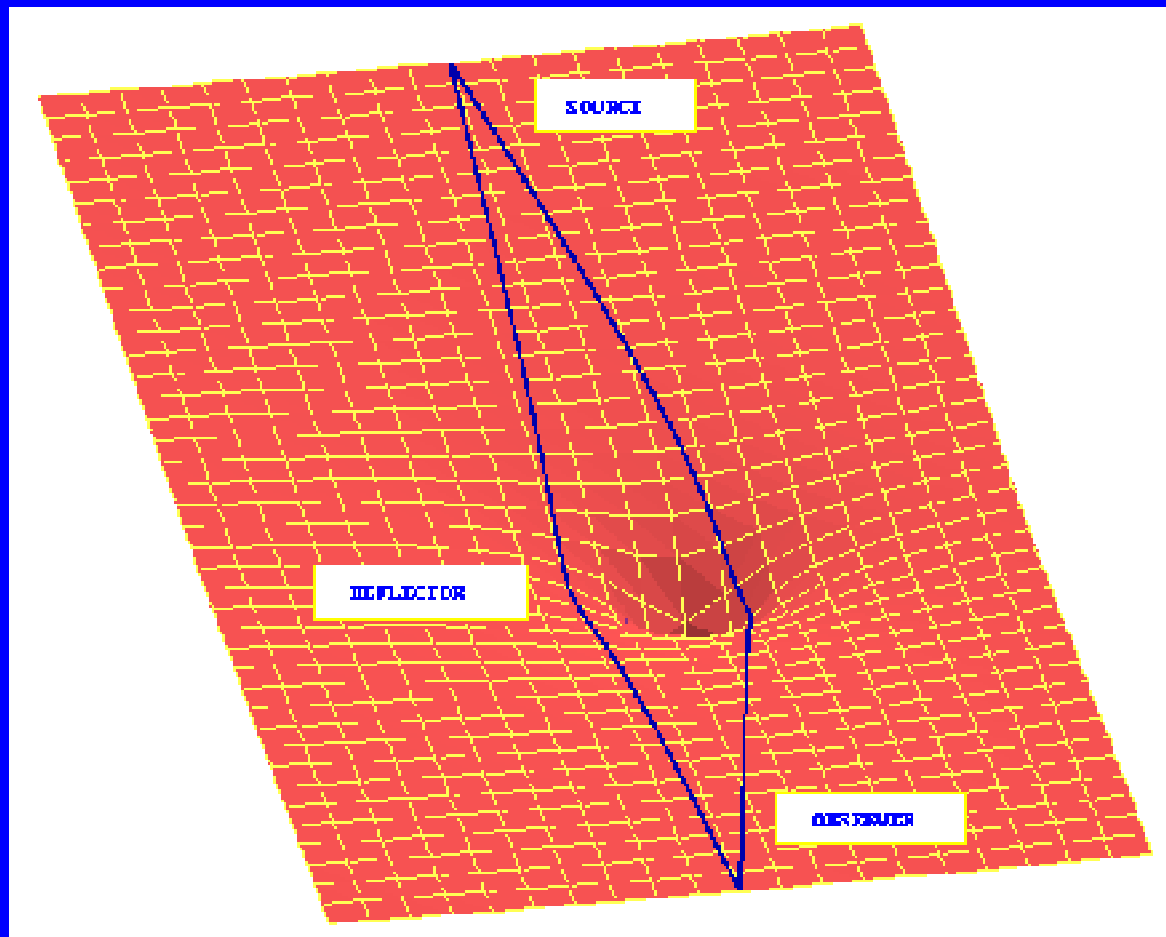
The picture is composite of three different sources of data ...

... and with simulated color

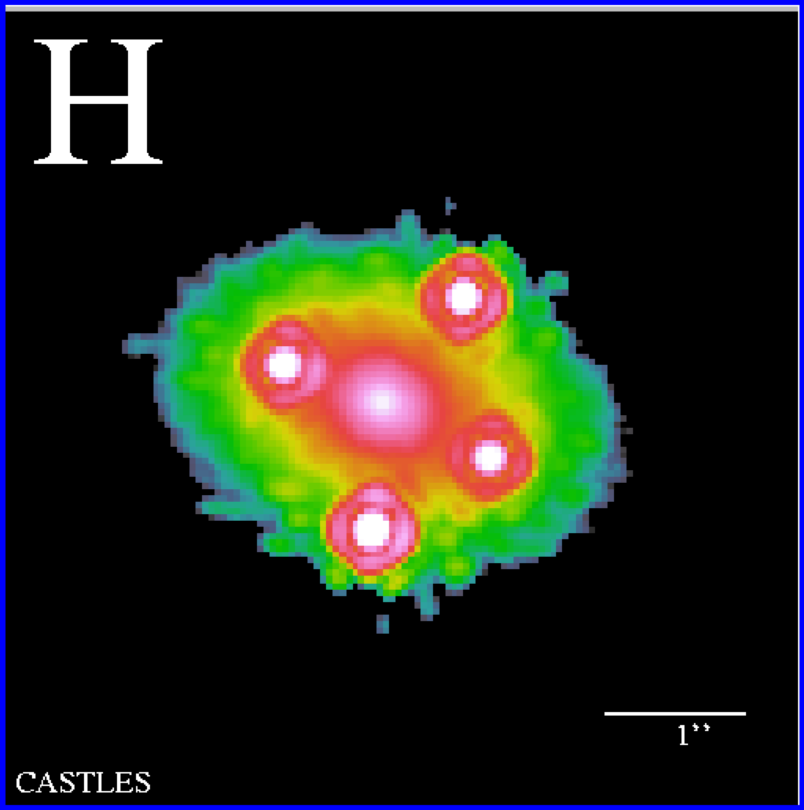
- ✔ Background of galaxies from Hubble Space Telescope
- ✔ Red gas from X-ray observation satellites Chandra and XMM Newton
- ✔ Blue gas (Dark Matter) from gravitational lensing

... What is this gravitational lensing?

Gravitational lensing



Example of lensing



Dark Energy

A blast from the remote past

Begin in the 1920's ...

New telescopes like Hale observatory and Mt. Palomar 200 in. telesope for the first time made galaxies visible in detail to human beings

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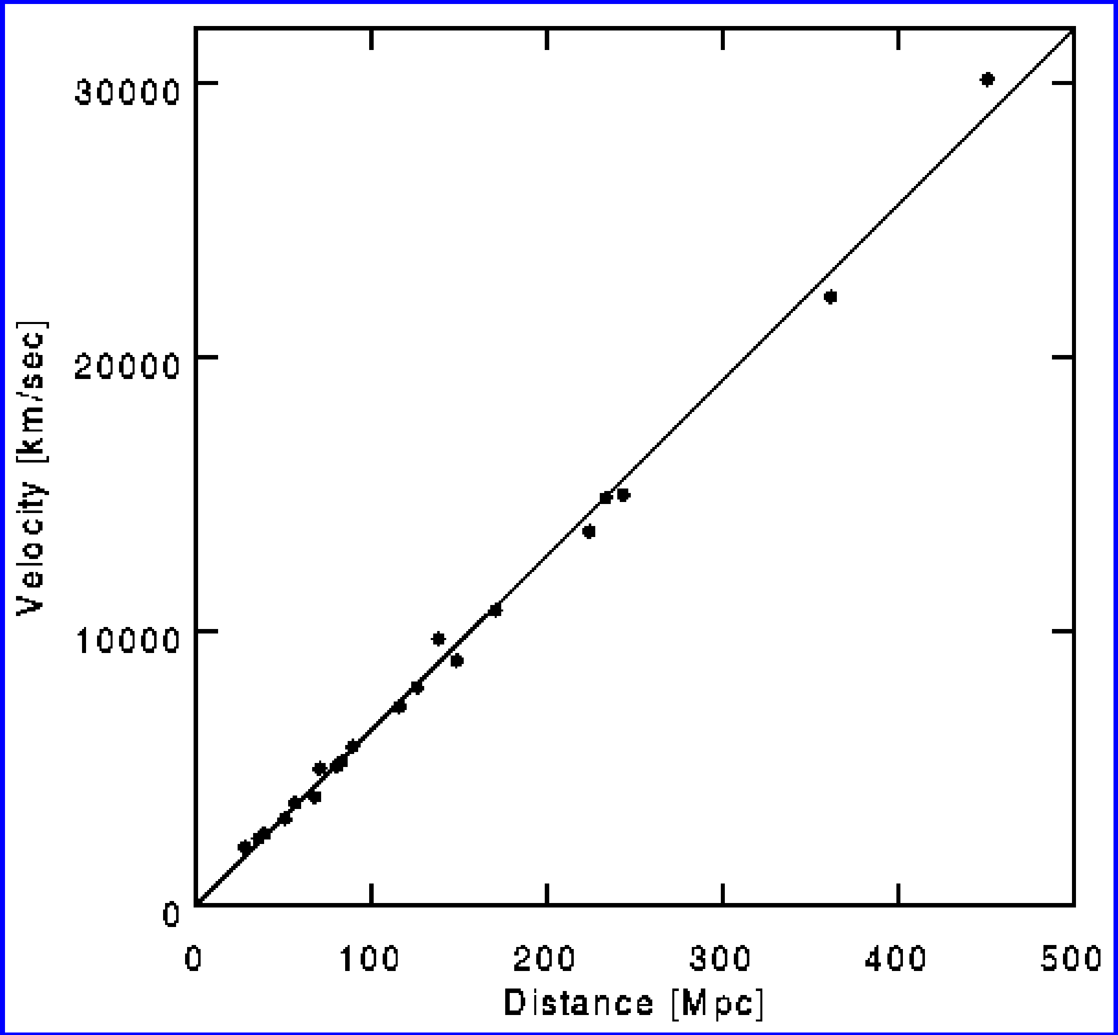
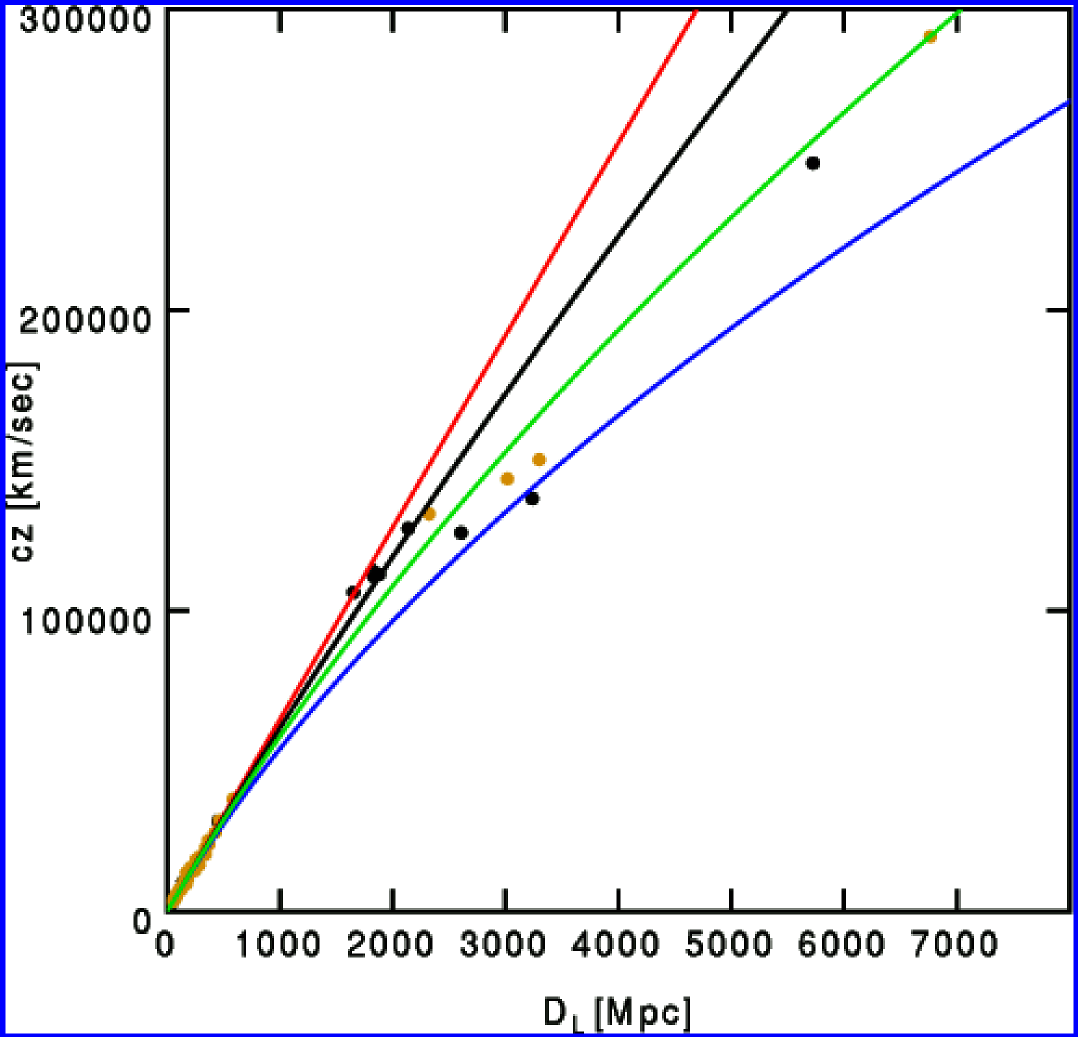
Edwin Hubble drew a line through the redshift vs. luminosity distance plot.

A Hubble Plot before Hubble Space Telescope



Modern Hubble plot



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This agreed well with having well known forms of matter-energy participating in the gravitaional expansion ....

until there came ...

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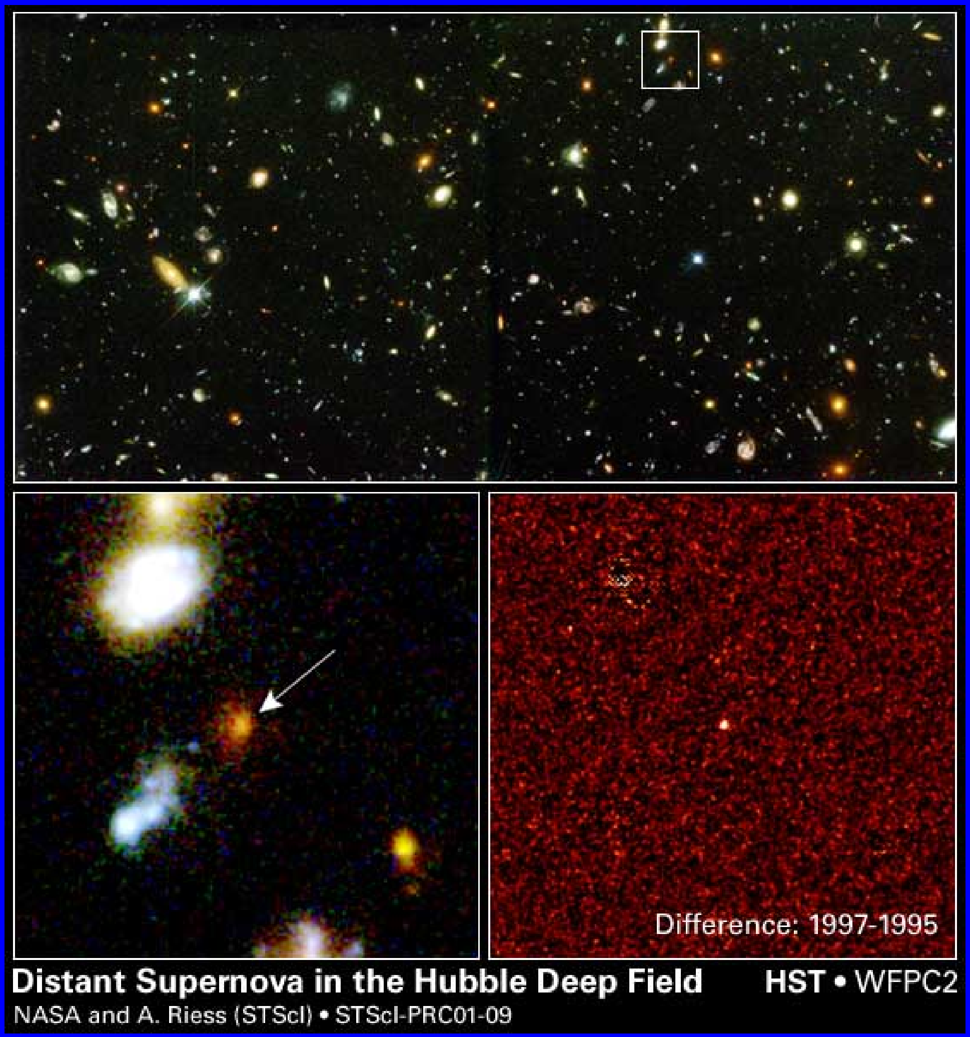

Show movie

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A little tutorial on Cosmology ...

The three laws of cosmology

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

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 $p = -\rho$.

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✔ 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 inroduced Λ term.
- ✘ The puzzle however persists – the whole of General Relatiovity 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..

Book keeping of Cosmic contents

another way of writing ...

$$1 + \frac{k}{H^2 R^2} = \Omega_\Lambda + \Omega_\rho$$

- Today LHS seems to be 1
  - ⋆ So in the curvature term, $k = 0$

Current best fit to data

- The accelerated expansion can be fitted if the Λ term dominates, $\Omega_\Lambda = 0.7$
- But most of matter-like ρ is not baryons! Let $\Omega_\rho = \Omega_{DM} + \Omega_B$
  - ⋆ Baryons contribute only $\Omega_B = 0.03$
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✔ Direct searches for baryonic matter – counting all the matter in stars and gaseous clouds

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Thus there is a gap of 70% in the energy-matter balance, and is best fitted by assuming a small cosmological constant which exactly explains the observed accelerated expansion.

The Big Bang

The Cosmic Expansion

Extrapolated sequence backwards in time

- Ionised Hydrogen 1 eV 10^4 K
- Free neutrons and protons 1 MeV 10^{10} K
- Quark-Gluon plasma 1 GeV 10^{13} K
- Electroweak scale 100 GeV 10^{15} K
- Quantum Gravity 10^{19} GeV

Neutral H formation $\sim 10^5$years after the Big Bang

Relic radiation 10^4 K then; 3 K now

Alpher, Bethe and Gamow (1942)

Cosmography : A summary

Current parameters of the Universe :

- Expansion rate 71 ± 4 (km/s)/MegaParsec
- Size of the visible Universe 3 GigaParsec
- Age of the Universe 13.7 ± 2 GigaYears
- Age at decoupling $380 \pm 7 \times 10^3$ Year

Inflationary Universe

A problem of scales

We expect a physical system to be governed by intrinsic scales.

eg. Sizes of animals, mountains, solar system, galaxies ...

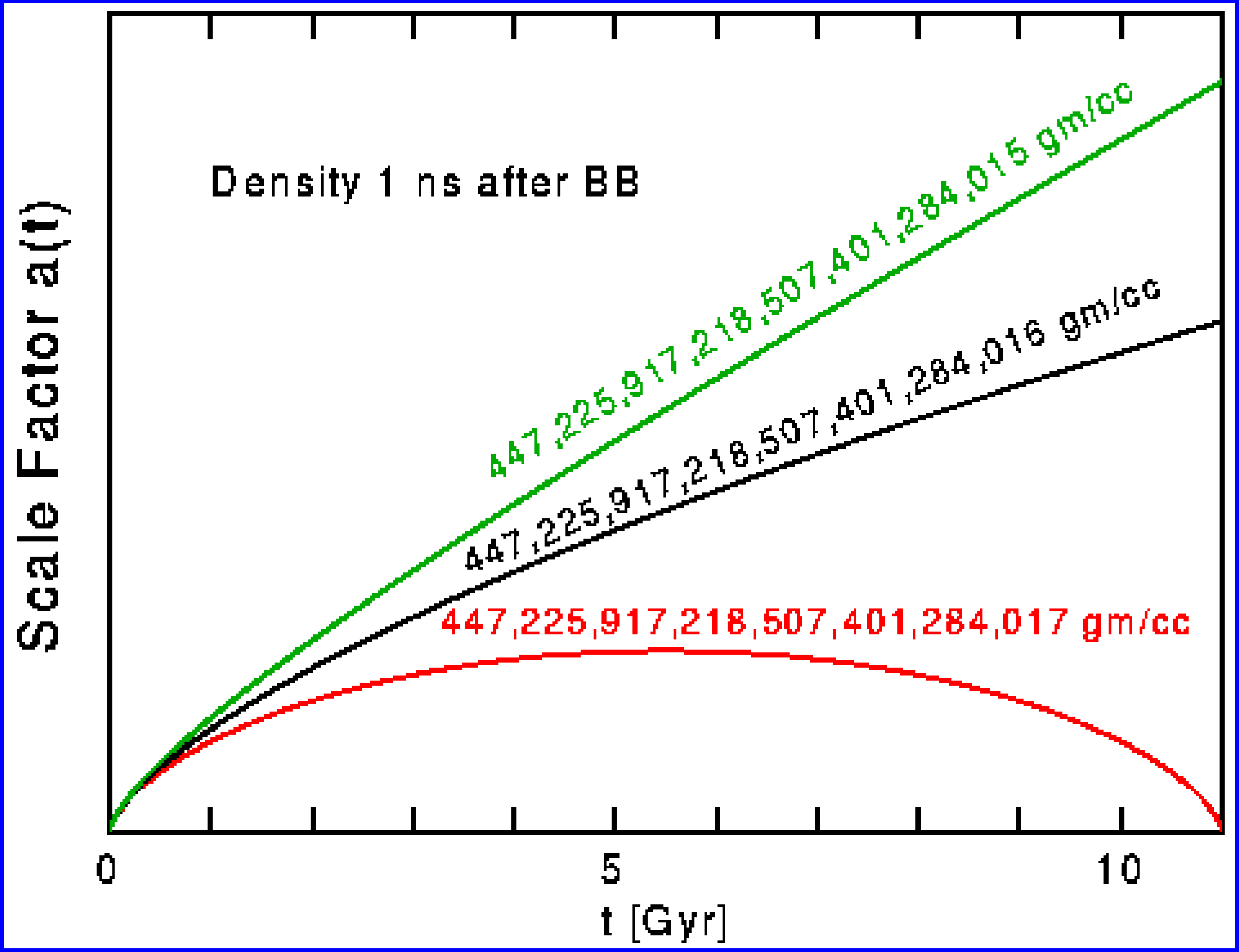
Such scales appear as (dimensionful) constants in the laws determining the state of the system

A system far too large or far too long lived compared to such intrinsic dimensions suggests ignorance of

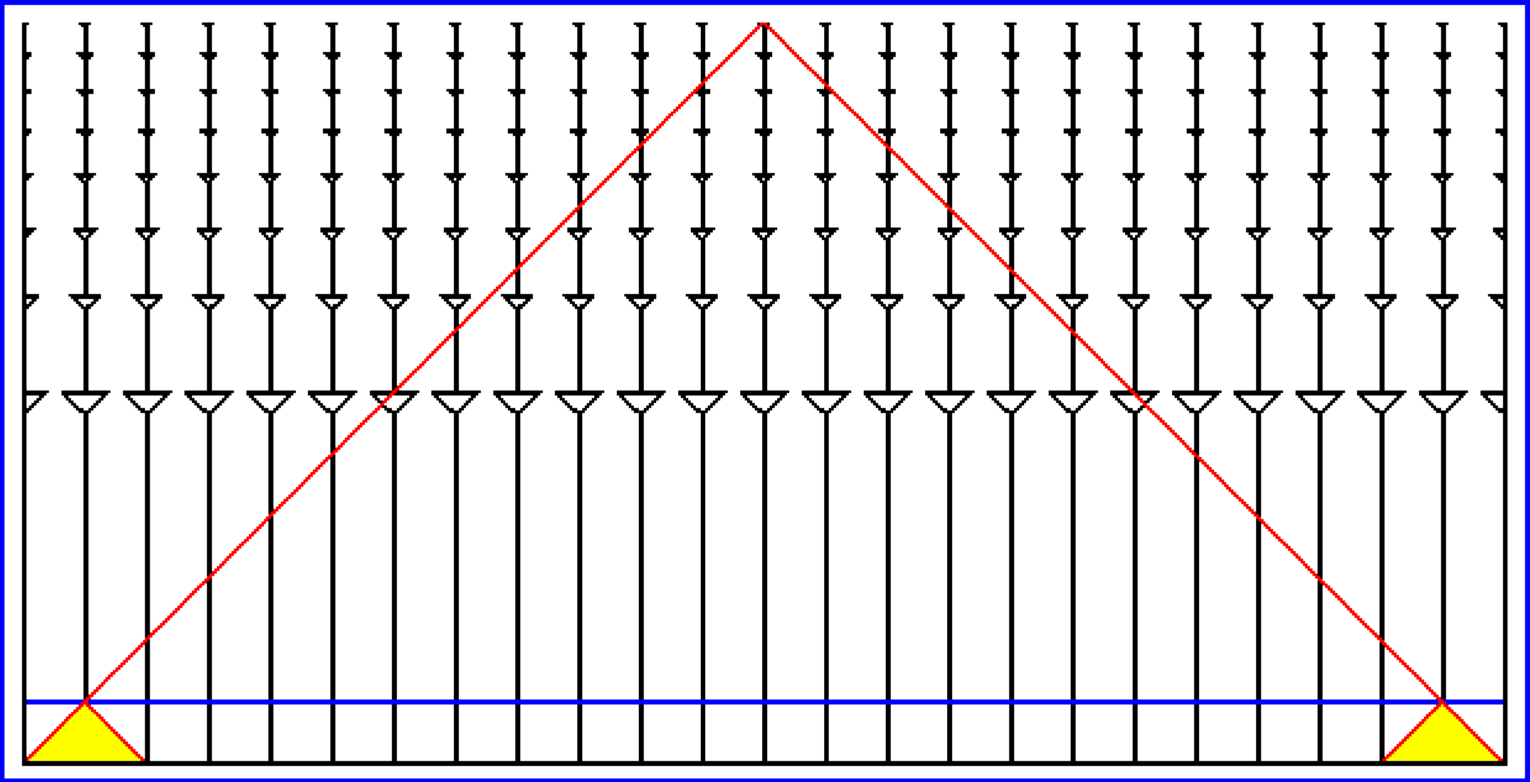
- Newer dynamics, or more importantly,
- Newer laws of nature

Oldness flatness problem

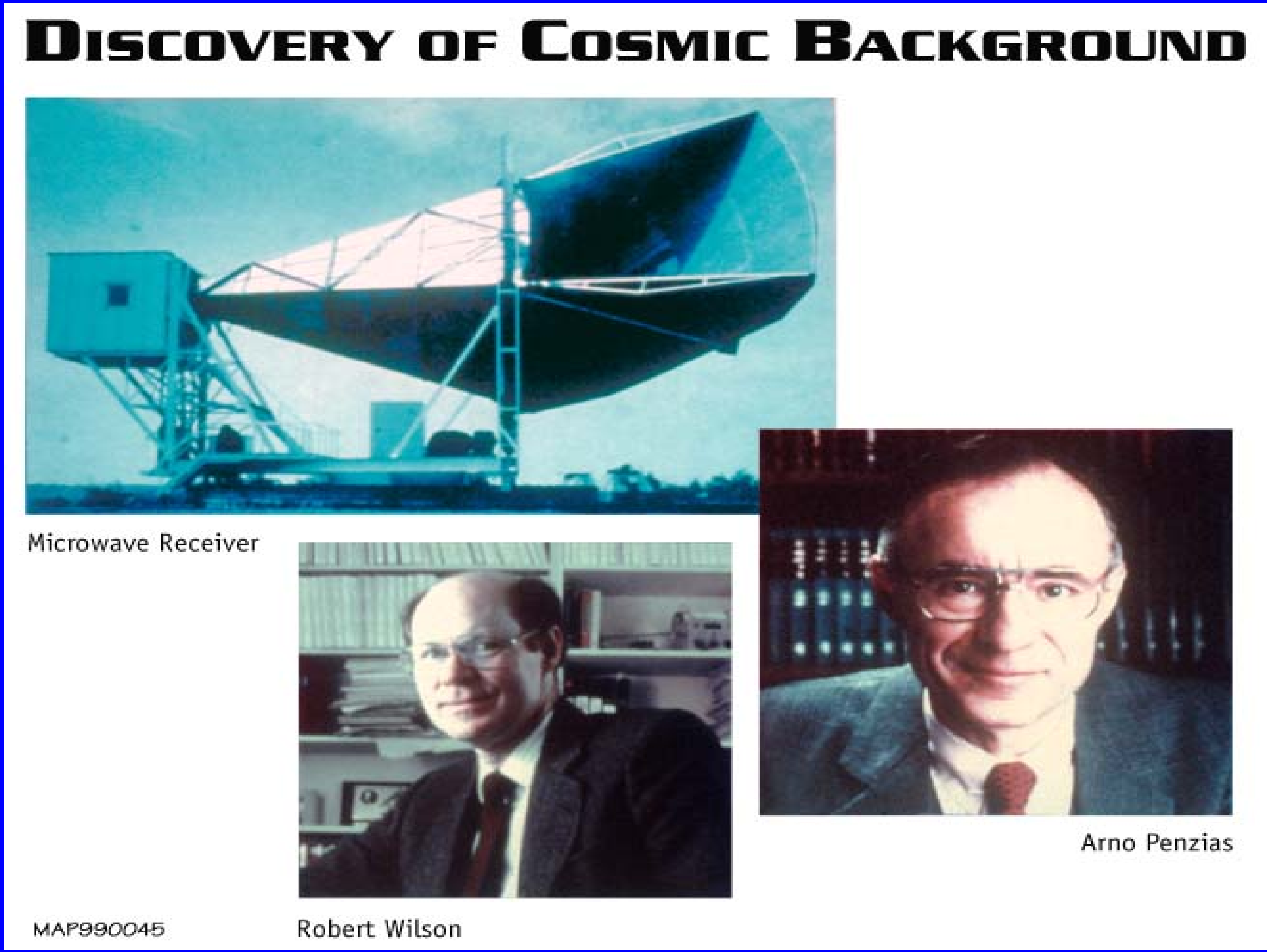
Inflation figures from Ned Wright's Online Cosmology Tutorial page


Density 1 ns after BB
447,225,917,218,507,401,284,015 gm/cc
447,225,917,218,507,401,284,016 gm/cc
447,225,917,218,507,401,284,017 gm/cc
Scale Factor a(t)
0
5
10
t [Gyr]

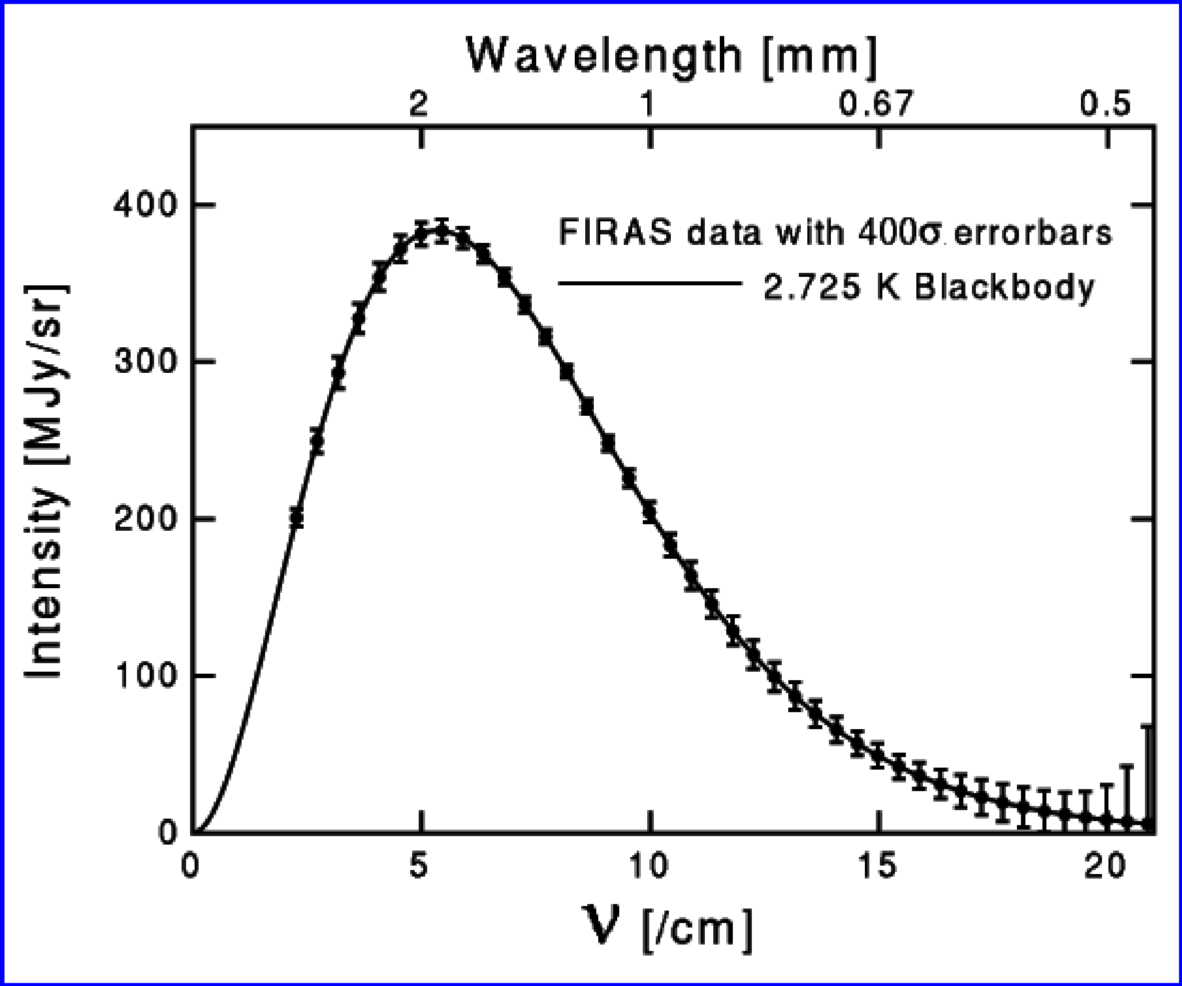
Horizon problem



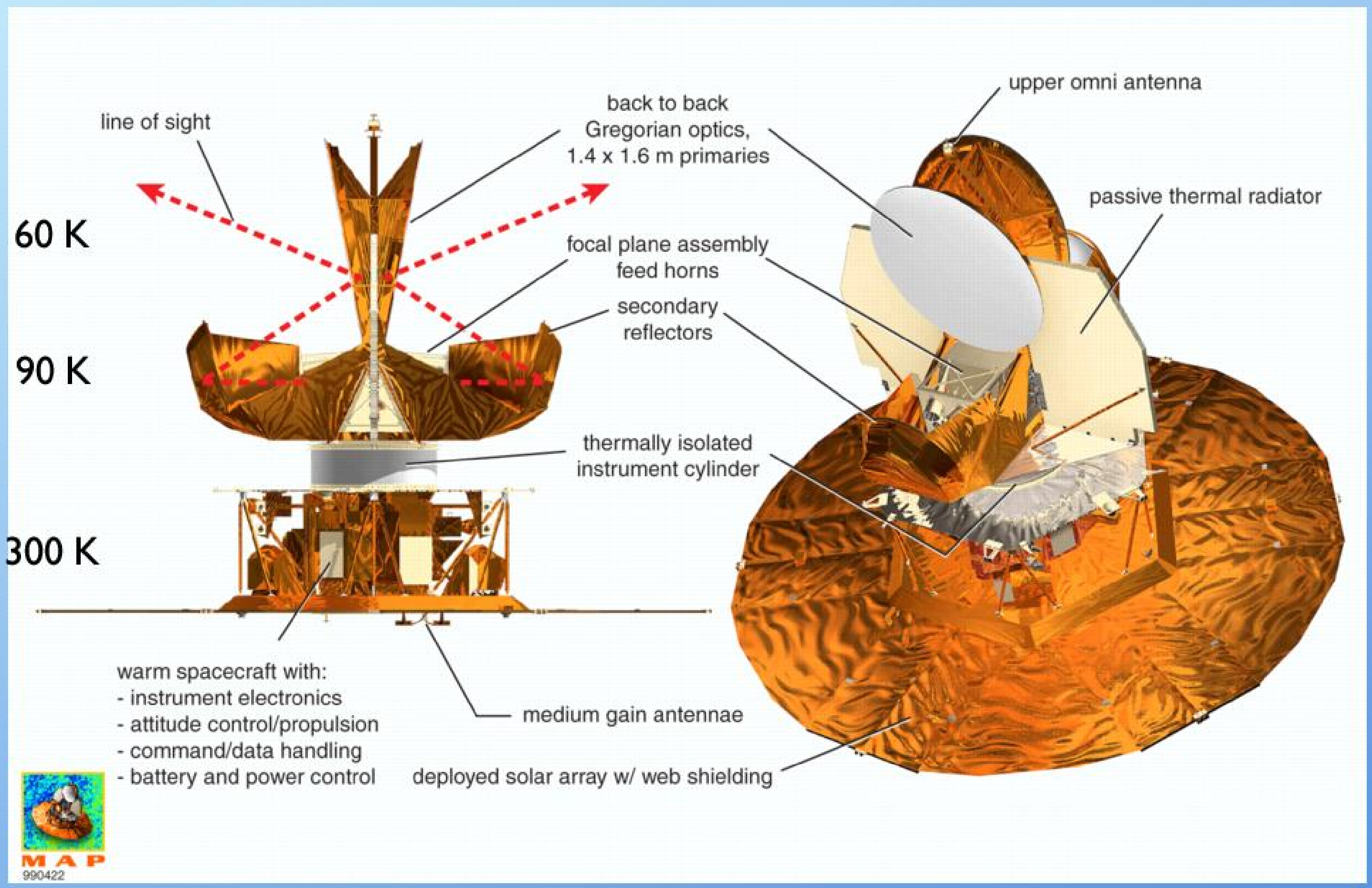
WMAP : fingerprinting the Universe

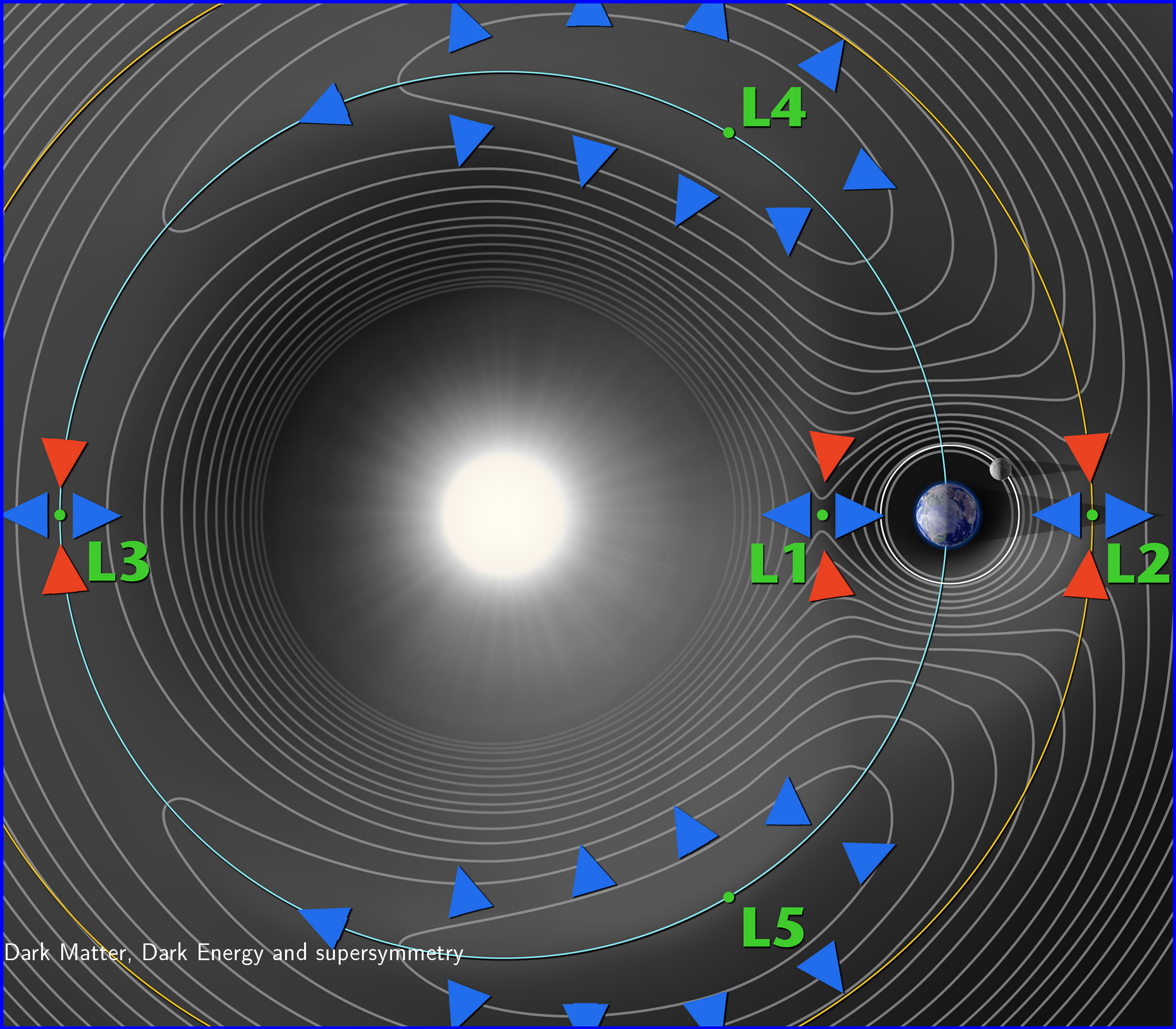

DISCOVERY OF COSMIC BACKGROUND
Microwave Receiver
Arno Penzias
MAP990045
Robert Wilson

COBE data (1992)

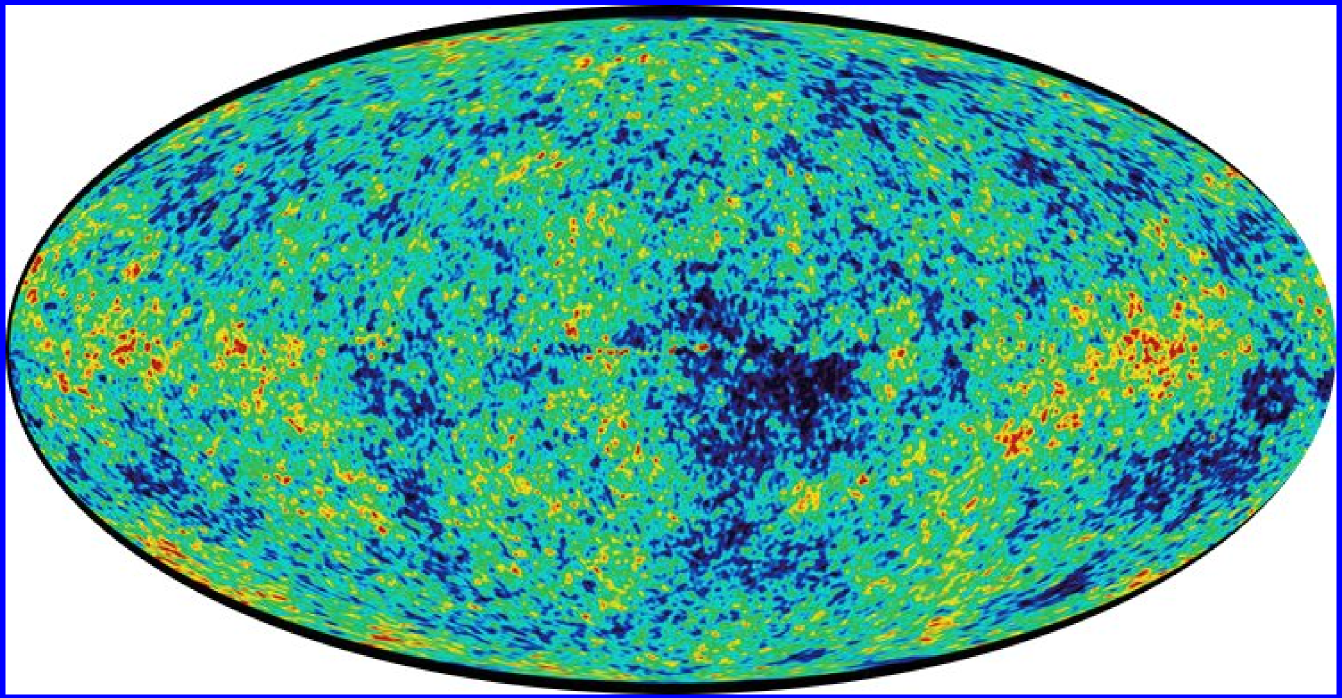


WMAP Spacecraft and Instrument

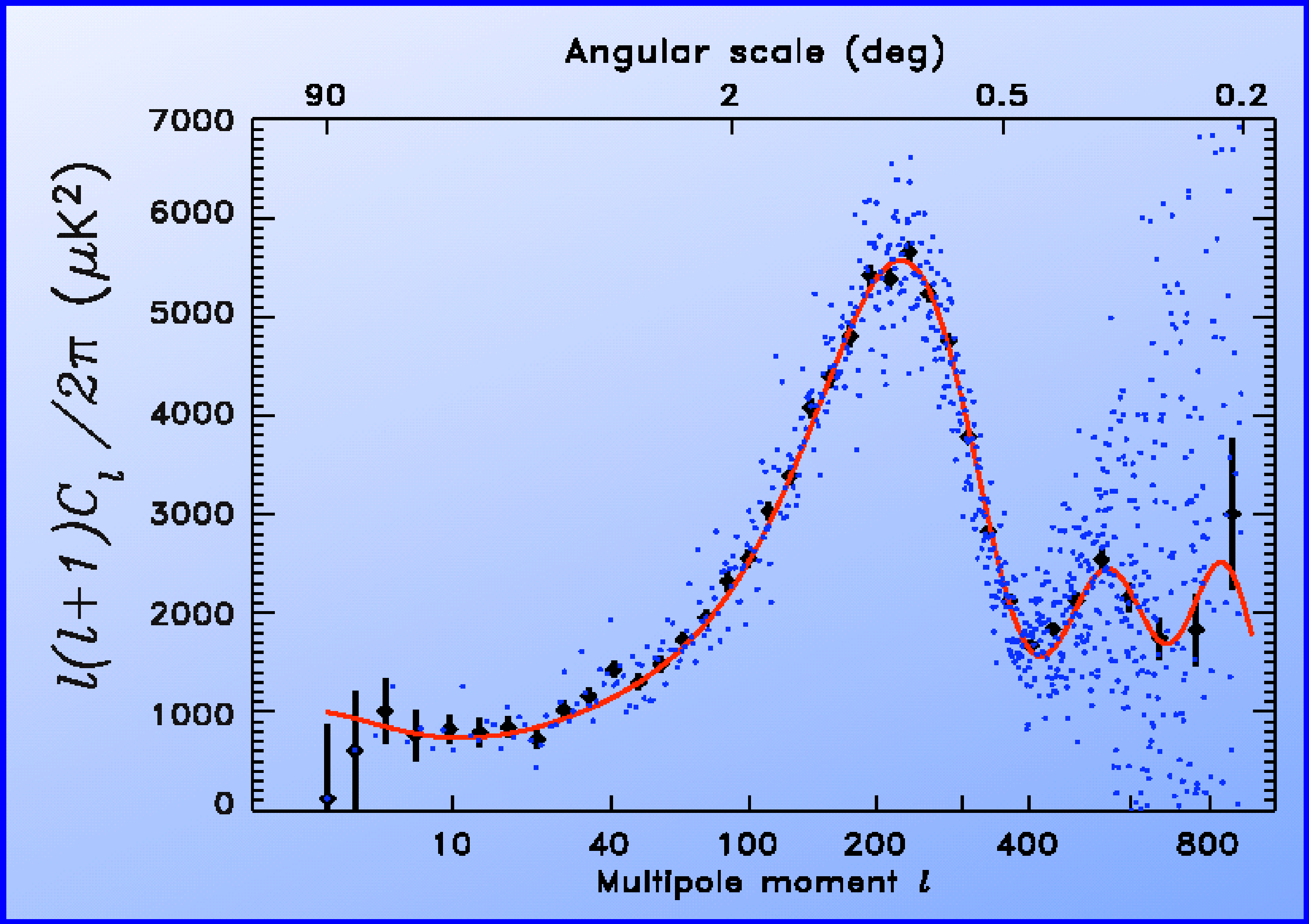



L4
L3
L1
L2
L5

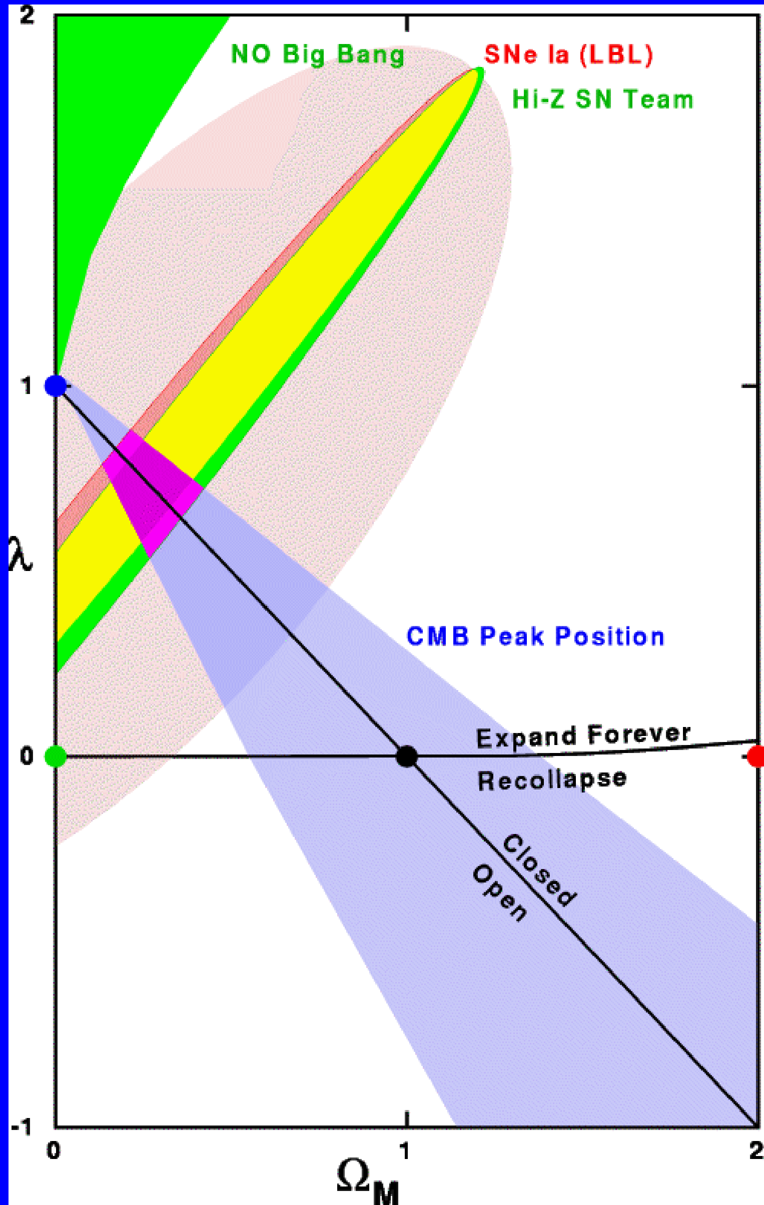
All sky microwave map of the Universe



Angular power spectrum of fluctuations



Combining supernova data and WMAP


NO Big Bang
SNe Ia (LBL)
Hi-Z SN Team
CMB Peak Position
Expand Forever
Recollapse
Closed
Open
λ
Ω_M
2
1
0
-1
0
1
2

Supersymmetry

An analogy

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- Proton is like the spin-up state and neutron like the spin-down state of "nucleon".

- Abstract Isospin "rotation" which mixes up these spin states does not affect the nuclear forces.

A more daring abstract rotation

In supersymmetry it is proposed that bosons and fermions can also be "rotated" into each other, leaving the interaction energy invariant.

For rotations we have the commutator algebra of the rotation generators

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For supersymmetry we propose generators Q and $Q^\dagger$, satisfying *anti-commuting* algebra

$$\{Q, Q^\dagger\} \equiv QQ^\dagger + Q^\dagger Q = i\hbar(E \cdot I + \mathbf{P} \cdot \boldsymbol{\sigma})$$

Note that two rotations produce another rotation. Here two supersymmetry operators give energy and momentum. Clearly, this symmetry has to do with spacetime itself.

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Consequences of supersymmetry :

- ✔ To every boson there corresponds a fermion or exactly same mass
- ✔ There are exactly as many fermionic degrees of freedom as there are bosonic ones
- ✔ *There are no further new symmetries possible in Quantum Mechanics explored by scattering experiments.*
- ✔ If present it holds for graviton as well, leading to Supergravity theory

A fact of nature :

- ✘ None of the observed particles can be the superpartners of each other
- ✘ We must have a whole new set of degrees of freedom
- ✘ photon <–> photino, electron <–> selectron (scalar electron) ... graviton <–> gravitino
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Example of solid lattices as a congealed state of highly symmetric state, plasma.

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- It would be present today as Dark Matter

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Proof :

$$Q|vac\rangle = 0 \quad and \qquad QQ^\dagger + Q^\dagger Q = i\hbar E \cdot I$$

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and of establishing in Physics a new profound symmetry principle – NEW GRASSMANN DIMENIONS AS PARTNERS OF THE COMMUTING CARTESIAN ONES.

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The future awaits your particiation!

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