

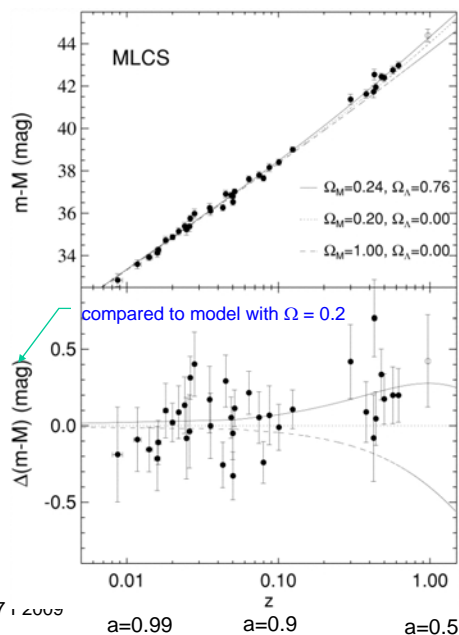
Weighing the Universe with Supernovae. Discovery of Dark Energy/ Cosmological Constant / Review — 11 Dec

- Final exam
 - Final from 2008 (with answers) is on angel.
 - Covers entire course with emphasis on 20th century cosmology (Oct 28 to end of term, Hwk 7–10)
 - One 8.5×11” cheat sheet
 - Mon, 14th, 3:00-5:00, 1410 BPS (large classroom next door)
- Office hours
 - Normal time on Mon.
- Please fill out on-line SOCT
<http://rateyourclass.msu.edu>
 - Will close when grades are submitted.

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Observations

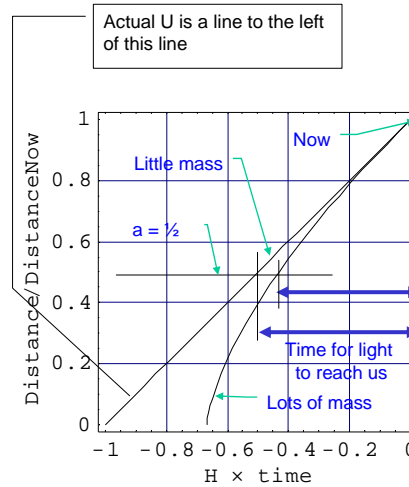
- Lower plot compares data to a model with density parameter
 - $\Omega = PE/KE = 0.2$
- Distant SN are 20% fainter than model with $\Omega = 0.2$.
- Distant SN are 15% fainter than model with $\Omega = 0$!
 - $f=L/D^2$
 - Fainter \Rightarrow distance is greater
 - Longer time to expand than for a universe having no mass at all!
 - Longer time means expansion sped up.



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Observations

- Distant SN are 15% fainter than model with $\Omega = 0$!
 - $f=L/D^2$
 - Fainter \Rightarrow distance is greater
 - Longer time to expand than for a universe having no mass at all!
 - Longer time means expansion sped up.
- Einstein (about 1920): I thought of a kind of stuff where gravity repels. E called it “cosmological constant.”



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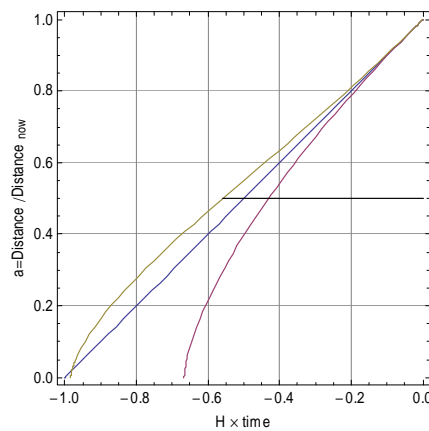
$a=0.99$

$a=0.9$

$a=0.5$

Observations

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$a=0.99$

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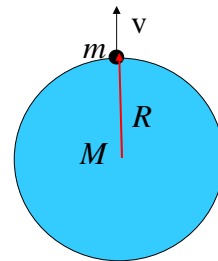
How did Einstein think of “cosmological constant,” stuff that repels?

- Example of how physicists create new ideas.
- Figure out the appropriate mathematics to describe gravity.
 - Newton: Vectors describe gravity.
 - Einstein’s happiest thought: “A man falling from a roof does not feel gravity” (until he hits the ground). Years of thought. Tensors describe gravity.
- Figure out the consequences of the theory.

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Einstein’s General Relativity

- What causes gravity?
- Newton’s answer: mass.
 - Force of gravity between what’s in the sphere and mass m
 - $F = G M m/R^2$.
- Einstein’s answer: mass and pressure
 - Force of gravity between what’s in the sphere and mass m
 - $F = G (M + 3PV/c^2) m/R^2$



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Source of Gravity

- Einstein's answer: mass and pressure

$$F = G (M + 3PV/c^2) m/R^2.$$

- Newton's Law of gravity

$$F = G M m/R^2.$$

- Einstein's Law of gravity

$$\text{Curvature of space} = 8\pi G (\text{Mass-Pressure tensor})$$

$$\mathbf{G} = 8\pi G \mathbf{T}$$

- Object feels curvature of space and changes its momentum

- \mathbf{G} and \mathbf{T} are tensors having 16 components

- If on average the material is at rest, then \mathbf{T} has 4 components. The source of gravity, $(M + 3PV/c^2)$, is the sum of the 4 terms on the diagonal of $\mathbf{T} V$.

- Ordinary matter has little pressure because speed is much smaller than c .

$$3PV/c^2 = M (v/c)^2 \text{ is negligible compared with } M.$$

- Radiation has positive pressure

$$3PV/c^2 = M.$$

$$F = G 2M m/R^2.$$

$$\mathbf{T} = \begin{pmatrix} M/V & 0 & 0 & 0 \\ 0 & P_x/c^2 & 0 & 0 \\ 0 & 0 & P_y/c^2 & 0 \\ 0 & 0 & 0 & P_z/c^2 \end{pmatrix}$$

$$\mathbf{T}_{\text{matter}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v/c)^2 & 0 & 0 \\ 0 & 0 & (v/c)^2 & 0 \\ 0 & 0 & 0 & (v/c)^2 \end{pmatrix}$$

$$\mathbf{T}_{\text{rad}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix}$$

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Cosmological Constant

- Einstein's answer: mass and pressure

$$\text{Force: } F = G (M + 3PV/c^2) m/R^2.$$

- If on average the material is at rest, then \mathbf{T} has 4 components. source of gravity, $(M + 3PV/c^2)$, is the sum of the 4 terms on the diagonal of $\mathbf{T} V$.

$$\mathbf{T}_{\text{matter}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v/c)^2 & 0 & 0 \\ 0 & 0 & (v/c)^2 & 0 \\ 0 & 0 & 0 & (v/c)^2 \end{pmatrix}$$

- Einstein in 1920s: My equations of gravity allow a special tensor. E called it a "cosmological constant."

- T_{cc} has same mathematical properties as T_{matter} and T_{rad} .

- The CC has mass and negative pressure. Normal pressure pushes. CC sucks.

- The CC may exist in Nature.

- "What is not forbidden is mandatory"—W Pauli

$$\mathbf{T}_{\text{rad}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix}$$

$$\mathbf{T}_{\text{cc}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

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Cosmological Constant

- Einstein's answer: mass and pressure
Force: $F = G (M + 3PV/c^2) m/R^2$. $T_{\text{matter}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v/c)^2 & 0 & 0 \\ 0 & 0 & (v/c)^2 & 0 \\ 0 & 0 & 0 & (v/c)^2 \end{pmatrix}$
 - If on average the material is at rest, then \mathbf{T} has 4 components. The source of gravity, $(M + 3PV/c^2)$, is the sum of the 4 terms on the diagonal of $\mathbf{T} V$.
1. Write the force of gravity for the case of the cosmological constant. (Watch the signs.)
- A. $F = G M m/R^2$
 B. $F = G (2M) m/R^2$
 C. $F = G (-2M) m/R^2$
- $$T_{\text{rad}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix}$$
- $$T_{\text{cc}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

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Cosmological Constant

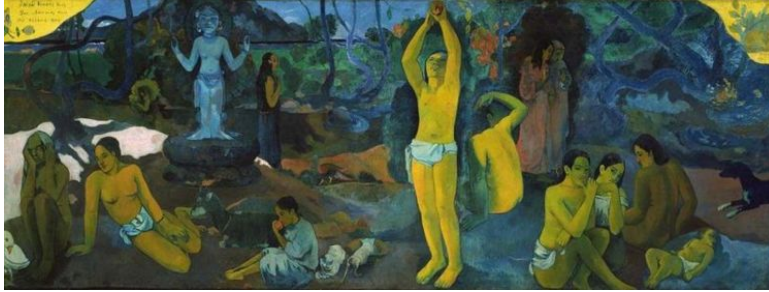
- Einstein's answer: mass and pressure
Force: $F = G (M + 3PV/c^2) m/R^2$.
- Einstein's Law of gravity
Curvature of space = $8\pi G$ Mass-Pressure
 $G = 8\pi G T$
 - Object feels curvature of space and changes its momentum
- Einstein in 1920s: My equations of gravity allow "cosmological constant"
 - T_{cc} has same mathematical properties as T_{matter} and T_{rad} .
 - Pauli: "What is not forbidden is mandatory."
 - $F = G (M - 3M) m/R^2$
 $F = -G 2M m/R^2$.
 - Repulsive gravity
- Einstein tried to make his theory of gravity prevent expansion or contraction of the universe. The cosmological constant balances gravity of matter.
 - In 1929, Hubble discovered the expansion of the U. Einstein said the cosmological constant was "his greatest blunder."
 - Had he lived to 1998, he would have called it his greatest discovery.

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Summarizing questions

- What is the evidence for dark energy? What was measured. If the result of the measurements were ____, there would be no evidence for dark energy.
- Ideas needed to answer the question:
 - SN are fainter than if U had no dark energy.
 - Flux of SN is related to distance.
 - With no DE, distance to SN is shorter.
 - Redshift of SN determines the amount U expands.
 - SN have the same luminosity: They are standard candles.
 - Astronomers can model flux vs redshift for different density parameters.
 - What plot did we look at? What about the plot indicated DE.

Review—11 Dec



- Goal of the class
 - van Gogh: “Where do we come from? What are we? Where are we going?”
 - Recurring theme: How was a discovery made? Interpret the data from which a discovery was made.
- Main sections
 - Copernican revolution
 - Solar system, stars
 - Expansion of the universe
 - Radiation from the Big Bang
 - What is the universe made of?

Copernican Revolution

- How would astronomers answer the question, “What are we?” after the Copernican revolution?
- What were important measurements made during the Copernican revolution?

Solar system, stars

- Where does the sun come from? What is the sun? Where is the sun going?
- Where do the elements in me come from?
- What was an important discovery? What was the evidence?

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Expansion of the universe

- Where do we come from?
- How do you know a Big Bang occurred?
- Questions about Hubble's Law.
 - Galaxies move away from us in all directions. Are we in a special place?
 - Many others

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Radiation from the Big Bang

- Where does helium come from?
- Why was the radiation hotter in the past?
- What evidence of Penzias & Wilson were consistent with the radiation being produced in the Big Bang?

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What is the universe made of?

- What are galaxies made of? How did Vera Rubin & her colleagues figure this out?
- What are galaxies made of? What is the evidence for the black hole in the center of our galaxy?
- What is the universe made of? How do measurements of supernovae tell us the answer?
- What are we? Describe the constituents of the universe.
- Where are we going? Will the universe expand forever?

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