• 1664 Newton's Theory of Gravitation
  He realizes the Universe must be infinite to prevent collapse and that equilibrium is unstable.

• 1917 Einstein obtains new set of equations of gravitational field (TGR)
  Unstable Universe, unless a "cosmological constant \( \Lambda \)" term is introduced.

• 1922-23 Friedman obtains set of expanding solutions of Einstein's equations.
  Independently obtained by Lemaitre in 1927.

• 1929 Hubble observes redshifts.
  He determines the expansion of the Universe is accelerating.

• late 1940s Gamow, Alpher and Herman postulate existence of cosmic radiation background with \( T \approx 5 \) K.

• early 1960s Quasars are shown to be at cosmological distances.

• 1964 Hoyle shows the He abundance can be explained by primordial nucleosynthesis.

• 1965 Penzias and Wilson detect Cosmic Microwave Background radiation.

• 1992 COBE detects fluctuations in the CMB.

• 2003 WMAP accurately determines main cosmological parameters.
In the late 1940s George Gamow and his co-workers, Alpher and Herman, postulate existence of a cosmic radiation background with a blackbody spectrum of $T \sim 5 \text{ K}$

In the early Universe, matter was ionized (electrons and protons and He nuclei - all electrically charged particles - were free). Electrically charged particles interact easily with radiation, so radiation and matter were in equilibrium: matter (mainly electrons) absorbed and re-emitted radiation continuously, through a process known as “Thomson scattering”.

Thus, any fluctuations in the energy density of matter were mirrored by fluctuations in the energy density of radiation.

About 350,000 years after the Big Bang, the Universe had cooled to less than 5000 K. Electrons and protons combining to form H atoms could not be ionized by collisions. Matter in the Universe became largely neutral, as electrons combined with nuclei to form atoms. Matter and radiation “decoupled”, and whatever fluctuations were imprinted in the radiation energy density at that time, remained “frozen” in the radiation field.
COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE

Theory and observation agree

T = 2.73 K

Intensity, $10^{-4}$ ergs / cm$^2$ sr sec cm$^{-1}$

Waves / centimeter
CMB Dipole

$\Delta T = 3.358 \text{ mK}$

V$_{\text{sun}}$ w.r.t CMB:

369 km/s towards $l = 264^\circ$, $b = +48^\circ$

Motion of the Local Group:

$V = 627 \text{ km/s}$ towards $l = 276^\circ$, $b = +30^\circ$
Explanation of the CMB Dipole:
Peculiar Velocity (~600 km/s) of the Local Group
A clear correlation exists between the rotational velocity of spiral galaxies and their luminosity.

Thus, a measure of the amplitude of the rotational velocity can be used to infer the luminosity, and thus the distance of a galaxy.
... but: does the measurement of the recessional velocity of a galaxy yield an accurate estimate of its distance?

Hubble Law

Recessional Velocity \( = H_0 \times \text{Distance} \)

“Hubble constant” units: (km/s)/Mpc
Given a field of density fluctuations $d(r)$, an observer at $r=0$ will have a peculiar velocity:

$$V_{\text{pec}} = \frac{H_0 \Omega^{0.6}}{4\pi} \int \delta(r) \frac{\vec{r}}{r^3} d\vec{r}^3$$

where $\Omega$ is $\Omega_{\text{mass}}$

The contribution to $\vec{V}_{\text{pec}}$ by fluctuations in the shell $(R_1, R_2)$ asymptotically tends to zero as $R \to \infty$

The cumulative $\vec{V}_{\text{pec}}$ by all fluctuations within $R$ thus exhibits the behavior:

If the observer is the LG, the asymptotic $\vec{V}_{\text{pec}}$ matches the CMB dipole
The Peculiar Velocity Field to $cz=6500$ km/s

SFI [Haynes et al 2000a,b]

Peculiar Velocities in the LG reference frame
The Peculiar Velocity Field to \(cz=6500\) km/s

SFI [Haynes et al 2000a,b]

Peculiar Velocities in the CMB reference frame
The reflex motion of the LG, w.r.t. field galaxies in shells of progressively increasing radius, shows:
convergence with the CMB dipole, both in amplitude and direction, near $cz \sim 5000$ km/s.

[Giovanelli et al. 2000]
Verrazzano Bias

Map by Gerolamo da Verrazzano (1529)

Pacific Ocean
Convergence to the CMB dipole is confirmed by the LG motion w.r.t. a set of 79 clusters out to $cz \sim 20,000$ km/s.

[Giovanelli et al. 1999; Dale et al. 1999]
Removing the Galactic Contamination:

see QuickTime movie mw in cosmology2
DMR's Two Year CMB Anisotropy Result
WMAP: CMB Fluctuations
Planck

Télescope : miroir primaire de 1,5 m de diamètre

Plan Focal contenant les instruments scientifiques réfrigérés

Plate-forme :
• Avionique (Contrôle d’attitude, gestion des données)
• Puissance électrique
• Télécommunications et instruments électroniques

Panneau solaire et module de service

Poids : 2 000 kg
Puissance électrique : 1 600 W
Durée de vie : 21 mois

Planck HFI, c’est aussi :
• 50 000 composants électroniques,
• 36 000 litres d’Helium 4,
• 12 000 litres d’Helium 3,
• 11 400 documents.
The sky as seen by Planck
<table>
<thead>
<tr>
<th>Parameter</th>
<th>TT + lowP</th>
<th>TT + lowP + lensing</th>
<th>TT + lowP + lensing + ext</th>
<th>TT, TLEE + lowP</th>
<th>TT, TLEE + lowP + lensing</th>
<th>TT, TLEE + lowP + lensing + ext</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02222 ± 0.00023</td>
<td>0.02226 ± 0.00023</td>
<td>0.02227 ± 0.00020</td>
<td>0.02225 ± 0.00016</td>
<td>0.02226 ± 0.00016</td>
<td>0.02230 ± 0.00014</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1197 ± 0.0022</td>
<td>0.1186 ± 0.0020</td>
<td>0.1184 ± 0.0012</td>
<td>0.1198 ± 0.0015</td>
<td>0.1193 ± 0.0014</td>
<td>0.1188 ± 0.0010</td>
</tr>
<tr>
<td>$10^9 M_\odot$</td>
<td>1.04085 ± 0.00047</td>
<td>1.04103 ± 0.00046</td>
<td>1.04106 ± 0.00041</td>
<td>1.04077 ± 0.00032</td>
<td>1.04087 ± 0.00032</td>
<td>1.04093 ± 0.00030</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.078 ± 0.019</td>
<td>0.066 ± 0.016</td>
<td>0.067 ± 0.013</td>
<td>0.079 ± 0.017</td>
<td>0.063 ± 0.014</td>
<td>0.066 ± 0.012</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>3.089 ± 0.036</td>
<td>3.062 ± 0.029</td>
<td>3.064 ± 0.024</td>
<td>3.094 ± 0.034</td>
<td>3.059 ± 0.025</td>
<td>3.064 ± 0.023</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9655 ± 0.0062</td>
<td>0.9677 ± 0.0060</td>
<td>0.9681 ± 0.0044</td>
<td>0.9645 ± 0.0049</td>
<td>0.9653 ± 0.0048</td>
<td>0.9667 ± 0.0040</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.31 ± 0.96</td>
<td>67.81 ± 0.92</td>
<td>67.90 ± 0.55</td>
<td>67.27 ± 0.66</td>
<td>67.51 ± 0.64</td>
<td>67.74 ± 0.46</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>0.685 ± 0.013</td>
<td>0.692 ± 0.012</td>
<td>0.6935 ± 0.0072</td>
<td>0.6844 ± 0.0091</td>
<td>0.6879 ± 0.0087</td>
<td>0.6911 ± 0.0062</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.315 ± 0.013</td>
<td>0.308 ± 0.012</td>
<td>0.3065 ± 0.0072</td>
<td>0.3156 ± 0.0091</td>
<td>0.3121 ± 0.0087</td>
<td>0.3089 ± 0.0062</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.1426 ± 0.0020</td>
<td>0.1415 ± 0.0019</td>
<td>0.1413 ± 0.0011</td>
<td>0.1427 ± 0.0014</td>
<td>0.1422 ± 0.0013</td>
<td>0.14170 ± 0.00097</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.09597 ± 0.00045</td>
<td>0.09591 ± 0.00045</td>
<td>0.09593 ± 0.00045</td>
<td>0.09601 ± 0.00029</td>
<td>0.09596 ± 0.00030</td>
<td>0.09598 ± 0.00029</td>
</tr>
<tr>
<td>$\sigma_8q^0$</td>
<td>0.829 ± 0.014</td>
<td>0.8149 ± 0.0093</td>
<td>0.8154 ± 0.0090</td>
<td>0.831 ± 0.013</td>
<td>0.8150 ± 0.0087</td>
<td>0.8159 ± 0.0086</td>
</tr>
<tr>
<td>$\sigma_8\Omega_0^{0.5}$</td>
<td>0.466 ± 0.013</td>
<td>0.4521 ± 0.0088</td>
<td>0.4514 ± 0.0066</td>
<td>0.4668 ± 0.0098</td>
<td>0.4553 ± 0.0068</td>
<td>0.4535 ± 0.0059</td>
</tr>
<tr>
<td>$\sigma_8\Omega_0^{0.25}$</td>
<td>0.621 ± 0.013</td>
<td>0.6069 ± 0.0076</td>
<td>0.6066 ± 0.0070</td>
<td>0.623 ± 0.011</td>
<td>0.6091 ± 0.0067</td>
<td>0.6083 ± 0.0066</td>
</tr>
<tr>
<td>$z_\text{re}$</td>
<td>9.9 ± 1.8</td>
<td>8.8 ± 1.2</td>
<td>8.9 ± 1.2</td>
<td>10.0 ± 1.5</td>
<td>8.5 ± 1.2</td>
<td>8.8 ± 1.1</td>
</tr>
<tr>
<td>$10^9 A_{s,0.00}$</td>
<td>2.198 ± 0.076</td>
<td>2.139 ± 0.063</td>
<td>2.143 ± 0.051</td>
<td>2.207 ± 0.074</td>
<td>2.130 ± 0.053</td>
<td>2.142 ± 0.049</td>
</tr>
<tr>
<td>$10^3 A_{s,0.000}$</td>
<td>1.880 ± 0.014</td>
<td>1.874 ± 0.013</td>
<td>1.873 ± 0.011</td>
<td>1.882 ± 0.012</td>
<td>1.878 ± 0.011</td>
<td>1.876 ± 0.011</td>
</tr>
<tr>
<td>$\text{Age}/\text{Gyr}$</td>
<td>13.813 ± 0.038</td>
<td>13.799 ± 0.038</td>
<td>13.799 ± 0.029</td>
<td>13.813 ± 0.026</td>
<td>13.807 ± 0.026</td>
<td>13.799 ± 0.021</td>
</tr>
<tr>
<td>$z_{\text{re}}$</td>
<td>1090.09 ± 0.42</td>
<td>1089.94 ± 0.42</td>
<td>1089.90 ± 0.30</td>
<td>1090.06 ± 0.30</td>
<td>1090.00 ± 0.29</td>
<td>1089.90 ± 0.23</td>
</tr>
<tr>
<td>$r_e$</td>
<td>144.61 ± 0.49</td>
<td>144.39 ± 0.44</td>
<td>144.43 ± 0.30</td>
<td>144.57 ± 0.32</td>
<td>144.71 ± 0.31</td>
<td>144.81 ± 0.24</td>
</tr>
<tr>
<td>$10^9 A_{s,0.000}$</td>
<td>1.04105 ± 0.00046</td>
<td>1.04122 ± 0.00045</td>
<td>1.04126 ± 0.00041</td>
<td>1.04096 ± 0.00032</td>
<td>1.04106 ± 0.00031</td>
<td>1.04112 ± 0.00029</td>
</tr>
<tr>
<td>$r_{\text{avg}}$</td>
<td>1059.57 ± 0.46</td>
<td>1059.57 ± 0.47</td>
<td>1059.60 ± 0.44</td>
<td>1059.65 ± 0.31</td>
<td>1059.62 ± 0.31</td>
<td>1059.68 ± 0.29</td>
</tr>
<tr>
<td>$r_{\text{avg}}$</td>
<td>147.33 ± 0.49</td>
<td>147.60 ± 0.43</td>
<td>147.63 ± 0.32</td>
<td>147.27 ± 0.31</td>
<td>147.41 ± 0.30</td>
<td>147.50 ± 0.24</td>
</tr>
</tbody>
</table>
Dark Matter 2013 - INSPIRE-HEP

The latest results from the Planck satellite (ref: planck) on the energy densities attributed to dark energy, dark matter and 'ordinary' baryonic matter.

- 68.3% Dark Energy
- 26.8% Dark Matter
- 4.9% Baryonic Matter
Qualitative Description of the CMB Power Spectrum

• As long as matter is ionized, baryons and photons are coupled via Thomson scattering: we refer to a “photon-baryon fluid”
• Photons provide the pressure of the fluid, while baryons provide the mass density, i.e. the inertia.
• Gravity tries to compress the fluid, while pressure resists it: acoustic oscillations are set.
• The Universe reaches the epoch of recombination with density fluctuations (of amplitude of ~1 part in 100,000).
• Acoustic oscillations take place within the potential wells of the density fluctuations: the compression phase of the oscillation produces a slight enhancement in temperature of the fluid, the rarefaction phase produces temperature decrement.
• As the Universe recombines, the coupling between baryons and photons ceases, and the two components separate. The photon fluid ceases to oscillate and the temperature fluctuations “freeze” at the epoch of last scattering.
• The physical scale of the fluctuations at that epoch translates into an angle, as seen from our vantage point at $z=0$: the larger the physical scale, the larger the angle.
The map of CMB $T$ fluctuations is analyzed in terms of their angular size.

The number $l$ is inversely prop. to the angular scale:

$$\alpha = 100^\circ / l$$

A fluctuation of comoving physical size $\lambda$ Mpc at the epoch of recombination subtends an angle $\alpha \sim 17'' \lambda$ in the sky at the present time.
CMB Power Spectrum according to WMAP
What is the Geometry of cosmic space?

It depends on the density of its matter+energy contents:

- A high density Universe has POSITIVE curvature.
- A low density Universe has NEGATIVE curvature.
- A Universe with zero curvature, said to be FLAT, has critical density.
We quantify Geometry by the parameter

\[ \Omega = \frac{\rho_{\text{actual}}}{\rho_{\text{critical}}}, \]

If \( \Omega = 1 \), the Universe is flat

\( \Omega < 1 \), the Universe has negative curvature and it is said to be “open”

\( \Omega > 1 \), the Universe has positive curvature and it is said to be “closed”
Dependence of power spectrum on $\Omega$

The position (l number) of the peaks of the power spectrum is strongly dependent on the curvature of space.

The identification of the first acoustic peak indicated that the Universe is spatially FLAT.
Dark Matter + Dark Energy effect the expansion of the universe

\[ \Omega_m \quad \Omega_v \]

- 0.3   0.7
- 0.3   0.0
- 1.0   0.0
- 5.0   0.0

Relative size of the universe

Billions of Years

Now

MAP990350
The Universe is Flat:

$$\Omega = 1$$

The current expansion rate is $H_0 = 70 \text{ (km/s)}/\text{Mpc}$

The Age of the Universe is 13.7 Gyrs
The cosmic matter/energy density budget
We quantify Geometry by the parameter

\[ \Omega = \frac{\rho_{\text{actual}}}{\rho_{\text{critical}}} \]

If \( \Omega = 1 \), the Universe is flat

\( \Omega < 1 \), the Universe has negative curvature and it is said to be “open”

\( \Omega > 1 \), the Universe has positive curvature and it is said to be “closed”
We can separate $\Omega$ into several contributions:

\[
\Omega_{\text{baryonic}} = \frac{\rho_{\text{baryon}}}{\rho_{\text{critical}}}
\]

\[
\Omega_{\text{dark}} = \frac{\rho_{\text{dark}}}{\rho_{\text{critical}}}
\]

\[
\Omega_{\text{radiation}} = \frac{\rho_{\text{radiation}}}{\rho_{\text{critical}}}
\]

\[
\Omega_{\text{other}} = \frac{\rho_{\text{other}}}{\rho_{\text{critical}}}
\]

so that

\[
\Omega = \Omega_{\text{baryon}} + \Omega_{\text{dark}} + \Omega_{\text{radiation}} + \Omega_{\text{other}}
\]

e.g. Dark Energy
CMB agrees with observed elemental abundances...

Figure 16.11: The data points are the temperature anisotropies in the cosmic microwave background measured by the WMAP satellite. The variance of the multipole amplitude is plotted vs. multiple number $\ell$ (the angular scale on the sky corresponding to multipole $\ell$ is $\theta \sim 200 \text{ deg}/\ell$). The continuous curves show the sensitivity of the power spectrum to $\Omega_{b,0}$, while keeping all other relevant cosmological parameters fixed. (Figure reproduced from Steigman 2004, astro-ph/0308511).
The Universe is FLAT (it has critical density of matter + energy)

however

Baryonic Matter constitutes only a tiny fraction of the critical density