COSMOLOGY

• How did the Universe Begin?
• How old is the Universe?
• How big is the Universe?
• Where are we in the Universe?
• What is the Universe made of?
• Will the Universe end?
The Scale of the Universe

Visible Universe: $10^{26}$

Galaxy Clusters: $10^{24}$

Milky Way: $10^{21}$

100 ly marconi: $10^{18}$

Nearest Star: $10^{16}$

Solar System: $10^{13}$

Earth - Sun: $10^{11}$

Earth: $10^{8}$

Tallest Mountain: $10^{4}$

Human: $10^{0}$

Protozoa: $10^{-3}$

Cell Nucleus: $10^{-6}$

Molecule: $10^{-9}$

Atom: $10^{-10}$

Nucleus: $10^{-12}$

Proton: $10^{-15}$

Quarks: $10^{-18}$

Planck Length: $10^{-35}$
Our Place in the Universe

Rutherford Appleton Laboratory

Scale ~ 1 km
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire

Scale ~ 10 km
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom

Scale ~ 100 km
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth

Scale ~ 1000 km
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System

Scale ~ 1 A.U. = 1.5x10^8 km or 7 lm
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion

Scale ~ 1000 light years = 9.5x10^{15} \text{ km}
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy

Scale ~ 100,000 light years ~ 30 kpc
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group

Scale ~ 1 million light years ~ 0.5 Mpc
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
Near the Virgo Cluster

Scale ~ 50 million light years
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
near the Virgo Cluster
The Local Supercluster

Scale ~ 100 million light years
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
near the Virgo Cluster
The Local Supercluster
The Universe

Scale ~ 90 billion light years ~ 28Gpc
The Birth of Cosmology

Ancient Greeks: The first cosmological model

Aristotle (384-322 B.C.)

Geocentric
The Birth of Cosmology

Ptolemy (90-168 A.D.)

Geocentric

Perfect motion should be in circles, so the stars and planets, being heavenly objects, moved in circles.
1. There is no one centre in the Universe.
2. The Earth's centre is not the centre of the Universe.
3. The centre of the Universe is near the sun.
4. The distance from the Earth to the sun is imperceptible compared with the distance to the stars.
5. The rotation of the Earth accounts for the apparent daily rotation of the stars.
6. The apparent annual cycle of movements of the sun is caused by the Earth revolution around it.
7. The apparent retrograde motion of the planets is caused by the motion of the Earth from which one observes.

The Birth of Cosmology

Copernicus (1473-1543)

Heliocentric

Copernican Cosmological Principle

The Earth does not occupy a special place in the Universe.
The Birth of Cosmology

Olbers’ Paradox: Why is the Sky so Dark?

In an infinitely large and old Universe populated by stars of number density, \( n \), average luminosity, \( L \):

Flux from star of Luminosity, \( L \), at distance, \( r \):

\[
S(r) = \frac{L}{4\pi r^2}
\]

Intensity, \( I \), from a shell of stars of thickness \( dr \):

\[
dI(r) = \frac{L}{4\pi r^2} n r^2 dr = \frac{nL}{4\pi} dr \quad \{Wm^{-2}sr^{-1}\}
\]

Intensity from shell is independent of distance. Integrating over all shells ⇒ Total Intensity, \( I \):

\[
I = \int_0^\infty dI(r) dr = \frac{nL}{4\pi} \int_0^\infty dr = \infty !!!!
\]

The Sky should be infinitely bright !!!
The Birth of Cosmology

Olbers’ Paradox: Why is the Sky so Dark?

Solutions?

1. Absorption by dust?
   - Dust would be heated until it emitted at the same temperature as the stars ✗

2. Not all lines of sight intersect a star?
   - Finite angular size of stars may block a line of sight ➔ Intensity = surface brightness of stars ✗

3. Number density and Luminosity not constant \((nL \neq \text{constant})\)?
   - would require \(nL\) to decline faster than \(1/r\), \(r \rightarrow \infty\) ✗

4. Universe is not infinitely large?
   - For a finite universe, the average stellar background intensity, \(I \sim (nL/4\pi)r_{\text{max}}\)

5. Universe is not infinitely old?
   - Not all light has reached us, the maximum intensity would be \(I \sim (nL/4\pi)c t_0\)

Primary Resolution to Olbers’ Paradox - The Universe is NOT infinitely old
Not all the light from stars in the Universe has yet had time to reach us

Thermodynamic interpretation:
why is the Universe so cold?- Stars have not had time to heat up Universe

Olbers’ Paradox - Evidence for a finite age of our Universe
The Birth of Cosmology

Velocity-Distance Relation among Extra-Galactic Nebulae.

Measure a Doppler shift in spectral lines: \( z = \frac{\lambda_o - \lambda_e}{\lambda_e} \)
1) (almost) all galaxies are moving away from us

2) More distant galaxies are moving away faster

\[ V \propto d \quad V = H_0 \cdot d \]

\[ H_0 : \text{The Hubble Constant} \]
The Cosmological Principle

**Fundamental Observer:**
Someone at rest with respect to the rest of the Universe in their locality. Universe ~ smooth fluid ~ substratum. *Fundamental observers are co-moving with it.*

**Homogeneity:**
Same picture of Universe at any time seen by all *Fundamental Observers.* *No preferred locations*

**Isotropy:**
The Universe looks the same in all directions to a *Fundamental Observer.* *No preferred Directions*
The Cosmological Principle

- Homogeneous
- Inhomogeneous
- Isotropic (about centre)
- Anisotropic
The Cosmological Principle

Isotropy + Copernican Principle implies Homogeneity

Castor sees Isotropic Universe

\[ \phi_x = \phi_a = \phi_y \]

Pollux sees Isotropic Universe

\[ \phi_x = \phi_b = \phi_y \]
The Cosmological Principle

**Copernican Cosmological Principle**
The Earth does not occupy a special place in the Universe

**The Cosmological Principle**
At any single epoch,
the Universe appears Homogeneous and Isotropic to all Fundamental Observers

**Perfect Cosmological Principle**
**AT ALL TIMES**
The Universe appears Homogeneous and Isotropic to all Fundamental Observers

**Anthropic Cosmological Principle**
*(WEAK)* The conditions necessary for sentient life will only exist in a Universe where the laws of physics are the way they are as seen by us.

*(STRONG)* There could be many different universes, or regions in a single Universe, where the laws of physics are different.
Cosmological Principle (Homogeneity) implies a cosmic time

Since the Universe appears the same to all fundamental observers at any given time, all observers see the same sequence of events => they can all synchronize their watches to some event which occurs in the history of the Universe, thereafter all the watches measure the same cosmological time.
The Cosmological Principle

Is the real Universe Isotropic and Homogeneous?

Matter

Small scales: Highly anisotropic

Large scales > 100Mpc

Clusters / Superclusters: fairly isotropic

Radio Sources: isotropic to a few percent
The Cosmological Principle
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

\[ r' = r - a \quad (r, r', a = \text{vectors}) \]

\[ \sqrt{'(r')} = \sqrt(r) - \sqrt(a) \]

\[ \sqrt{'(r')} = \sqrt{(r - a)} \]

**Cosmological Principle**

**Homogeneity** => O & O' see same events

\[ \sqrt{(r - a)} = \sqrt{(r - a)} \]

\[ \sqrt(r - a) = \sqrt(r) - \sqrt(a) \]
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

\[ \mathbf{v}(r - a) = \mathbf{v}(r) - \mathbf{v}(a) \]

General Solution

\[ \mathbf{v}(r) = \sum_{j=1}^{3} h_{ij} r_j \]

or

\[
\begin{pmatrix}
  h_{11} & h_{12} & h_{13} \\
  h_{21} & h_{22} & h_{23} \\
  h_{31} & h_{32} & h_{33}
\end{pmatrix}
\begin{pmatrix}
  r_1 \\
  r_2 \\
  r_3
\end{pmatrix}
\]

Can check by substituting \( v_i = h_{11} r_1 + h_{12} r_1 + h_{13} r_1 \) into 5

For all observers at all epochs \( h_{ij} \) is \( f_n(t) = h(t)_{ij} \)

Cosmological Principle

Isotropy => matrix is rotationally invariant

\[ h_{ij} = 0 \text{ for } i \neq j \]

and \( h_{11} = h_{22} = h_{33} = \text{constant} = H(t) \)

\[ v_1 = H(t) r_1 \]
\[ v_2 = H(t) r_2 \]
\[ v_3 = H(t) r_3 \]

\[ \mathbf{v} = H(t) \mathbf{r} \]
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

Assuming the Cosmological Principle of an isotropic and homogeneous has led us to Hubble’s Law!

\[ \mathbf{v} = H(t) \mathbf{r} \]

\( H(t) \) is the Hubble Parameter

That the velocity of any co-moving particle is either:

- zero \((H=0)\)
- moving radially away \((H>0)\)
- moving radially toward us \((H<0)\)

with a velocity proportional to the distance: i.e. HUBBLES LAW
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

Assuming the Cosmological Principle of a isotropic and homogeneous has led us to Hubble’s Law!

\[ v = H(t) \cdot r \]

\( H(t) \) is the Hubble Parameter

That the **Universe** is either;

- Static (H=0)
- uniformly expanding (H>0)
- uniformly contracting (H<0)

with a velocity proportional to the distance: i.e. **HUBBLES LAW**
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

Cosmological Expansion:
Cosmic coordinates don’t change but they are scaled with time

\[ r(t) = R(t)x \]

\( x \) = co-moving position
\( r(t) \) = proper position
\( R(t) \) = the Scale Factor

All distances scaled by factor \( R(t) \) with time with isotropic expansion
Volumes also scale as \( R(t)^3 \)
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

Cosmological Expansion:
Cosmic coordinates don’t change but they are scaled with time

\[ r(t) = R(t)x \]

\[ \frac{dr}{dt} = \frac{dR(t)}{dt}x = \frac{\dot{R}}{R}r \]

\[ v(r, t) = H(t)r(t) \]

\[ H(t) = \frac{\dot{R}(t)}{R(t)} \]

The Hubble parameter measures the expansion of the Universe
The Expanding Universe
According to Newton

Consider a particle $P$, on the edge of an isotropically expanding sphere

Multiply by $\dot{r}$ and integrate

$$F = -\frac{GMm}{r^2} \quad \ddot{r} = -\frac{GM}{r^2}$$

$$\frac{1}{2} \dot{r}^2 = \frac{GM}{r} + U_{\text{constant}}$$

$$\frac{1}{2} \dot{r}^2 \left(\frac{r_o}{R_o}\right)^2 = 4\pi G \rho \frac{8 \pi G \rho}{3} R^2 \left(\frac{r_o}{R_o}\right)^2 + U$$

$$\dot{R}^2 = \frac{8 \pi G \rho}{3} R^2 + U$$
The Expanding Universe

According to Newton

\[ \dot{R}^2 = \frac{8\pi G \rho}{3} R^2 + U \]

**Friedmann Equation**

**U>0:** RHS >0 for all time

**U<0:** RHS will become negative at some value of

**U=0:** RHS >0 for all time

\[ R_{\text{max}} = \frac{2GM}{U} \]

\[ \dot{R} \to 0 \quad (t \to \infty) \quad \rho \to 0 \]

**U ~ static potential of Universe (curvature)**
Einstein’s Universe

**Einstein Tensor:**
The Geometry of the Universe

\[ G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R \]

**Energy Momentum Tensor:**
The matter in the Universe

\[ T^{ik} = (P + rc^2) u^i u^k - g^{ik} \rho \]

**Einstein Equation:**
Relates the Matter Energy to the Geometry of the Universe

\[ G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R = \frac{8 \pi G}{c^4} T^{ik} \]
Einstein’s Universe

“Matter tells space how to curve. Space tells matter how to move.”

Fabric of the Spacetime continuum and the energy of the matter within it are interwoven

\[ G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R = \frac{8 \pi G}{c^4} T_{ik} \]

Einstein Equation does not give a static solution!
Einstein’s Universe

“Matter tells space how to curve. Space tells matter how to move.”

Fabric of the Spacetime continuum and the energy of the matter within it are interwoven

\[ G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R - \Lambda g_{ik} = \frac{8 \pi G}{c^4} T_{ik} \]

\[ \dot{R}^2 = \frac{8 \pi G \rho}{3} R^2 - \kappa c^2 \left( + \frac{\Lambda R^2}{3} \right) \]

The Friedmann Equation

Where  \( \kappa \)  is the curvature
Einstein’s Universe

Events in Spacetime

Euclidean

\[ ds^2 = dx^2 + dy^2 \]

2-D

\[ ds^2 = dx^2 + dy^2 + dz^2 \]

3-D

\[ ds^2 = dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \]

3-D
Einstein’s Universe

Events in Spacetime

Special Relativity

\[ ds = \sqrt{dx^2 + dy^2 + dz^2} \]

\[ ds^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2 \]

4-D

\[ ds^2 = [dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2] - c^2 dt^2 \]
Einstein’s Universe

Events in Spacetime

General Relativity

Curved Spacetime: \[ ds^2 = \sum_{i,j=0}^{n} g_{ij} dx^i dx^j \]

\[ ds^2 = c^2 dt^2 - R^2(t) \left( \frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right) \]

The Robertson-Walker Metric
Einstein’s Universe

\[ ds^2 = c^2 dt^2 - R^2(t) \left( \frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right) \]

- The Robertson-Walker Metric and the Geometry of the Universe

\( k = 0 \) : Flat Space

\( k = -1 \) : Hyperbolic Space

\( k = +1 \) : Spherical Space
Cosmological World Models

matter tells spacetime how to curve

\[ \frac{\dot{R}^2}{R^2} = \frac{8\pi G \rho}{3} - \frac{kc^2}{R^2} = H^2 \]

for a flat \((k=0)\) universe
define a critical density
\[ \rho = \rho_c = \frac{3H^2}{8\pi G} \]
define \[ \Omega = \frac{\rho}{\rho_c} = \frac{8\pi G \rho}{3H^2} \]

\(\Omega : \text{The Density Parameter}\)

\[ \frac{kc^2}{H^2 R^2} = \Omega - 1 \]

- \(\Omega > 1\) then \(k>0\)
- \(\Omega < 1\) then \(k<0\)
- \(\Omega = 1\) then \(k=0\)
Cosmological World Models

**Ω**: The Density Parameter

\[
\frac{kc^2}{H^2R^2} = \Omega - 1
\]

- **Ω > 1 then** \( k > 0 \)
- **Ω < 1 then** \( k < 0 \)
- **Ω = 1 then** \( k = 0 \)

**Ω < 1**: low density, expands forever
**Ω = 0**: no matter, expands forever
**Ω = 1**: expands forever gradually slowing
**Ω > 1**: expands to maximum and then re-contracts
Cosmological World Models

Einstein DeSitter Universe

Solution to the Friedmann equation for:
- Flat, $k=0$ universe
- Matter dominated $r = r_o (R_o/R)^3$
- No Cosmological Constant: $Λ=0$
- Density Parameter $Ω=1$

Universe expands uniformly and monotonically but at an ever decreasing rate:

$R = ± R_o \left( \frac{t}{t_o} \right)^{2/3}$ $\propto t^{2/3}$

Age: $t_o = (2/3H_o)$

$R \rightarrow \infty$
$\dot{R} \rightarrow 0$
Cosmological World Models

- Einstein
- De Sitter

Closed Cosmologies

Open Cosmologies

Age ($H_0^{-1}$)

$\Omega_0$
The Friedmann Equations including Cosmological Constant

\[
\begin{align*}
\dot{R}^2 &= \frac{8\pi G \rho}{3} R^2 - \kappa c^2 + \frac{\Lambda R^2}{3} \\
\ddot{R} &= -\frac{4\pi G \rho}{3} R + \frac{\Lambda R}{3}
\end{align*}
\]

- Modifies gravity at large distances
- Repulsive Force ($\Lambda > 0$)
- Repulsion proportional to distance (from acceleration eqn.)
# Cosmological Constant Universes

<table>
<thead>
<tr>
<th>Λ</th>
<th>k</th>
<th>Name</th>
<th>Dynamics</th>
<th>Evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0</td>
<td>∀k</td>
<td>Oscillatory (1st kind)</td>
<td>$\exists R_c \Rightarrow \dot{R}=0, \ddot{R}&lt;0$</td>
<td>contract back to $R=0$ (oscillatory)</td>
</tr>
<tr>
<td>&gt;0</td>
<td>≤0</td>
<td></td>
<td>$\ddot{R}&gt;0 \ \forall \ R$</td>
<td>monotonically expanding</td>
</tr>
<tr>
<td>&gt;0</td>
<td>0</td>
<td>De Sitter</td>
<td>$\rho=0 \ \ddot{R}&gt;0 \ \forall \ R$</td>
<td>monotonically expanding</td>
</tr>
<tr>
<td>Λ_C</td>
<td>1</td>
<td>Einstein Static</td>
<td>$\exists R(\Lambda_C) \Rightarrow \dot{R}=0, \ddot{R}=0$</td>
<td>Static $\forall t$ at $R=R_E$ with $\Lambda=\Lambda_C$</td>
</tr>
<tr>
<td>&gt;Λ_C</td>
<td>1</td>
<td></td>
<td>$\ddot{R}&gt;0 \ \forall \ R$</td>
<td>monotonically expanding</td>
</tr>
<tr>
<td>Λ_C+ε</td>
<td>1</td>
<td>Eddington Lemaitre (EL1)</td>
<td>$\dot{R} \to 0, \ R \to R_E, \ t \to \infty$</td>
<td>Big Bang $\to$ Einstein Static universe</td>
</tr>
<tr>
<td>Λ_C+ε</td>
<td>1</td>
<td>Eddington Lemaitre (EL2)</td>
<td>$R \to R_E, \ t \to \infty$</td>
<td>expand from Einstein Static $\to \infty$</td>
</tr>
<tr>
<td>Λ_C+ε</td>
<td>1</td>
<td>Lemaitre</td>
<td>$R:0 \to R_E$, $R \to \infty$</td>
<td>Long coasting period at $R=R_E$</td>
</tr>
<tr>
<td>0&lt;Λ &lt;Λ_C</td>
<td>1</td>
<td>Oscillatory (1st kind)</td>
<td>$\exists R_{max} \Rightarrow \dot{R}=0, \ddot{R}&lt;0$</td>
<td>contract back to $R=0$ (oscillatory)</td>
</tr>
<tr>
<td>0&lt;Λ &lt;Λ_C</td>
<td>1</td>
<td>Oscillatory (2nd kind)</td>
<td>$(\dot{R}=0) R_{max} &gt; R &gt; R_{p}(\dot{R}&gt;0)$</td>
<td>Universe bounces at $R_B$</td>
</tr>
</tbody>
</table>
Cosmological Constant Universes

\[ \Omega_{\Lambda,0}, \Omega_{m,0} \]

- **k = -1**
  - BOUNCE MODEL
- **k = 0**
  - COAST MODEL
- **k = +1**
  - BIG CRUNCH
  - COLD DEATH
Our Universe

- What kind of Universe do we live in?
- How can we measure it?
- Would like to know;
  - Hubble Constant
  - Density Parameter
    - $\Omega_{\text{total}}$
    - $\Omega_{\text{matter}}$
    - $\Omega_{\Lambda}$

Need to measure distances
Our Universe

\( \Omega_\Lambda \) changes relationship between redshift, time and distance

- constant
- decelerating
- accelerating

For a population of objects of
  - standard proper size (standard ruler)
- or
  - standard luminosity (standard candle)
- and
  - high luminosity

can calculate
  - Distance
  - Measuring redshift \( \Rightarrow \) cosmological parameters \( H_0, \Omega_{m.o}, \Omega_{\Lambda.o} \)
Our Universe: Evidence from Supernova

**Standard Candles: Type 1a Supernova**
- After supernova occurs the light gradually fades.
- Peak brightness of supernovae depends on shape of light decay curve.
- Brighter Supernovae - slower climb and decay of light curve.
- Measure luminosity, observed flux ➔ DISTANCE !!!
Our Universe: Evidence from Supernova

Relationship between observed flux, intrinsic luminosity and distance

\[ m - M = 5 \log d_{L,\text{Mpc}} + 25 \]

\[ m - M = 43 - 5 \log \left( \frac{H_0}{100 \text{h km s}^{-1} \text{Mpc}^{-1}} \right) + 5 \log z + 1.086(1 - q_0)z \]

Expansion rate
Low z observations \( \Rightarrow H_0 \)

Acceleration
Higher z observations \( \Rightarrow q_0 \)

\( q_0 < 0 \Rightarrow \) Universe is accelerating \( \Rightarrow \) standard candle of lower brightness

\( q_0 > 0 \Rightarrow \) Universe is decelerating \( \Rightarrow \) standard candle of higher brightness
Our Universe: Evidence from Supernova

Best Fit
Ho = 72
Ω_{m,o} = 0.3
Ω_{Λ,o} = 0.7
Our Universe is accelerating due to a repulsive force equivalent to $\Omega_{\Lambda, o} = 0.7$. 
Our Universe: Evidence from Hubble

Hubble Key Project
- Discovery of distant Cepheids with the HST
- Comparison of many distance determination methods
- Comparison of systematic errors
- Determination of $H_0 \pm 10\%$
Our Universe: Evidence from Hubble

\[ H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad t_0 = 1.37 \times 10^{10} \text{ yr} \]
Our Universe: Evidence from WMAP/Planck

Wilkinson Microwave Anisotropy Probe (2001)
Planck Satellite (2009)

Detailed full-sky map of the oldest light in Universe.
It is a "baby picture" of the 380,000yr old Universe

- Temperature fluctuations imprinted on CMB at surface of last scattering

- Temperature fluctuations over angular scales in CMB correspond to variations in matter/radiation density
Our Universe: Evidence from WMAP/Planck

- WMAP / Planck - fingerprint of our Universe
- Flat Universe - sonic horizon ~ 1 sq. Deg. ($l=180$)
- Open Universe - photons move on faster diverging pathes => angular scale is smaller for a given size
- Peak moves to smaller angular scales (larger values of $l$)
Our Universe: Evidence from WMAP/Planck

Consistent with $\Omega_{\text{Total}} = 1$
Our Universe

$H_0 = 67.3$
$\Omega_{m,o} = 0.315$
$\Omega_{\Lambda,o} = 0.685$
$\tau_{age} = 13.81$
Our Universe

Friedmann Equations: Cosmological Models depending on the density $\Omega$

Discovered a large family of cosmological World Models

Identified the most likely candidate for our own Universe

$H_0 = 67.3 \pm 0.012$ km/s/Mpc

$\Omega_{\Lambda, o} = 0.685 \pm 0.017$

$\tau_{\text{age}} = 13.81 \pm 0.05$ Gyr

$\Omega_{m, o} = 0.315 \pm 0.016$

$\Omega_{DM, o} = 0.2662 \pm 0.016$

$\Omega_{b, o} = 0.0487 \pm 0.00027$
The End of the Story?

Visible matter
4.9%

Dark matter
26.8%

Dark energy
68.3%

This is the stuff that makes up everything we can see and touch – all the dust, asteroids, comets, planets, stars, galaxies and you and me.

The dark side of matter doesn’t interact with light, so it is invisible. We can detect how its gravity affects visible matter. It is a bit like visible matter’s invisible friend – helping to hold the galaxies and clusters of galaxies together.

While dark matter holds stuff together, dark energy is pushing everything apart. It is causing the Universe’s expansion to speed up. The more space expands, the more dark energy there is.
The End of the Story?

Not Likely …..