# The accelerating Universe : a perspective on the Physics Nobel Prize 2011

URJIT A YAJNIK *Physics Department, IIT, Bombay*

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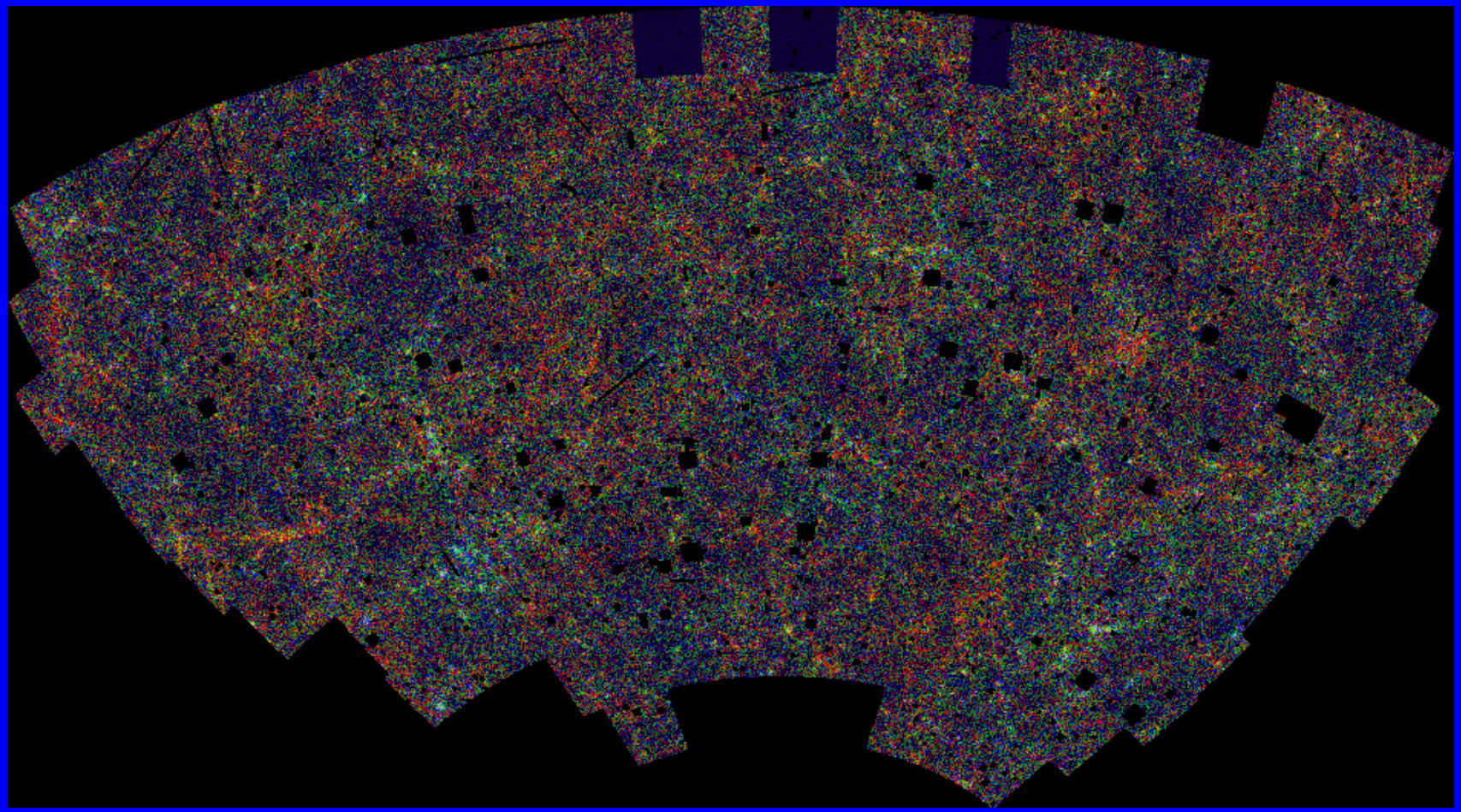
# Outline

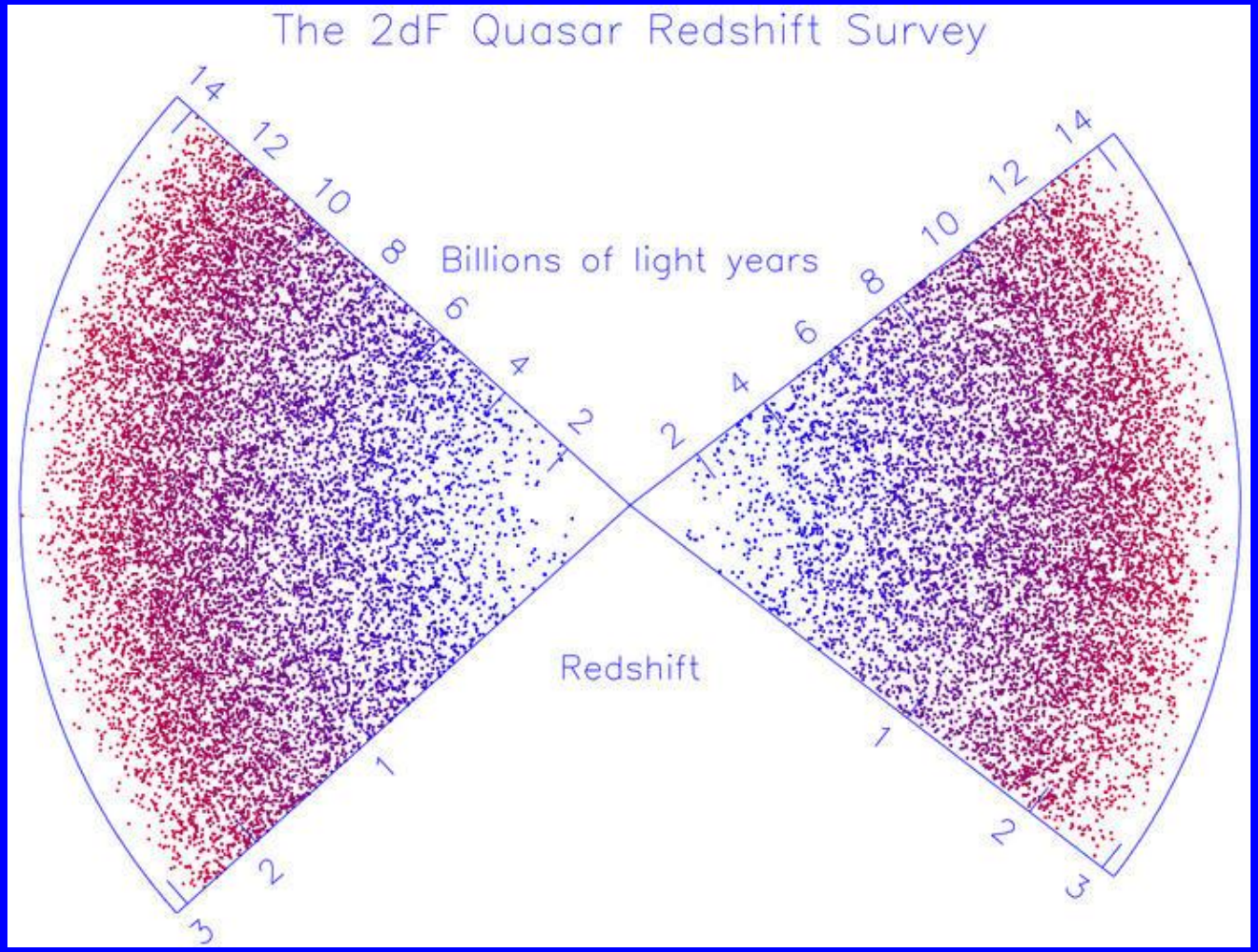
- The expanding Universe (1929)
- Three laws of Cosmology (General Relativity )
- A blast from the remote past - ancient supernovae
- How it all ties up

# The Universe observed

# Distribution of galaxies (2-degree-Field survey)



# Quasar distribution



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- Total flux from every slice must be a constant ...
- ergo, the received flux on earth must be infinite

# Cosmology arrives as a science

- Around 1915 several large telescopes got built,
  - ⋆ Yerkes 40 in WI, Lowell , Mt Wilson 100 in. in Pasadena
- Cepheid variables are a category of stars whose intensity is variable
  - ⋆ The period of variation ( fews to months) is dependent upon the absolute luminosity
- "Standard candles" to measure distances

# Redshift vs distance

- Cepheid variables were calibrated (Henrietta Leavitt 1908 )
- It also became possible to resolve galaxies into their constituent stars
- Hubble could demonstrate decisively that the Andromeda galaxy was an "island Universe"
- Hydrogen being the most abundant, it was possible to measure redshift of the H spetra of galaxies From Doppler law,
  - ⋆ this gave the relative velocity of the galaxy from ours

# Hubble draws the line!

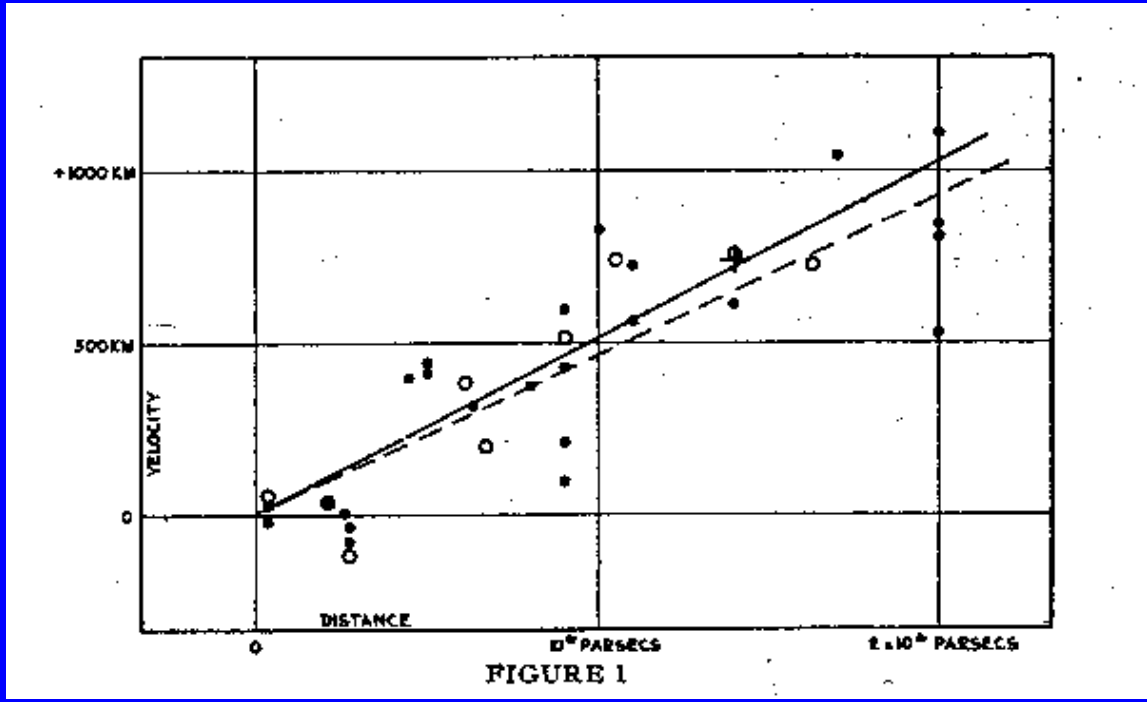

FIGURE 1

# Edwin Hubble trivia

Trained as a lawyer to satisfy father's wishes, moved into Astrophysics after father's death.

Had to lobby to get Astrophysics accepted as a branch of Physics, however the Nobel committee was not convinced.

# Expansion of the Universe has now been very well established

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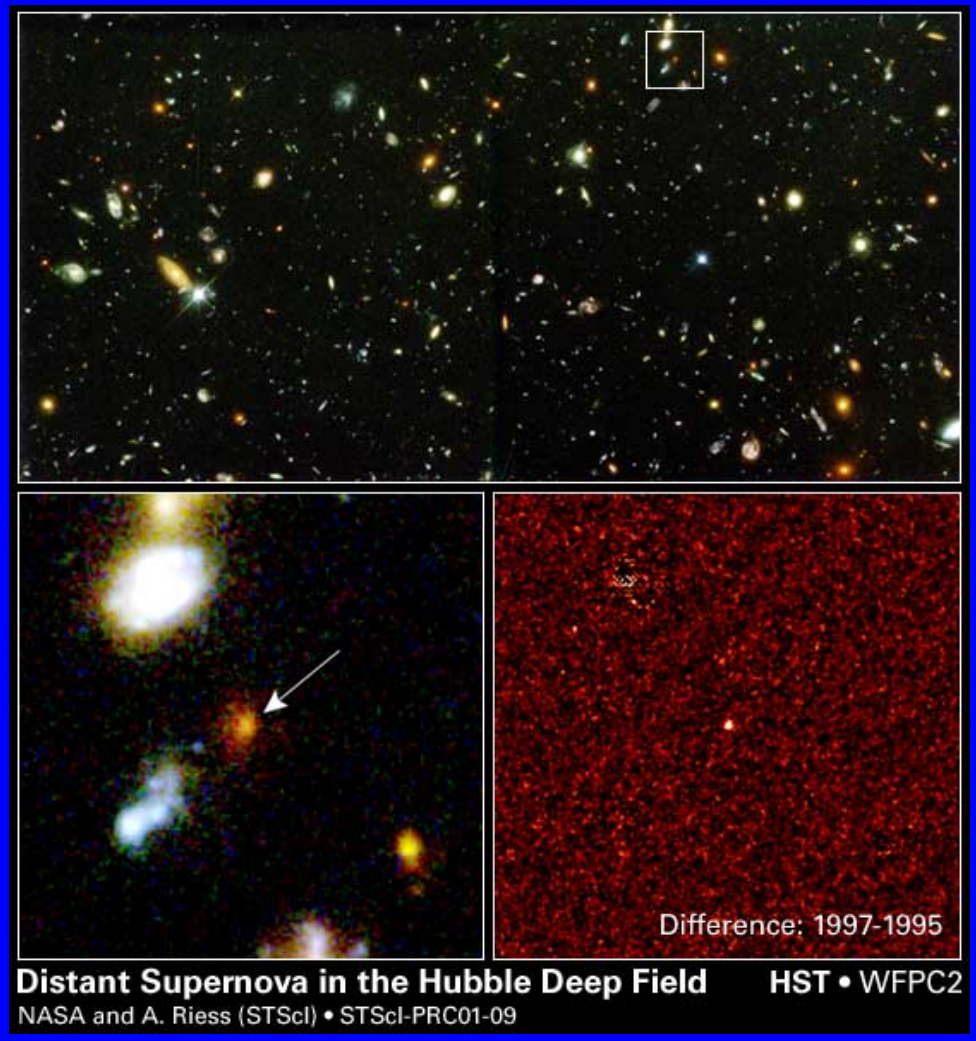
This agreed well with having well known forms of matter-energy participating in the gravitaional expansion ....

until there came ...

# A blast from the remote past



*Show movie*

# New standard candles

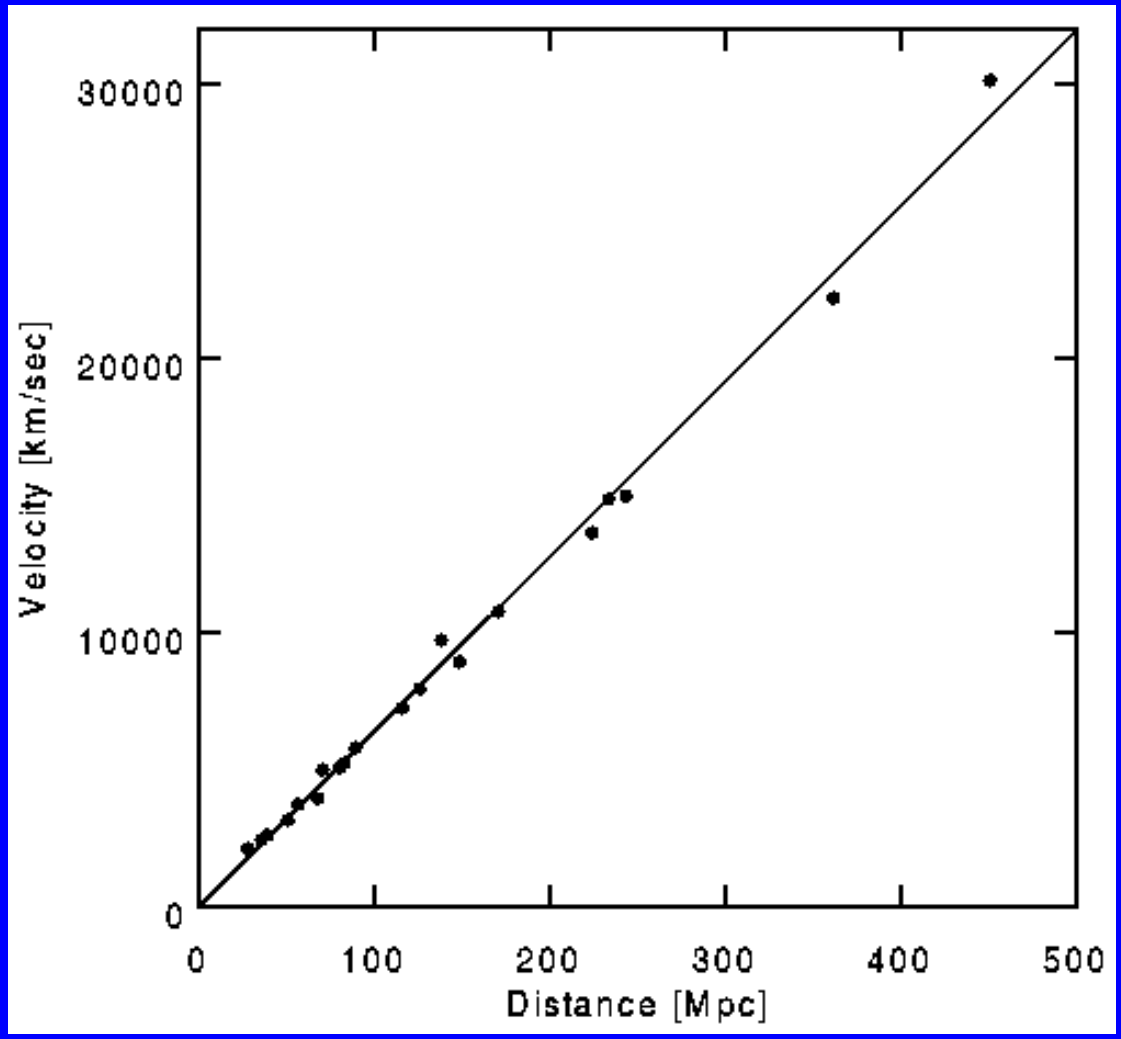
- Determination of Hubble rate crucially dependent upon *standard candles*
- Hubble Space Telescope helped to locate Type Ia supernovae whose time of flare up ( a few weeks) is directly related to their absolute luminosity.
  - ⋆ Type Ia -> White dwarfs which begin accreting material from another star
  - ⋆ Upper limit on White dwarf mass is 1.4 solar mass ( Chandrasekhar, Nobel 1983)
  - ⋆ Universal spectral features, absence of H lines, prsence of Si lines
- The Type Ia supernovae caught in real time ( 7 b. years after they actually flared up!) are the new far reaching standard candles

- ⋆ The shape of the light curve over the full event gives away the Type, ( see the sudden change in slope in the movie)
- ⋆ The total time baseline gives the absolute magnitude

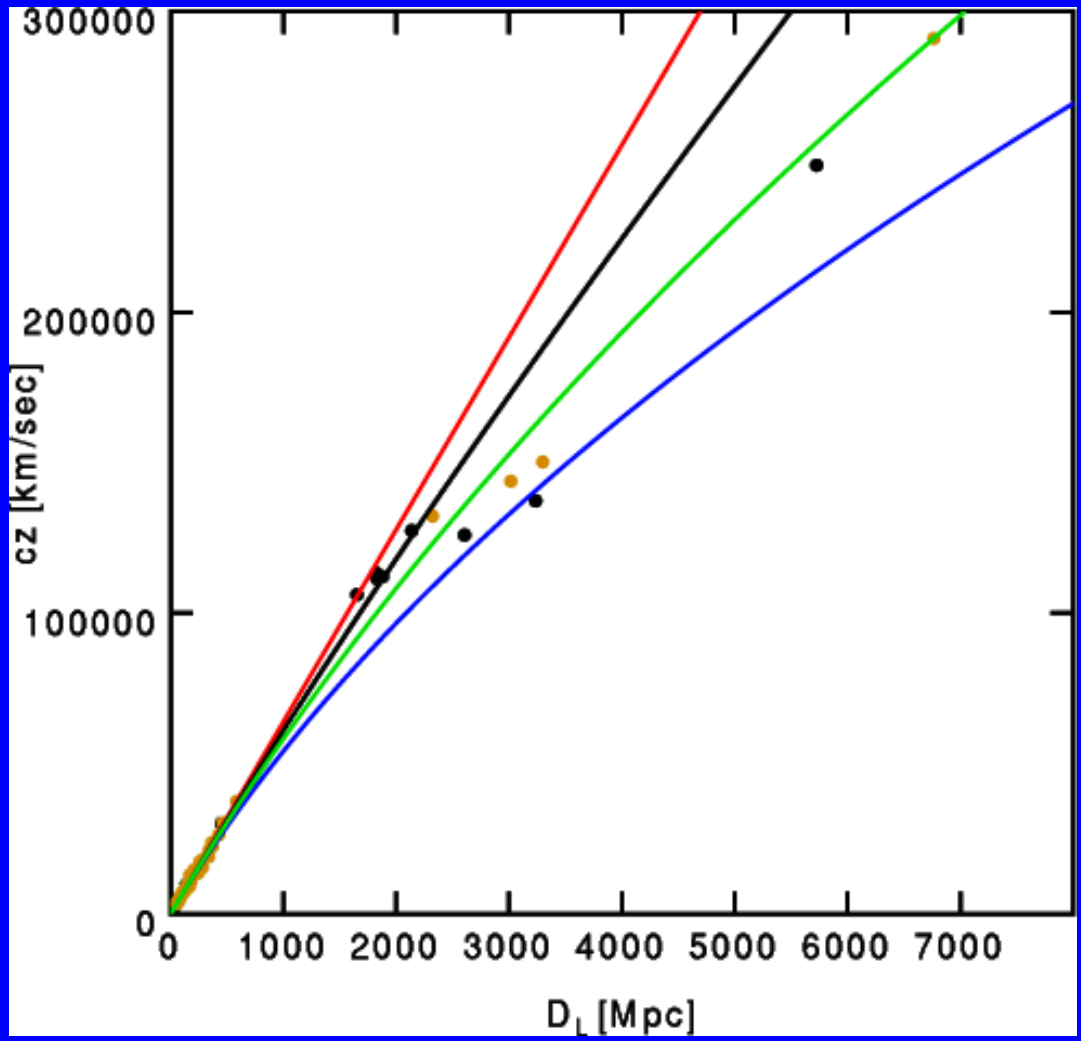
- Upto now almost 550 such ancient Type Ia supernovae recorded

Supernova real time simulation

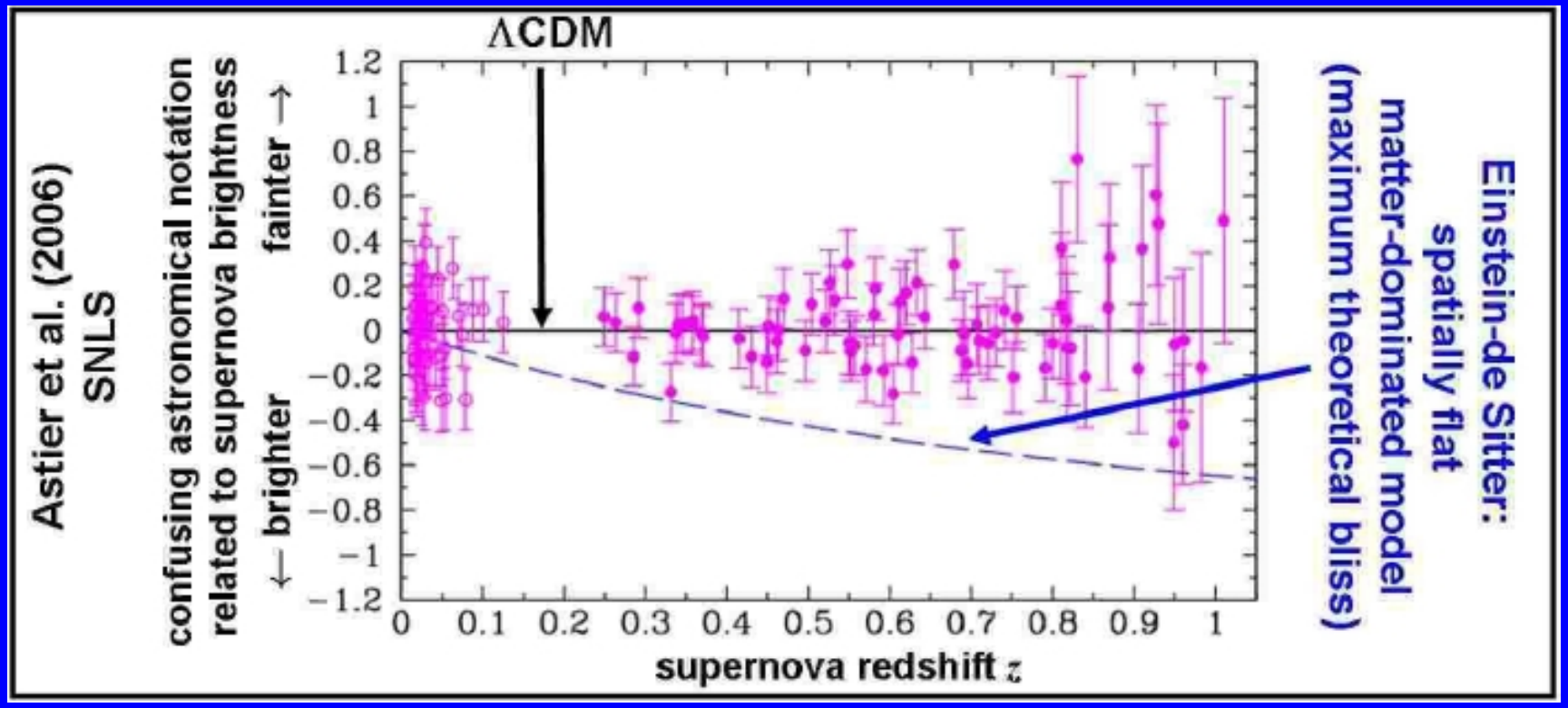
# A Hubble Plot before Hubble Space Telescope



# Modern Hubble plot



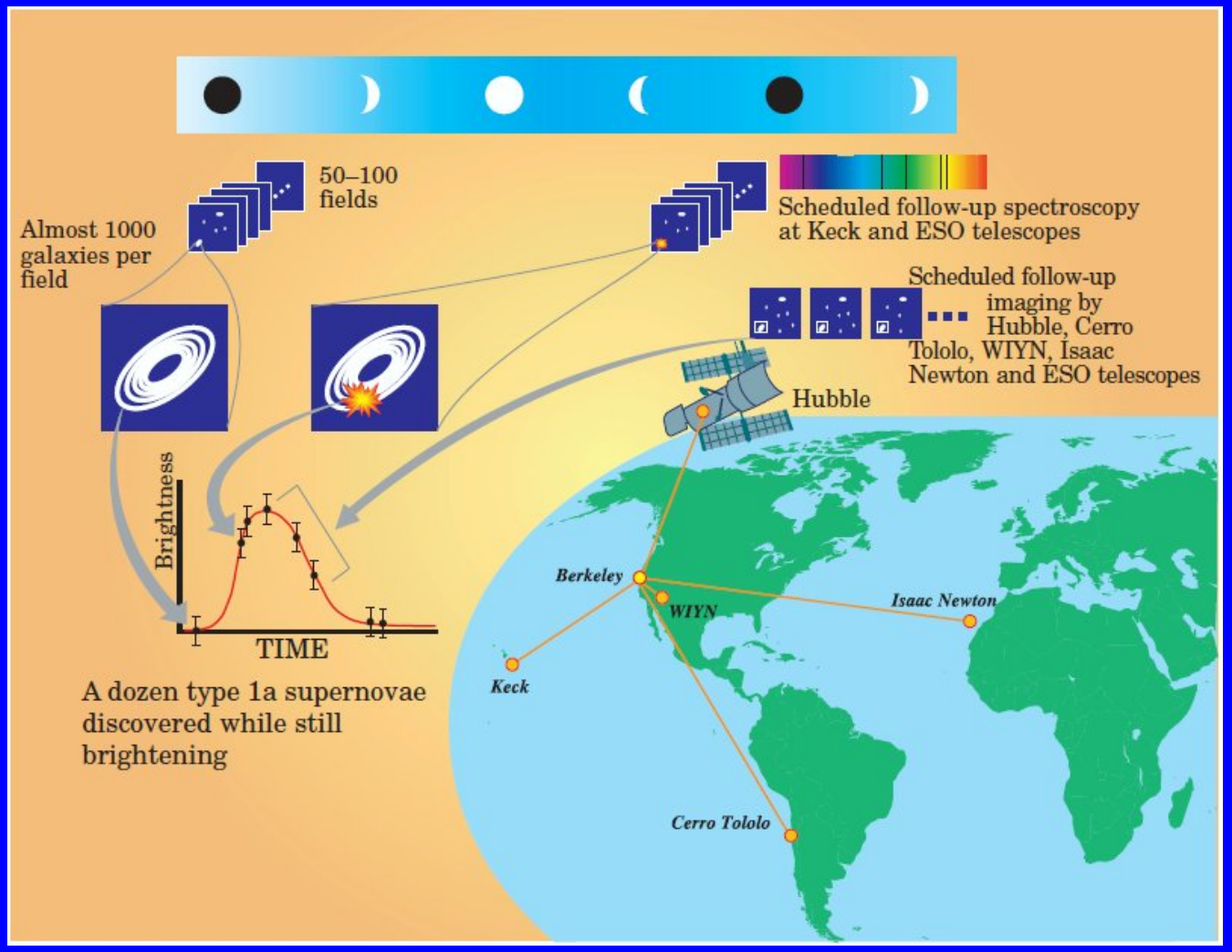
# Recent data confirming accelerating Universe



# The Laureates

Saul PerlMutter, Brian P. Schmidt and Adam Riess

# A worldwide observation strategy



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A little tutorial on Cosmology ...

# The three laws of cosmology

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**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

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

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

$R(t)$ the Scale factor ... introduced by A. A. Friedmann (1922)

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

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

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 $\Lambda$ (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 $\rho$, satisfying the unusual equation of state $p = -\rho$.

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- By 1929 Hubble's Law was discovered and Einstein soon retracted the $\Lambda$term : 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 $\Lambda$ 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 $\Lambda$ term dominates, $\Omega_\Lambda = 0.7$
- But most of matter-like $\rho$ is not baryons! Let $\Omega_\rho = \Omega_{DM} + \Omega_B$
  - ⋆ Baryons contribute only $\Omega_B = 0.03$
  - ⋆ $\Omega_{DM} = 0.27$ So much is the "Dark Matter"

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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.

# Ancilliary evidence : 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 :

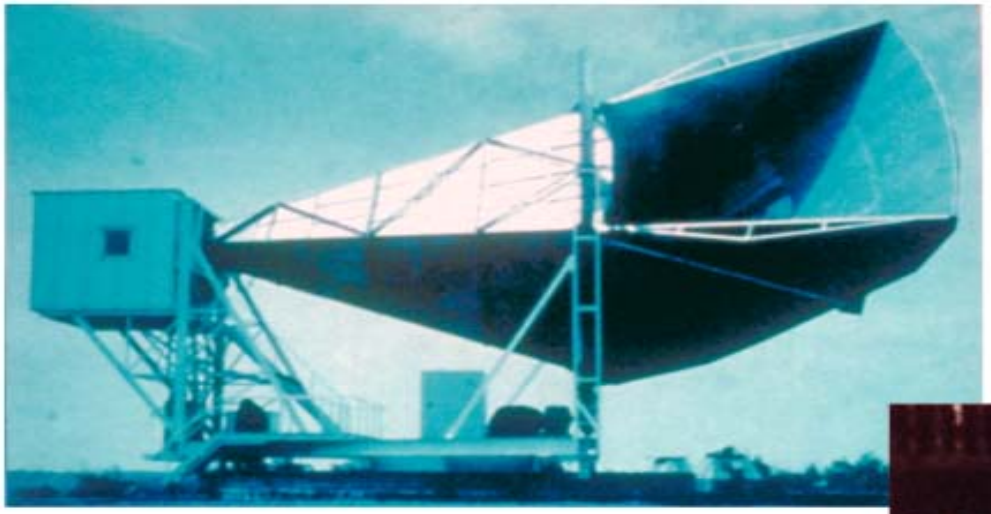
- Expansion rate $71 \pm 4$ (km/s)/MegaParsec
- Size of the visible Universe $3$ GigaParsec
- Age of the Universe $13.7 \pm 2$ GigaYears
- Age at decoupling $380 \pm 7 \times 10^3$ Year

# Electromagnetic fingerprints of the Universe

# Cosmic Microwave Backgrond Radiation (Bell Labs; 1964)

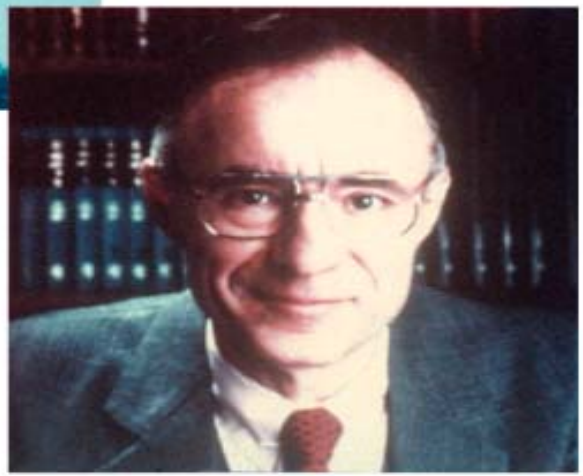
Nobel prize 1978

# Discovery of Cosmic Background



Microwave Receiver

Robert Wilson

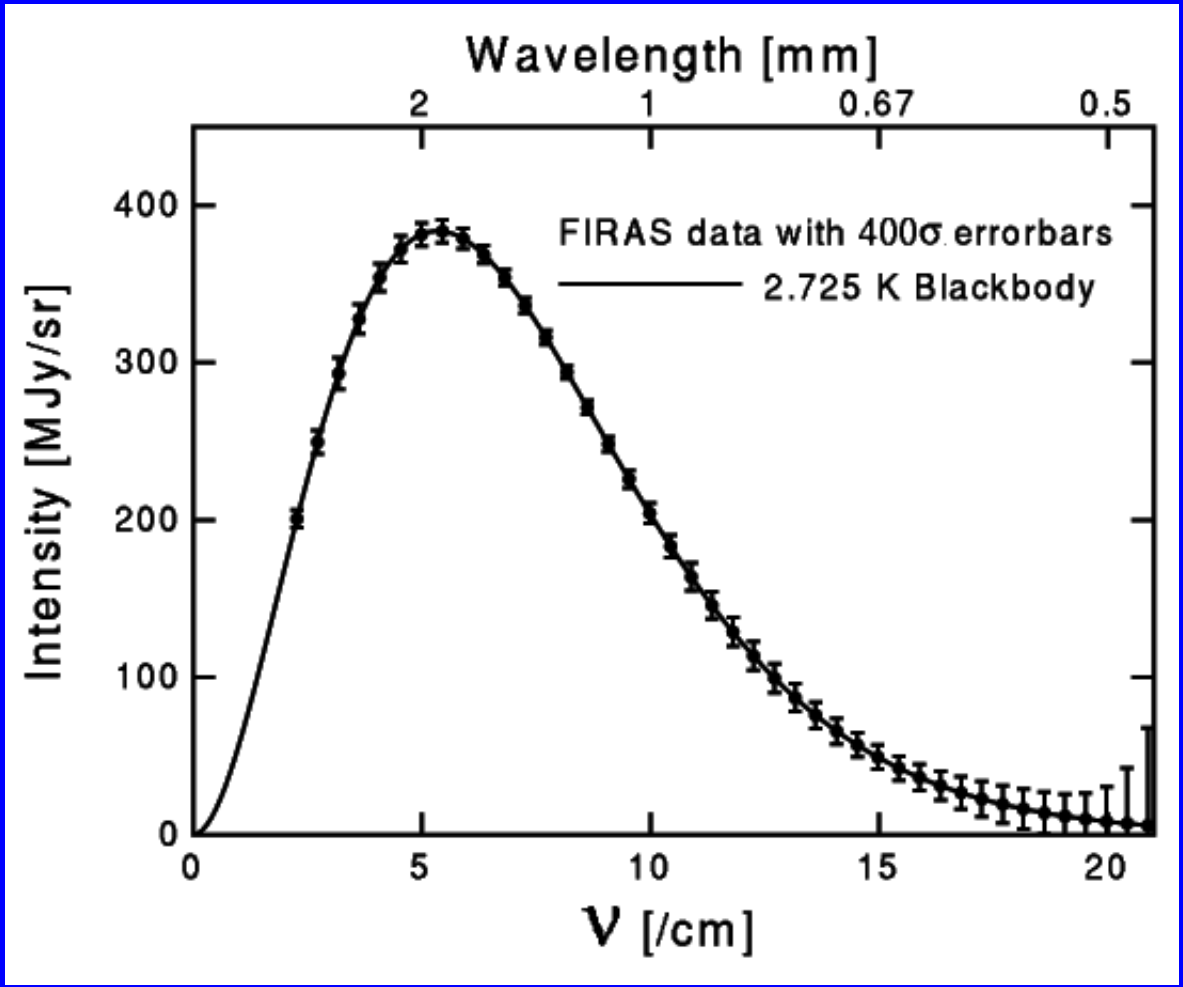


Arno Penzias

MAP990045

# COsmic Background Explorer (COBE 1992)

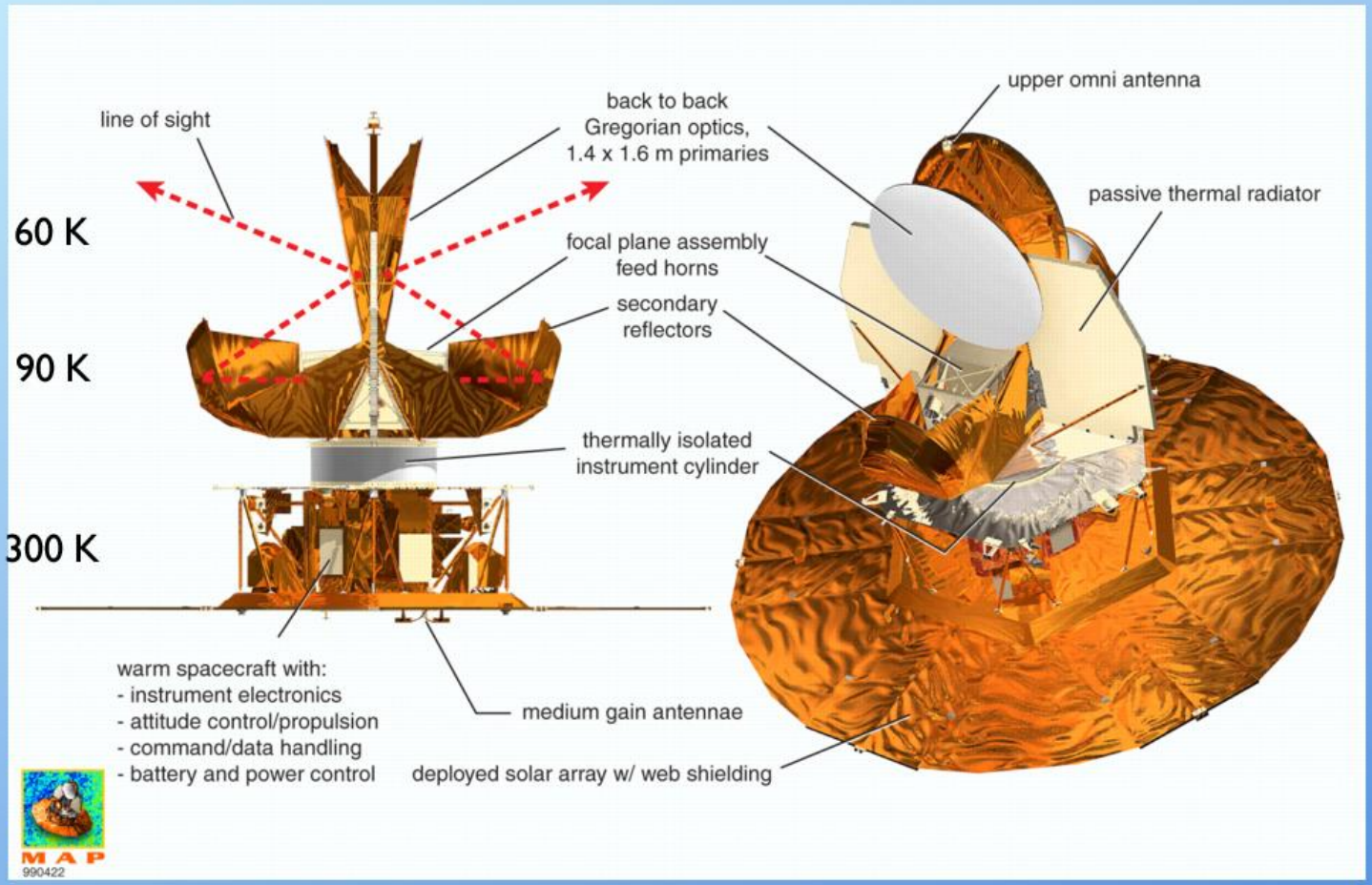
Nobel prize Smoot and Mather 2006


Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
5
10
15
20
ν [/cm]

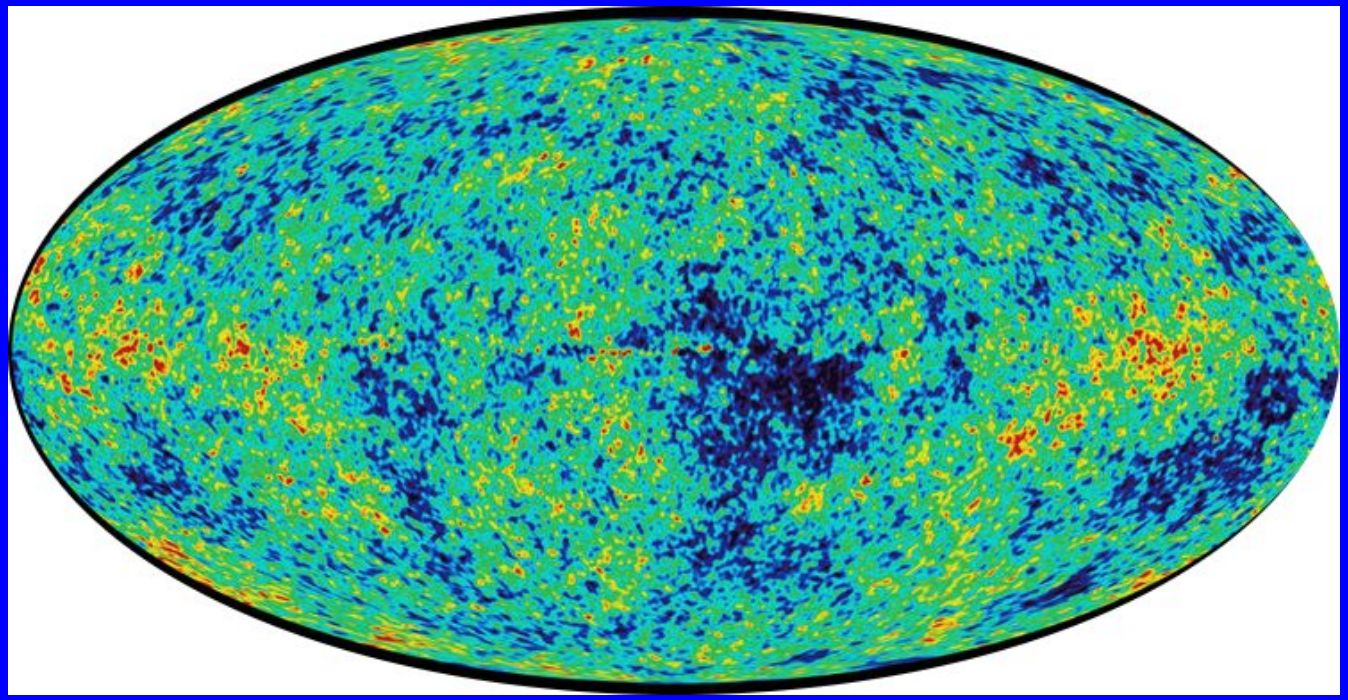
# Wilkinson Microwave Anisotropy Probe (WMAP 2003)

Nobel prize ???

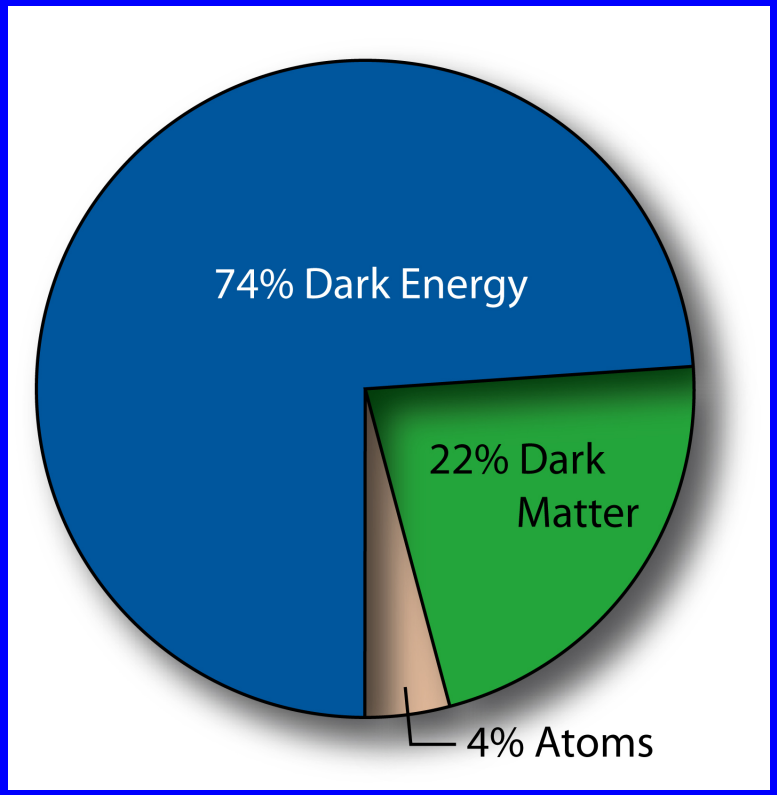
# *WMAP* Spacecraft and Instrument



# All sky microwave map of the Universe



# Combining supernova data and WMAP



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- There seems to be 26% Dark Matter ( pressureless, massive)
- There seems to be 70% Dark Energy ( space-filling, featureless vacuum energy)
- These features require new forms of energy/matter
- And also perhaps new laws of Physics

*– Typeset using Linux and LaTex –*