The Age of the Universe

Carolin Crawford
Gresham Professor of Astronomy
Arthur Holmes
1890 - 1945
Alan Friedman (Averted Imagination)
\[ E = mc^2 \]
cosmological constant

LeMaitre

Friedmann
Flux = \frac{\text{Luminosity}}{4 \pi d^2}
combined measurements of distances to and velocities of the ‘spiral nebulae’

all galaxies are receding
Hubble's Law

The slope of the plot is $v/d$, and it is known as Hubble's constant.
uniform expansion of space

Galaxy twice as far away has moved twice as far/as fast
– the universe is expanding
– it was smaller in the past

Big Bang!

A galaxy a distance $d$ away moving away from us at velocity $v$ has taken a time of $\sim \frac{d}{v}$ to travel to that point
The slope of the plot is $v/d$ and is known as Hubble's constant. The Hubble parameter is $\frac{1}{H}$.
• **Luminosity** of a star depends on its mass
• **Luminosity** of a star depends on its mass
• **Age** of a star depends on its mass
• **Luminosity** of a star depends on its mass
• **Age** of a star depends on its mass

Faintest ➤ lowest-mass ➤ oldest stars
73 km s$^{-1}$ per Megaparsec
“matter tells space how to curve, and space tells matter how to move”

Wheeler

NASA/ESA/ Rigby, Sharon, Gladders & Wuyts
GEOMETRY OF THE UNIVERSE

FLAT

NASA/WMAP science team
GEOMETRY OF THE UNIVERSE

OPEN

FLAT

CLOSED

NASA/WMAP science team
recollapsing Universe
Universe

present

future

past

open Universe

recollapsing Universe
future

present

critical Universe

open Universe

recollapsing Universe

past
an important cosmological parameter...

*density parameter of the Universe*

\[ \Omega = \frac{\rho}{\rho_c} \]

where \( \rho_c \) is the *critical density* of matter needed to close the Universe

if \( \Omega > 1 \) *closed Universe*

universe will eventually stop expanding, then collapse

If \( \Omega < 1 \) *open Universe*

the universe expands forever
recollapsing Universe

open Universe

critical Universe

recollapsing Universe

future

present

past

Ω < 1

Ω = 1

Ω > 1
The cosmic microwave background

NASA/WMAP science team
Universe

- recollapsing
- open
- present
- future
- past

**Ω < 1**
- open Universe

**Ω = 1**
- critical Universe

**Ω > 1**
- recollapsing Universe

The size of CMB fluctuations shows we live in a flat (‘critical’) universe. All the matter + radiation in the Universe is only 25% of what is required.
Baryonic mass of cluster is determined from the amount of light radiated – at all wavelengths

Total gravitating mass of cluster (including dark matter) obtained through many methods (X-rays, galaxy motions, gravitational lensing)

NASA/ESA/J Richard & JP Kneib
the observed *baryonic fraction*

\[ f_b = \frac{\text{baryonic mass}}{\text{total mass}} \]
Observations of nearby clusters show $f_b \sim 0.12$
Observations of clusters of galaxies tell us the ratio of ordinary mass / total (dark+ordinary) mass \( \sim 0.12 \)

calculations of primordial synthesis fix how much ordinary matter was created in the Big Bang

so we know the total amount of matter in the Universe
baryon fraction should be the same all across the Universe

change reference cosmology used to derive these observables until the fraction of baryonic mass is the same for all clusters

Allen et al
Supernova type 1a
Sun-like star expands to red giant sheds outer layers cools and contracts to white dwarf...

...but if it can accrete mass from a binary partner

once over $1.4 \, M_{\text{sun}}$ it will suddenly explode into a type Ia supernova
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Brighter supernovae fade more slowly…

Supernova explosion

Kim et al 1997
velocity
distance
distant supernovae are: dimmer and so further away than expected
distance expected

distance measured
The supernova results show that:

- the expansion of the Universe is *speeding up*
- this acceleration started about 6 billion years ago

– the Universe is younger than we thought
– gravity does not control the Universe

Johannes Schedler (Panther Observatory)
All matter (+radiation) accounts for only \( \frac{1}{4} \) of the mass-energy density of the Universe. The other \( \frac{3}{4} \) must take the form of energy; we call this ‘dark energy’...

...and this ‘dark energy’ is responsible for the accelerated expansion of the Universe.
Dark energy 75%
Dark matter 20%
Visible matter 5%
The attractive force of gravity is a property of matter.

The repulsive force of dark energy is a property of space.

Thus as the universe expands, dark energy begins to dominate over gravity.
recollapsing Universe
open Universe
present
future
past

critical Universe
recollapsing Universe
accelerating Universe

$\Omega > 1$
$\Omega = 1$
$\Omega < 1$
What is the dark energy?

The cosmological constant
What is the dark energy?

The cosmological constant

The vacuum energy of space
What is the dark energy?

- The cosmological constant
- The vacuum energy of space
- Quintessence
13.772±0.059 billion years
Exoplanets... ...and how to find them

Wed 6th March 1pm