

Tracing our origins in the Universe

BY

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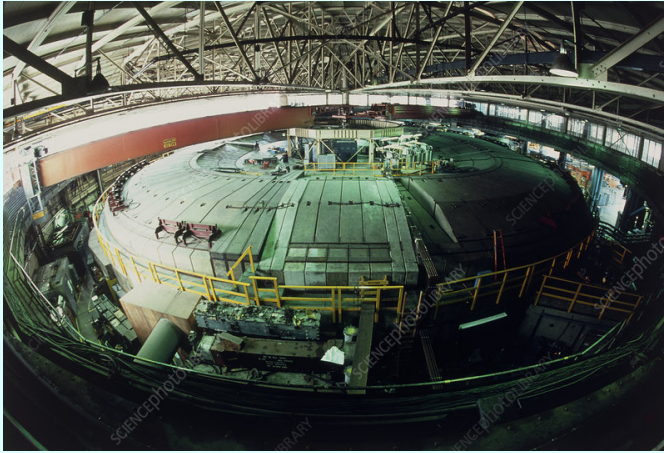


St Joseph's University, Bangalore 19 January 2026

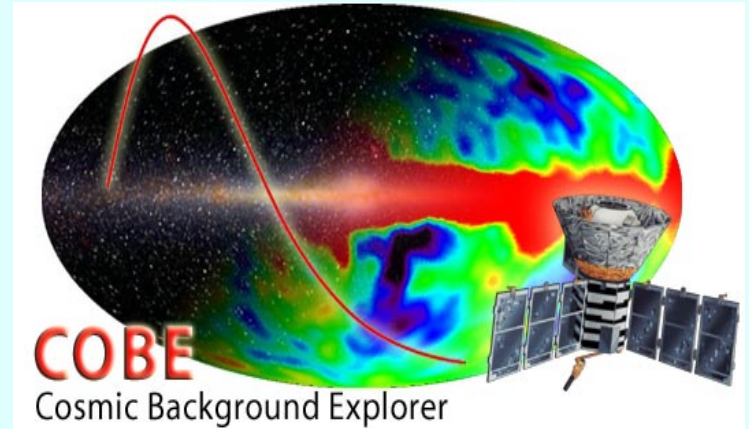
1 Overview

- Big Bang → homogeneous Universe on the average
 - Small fluctuations in detail
 - otherwise where will galaxies, the Sun, ... and us, will come from?
- Fundamental interactions → both particles and anti-particles
 - Proton ↔ antiproton, electron ↔ positron
 - where are all the anti-protons and the positrons??
- What is Dark Matter and what is its role?
- What is Dark Energy and what is its role?

2 The birth of Particle - Cosmology

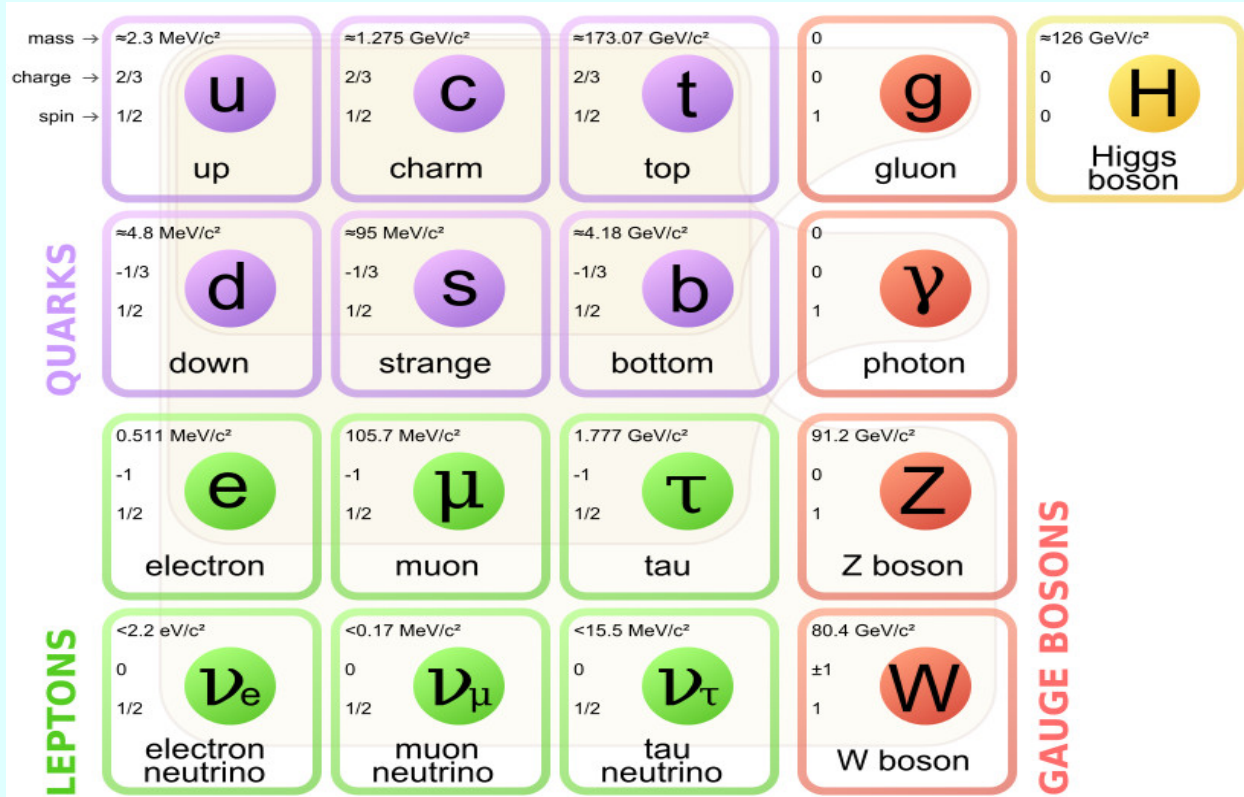


Bevatron -Berkeley 1960's



COBE 1990 - Nobel 2006

2.1 Standard Model of elementary particles



3 Salient features of the Standard Model

3.1 Dynamical symmetries and global charges

- i. Strong force charge "color"
- ii. Weak force charge "Weak isospin"
- iii. Electromagnetic charge

* Global "charge" (i) Baryon (ii) Lepton

- i. Flavour of B or L : All charges identical, only mass values

differ. 3 families for baryons, 3 families for leptons, each family in both cases has 2 members, totally 6 generations.

Note, ν_R the Right-handed neutrino state is missing from low energy physics described by the Standard Model Electro-Weak force.

Flavor is an unsolved “problem”.

The Standard Model

- All fermions **chiral** ... left and right helicities have differing charges
- “Electroweak” theory spontaneously broken

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$$

- Quarks come in 3 “colour”s

$$SU(3)_C$$

- Quantum Chromodynamics; unbroken but “confined”
- All masses, fermions and gauge bosons, derived from “**spontaneous symmetry breaking**” with a massive scalar Higgs boson as the residual signature of this mechanism

3.2 Discrete symmetries take centre stage in signalling the existence of new forces.

Lorentz group of symmetries are fundamental.

But there are four disconnected subsets.

P -> parity or handedness e.g., $e_L^- \leftrightarrow e_R^-$

T -> Time reversal - not operationally possible but in-built

Additionally, Relativistic causality opens up ...

C -> charge conjugation e.g., $e^- \leftrightarrow e^+$

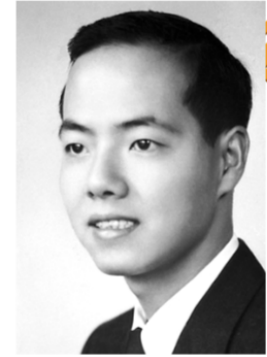
from Parity violation to chirality

- Only Left “Chiral” electron and neutrino in charged Weak transitions

Madam C-S WU



C N Yang



T D Lee



R E Marshak



E C G Sudarshan



The Standard Model :

Nobel Laureates

4 Cosmology becomes a science !

The simplicity of the Universe an outcome of elegant dynamics.

- Einstein believed in static Newtonian universe
- Friedmann 1921 - 22 found dynamical solutions in Einstein's own General Relativity
- Edwin Hubble boldly drew the straight line 1929

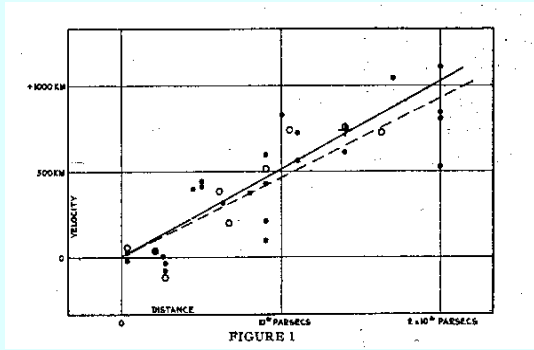


Edwin Hubble



Scanned at the American
Institute of Physics

Henrietta Leavitt



Hubbles original plot
above; SHOES modern
collaboration right

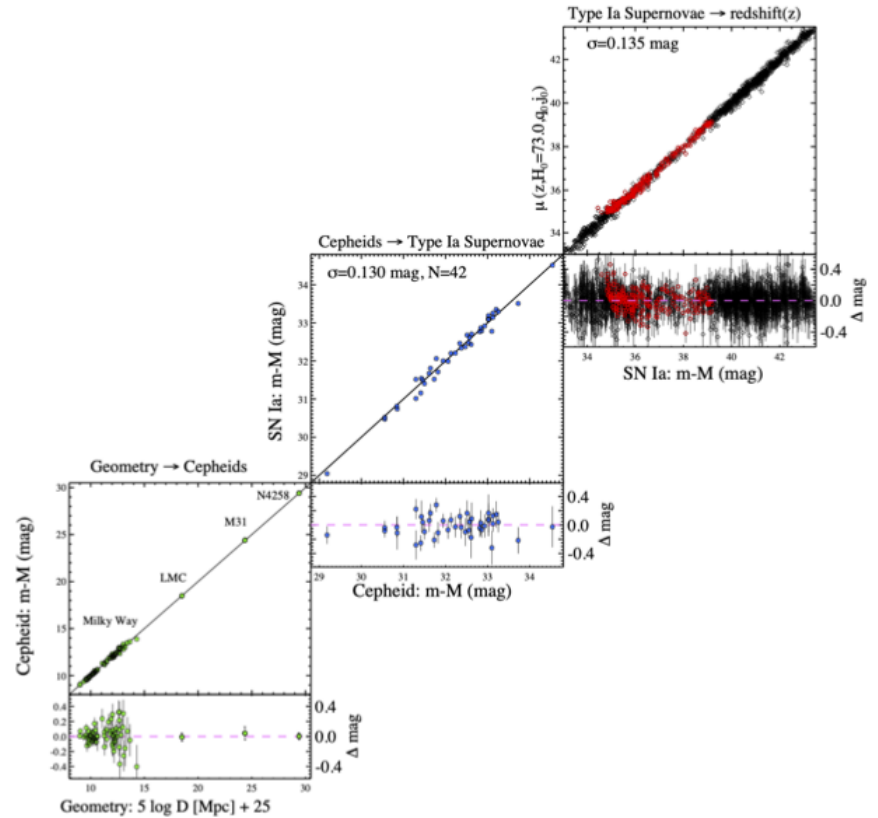
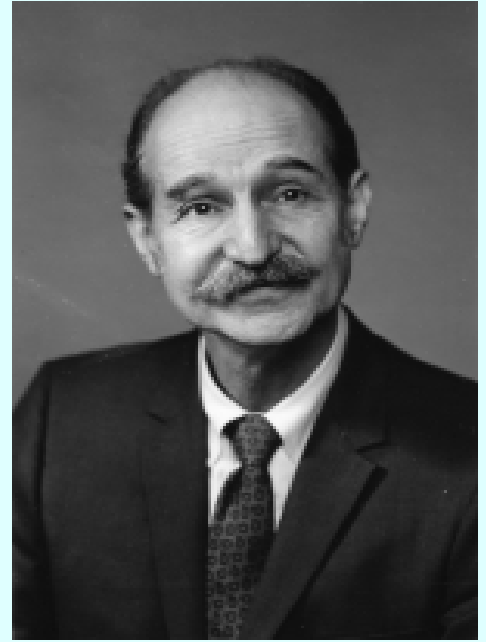
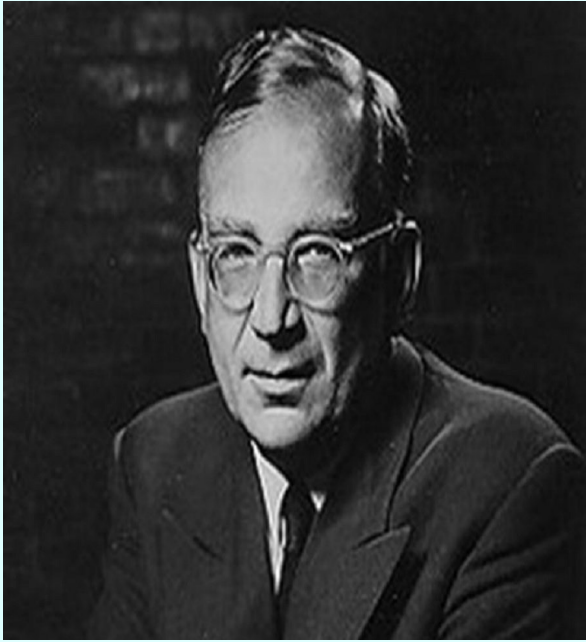


Figure 3

The cosmic distance ladder used by SHOES to infer H_0 . The luminosities of nearby Cepheid variables are calibrated to parallaxes. Supernova luminosities are then calibrated to Cepheid

4.1 Particle cosmology is born ...

- 1920's the decade of expanding Universe
 - Friedmann, Hubble, LeMaitre ...
- 1948-49 Nucleosynthesis and CMB in “Big Bang” universe
 - Alpher “Bethe” and Gamow; Alpher and Herman



Gamow; Alpher; Herman

Gamow's joke : Alpher Bethe Gamow

No Nobel -(:

4.2 Annus mirabilis of particle-cosmology

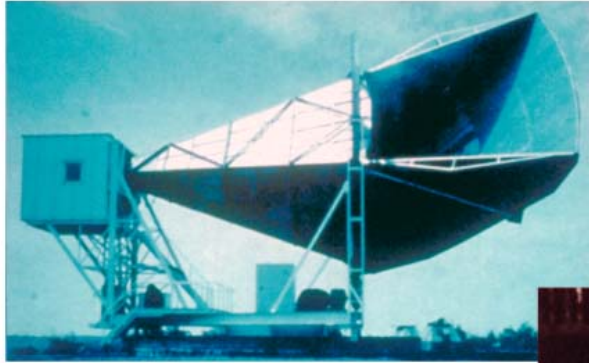
1964–65 : *the classic year!*

Hints of dynamical origins of the matter-anti-matter asymmetry

- Accidental discovery of cosmic microwave background
- Discovery of CP violation in K -meson decays

4.3 Cosmic Microwave background

DISCOVERY OF COSMIC BACKGROUND

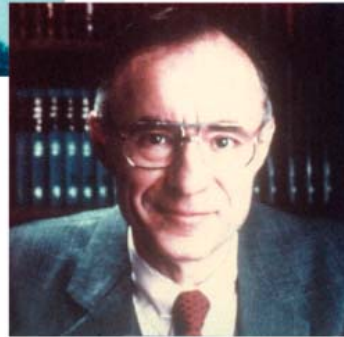


Microwave Receiver



MAP990045

Robert Wilson



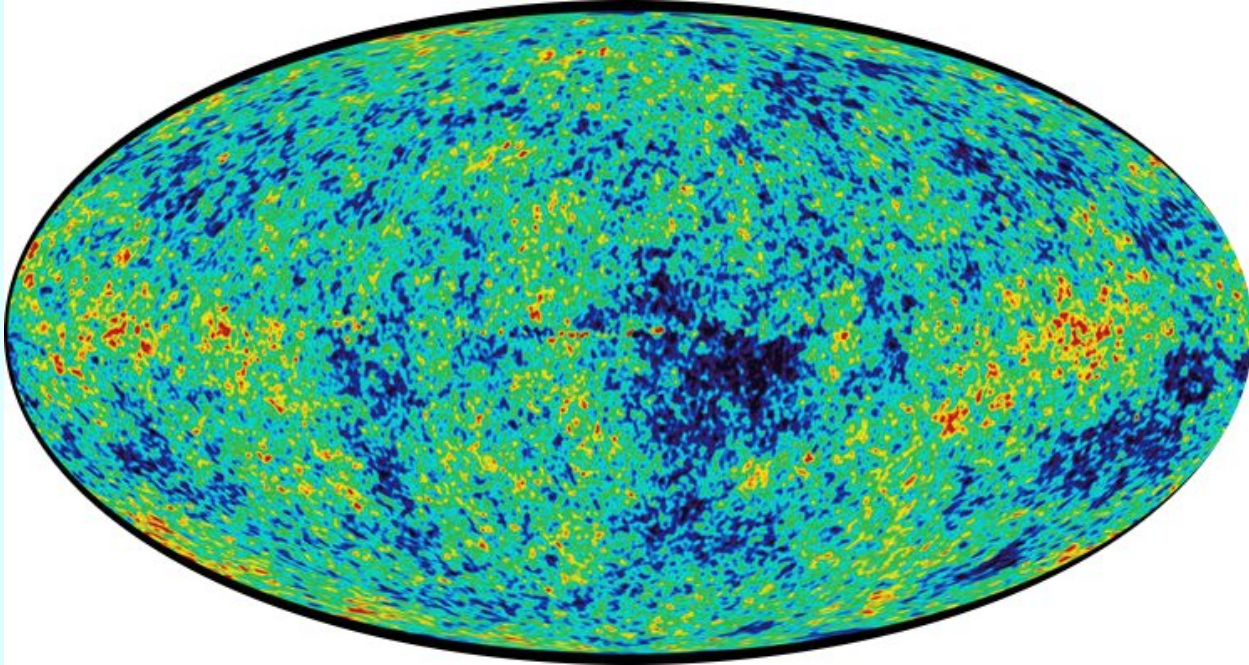
Arno Penzias

Discovery by electrical engineers Panzias and Wilson at Bell Labs, NJ, 1964

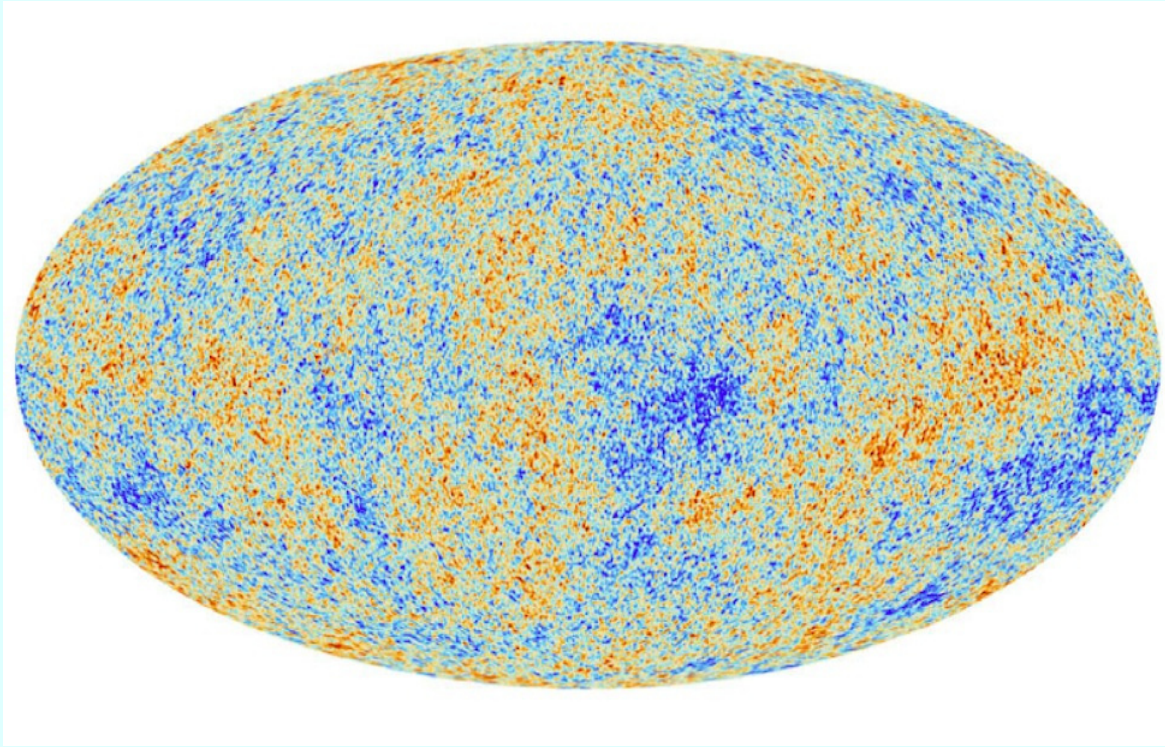
Nobel Prize 1978, shared with Pyotr Kapitza of cyogenics

Mather and Smoot Nobel 2006 for COBE confirmation

WMAP (Wilkinson Microwave Anisotropy Probe) results



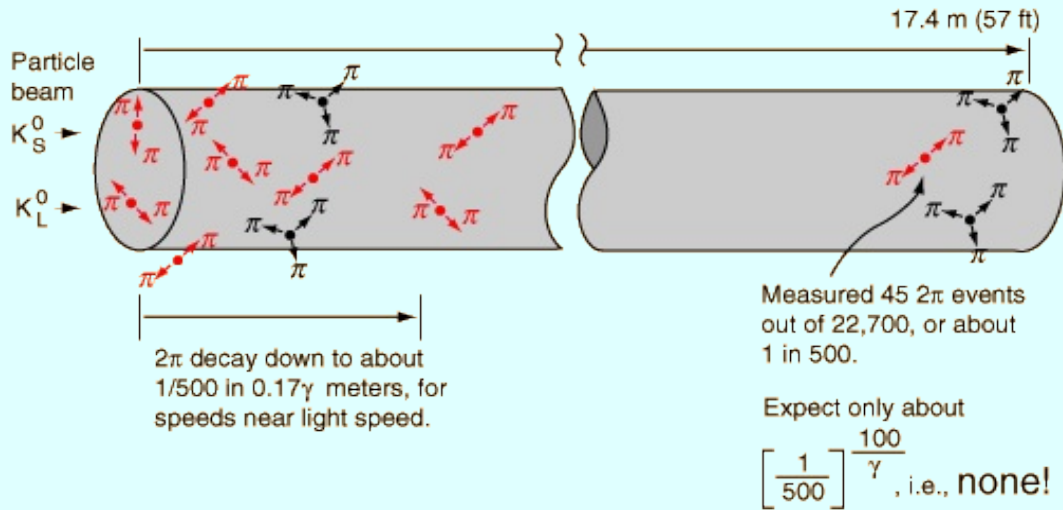
As reported around 2005



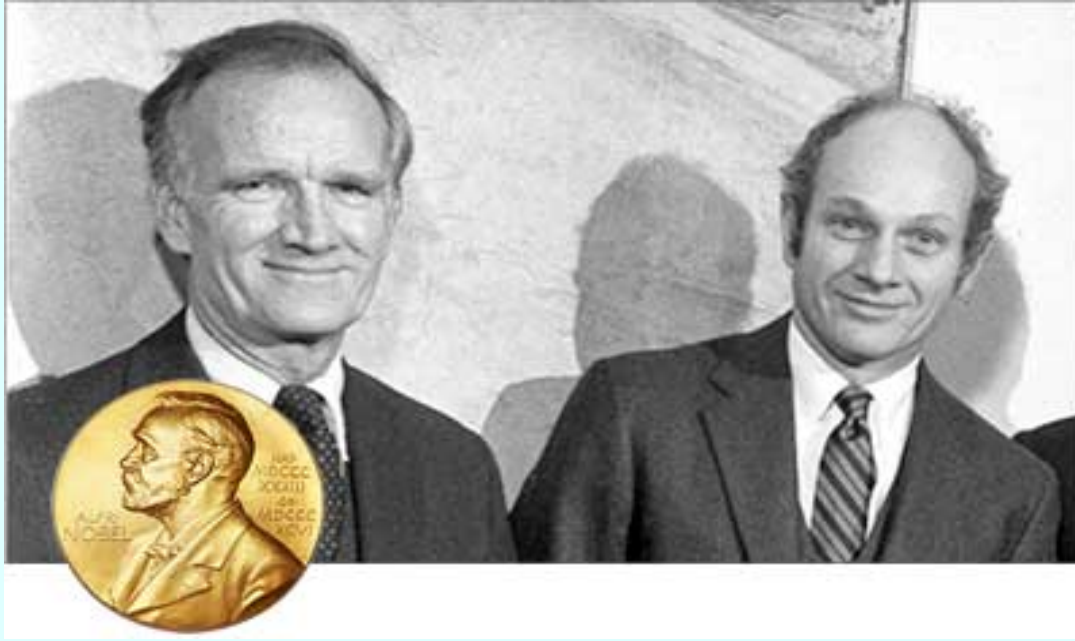
As refined by Planck satellite 2015

- The Universe as a whole a single glowing ball 13 billion years ago!!
- Its light today is “red shifted” into microwaves
- with almost exactly same black body radiation temperature 2.73 K in every direction in the sky.
- The temperature difference between the hottest and coldest spots is 0.1 Kelvin
- Root-mean-squared deviations in temperature across all directions $\frac{\Delta T}{T} \sim 10^{-5}$
- Penzias and Wilson (with Kapitza) Nobel 1978, and WMAP experiment Nobel 2006

4.4 CP violation : Brookhaven National Lab



The two facts together – hot big bang and CP violation have the potential to explain the baryon asymmetry of the Universe!!



Val Fitch and James Cronin Nobel 1980

5 The great cosmology conundrums

- Matter-anti-matter asymmetry
- Dark Matter
- Dark Energy
 - [A wide discrepancy in H_0 measurement from “direct” observations vs. CMB evolution]
- The uncanny homogeneity and enormous scales (Inflation!)
- [James Webb reporting fully formed galaxies very early (seems resolved)]

5.1 The three laws of Cosmology

1. The Friedmann paradigm : A homogeneous isotropic universe is essentially described by one function - the scale factor $a(t)$

$$ds^2 = dt^2 - a(t)^2(dr^2 + r^2d\theta^2 + r^2\sin^2\theta)d\phi^2$$

2. It evolves according to

$$\left(\frac{1}{a} \frac{da}{dt}\right)^2 + \frac{k}{a^2} - \Lambda = \frac{8\pi}{M_{\text{Pl}}^2} \rho$$

3. General Relativity as well as thermodynamics require

$$\frac{d(\rho a^3)}{dt} + p \frac{d(a^3)}{dt} = 0 \quad [dU + pdV = 0]$$

and needs to be complemented by an equation of state

$$p = w \rho$$

In the current universe we find

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{M_{\text{Pl}}^2}(\rho_{\text{known}} + \rho_{\text{DE}}) \quad (k = 0)$$

- With $\rho_{\text{known}} = \rho_{\text{baryons}} + \rho_{\text{DM}}$; $\rho_{\text{baryons}} \approx 0.04$ and $\rho_{\text{DM}} \approx 0.26\rho_0$;
- We also see $\rho_{\text{DE}} \approx 0.7\rho_0 \sim 10^{-10}(\text{eV})^4$
 - Smallness compared to any HEP scale
- Cosmic coincidence in the Dark Sector at t_0 ?
 - $\rho_{\text{DM}} \approx \rho_{\text{DE}}$ in the late universe

6 Dark Matter

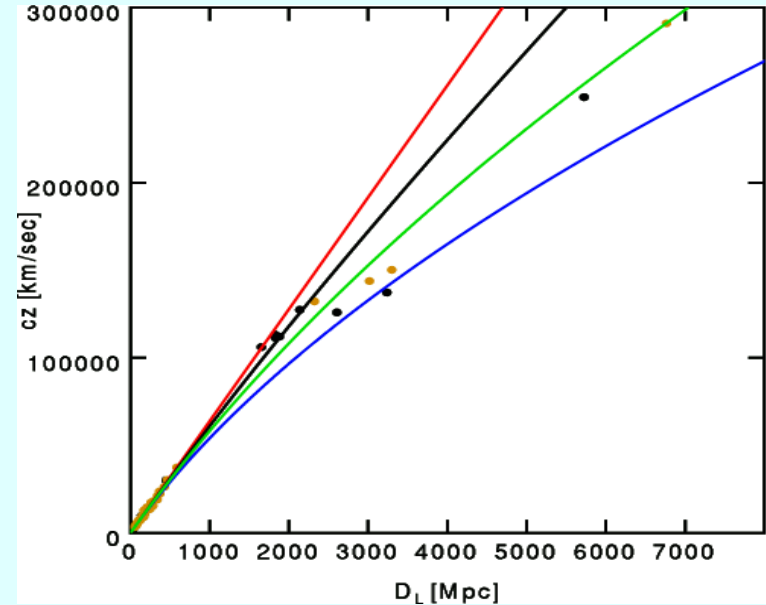
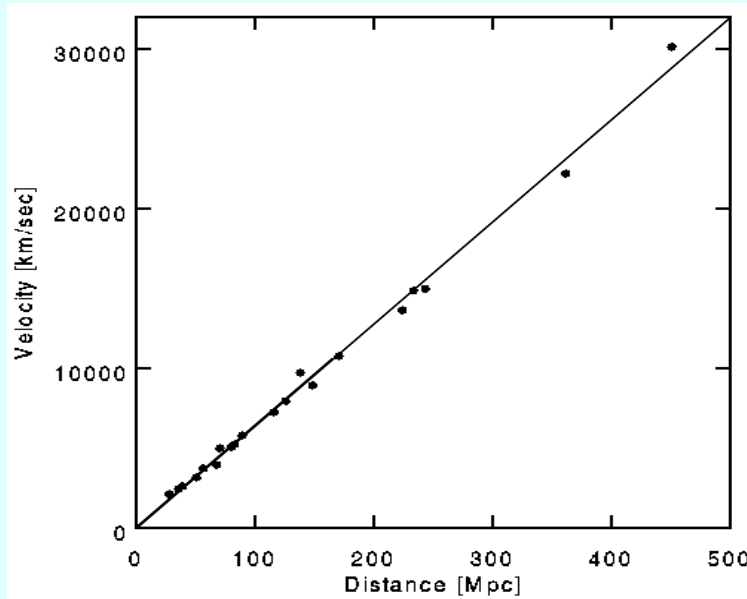


The “bullet cluster” via
(i) optical (ii) X-ray (pink) (iii) gravitational lensing (blue)

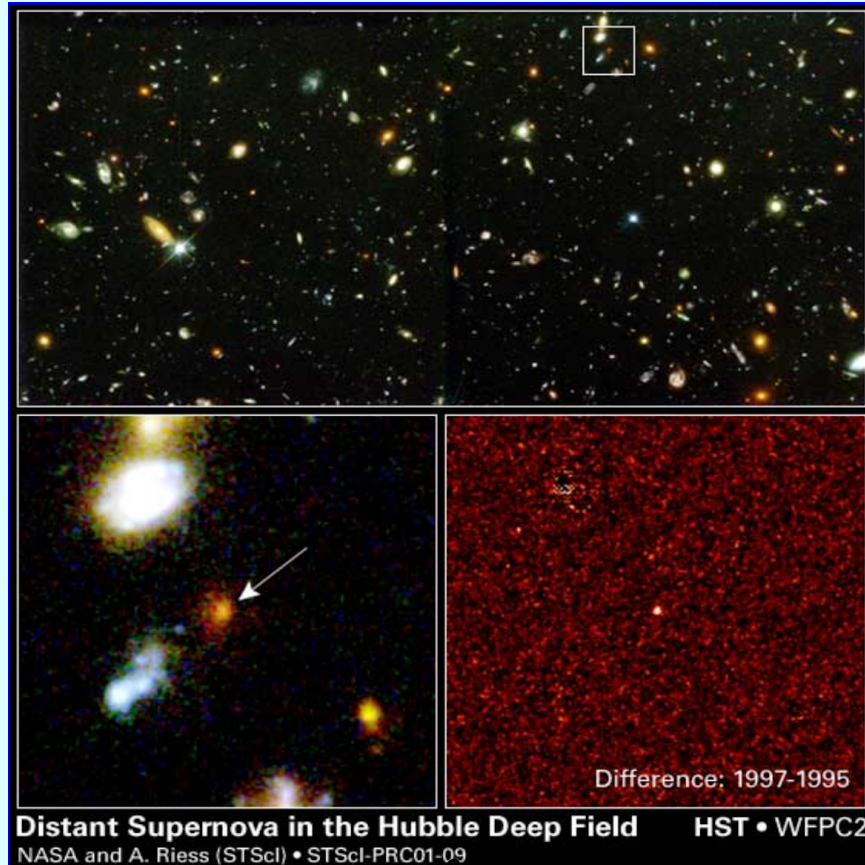
Note the power of
“Multimessenger astronomy”

7 Dark Energy

A new class of "standard candles", supernovae called SN Ia



7.1 A blast from remote past

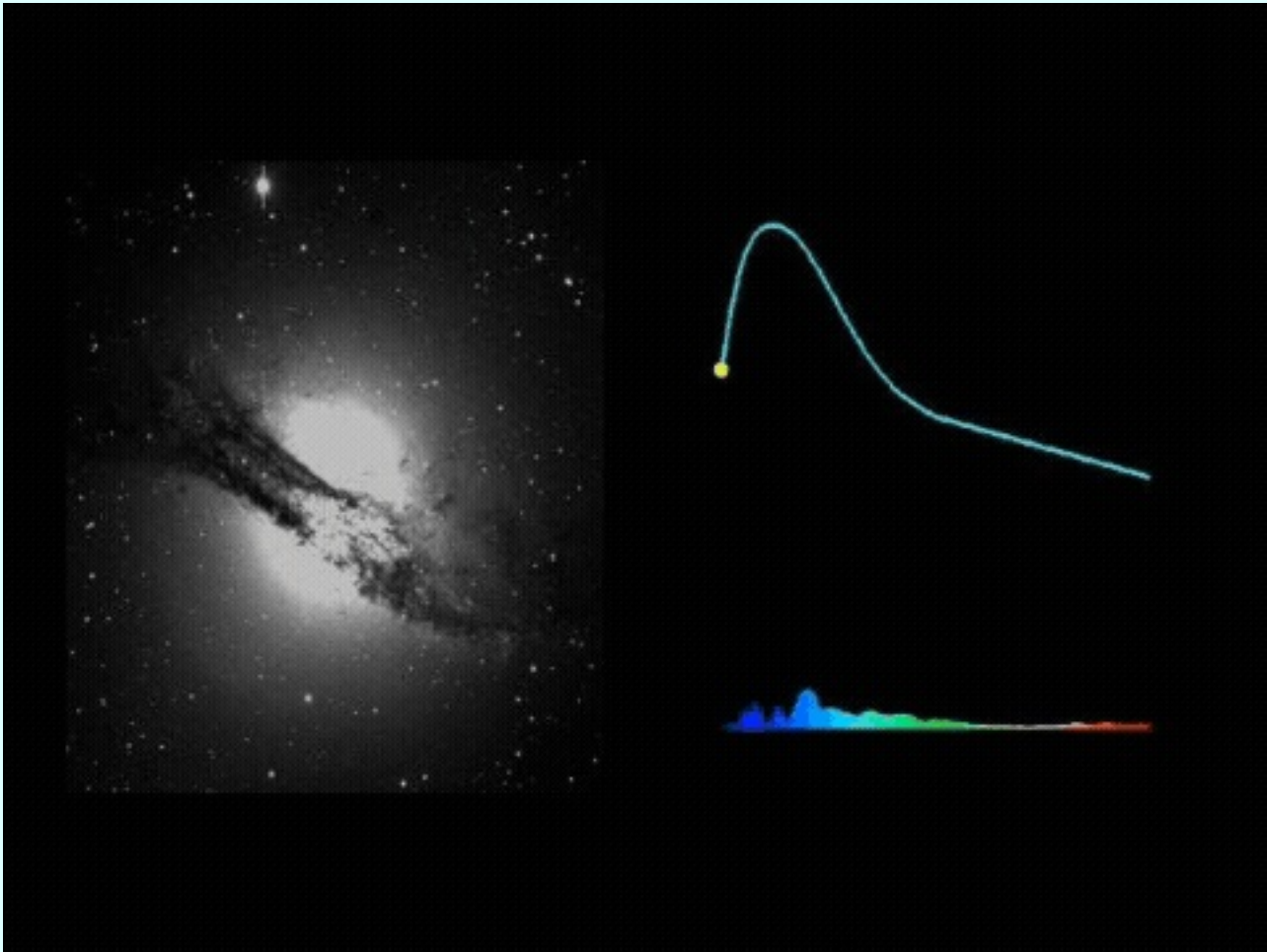


New standard candles

- 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

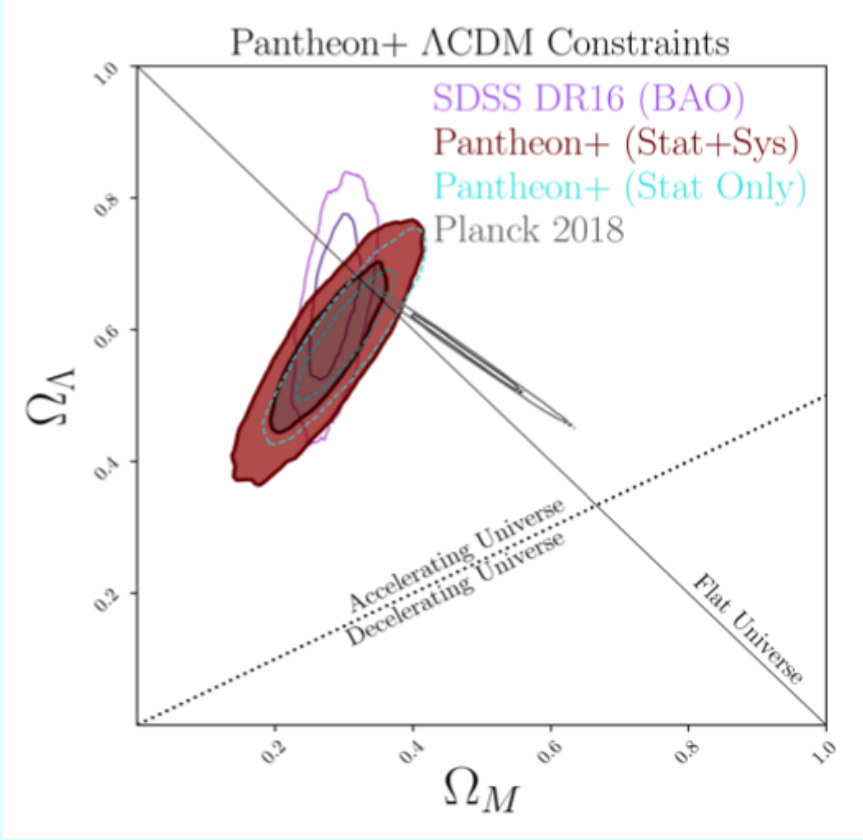
Show Perlmutter video clip (saul_sm.mpg) !



Summary : Current contents of the Universe

but ...
Dark Energy need not be a constant contribution, nor completely homogeneous

[arxiv:1901.00995](https://arxiv.org/abs/1901.00995)



8 Baryon asymmetry of the Universe

Just a little asymmetry

Annus Mirabilis of Cosmology

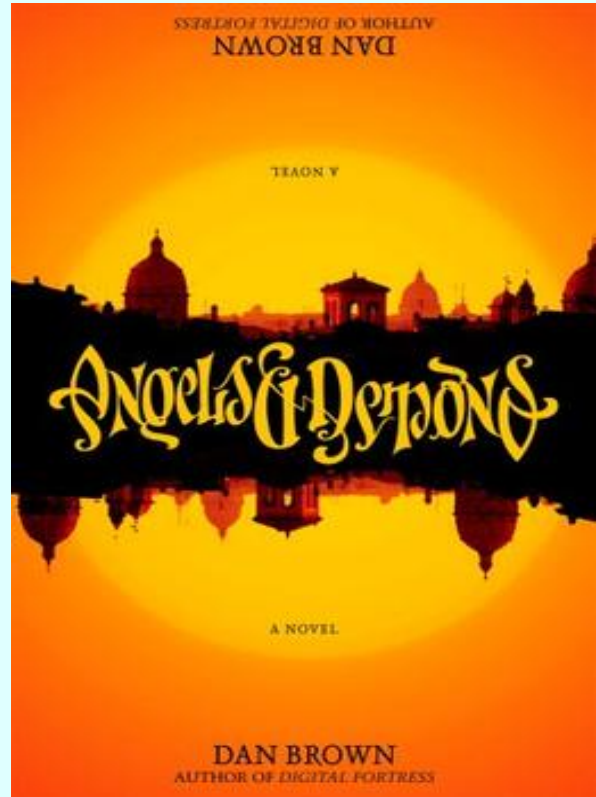
Two discoveries of 1964

→ CP violation in $K^0 - \bar{K}^0$

→ CMB !!!

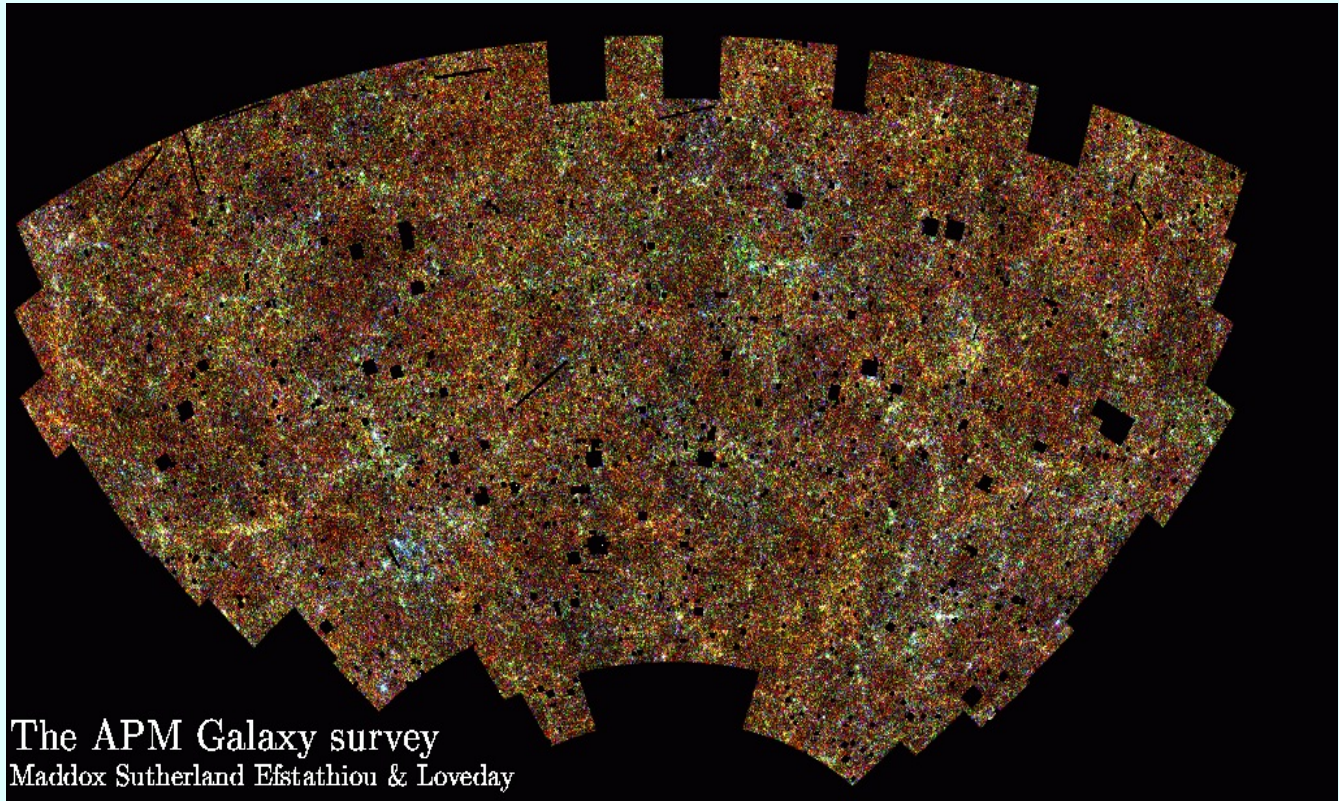
Weinberg comment in Brandeis Lectures 1964.

Sakharov model elucidating the criteria 1967

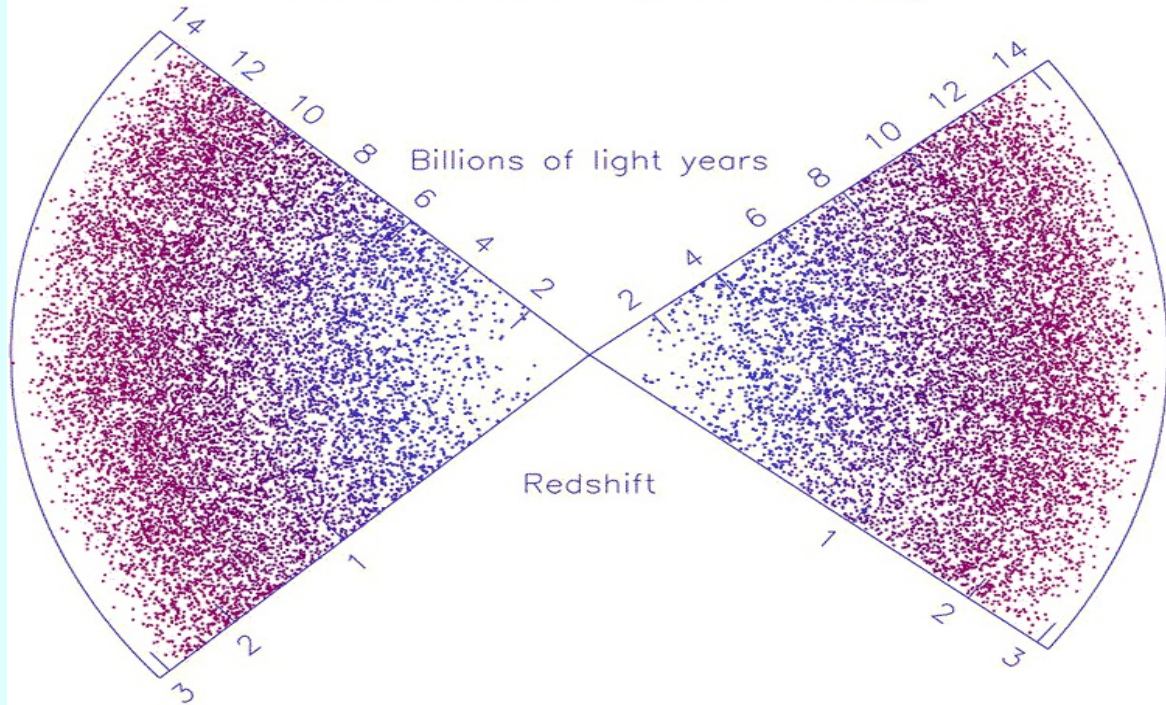


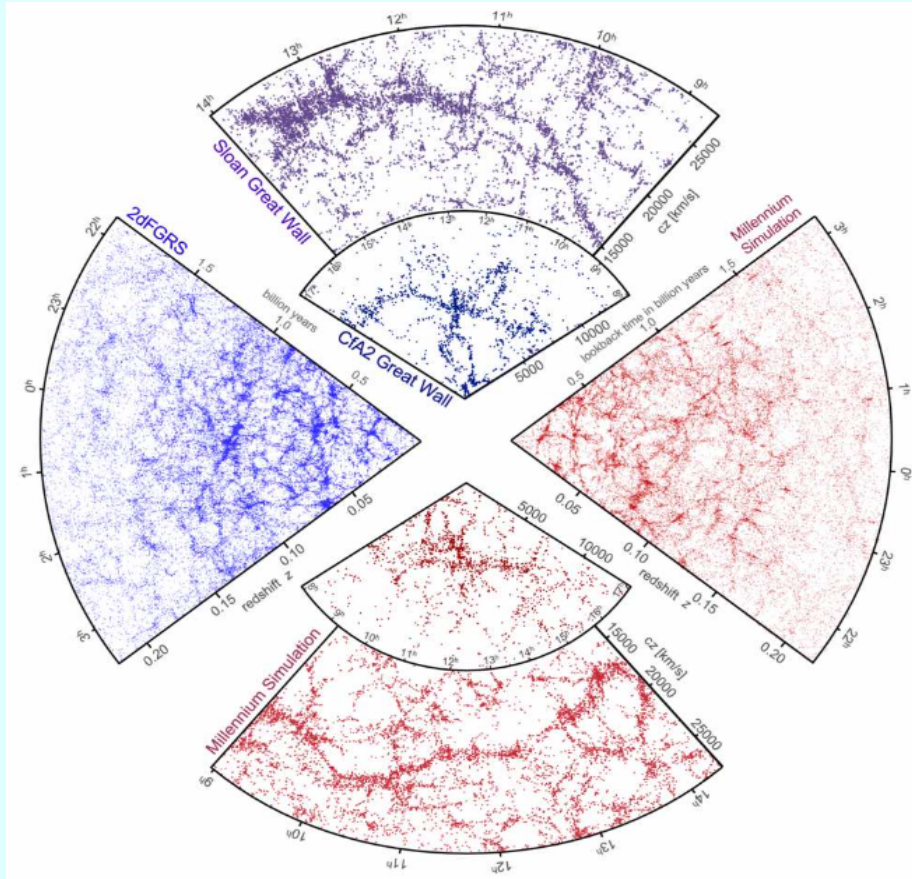
- No smoking gun signs of anti-matter
 - Uniform distribution of galaxies – with irregularities within statistical tolerance
- *Where are all the anti-protons?* and positrons??
- Quantifying the asymmetry : “Baryon to photon ratio”

$$\eta = \frac{n_B - n_{\bar{B}}}{s_\gamma} = 5 \times 10^{-10}$$



The 2dF Quasar Redshift Survey





Springel et al
 Nature 2006

Surveys upper left
 simulations lower right

8.1 Creation of the asymmetry

(Weinberg 1964 and 1978; Sakharov 1967; Yoshimura 1978)

1. There should exist baryon number B violating interaction

$$\begin{array}{ll} X \rightarrow qq & \Delta B_1 = \frac{2}{3} \\ & \bar{q}\bar{l} \quad \Delta B_2 = -\frac{1}{3} \end{array}$$

2. Charge conjugation C must be violated

$$\mathcal{M}(X \rightarrow qq) \neq \mathcal{M}(\bar{X} \rightarrow \bar{q}\bar{q})$$

3. **CP violation** (equivalently, **Time reversal** violation)

$$r_1 = \frac{\Gamma(X \rightarrow qq)}{\Gamma_1 + \Gamma_2} \neq \frac{\bar{\Gamma}(\bar{X} \rightarrow \bar{q}\bar{q})}{\bar{\Gamma}_1 + \bar{\Gamma}_2} = \bar{r}_1$$

4. **Out of equilibrium** conditions

Reverse reactions don't get the time to reverse the products

5. Net baryon asymmetry

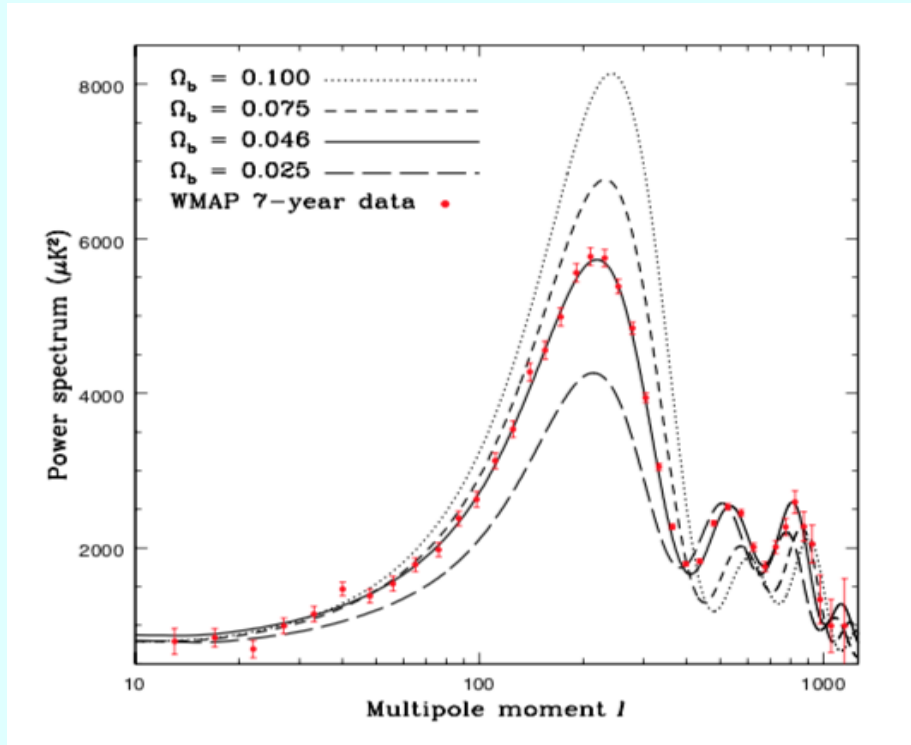
$$\begin{aligned} B &= \Delta B_1 r_1 && + \Delta B_2 (1 - r_1) \\ &+ (-\Delta B_1) \bar{r}_1 && + (-\Delta B_2) (1 - \bar{r}_1) \\ &= (\Delta B_1 - \Delta B_2) (r_1 - \bar{r}_1) \end{aligned}$$

6. The Particle Physics rates and expansion rate of the Universe compete : **out-of-equilibrium decays**

$$\Gamma_x \cong \alpha_x m_x^2 / T;$$

$$H \cong g_*^{1/2} T^2 / M_{\text{Pl}}$$

8.2 Deducing the “Baryon to photon ratio” - I

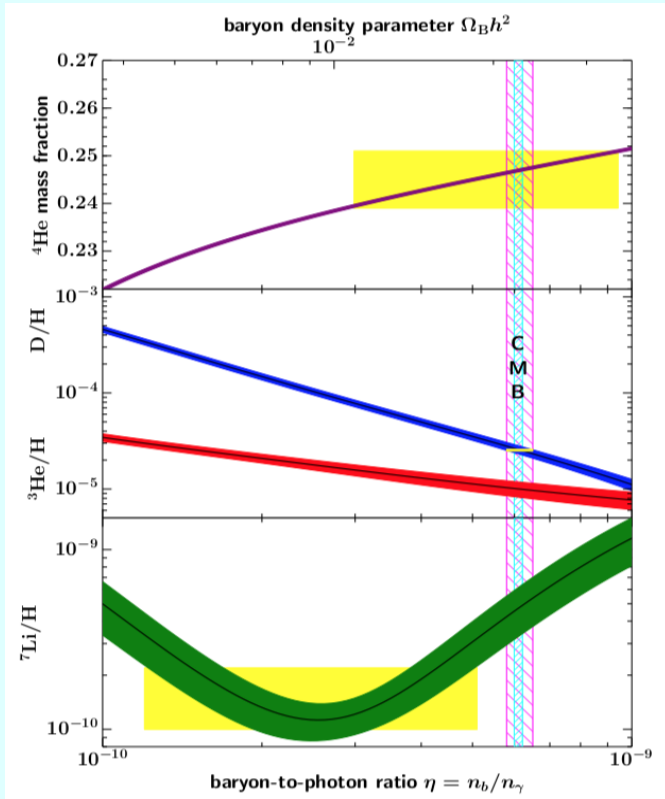


The fluctuation spectrum of CMB a sensitive probe.

The location of the first peak very sensitive to Baryon content.

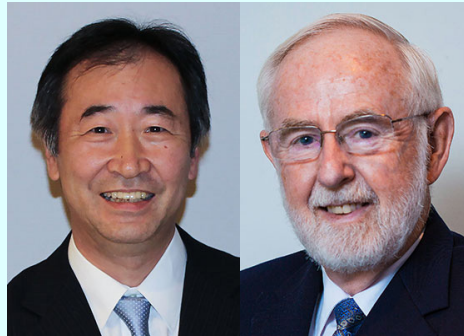
Photon content from T_{CMB} !

8.3 Deducing the “Baryon to photon ratio” - II



- Primordial abundance of elements
- Huge photon temperature prevents heavier elements from getting cooked
- Theory expectations from measured x-sections in bands
- Astrophysical ranges in yellow boxes

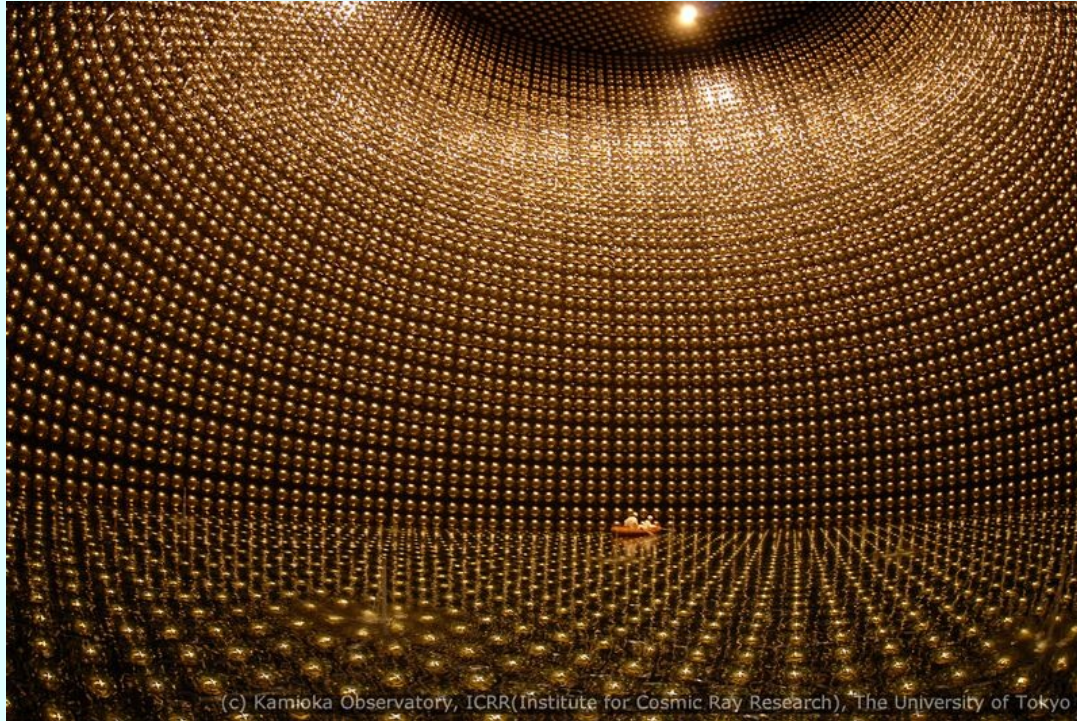
8.4 Baryogenesis from leptogenesis



- Neutrino oscillations observed 1998
 - Takaki Kajita and Arthur MacDONALD Nobel 2015
 - strong hints of Majorana neutrinos which can give Lepton asymmetry

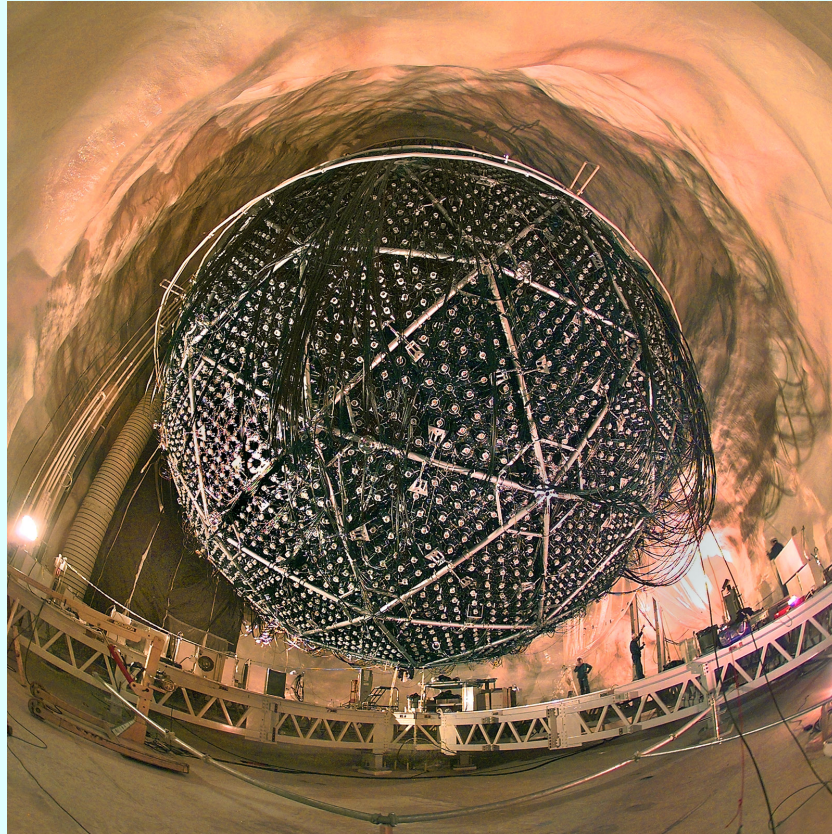
8.5 Hunting the elusive neutrinos

8.5.1 super-Kamiokande Japan

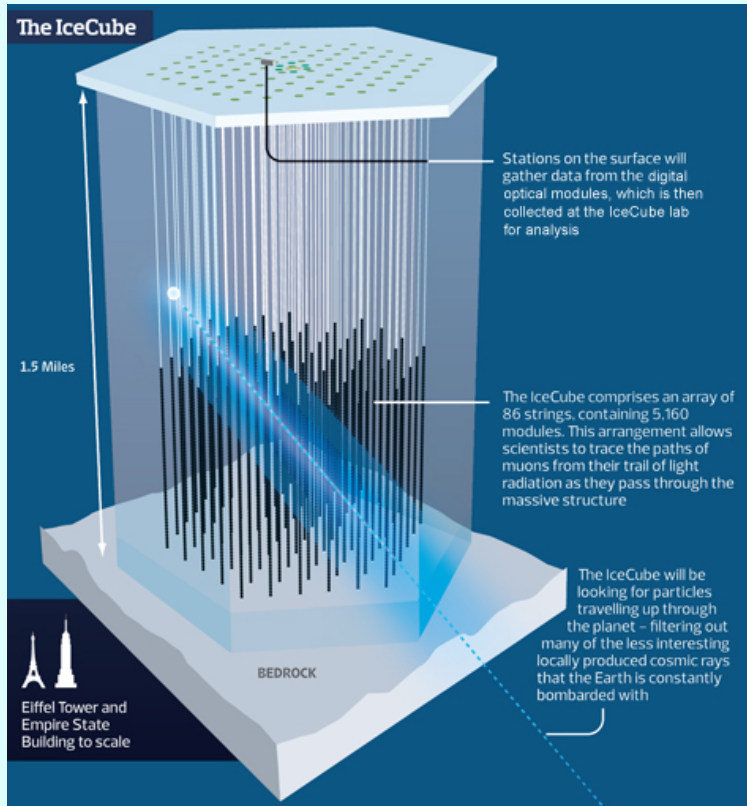


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

8.5.2 Sudbury Neutrino Observatory Canada



8.5.3 IceCube observatory – Antarctica



9 Inflationary Universe

A large discrepancy of scale !!!

- Fundamental constant of Gravitational physics is $\sim 10^{-44}$ sec
- But the Universe is $\sim 10^{17}$ sec old

Guth, Linde, Albrecht, Steinhardt in 1980-83 :

- a scalar field in the early (possibly late) Universe intervenes to greatly amplify the expansion of the very early Universe
 - An **inflaton**
- Peculiar properties of the field induce a temporary “cosmological constant” or a **de Sitter phase** in the early Universe

- There are quantum fluctuations in this field which accumulate to manifest classically
- Properties of the de Sitter phase allow spontaneous perturbations to persist with exact same amplitude
- When the de Sitter phase ends, the Universe becomes radiation dominated
- The perturbations then come back to life
 - all the perturbations have the same amplitude regardless of their wavelength
 - Reproduces the scale invariant spectrum of perturbations observed in the CMB and the matter distribution!

9.1 Who is Mr/Ms Inflaton?

- As of now Inflation is a “paradigm” : a broad formalism prescribing the required mathematical and physical properties
- As of now we know no connection to the Standard Model of Particle Physics
- An ancillary consequence is the presence of primordial gravitational waves just like the inflaton perturbations themselves
- CMB should have shown the presence of such gravitational waves but the search is still on

Acknowledgement before conclusions :

Typeset with TEX_{MACS}

10 Conclusions

- The Standard Model of particle physics sets strong standards for extending beyond it
- Cosmology has grown into a high precision science
 - The Friedmann paradigm is still adequate
- Inflation proposed to explain the large scales of the Universe
 - also gives rise to the $\sim 10^{-5}$ perturbations needed to create galaxies
- Dark Matter plays the role of helping baryons collapse to form the galaxies

- There is (or occurred for an epoch) just enough Dark Energy to not interfere with galaxy formation (Weinberg, Vishniac)

Thank you!

Hope you enjoyed it!