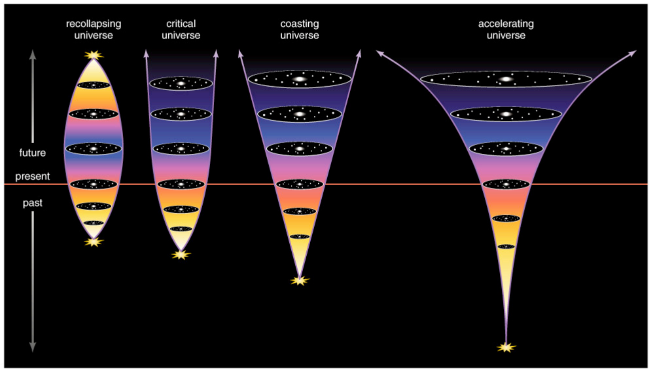
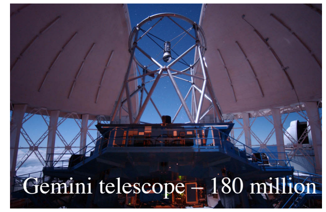
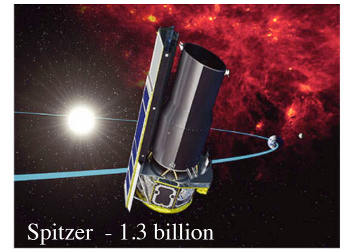
Lecture 19: Cosmology
A2020 Prof. Tom Megeath





How are astronomical facilities funded?

National Science Foundation



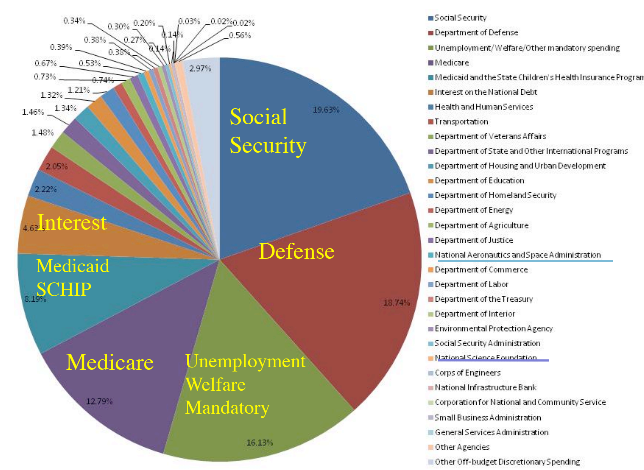
NASA

What Fraction of National Budget Goes into NASA?

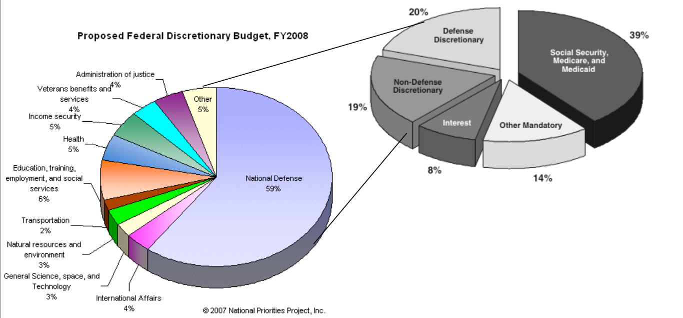
In a poll of the public, the average guess was that approximately 24% of the national budget went to NASA.

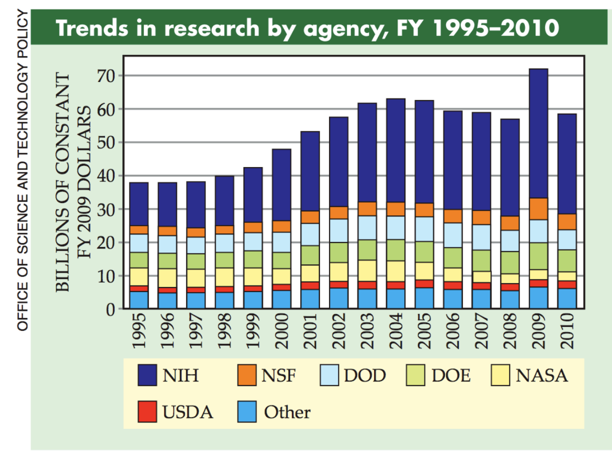
The answer is less 0.5 %

Total Budget 3.6 trillion in FY 2010



How is Science Funded?





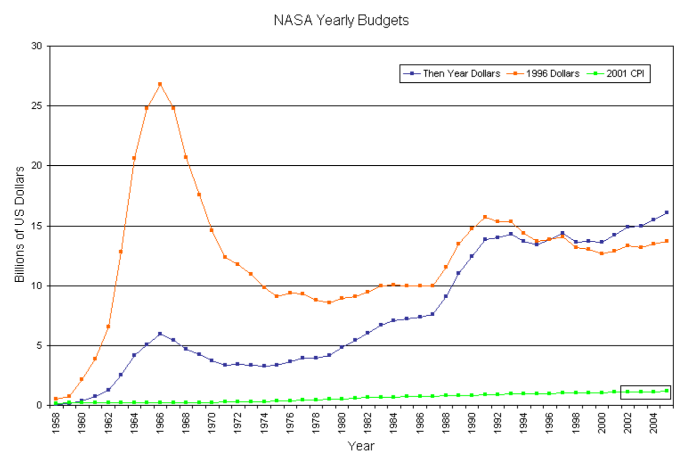
www.physicstoday.org

1.75% of total budget
is spent on Science in 2010

NASA budget

0.4% of federal budget in 2009

Budget Authority, $ in million								
By Appropriation Account By Theme	FY 2008 Actuals	FY 2009 Enacted	Recovery Act	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014
Science	**4,733.2**	**4,503.0**	**400.0**	**4,477.2**	**4,747.4**	**4,890.9**	**5,069.0**	**5,185.4**
Earth Science	1,237.4	1,379.6	325.0	1,405.0	1,500.0	1,550.0	1,600.0	1,650.0
Planetary Science	1,312.6	1,325.6		1,346.2	1,500.6	1,577.7	1,600.0	1,633.2
Astrophysics	1,395.6	1,206.2	75.0	1,120.9	1,074.1	1,042.7	1,126.3	1,139.6
Heliophysics	787.6	591.6		605.0	672.6	720.5	742.7	762.6
Aeronautics	**511.4**	**500.0**	**150.0**	**507.0**	**514.0**	**521.0**	**529.0**	**536.0**
Exploration	**3,299.4**	**3,505.5**	**400.0**	**3,963.1***	**6,076.6***	**6,028.5***	**5,966.5***	**6,195.3***
Constellation Systems	2675.9	3033.2	400.0	3505.4	5543.3	5472.0	5407.6	5602.6
Advanced Capabilities	623.5	472.3		457.7	533.3	556.5	558.9	592.7
Space Operations	**5,427.2**	**5,764.7**	**0.0**	**6,175.6**	**3,663.8**	**3,485.3**	**3,318.6**	**3,154.8**
Space Shuttle	3,295.4	2,981.7		3.157.1	382.8	87.8	0.0	0.0
International Space Station	1,685.5	2,060.2		2,267.0	2,548.2	2,651.6	2,568.9	2,405.9
Space and Flight Support	446.2	722.8		751.5	732.7	745.9	749.7	748.9
Education	**146.8**	**169.2**	**0.0**	**126.1**	**123.8**	**123.8**	**123.8**	**125.5**
Education	146.8	169.2		126.1	123.8	123.8	123.8	125.5
Cross-Agency Support	**3,251.4**	**3,306.4**	**50.0**	**3,400.6**	**3,468.4**	**3,525.7**	**3,561.4**	**3,621.4**
Center Management and Operations	2,011.7	2,024.0		2,084.0	2,119.2	2,142.5	2,166.1	2,189.9
Agency Management and Operations	834.1	921.2		961.2	956.9	964.5	972.3	981.5
Institutional Investments	325.5	293.7	50.0	355.4	392.3	418.7	423.0	450.0
Congressionally Directed Items	80.0	67.5		0.0	0.0	0.0	0.0	0.0
Inspector General	**32.6**	**33.6**	**2.0**	**36.4**	**37.0**	**37.8**	**38.7**	**39.6**
NASA FY 2010	**17,401.9**	**17,782.4**	**1,002.0**	**18,686.0**	**18,631.0**	**18,613.0**	**18,607.0**	**18,858.0**
Year to Year Change		2.2%		5.1%	-0.3%	-0.1%	0.0%	1.3%



Over the entire 50 years of the space program, the amount of money spent was about 800 billion.

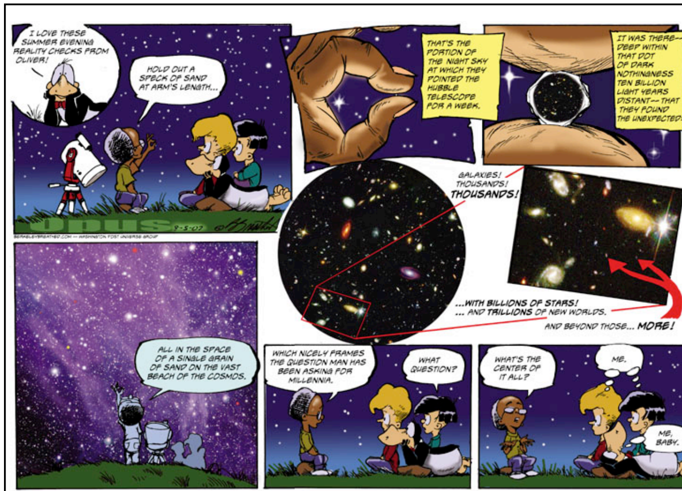
National Science Foundation
7 billion (0.2 % of US budget)

MATHEMATICAL AND PHYSICAL SCIENCES **$1,380,000,000**
+$124,040,000 / 9.9%

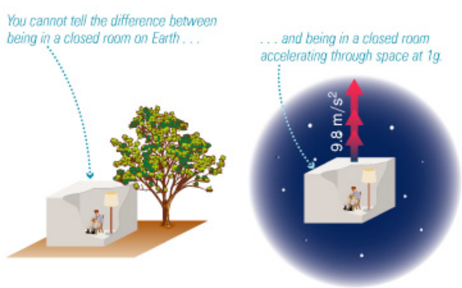
Mathematical and Physical Sciences Funding
(Dollars in Millions)

	FY 2008 Actual	FY 2009 Current Plan	FY 2009 ARRA Estimate	FY 2010 Request	Change Over FY 2009 Plan Amount	Change Over FY 2009 Plan Percent
Astronomical Sciences	$217.90	$228.62	$85.80	$250.81	$22.19	9.7%
Chemistry	194.62	211.35	103.00	238.60	27.25	12.9%
Materials Research	262.55	282.13	106.90	308.97	26.84	9.5%
Mathematical Sciences	211.75	226.18	98.00	246.41	20.23	8.9%
Physics	251.64	274.47	96.30	296.08	21.61	7.9%
Office of Multidisciplinary Activities	32.67	33.21	-	39.13	5.92	17.8%
Total, MPS	**$1,171.13**	**$1,255.96**	**$490.00**	**$1,380.00**	**$124.04**	**9.9%**
Major Components:						
Research and Education Grants	773.16	845.24	403.45	934.55	89.31	10.6%
Instrumentation	52.25	47.71	25.95	69.68	21.97	46.0%
Centers Programs	97.37	114.95	-	114.27	-0.68	-0.6%
Facilities Operation & Maintenance	248.35	248.24	60.60	261.50	13.26	5.3%

Totals may not add due to rounding.

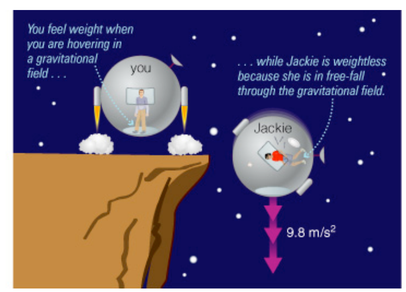


Review: General Relativity (Einstein 1915)
1. The Equivalence Principle



- The effects of acceleration are indistinguishable to gravity

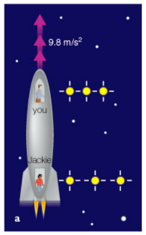
Gravity and Relative Motion



- Force of standing on surface of Earth, hovering near the surface of the Earth, or accelerating at 9.8 meter sec^2 in empty space are indistinguishable.
- Someone who feels weightless may be in free-fall
  - interial reference frames and free fall frames equivalent

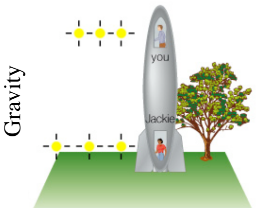
Time in an Gravitational Field

Acceleration



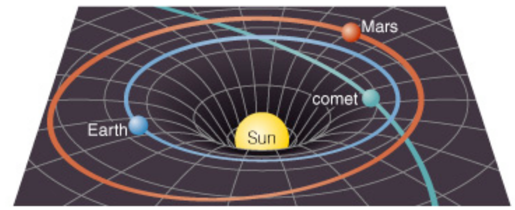
- Jackie sends flashes of light to you every second.
- Since you are accelerating, by the time the flashes hit you, you are moving faster.
- Longer time for light to catch up with you.
- You see light flashes from Jackie separated by more than 1 second.

Gravity



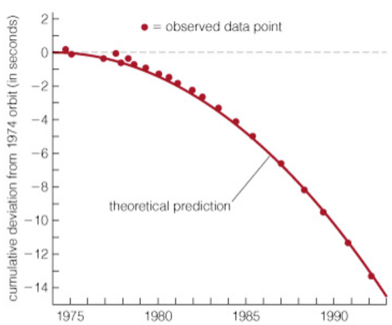
- Effects of gravity are exactly equivalent to those of acceleration
- Time must run more quickly at higher altitudes in a gravitational field than at lower altitudes

The Curvature of Spacetime



- Matter and energy determine curvature of spacetime
- Curvature determined by total mass of all matter and energy in a volume of space (remember $E=mc^2$)
- Curvature of spacetime determine motions of matter and energy.
- Space is locally flat - objects move as though they are moving in empty space, flat space.

What are gravitational waves?



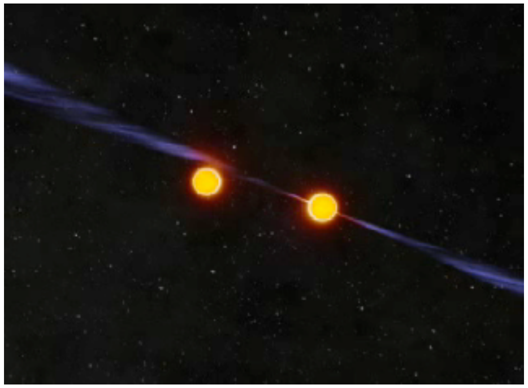
Space is Dynamic
Example: Black Holes in Merging Galaxies

John Rowe Animation/Australia Telescope National Facility, CSIRO
http://www.atnf.csiro.au/research/pulsar/array/gallery.html

Gravitational Waves

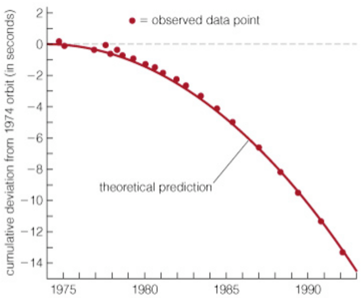
- General relativity predicts that movements of a massive object can produce gravitational waves just as movements of a charged particle produce light waves
- Gravitational waves have not yet been directly detected

Binary Pulsars Emit Gravity Waves



John Rowe Animation/Australia Telescope National Facility, CSIRO
http://www.atnf.csiro.au/research/pulsar/array/gallery.html

Indirect Detection of Waves



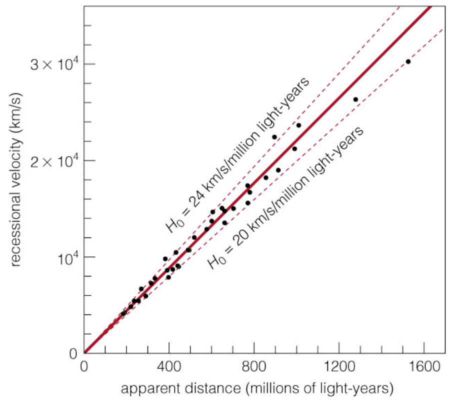
- Observed changes in orbit of a binary system consisting of two neutron stars agree precisely with predictions of general relativity
- Orbital energy is being carried away by gravitational waves

Cosmology: the study of the universe as a whole

Let's Now Apply General Relativity to cosmology

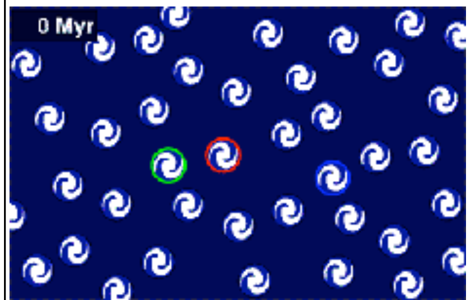
We know two important things about the universe as a whole.

Number 1: Hubble's Law



Hubble's Law: velocity = H_0 x distance

Hubble's Law and the Expanding Universe



The Universe is expanding by following the Hubble law:

The more distant the object, the faster it is moving away from us.

http://www.einstein-online.info/en/elementary/cosmology/expansion/index.html

Number 2: The Distribution of Galaxies is Isotropic

Distribution of galaxies in the sky. Each dot is a galaxy. The galaxies are approximately isotropic, although somoe clusters, filaments and voids are detected.

Z = redshift of galaxy
Z = Δλ/λ (λ = wavelength of light)
Z = V/c (c = speed of light)
(approximately - does not take into account relativity)

From Hubble Law
V = Ho D V = velocity
D = V/Ho D = distance
D = c Z/Ho Ho = Hubble's constant

Z is a measurement of cosmological distance

Z = 0.08 => 1 billion light years

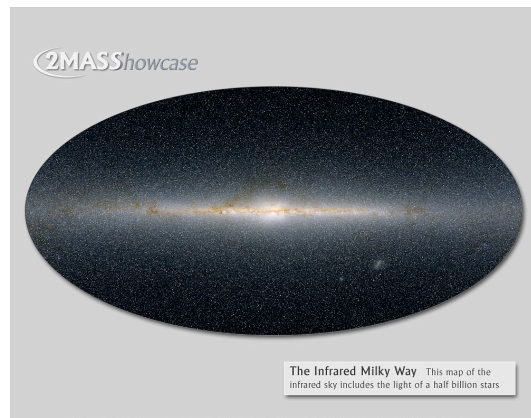
Z = 0.5 => 5 billion light years

Z = 1.9 => 10 billion light years

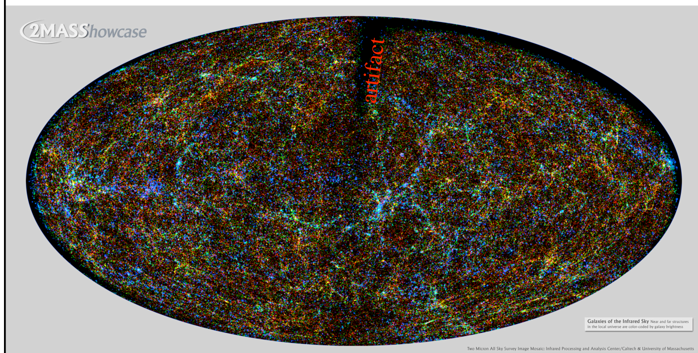
Z = 2.5 => 11 billion ligh years

Z = 7.8 => 13 billion light years

The Distribution of Stars in our Galaxy



The Distribution of Galaxies



The color dots give the distribution of other Galaxies in the sky.

The Distribution of Galaxies are *isotropic*.

The Universe is Isotropic and Homogenous

Isotropic – it looks the same in all directions (the distribution of galaxies is basically the same any direction in the sky).

Homogenous – it looks the same from any point in the Universe (i.e. the universe looks basically the same to us and aliens in another solar system in a very distant galaxy).

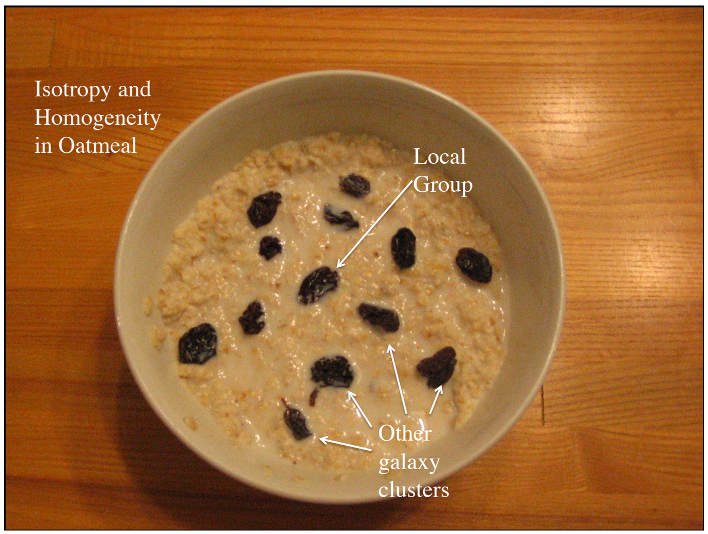
We know that the universe does not look exactly the same in every direction:

We see the disk of our galaxy (i.e. the Milky Way)

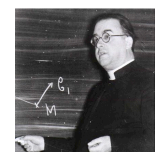
We know that the universe doesn't look exactly the same from every galaxy:

For example, the the universe may look very different to an alien race in the middle of a galaxy cluster.

How do we think about this?



Cosmology: Study of the Universe as a Whole



Georges Lemaitre, Priest and Physicist

Alexander Friedmann and Georges Lemaitre first applied Einstein's general relativity to Cosmology.

They assumed (as an approximation) that the universe is isotropic and homogeneous

1. Isotropic - the distribution of stars and galaxies looks the same in every direction to every observer
2. Homogeneous - the distribution of stars and galaxies is relatively smooth and constant (i.e no *big* lumps, just little ones like *galaxies*)

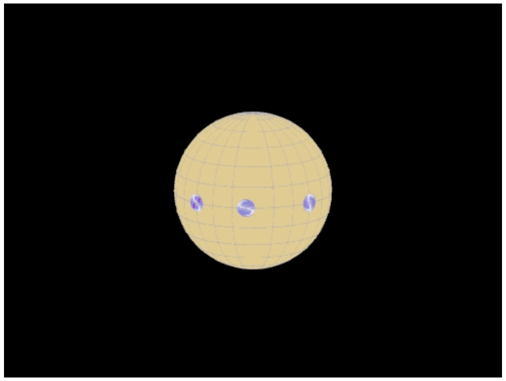
Solving Einstein's equations, they predicted in 1927 that Universe is *expanding*!

Einstein did not believe the Universe was expanding, and so he introduced a new "force" in his equation: the cosmological constant. This new force would balance gravity so that the Universe could be static (no expansion).

In 1929, Edwin Hubble showed that the universe was indeed expanding.

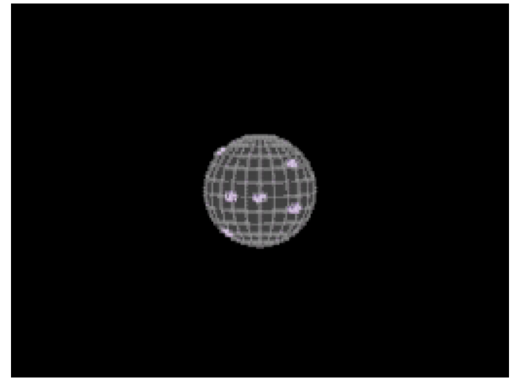
Einstein later referred to the cosmological constant as his *greatest blunder*.

Hubble's Law and the Expanding Universe



http://phys23p.sl.psu.edu/phys_anim/astro/indexer_astro.html

Hubble's Law and the Expanding Universe



http://phys23p.sl.psu.edu/phys_anim/astro/indexer_astro.html

Is Everything in the Universe is Expanding?

Hubble's law velocity = 71 km s^{-1}/Megaparsec x Distance

(1 megaparsec = 1 million parsecs)

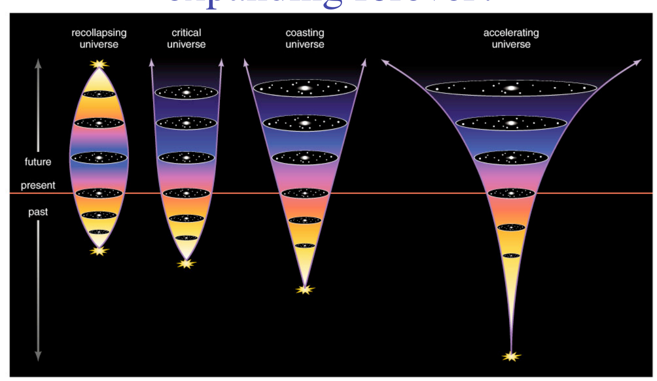
Distance from Sun to Pluto = 40 AU = 6 x 10^{14} cm
= 2 x 10^{-10} Megaparsec

Velocity = 71 km s^{-1} / Megaparsec x 2 x 10^{-10}

Velocity = 1.4 x 10^{-8} km s^{-1} = 0.44 km per year

Thus. Pluto would drift away from the Sun. However, *in reality*, the gravity of the Sun overcomes the Hubble expansion and keeps Pluto and the other planets from drifting away as the Universe expands.

Will the universe continue expanding forever?



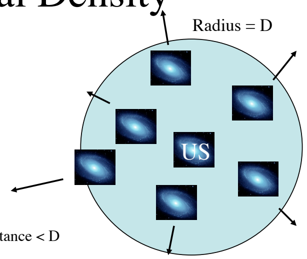
Critical Density

Kinetic Energy of Galaxy = $1/2\ m V^2$

m = Mass of Galaxy
V = Velocity of Galaxy

V = Ho D (Hubble's Law)

D = distance to Galaxy



Gravitational energy of Galaxy = -G M m/D

Where M is total mass of all galaxies at a distance < D

$M = 4/3\ \pi \rho D^3$ where ρ is the density of all matter (dark, baryonic, whatever)

Critical density when Kinetic Energy + Gravitational Energy = 0

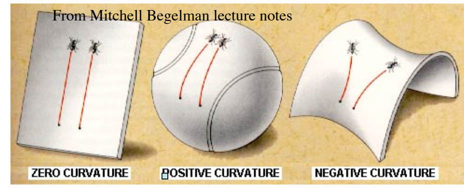
Kinetic Energy = -1 * Gravitational Energy

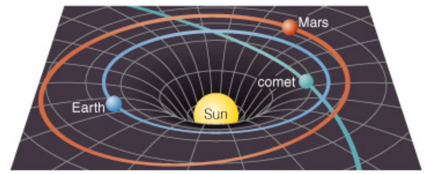
$1/2\ m (HoD)^2 = G\ m\ 4/3\ \pi \rho D^3/D$

$\rho = 3/8\ Ho^2 / G \pi = 1 \times 10^{-29}\ gm\ cm^{-3}$

Critical density = 6 hydrogen atom per cubic meter (averaged over universe)

Gravity and Tides in General Relativity





In empty space, two objects moving in parallel lines continue are equal distant to each other.

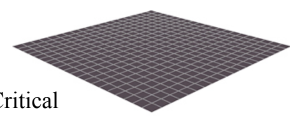
In curved space two effects:

Two objects moving on initially parallel lines can diverge or converge.

Sources nearer the Sun see more curvature.

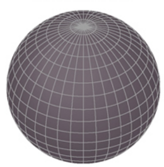
Tides are a result of curved spacetime.

Density = Critical



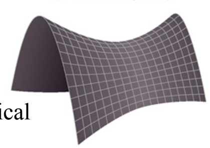
flat (critical) geometry

Density > Critical



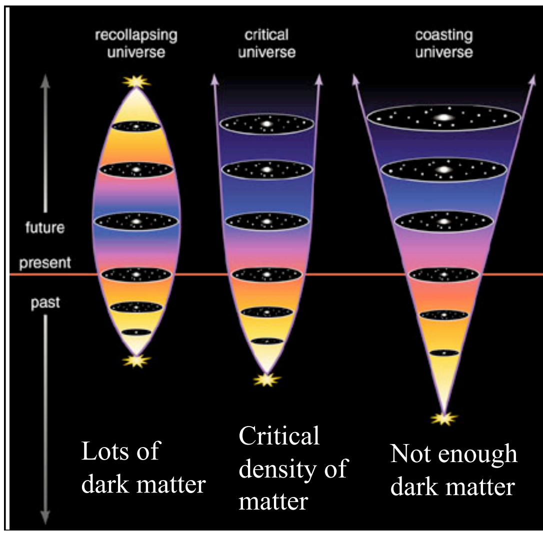
spherical (closed) geometry

Density < Critical



saddle-shaped (open) geometry

Overall geometry of the universe is closely related to total density of matter & energy



Fate of universe depends on the amount of dark matter

Fire and Ice

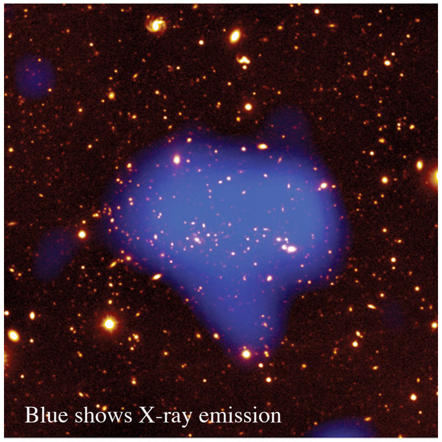
by Robert Frost.

Some say the world will end in fire;
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate to know that for destruction
ice is also great and would suffice.

Two methods for determining the critical density and the future of the universe:

1. Count up all the mass and see how it compares to the critical density.
2. Measure the de-acceleration of the universe

Counting up the mass: Can Dark Matter Stop the Expansion of the Universe?



Blue shows X-ray emission

From clusters of galaxies, we know that about 15% of the gas is Baryonic (made out of normal protons, neutrons, electrons)

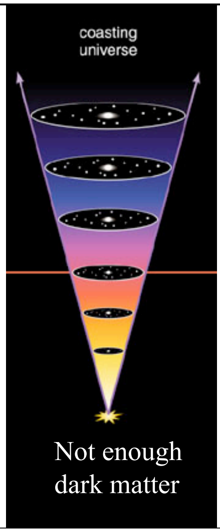
2% stars
13% hot gas

The remainder has to be something "else":

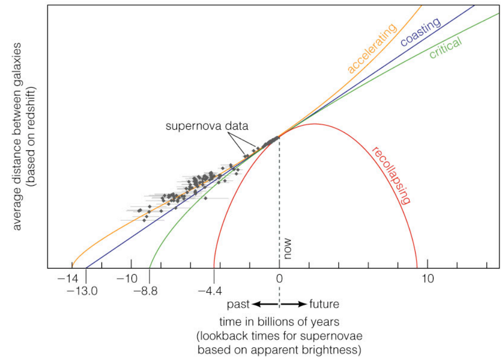
85% dark matter

But the total density is still only 25% that of the critical density!!!

Amount of dark matter is ~25% of the critical density suggesting fate is eternal expansion

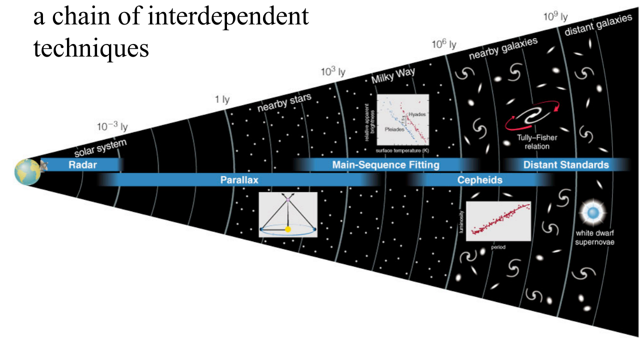


Measuring the De-acceleration of the Universe…

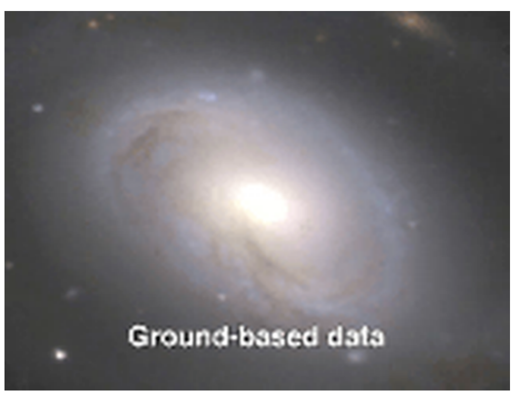


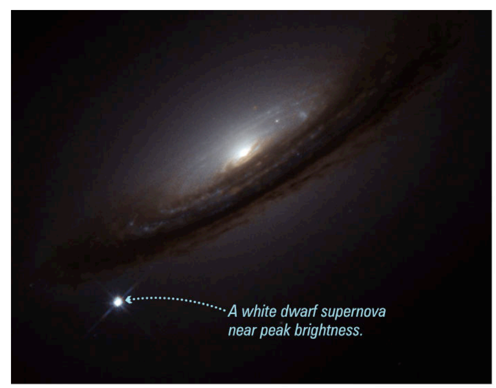
Cosmic Distance Ladder

We measure galaxy distances using a chain of interdependent techniques

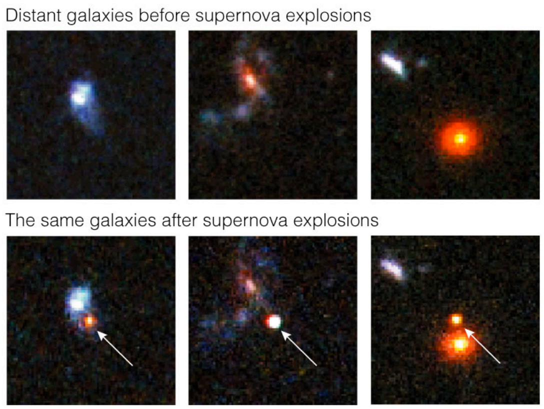


Rung 5 (the ultimate rung): White Dwarf Supernova

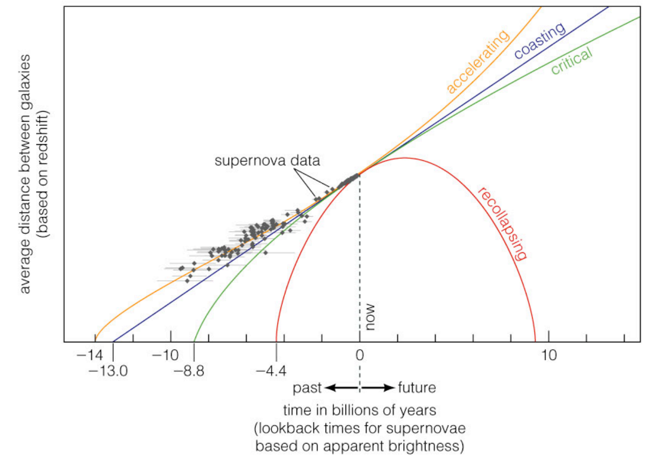




White-dwarf supernovae can also be used as standard candles

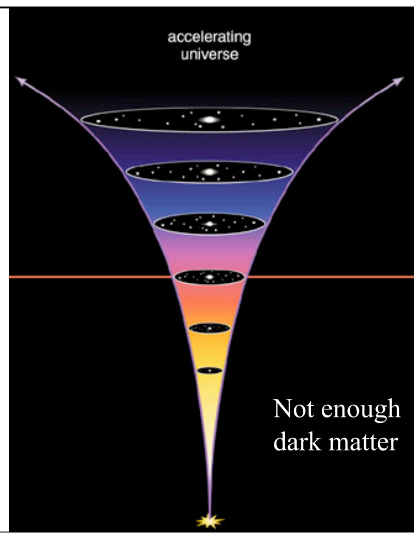


Brightness of distant white-dwarf supernovae tells us how much universe has expanded since they exploded



Accelerating universe is best fit to supernova data

But expansion appears to be speeding up!



Dark Energy?

Not enough dark matter

Unseen Influences

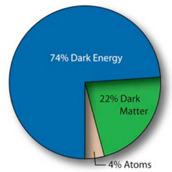
Dark Matter: An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence

Dark Energy: An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate

Contents of Universe

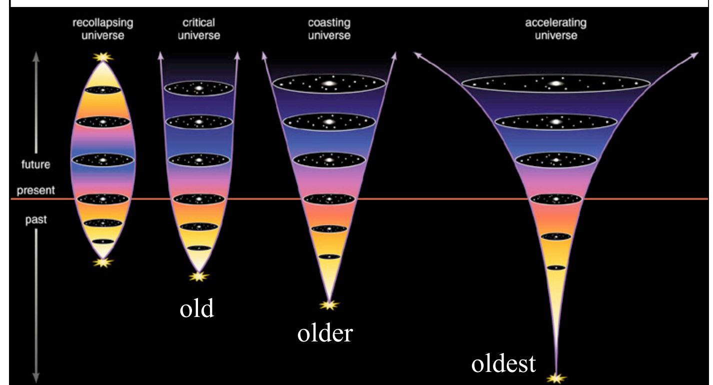
Current data indicate the following breakdown:

- "Normal" Matter: ~ 4.4%
  - Normal Matter inside stars: ~ 0.6%
  - Normal Matter outside stars: ~ 3.8%
- Dark Matter: ~ 22%
- Dark Energy ~ 75%



Density of Baryonic Matter + Dark Matter + Dark Energy = Critical Density

The Universe appears to be Flat (or very close to Flat) !!!



Estimated age depends on both dark matter and dark energy

Current 13.6 billion year estimate takes acceleration into account

Thought Question

Suppose that the universe has more dark matter than we think there is today – how would that change the age we estimate from the expansion rate ?

A. Estimated age would be larger
B. Estimated age would be the same
C. Estimated age would be smaller

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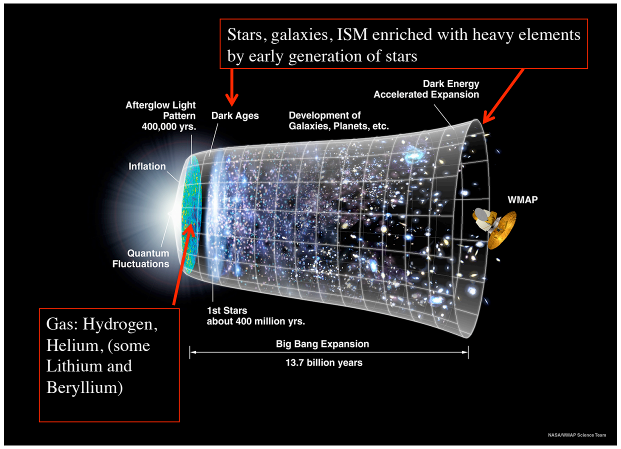
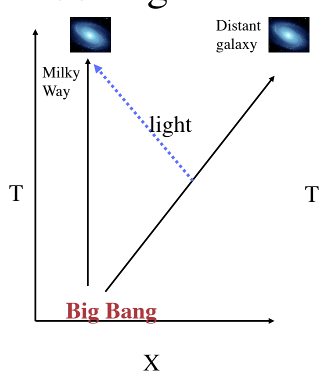
An Overview of the History of the Universe

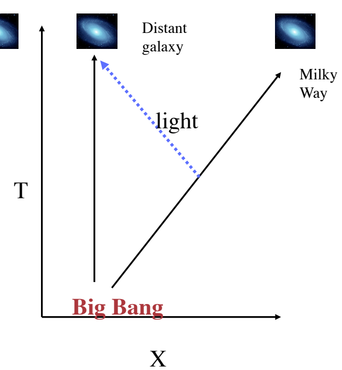


Can we find further proof of the big bang?

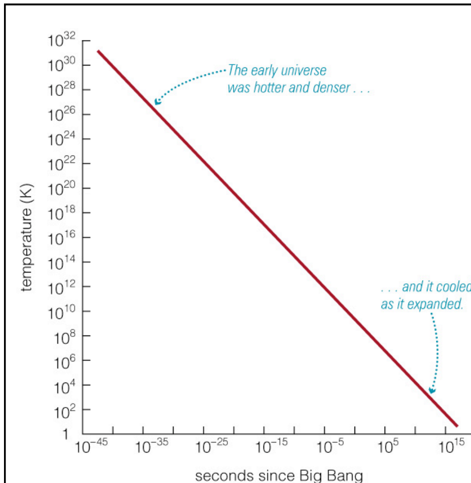
Looking Back in Distance and Time



Spacetime diagram: Milky Way Reference Frame



Spacetime diagram: Other Galaxy Reference Frame



The early universe must have been extremely hot and dense

The Cosmic Microwave Background

In 1965, Arno Penzias and Robert Wilson mapped the sky in microwave (a type of electromagnetic radiation with a wavelength of millimeters – somewhat shorter than radio waves).

They discovered that the entire sky was emitting radio waves.

They tried to discover if it was a problem with their telescope – but despite all their skepticism and hard work, they could not disprove the emission.

The Cosmic Microwave Background

- This glow is now known as the cosmic microwave background.
- It is radiation emitted 400,000 years after the big bang – it had been predicted in 1948
- In 1979 Arno Penzias and Robert Wilson received the Nobel Prize for their discovery

Stop and Think

We started by measuring the positions, velocities and distances of galaxies.

From this:

- We discovered that space was expanding (needed Relativity to understand this).
- We measured the age of the universe.
- We discovered that what we are made out of is only 4% of the matter/energy of the universe.

What have we learned?

- How does the curvature of the Universe depend on the density of matter?
  - Positive Curvature if density high enough to stop universe from expanding
  - Negative Curvature if density is to low to stop universe from expanding
  - Flat if universe is critical (stop expanding as time approaches infinity
- Will the universe continue expanding forever?
  - Current measurements indicate that there is not enough dark matter to prevent the universe from expanding forever
- Is the expansion of the universe accelerating?
  - An accelerating universe is the best explanation for the distances we measure when using white dwarf supernovae as standard candles
- What are the main ingredients of the Universe?
  - 4% "normal" baryonic matter (everything we know of in our common experience)
  - 22% dark matter (neutrinos and WIMPS)
  - 74% dark energy

  96% of the Universe consists of "exotic" dark matter and dark energy - what these are is not understood!

  In reality, the matter from which we are made is "exotic" and rare.