

Observational Cosmology

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Wednesday 11:15 – 12:45, MPIfR, HS 0.01

An introduction to cosmology from an observational, experimental perspective.

<http://www.astro.uni-bonn.de/~bertoldi/vorlesung/cosmology>

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A Science Vision for European Astronomy

What is the origin and evolution of stars and planets?

How do galaxies form and evolve?

Do we understand the extremes of the Universe?

How do we fit in?

Do we understand the extremes of the Universe?

How did the Universe begin?

gravity waves:
CMB B-mode polarization
LISA
Pulsar timing (SKA)

What is dark matter and dark energy?

CMB polarization
gravitational lensing / cosmic shear (optical/radio imaging)
BAO, LSS, clusters (large scale imaging)
SNIa (NIR)

Can we observe strong gravity in action?

gravity waves from tight double NS or BH: pulsar timing
Shapiro time delay
black holes: mergers, event horizon imaging, Fe X-ray monitoring

How do supernovae and gamma-ray bursts work?

monitor explosions at all wavelengths, incl neutrinos

How do black hole accretion, jets and outflows operate?

high-res. & survey radio, X/gamma monitoring

What do we learn from energetic radiation and particles?

Cherenkov arrays to TeV, air shower detectors

How do galaxies form and evolve?

How did the Universe emerge from its Dark Ages?

How did the structure of the cosmic web evolve?

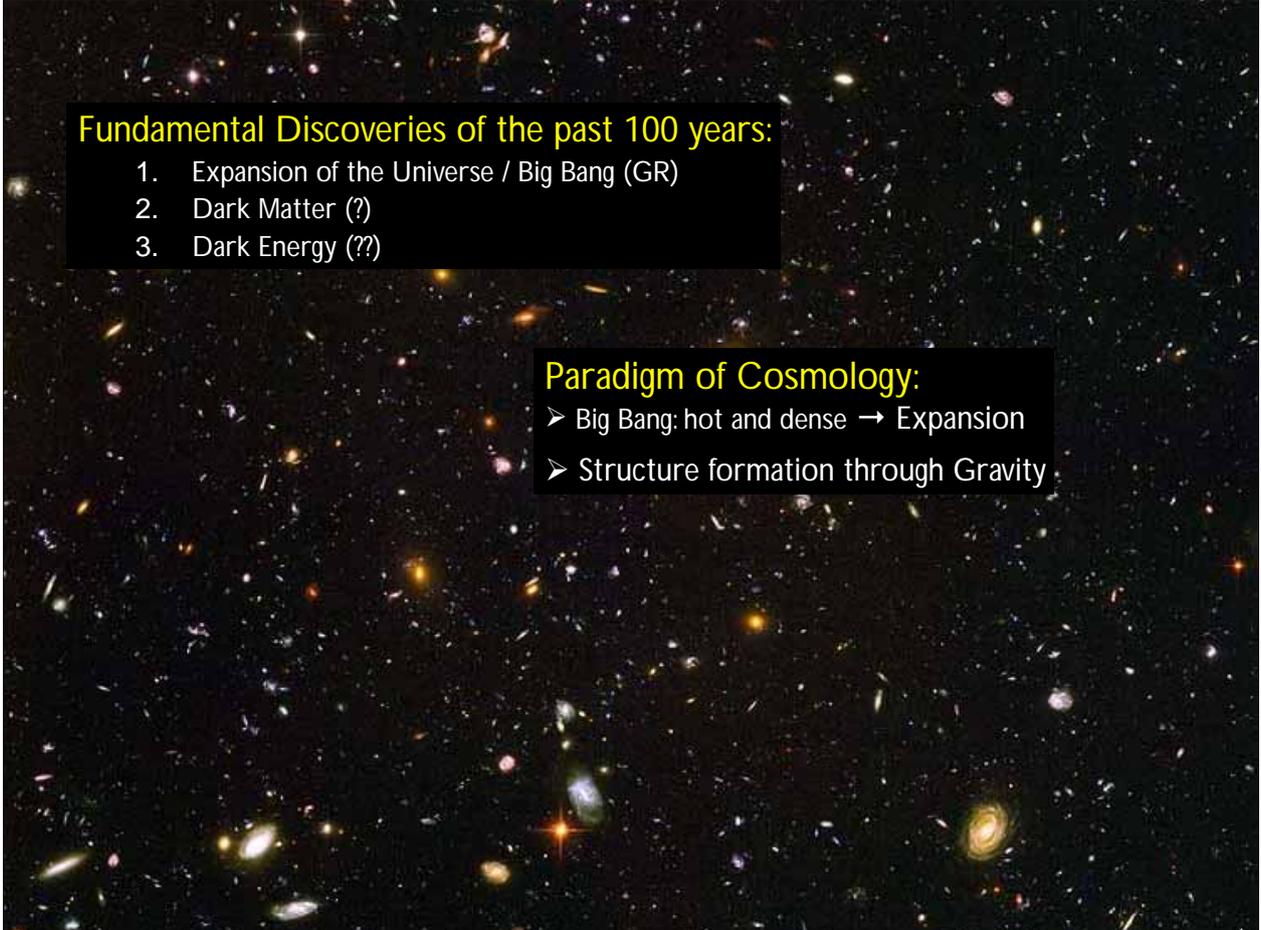
Where are most of the metals throughout cosmic time?

How were galaxies assembled?

How did our galaxy form?

What is the origin and evolution of stars and planets?

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Fundamental Discoveries of the past 100 years:

1. Expansion of the Universe / Big Bang (GR)
2. Dark Matter (?)
3. Dark Energy (??)

Paradigm of Cosmology:

- Big Bang: hot and dense → Expansion
- Structure formation through Gravity

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Cosmology is about ...

Standard candles:

History: Shapley, Hubble

Distance scale:

Cepheids, SN1a, gravitational lenses, galaxy clusters
(HST, JDEM)

Standard rulers:

CMB anisotropies (COBE, WMAP)

Baryonic Acoustic Oscillations (SDSS, EUCLID, JDEM > IDECS)

Structure formation:

reionization (LOFAR, SKA, EVLA, ALMA)

large scale structure (CFHTLS, KIDS, Pan-Starrs)

galaxy clusters (APEX-SZ, ACT, SPT, Planck, eROSITA)

galaxies and supermassive black holes

Dark Matter

Dark Energy (JDEM, EUCLID > IDECS)

Inflation: gravity waves > polarization, pulsar timing

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Dark energy projects proposed or under construction

Survey	Description	Probes	Stage
Ground-based:			
ACT	SZE, 6-m	CL	II
APEX	SZE, 12-m	CL	II
SPT	SZE, 10-m	CL	II
VST	Optical imaging, 2.6-m	BAO, CL, WL	II
Pan-STARRS 1(4)	Optical imaging, 1.8-m(×4)	All	II(III)
DES	Optical imaging, 4-m	All	III
Hyper Suprime-Cam	Optical imaging, 8-m	WL, CL, BAO	III
ALPACA	Optical imaging, 8-m	SN, BAO, CL	III
LSST	Optical imaging, 6.8-m	All	IV
AAT WiggleZ	Spectroscopy, 4-m	BAO	II
HETDEX	Spectroscopy, 9.2-m	BAO	III
PAU	Multi-filter imaging, 2-3-m	BAO	III
SDSS BOSS	Spectroscopy, 2.5-m	BAO	III
WMOS	Spectroscopy, 8-m	BAO	III
HSHS	21-cm radio telescope	BAO	III
SKA	km ² radio telescope	BAO, WL	IV
Space-based:			
<i>JDEM Candidates</i>			
ADEPT	Spectroscopy	BAO, SN	IV
DESTINY	Grism spectrophotometry	SN	IV
SNAP	Optical+NIR+spectro	All	IV
<i>Proposed ESA Missions</i>			
DUNE	Optical imaging	WL, BAO, CL	
SPACE	Spectroscopy	BAO	
eROSITA	X-ray	CL	
<i>CMB Space Probe</i>			
Planck	SZE	CL	
<i>Beyond Einstein Probe</i>			
Constellation-X	X-ray	CL	IV

<http://arxiv.org/pdf/0803.0982v1>

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Wie ist das Universum entstanden?



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BEYOND EINSTEIN
FROM THE BIG BANG TO BLACK HOLES
2012-2024

<http://universe.nasa.gov/program/probes.html>
<http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41177>

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Today we presume that the initial conditions were the origin of ...

- homogeneity, isotropy, flatness
- matter, dark matter, radiation, dark energy
- matter-antimatter asymmetry
- primordial seeds for structure
- Big Bang

specifically, that at the end of Inflation the Universe reheated, following the

- creation of matter and radiation (from the energy density of the vacuum?)
- production of matter-antimatter asymmetry
- supermassive / weakly interacting dark matter particles
- gravitational waves: 10^{-9} - 10^{-6} Hz (polariz., pulsars)
- magnetic fields

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A historical Perspective

200 years ago: solar system = Universe

~1900: MW galaxy disk-shaped and isolated.

Shapley: sun is far from center of MW.

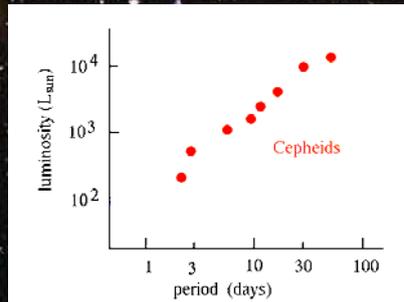
But what were the spiral nebulae (M31)?

Kant: other island universes?

Slipher 1912: spectra of 'nebulae': Doppler-shifted

1924: 41 spectra, 36 receding

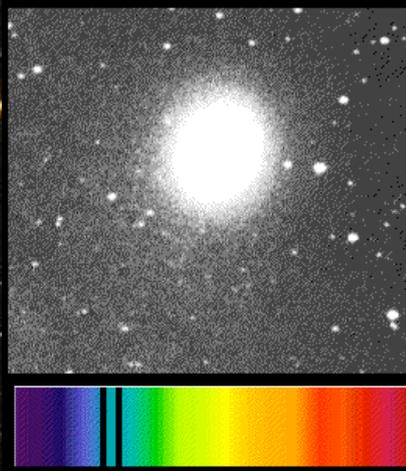
Shapley 1918: measure distances to 'nebulae' with Cepheids (calibrated LMC)



F-K supergiants - yellow, pulsating 3-50d
 $L=1000-10,000 L_{\text{sun}}$
 $\delta L = \text{few \% to } 10$

several 100 in MW
 Polaris: 4d

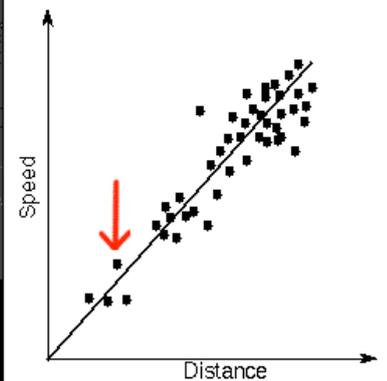
Edwin Hubble
 1929



Hubble's Law

Distant galaxies recede faster

$$\text{recession speed} = H_0 \times \text{distance}$$

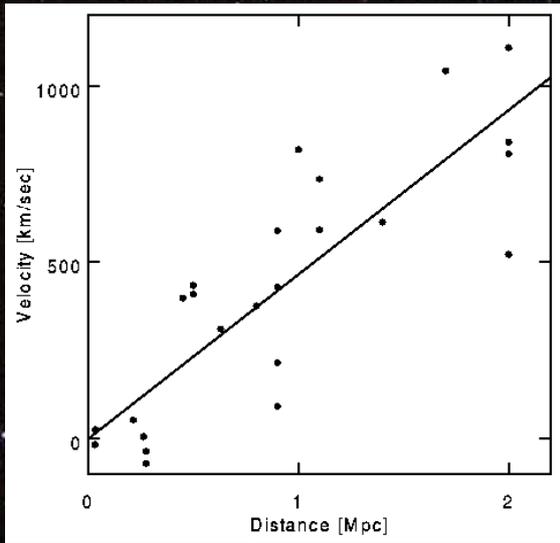


$$\text{Redshift: } z = \frac{\lambda_{\text{beob}} - \lambda_0}{\lambda_0} = v/c$$

1923: Mt Wilson. M31 is beyond the Milky Way

1924: Cepheids in Spiral Nebulae

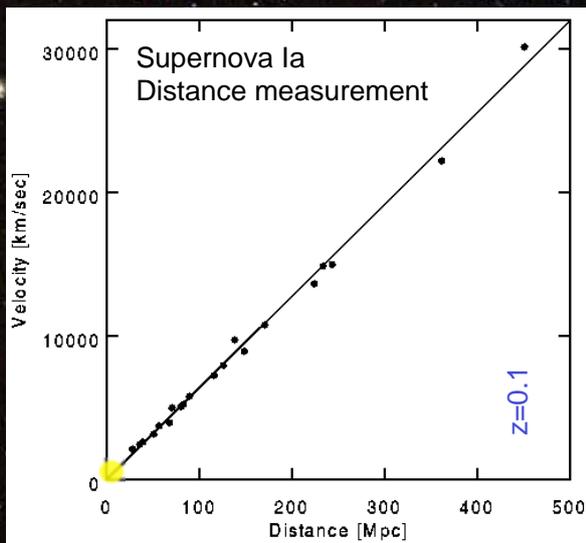
1929



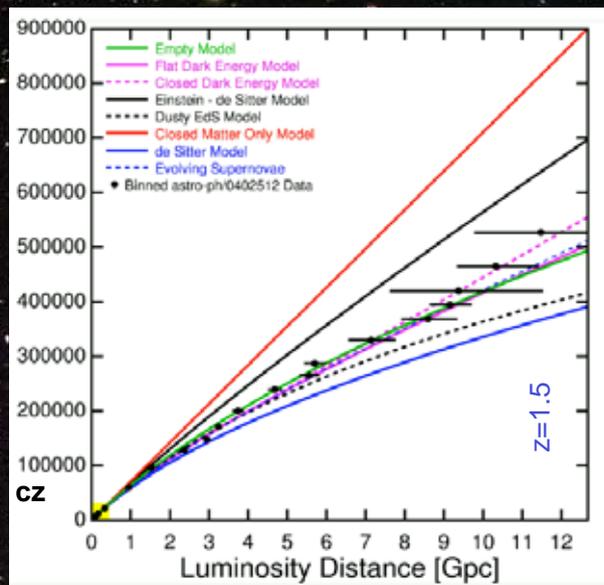
$v = H_0 D$
 $H_0 \approx 500 \text{ (km/s) / Mpc}$
 $\tau = 1 / H_0 = 2 \text{ billion yr}$

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1995

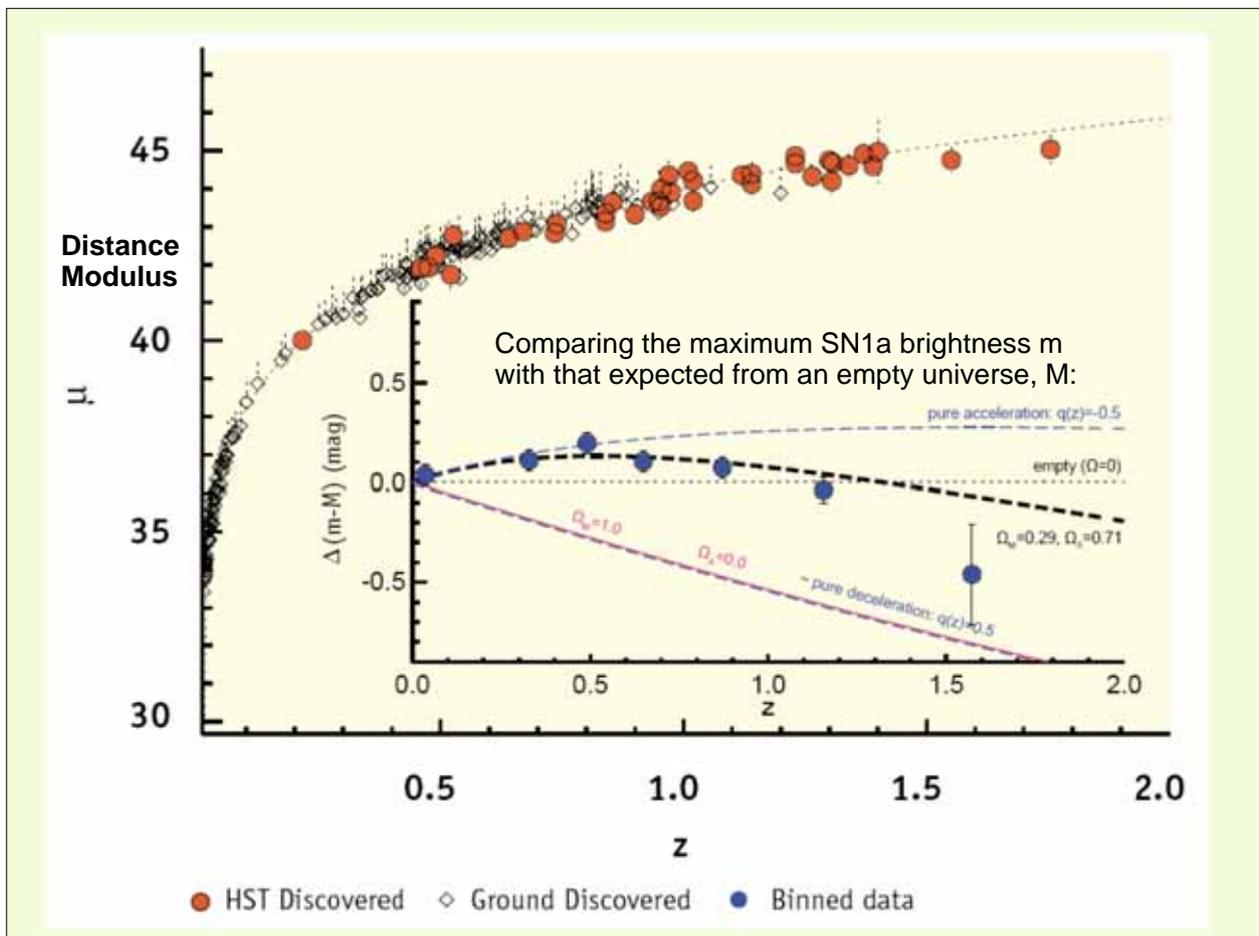


2004



Hubble's Law + Isotropy = uniform expansion of the Universe

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Evidence for Dark Energy:

- expansion rate is accelerating (SNIa)
- Universe is flat (CMB)
- $\rho(\text{DM}) < \rho_{\text{critical}}$

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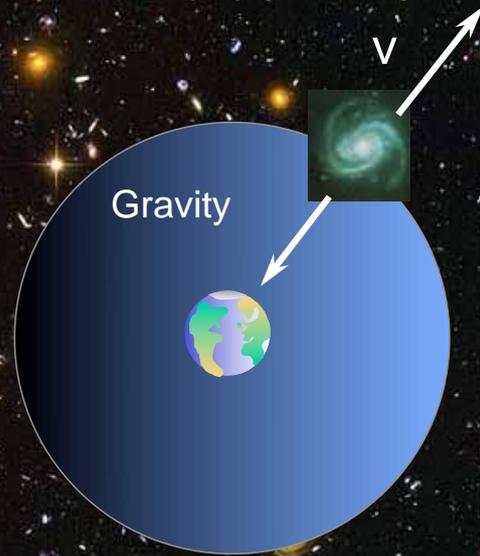
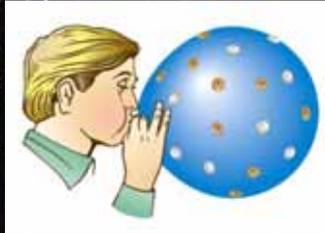
The Standard Model:

- The Universe as a uniformly expanding space. Each place is like the other

And at late times?

"Escape speed" depends on mean density!

Critical density $\Omega_M = \rho_0 / \rho_{crit}$



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Newton: $\frac{dv}{dt} = -\frac{GM}{R^2} = -\frac{(4\pi\rho_0 R^3/3)G}{R^2}$
 $= -(4\pi/3)\rho_0 R G$

Hubble: $v = H_0 R$ \Rightarrow $dv/dt = H_0 v$

Critical Density

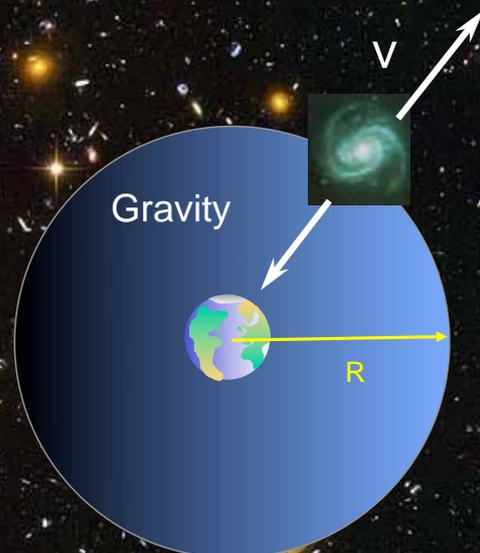
$$\rho_{cr} = 3H_0^2 / 8\pi G$$

$$\rho_{cr} = 10^{-26} \text{ kg/m}^3 = 6 \text{ Protons/m}^3$$

$$= 1.4 \times 10^{11} M_{\text{sun}}/\text{Mpc}^3$$

$$\text{photon density} = 2 \times 10^8 L_{\text{sun}}/\text{Mpc}^3$$

$\Omega_B \sim 0.04$ from nucleosynthesis



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The Standard Model:



De Sitter (1917, Λ , no matter)
 Friedmann (1922, matter)
 Eddington
 Lemaître (1927)
 Einstein-deSitter (1932): $k=p=\Lambda=0$

Einstein 1917:

Fully self-consistent model of the Universe.
 Expansion yet unknown:

Static solution with **cosmological constant** Λ

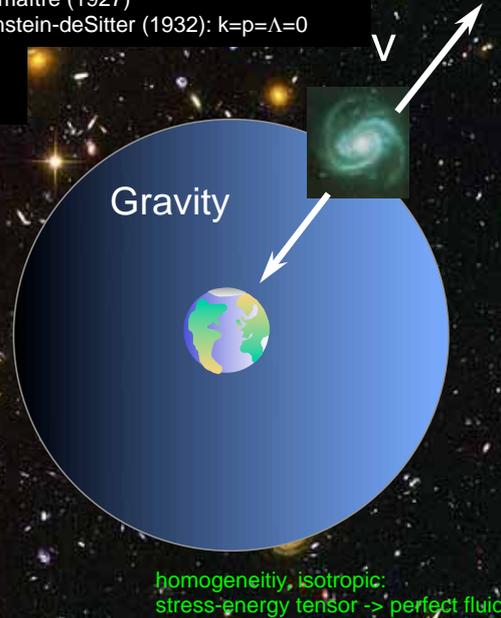
$$\Omega_{\Lambda} = \Lambda/3H_0^2$$



Friedman equation
 (field eq. applied to FRW)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

Today interpreted as
 energy density of the
 vacuum



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Einstein and de Sitter both developed cosmological models in 1917.

Einstein obtained a static universe by “tinkering” with his own equations of general relativity: he added the so-called **cosmological constant** to prevent his presumed static universe from contracting and collapsing under its own gravity.

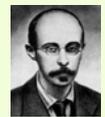
De Sitter’s model was purely academic in nature, because it contained no matter at all. However, in a universe that expands forever, like is the believe today, the density of matter will eventually become negligible and the universe will approach the de Sitter universe.

In 1922, **Friedmann** and independently in 1927, **Lemaitre**, discovered solutions to Einstein’s field equations that contained realistic amounts of matter, but with no cosmological constant. They accepted that the universe is expanding, as determined by Hubble in 1924.

There are 3 possible **Friedmann-Lemaitre models**:

- i) If there is enough matter in the expanding universe, the expansion will one day stop and the universe will contract again - positive space-time curvature.
- ii) If there is too little mass in the universe, it will expand forever - negative space-time curvature.
- iii) If the amount of matter is “just right”, the expansion rate will approach zero, but the universe will never contract - zero space-time curvature.

In 1932 Einstein and de Sitter together proposed that this “just right” cosmological model be accepted. The **Einstein-de Sitter model** assumes a homogeneous, isotropic universe, with zero curvature, zero cosmological constant and zero pressure.



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Einstein's Static Universe:

- Einstein used Λ to explain a static Universe. In 1917 the Hubble law was not known.
- But a static Universe filled with light-emitting stars cannot be static, it fills with photons and gets brighter. (Olbers Paradox). Furthermore, it is unstable.
- Expanding de Sitter & Friedmann models are consistent with a dark night sky.

After the discovery of cosmic expansion:

- Expanding models with or without Λ are possible.
- Λ was not needed and it was deprecated.

Λ has a repulsive effect

- In General Relativity energy has gravitational effects.
- Vacuum energy increases during expansion by: $dE = \rho dV$.
- thermodynamic work done to increase volume: $dE = -p dV$, thus $P = -p$ (tension)
- Net gravity from positive vacuum energy density plus negative pressure is repulsive.
- Λ is part of the *inflationary scenario*:

Λ causes a rapid exponential expansion of the Universe called *inflation* that occurred during the first picosecond after the Big Bang. Then this Λ disappeared in a phase transition.

Estimate vacuum energy density: $h=6.6e-27$ erg s, $c=3e10$ cm/s, $G=6.7e-8$ cm³ g⁻¹ s⁻²
Planck mass, Compton wavelength

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The reason why a cosmological constant has negative pressure can be seen from classical thermodynamics; Energy must be lost from inside a container to do work on the container. A change in volume dV requires work done equal to a change of energy $-p dV$, where p is the pressure. But the amount of energy in a box of vacuum energy actually increases when the volume increases (dV is positive), because the energy is equal to ρV , where ρ is the energy density of the cosmological constant. Therefore, p is negative and, in fact, $p = -\rho$.

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$$w = p / \rho = \text{const.}$$

$$\rho \sim (1+z)^{3(1+w)}$$

else integral in z

non-rel. $w=0$

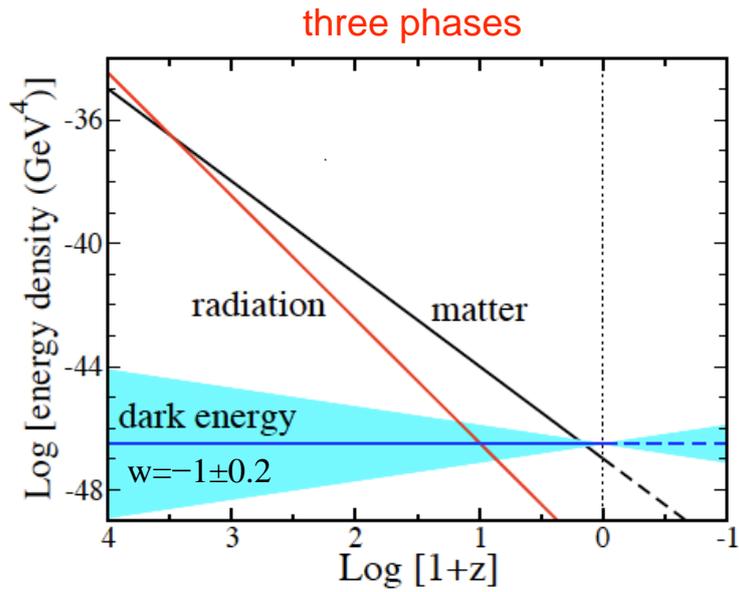
relativ. $w=1/3$

vacuum $w=-1$

scale factor:

$$a(t) \sim t^{2/3(1+w)}$$

for $w=-1$: $\sim e^{Ht}$



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21

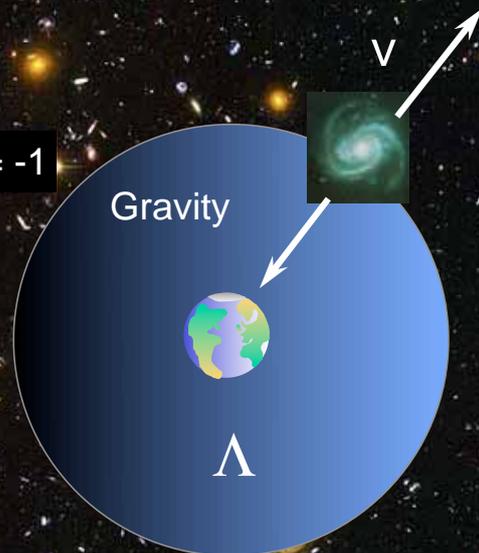
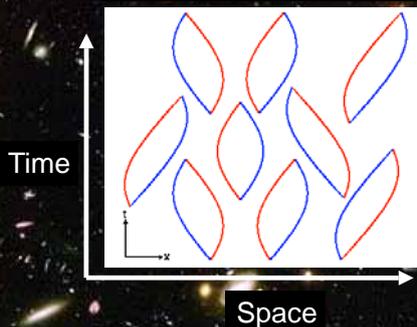
Naïve estimate of the vacuum energy density

one Planck-Mass per Compton-Volume:

$$\left. \begin{aligned} M_{\text{Planck}} &= (h c / G)^{1/2} \\ \lambda_{\text{Compton}} &= h / M c \end{aligned} \right\} \rho_{\text{vacuum}} = 10^{94} \text{ kg/m}^3$$

Pressure: $P / \rho = w = -1$

virtual particles (Casimir)



$$h=6.63e-34 \quad G=6.67e-11 \quad c=3e8$$

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Vacuum Energy

Quantum field theory considers the vacuum ground state not to be completely empty, but to consist of a seething mass of virtual particles and fields. Since these fields do not have a permanent existence, they are called vacuum fluctuations.

In the description of the interaction between elementary particles in quantum field theory, a virtual particle is a temporary elementary particle, used to describe an intermediate stage in the interaction.

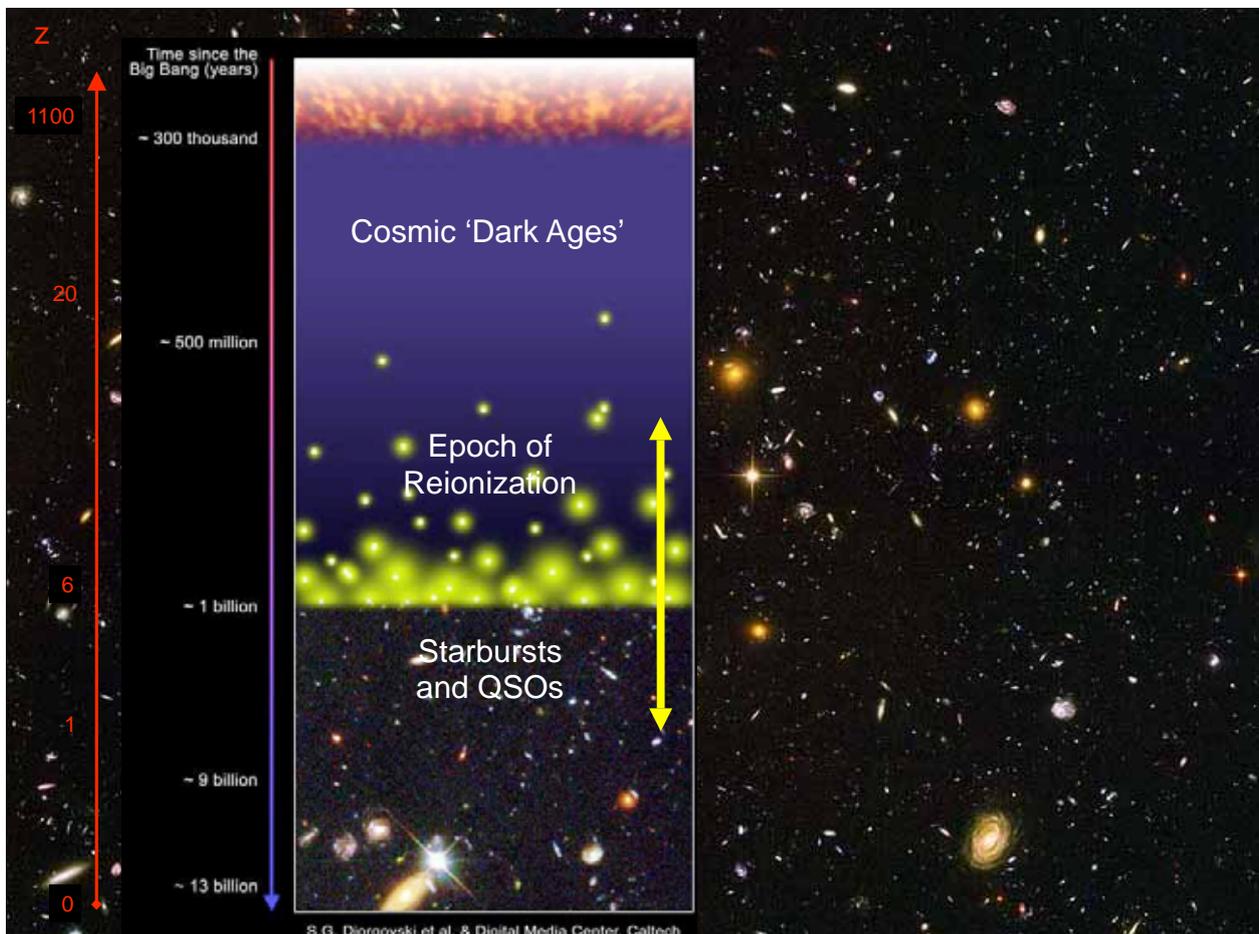
In 1948 Dutch physicist Hendrik B. G. **Casimir** of Philips Research Labs predicted that two uncharged parallel metal plates will be subject to a force pressing them together. In the Casimir effect, two metal plates can cause a change in the vacuum energy density between them which generates a measurable force.

Some believe that vacuum energy might be the "dark energy" (also called **quintessence**) associated with the cosmological constant in general relativity and thought to be similar to a negative force of gravity. But this raises the question of why the cosmological constant is many orders of magnitude smaller than even the **electroweak scale** (much less the **GUT or Planck scale**) — and if the the cosmological constant is so small, why is it not zero?

Observations that the expanding Universe appears to be accelerating seem to support the cosmic inflation theory first proposed by Alan **Guth** (1981) — in which the nascent Universe passed through a phase of exponential expansion driven by a negative vacuum energy density (positive vacuum pressure).

History

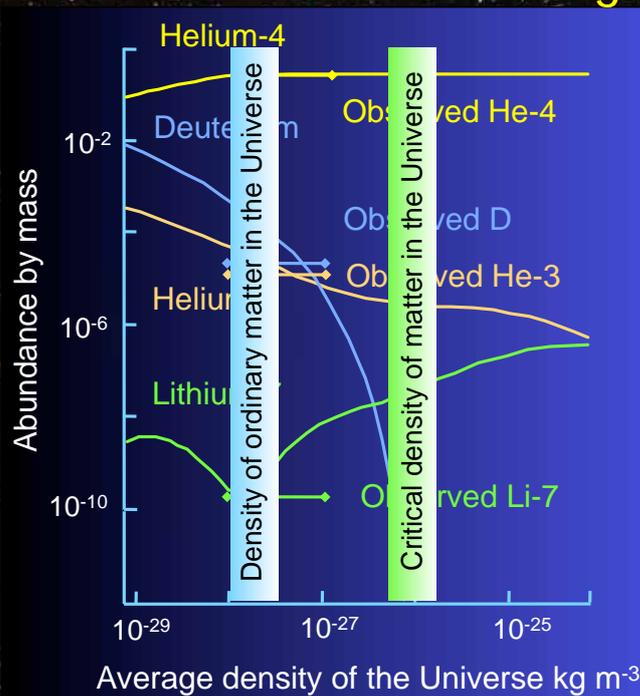
In 1934, Georges **Lemaître** used an unusual perfect-fluid equation of state to interpret the cosmological constant as due to vacuum energy. In 1973, Edward **Tryon** proposed that the Universe may be a large scale quantum mechanical vacuum fluctuation where positive mass-energy is balanced by negative gravitational potential energy. During the 1980s, there were many attempts to relate the fields that generate the vacuum energy to specific fields that were predicted by the **Grand unification theory**, and to use observations of the Universe to confirm that theory. These efforts had failed so far, and the exact nature of the particles or fields that generate vacuum energy, with a density such as that required by the Inflation theory, remains a mystery.



Stage	Time	Temperature (Energy)	Description
First	10^{-45} to 10^{-32} sec	Greater than 10^{15} K (100 GeV)	Inflation; generation of density fluctuations
Second	10^{-6} sec	Greater than 10^{12} K (100 MeV)	Quark Soup (QG Plasma)
Third	10^{-4} sec to 3 min	10^{12} to 10^9 K (0.1 MeV)	Nucleosynthesis; formation of D, He and Li
Fourth	400,000 years	4,000 K (1 eV)	Formation of neutral atoms; radiation decouples
Fifth	1 billion years	20–3 K (1 meV)	Formation of first-generation stars and galaxies
Sixth	3 billion years	20–3 K (1 meV)	Formation of heavy elements by supernovae; Formation of second-generation stars.
Seventh	3–15 billion years	3 K (0.25 meV)	Genesis of planets and LIFE

The Cosmic Calendar

Evidence for hot Big Bang: Formation of light elements



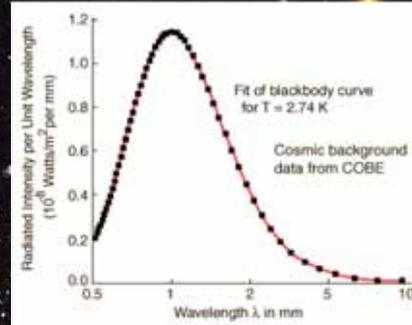
The light elements, ${}^4\text{He}$, ${}^3\text{He}$, D, ${}^7\text{Li}$, created in the early phases of the Big Bang are **very difficult** to account for by nucleosynthesis inside stars. The predicted Big Bang abundances turn out to agree well with the observations.

$$\frac{n_n}{n_p} = \exp\left(-\frac{\Delta mc^2}{k_B T}\right)$$

Strongest evidence for a hot Big Bang: cosmic microwave background radiation



predicted in 1948 by Gamow, Alpher, Herman: 4-28 K
revived 1964: Doroshkevich & Novikov; Wilkinson, Roll & Dicke,

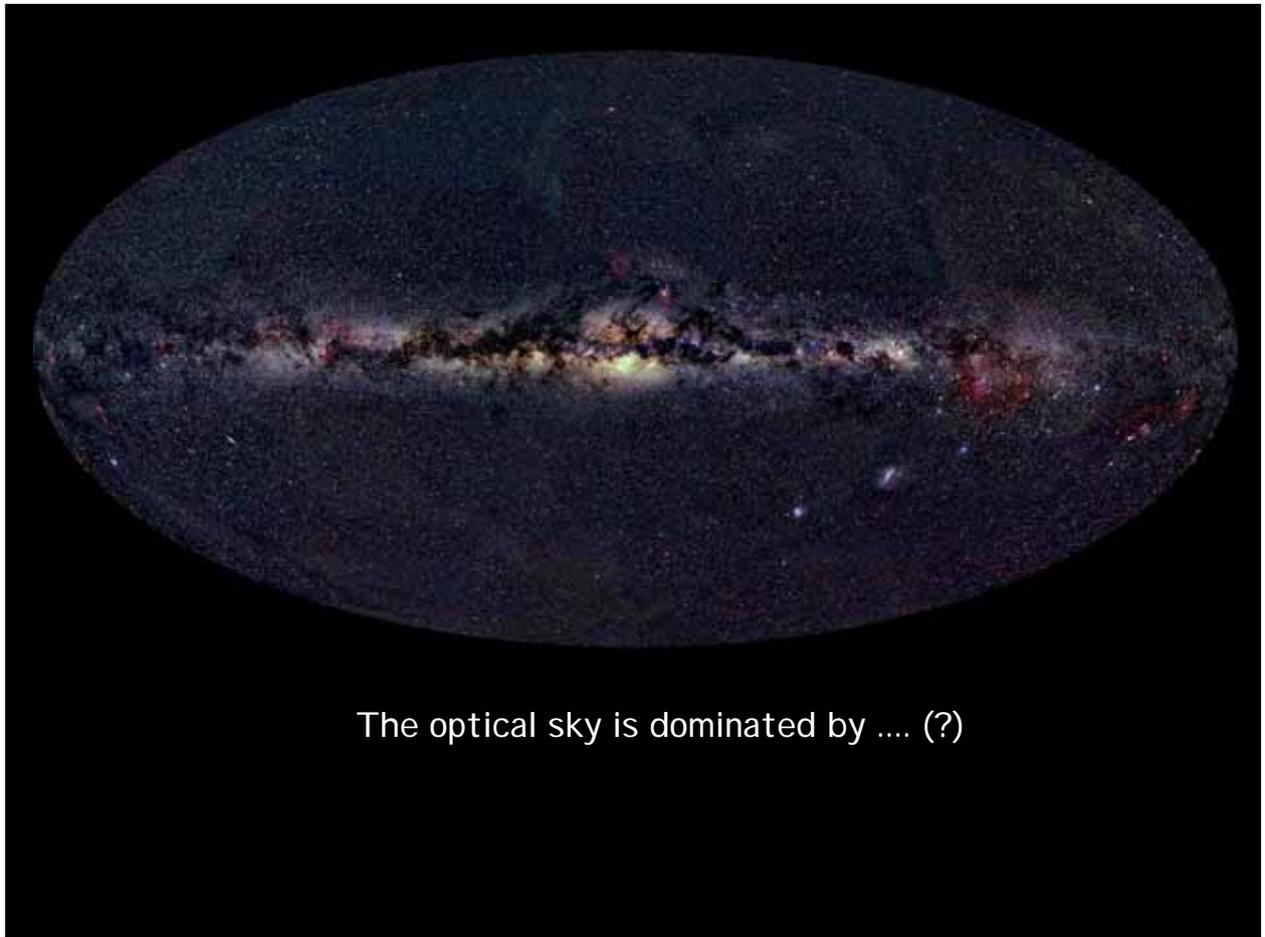


1965 by Arno Penzias and Bob Wilson
Nobel prize 1978
Robert Dicke: "Boys, we've been scooped."

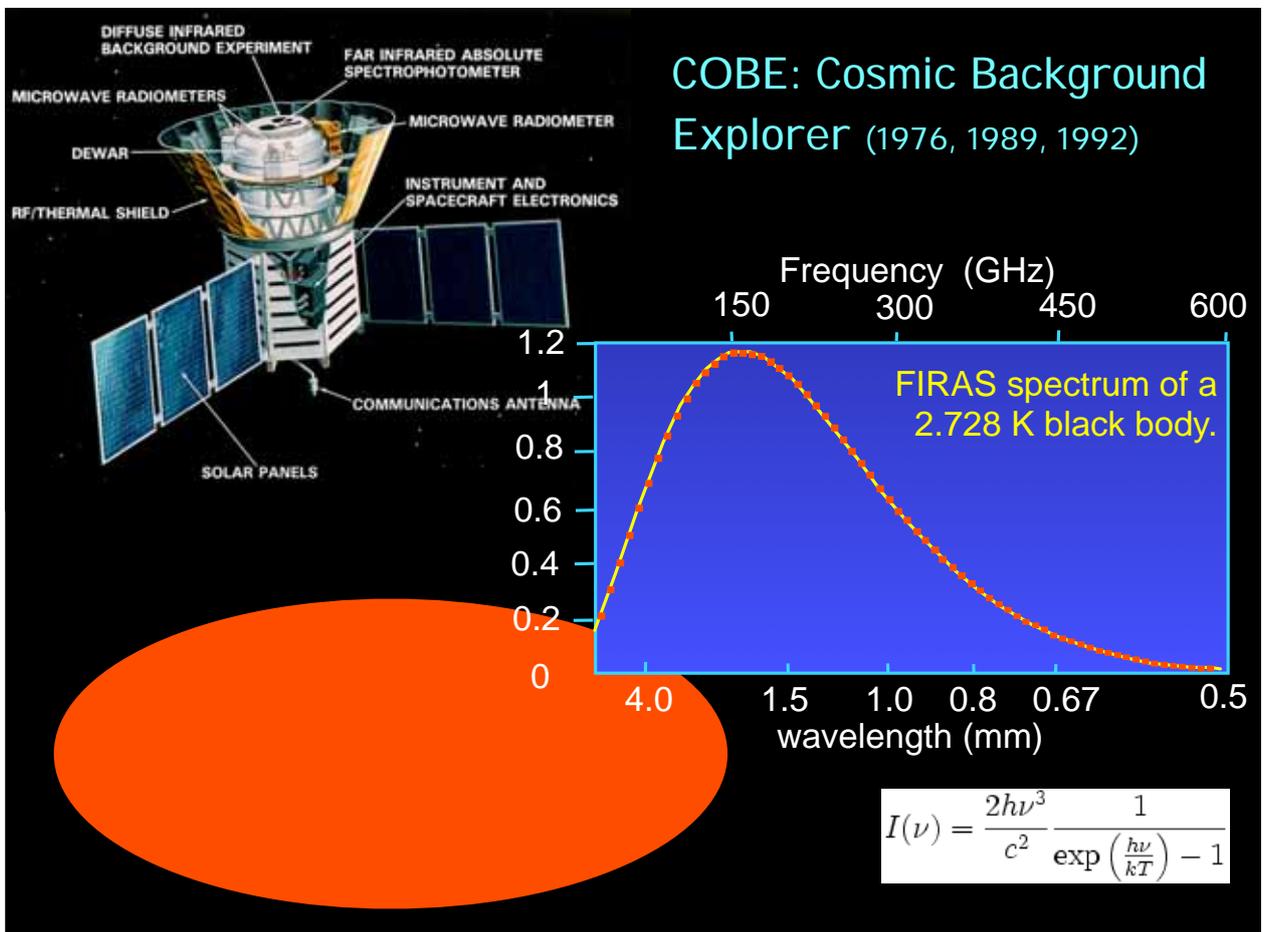
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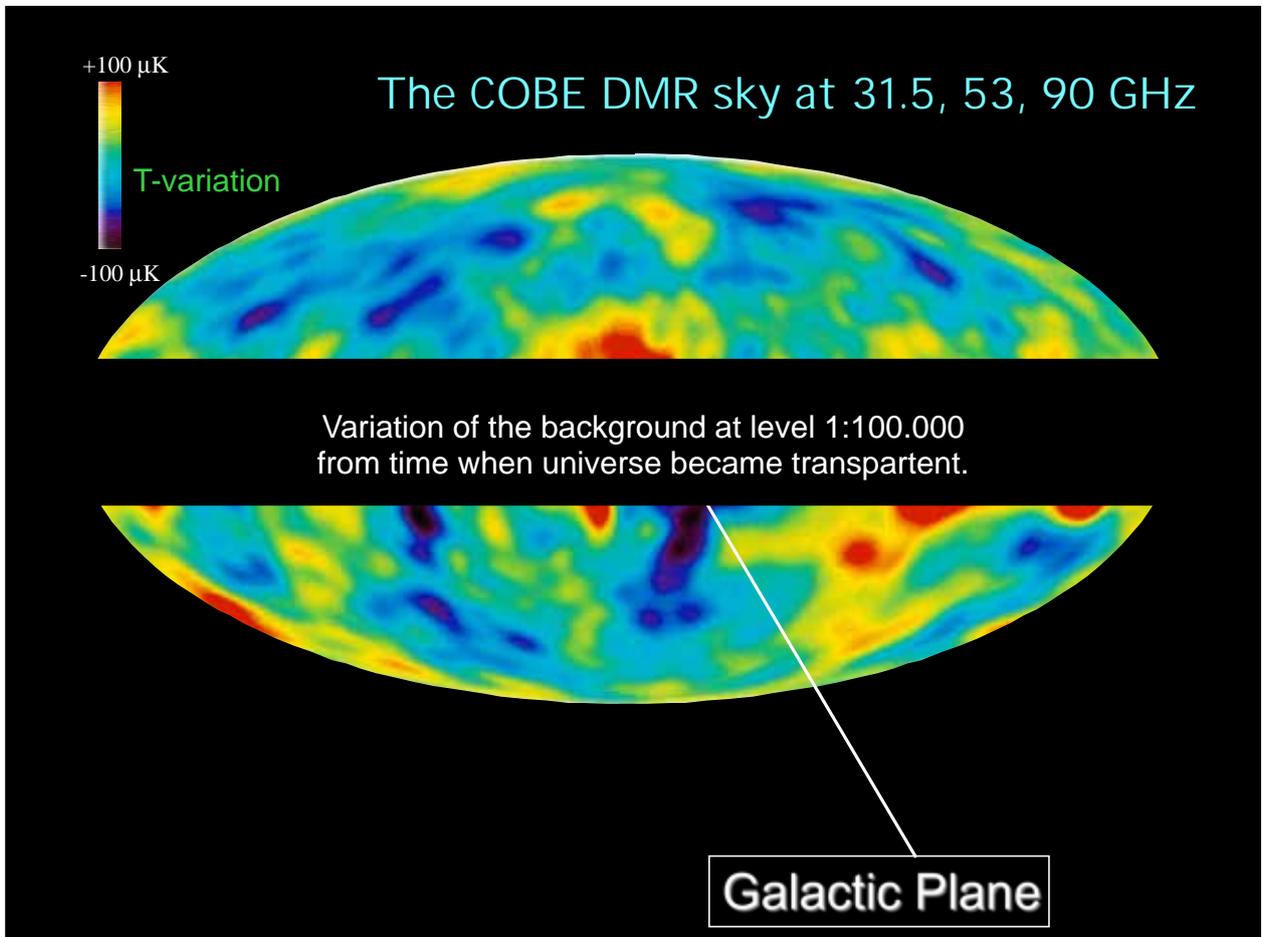
Arno Penzias and Robert Wilson of AT&T Bell Laboratories detected the CMB radiation in 1965 while trying to find the source of a mysterious background noise in their radio antenna. The discovery firmly established the big bang theory, which states that the early universe was a hot, dense plasma of charged particles and photons. Since that time, the CMB has been cooled by the expansion of the universe, and it is extremely cold today—comparable to the radiation released by a body at a temperature of 2.7 K. But when the CMB was released, its temperature was nearly 3,000 K.

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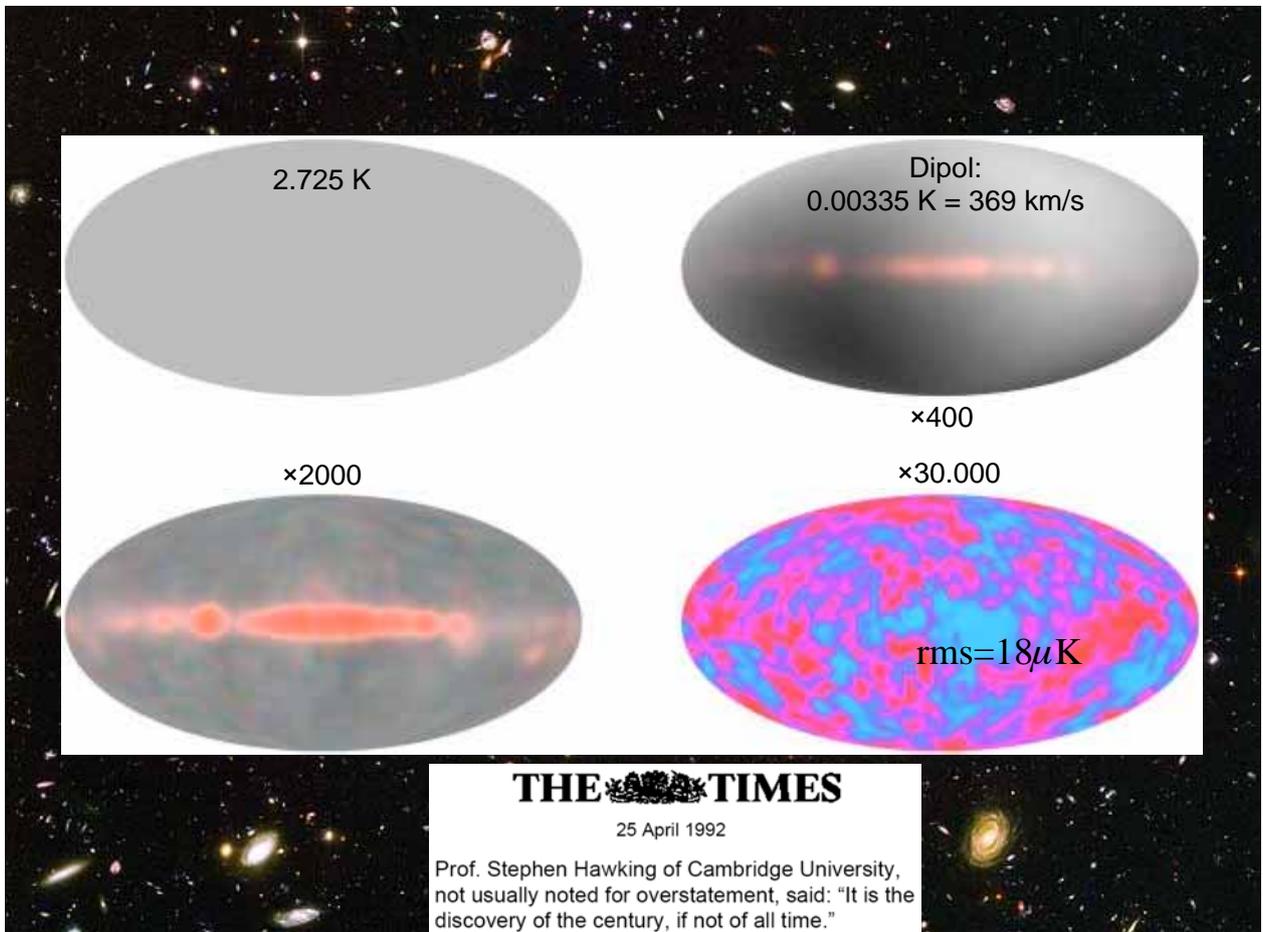


The optical sky is dominated by (?)





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When it was discovered in the 1960s, the CMB was found to be remarkably uniform across the sky. It was not until 1992 that the Cosmic Background Explorer (COBE) satellite discovered temperature variations (or ripples) at the level of 1 part in 100,000. Temperature maps of the CMB form a snapshot image of the universe when it was extremely young. So these ripples reflect tiny density fluctuations in the primordial soup of particles. These same density fluctuations are thought to grow by gravitational attraction into the familiar structures we see today (stars, galaxies, and clusters of galaxies). This is the gravitational instability model of structure formation.

COBE told us what the large-scale fluctuations in the background look like, but today we are more interested in the small-scale fluctuations, their amplitude, power spectrum, and polarization.

One can divide up the sky into angular degrees, so that 90 degrees is the distance from the horizon to a point directly overhead. COBE measured temperature ripples from the 10 degree to 90 degree scale. This scale is so large that there has not been enough time for structures to evolve. Hence COBE sees the so-called initial conditions of the universe. At the degree scale, on the other hand, the process of structure formation imprints information in the ripples about conditions in the early universe.

The anisotropy of the cosmic microwave background (CMB) consists of the small temperature fluctuations in the blackbody radiation left over from the Big Bang. The average temperature of this radiation is 2.725 K as measured by the FIRAS instrument on the COBE satellite. Without any contrast enhancement the CMB sky looks like the upper left panel of the figure above. But there are small temperature fluctuations superimposed on this average. One pattern is a plus or minus 0.00335 K variation with one hot pole and one cold pole: a dipole pattern. This indicates that the Solar System is moving at 369 km/sec relative to the observable Universe. If we subtract the average temperature and expand the contrast by a factor of 400, we get the upper right panel. This shows the dipole pattern and the emission from the Milky Way which dominates the red color in the picture, which represents the longest wavelength data. After the average temperature and the dipole pattern are removed, there are intrinsic fluctuations in the CMB which can be seen faintly away from the Milky Way in the lower left panel below, which has contrast enhanced by 2000X. Finally we can combine the multiple frequencies in a way that eliminates the Milky Way, giving the CMB map in the lower right with a 30,000X contrast enhancement.

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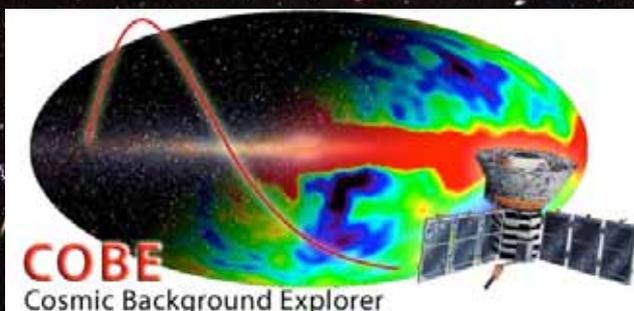
The Nobel Prize in Physics 2006



John C. Mather
NASA



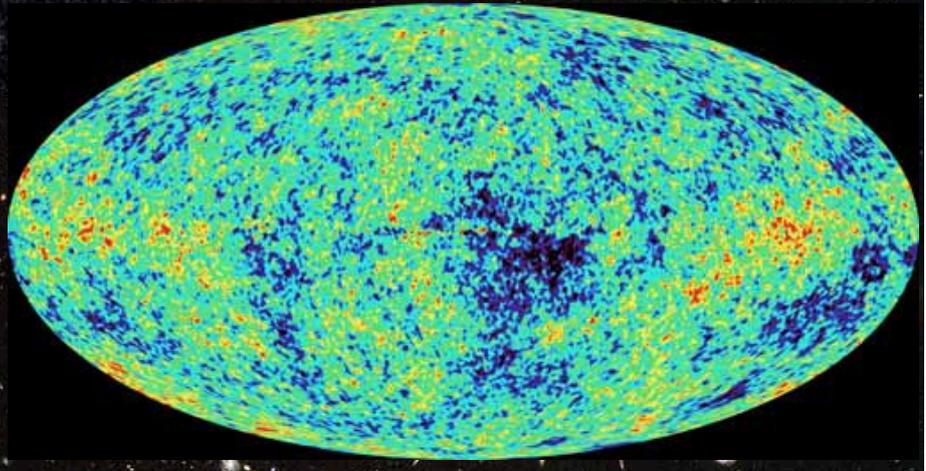
George F. Smoot
U.C. Berkeley



The success of COBE was the outcome of prodigious team work involving more than 1,000 researchers, engineers and other participants. **John Mather** coordinated the entire process and also had primary responsibility for the experiment that revealed the blackbody form of the microwave background radiation measured by COBE. **George Smoot** had main responsibility for measuring the small variations in the temperature of the radiation.

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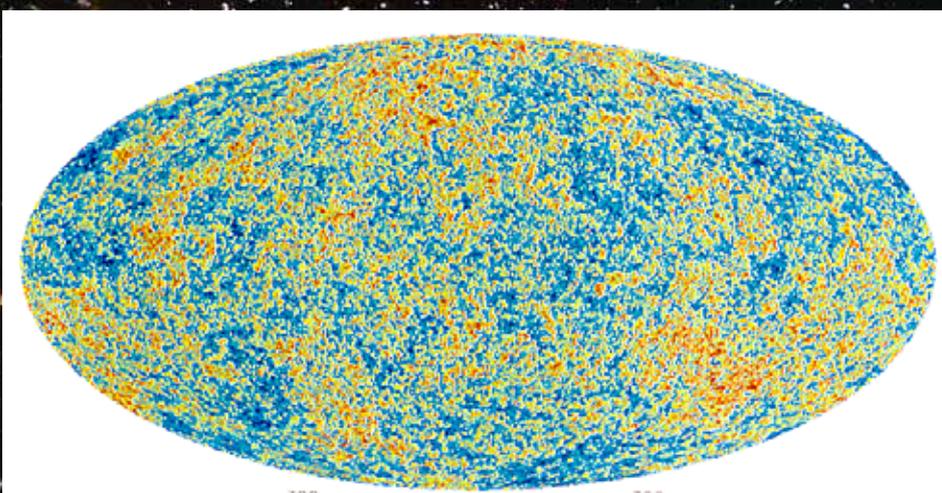
Wilkinson Microwave Anisotropy Probe (WMAP)
Launch 30.6.01



WMAP Sky:
Variations 1:100000

COBE: 7° WMAP: 13-49' Planck: 5'

Wilkinson Microwave Anisotropy Probe
(WMAP) launched 30.6.01



-300 300

Planck Satellite
Launch: 2009 ?

