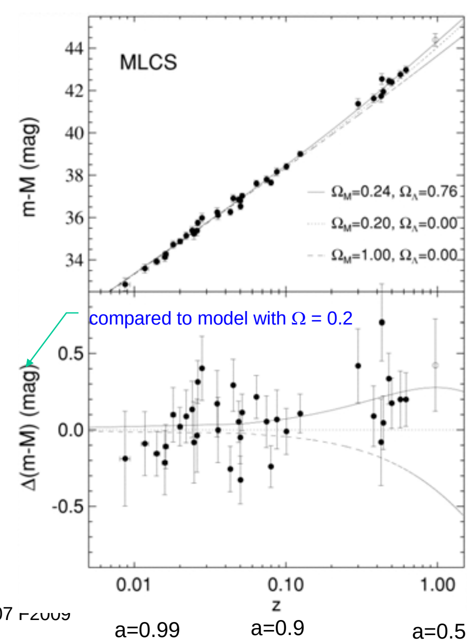
Weighing the Universe with Supernovae. Discovery of Dark Energy/ Cosmological Constant / Review — 11 Dec

- 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.

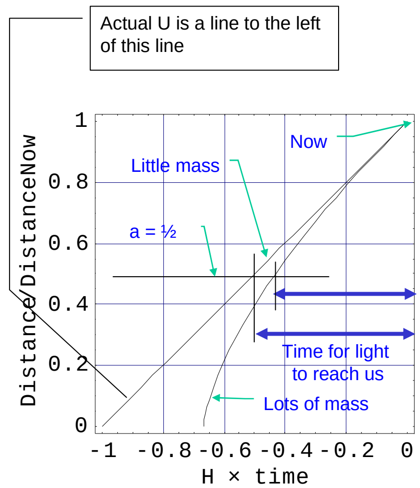
Observations

- 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 ⇒ distance is greater
  - Longer time to expand than for a universe having no mass at all!
  - Longer time means expansion sped up.



Observations

- Distant SN are 15% fainter than model with Ω =0!
  - f=L/D2
  - Fainter ⇒ 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.”



a=0.99 a=0.9 a=0.5

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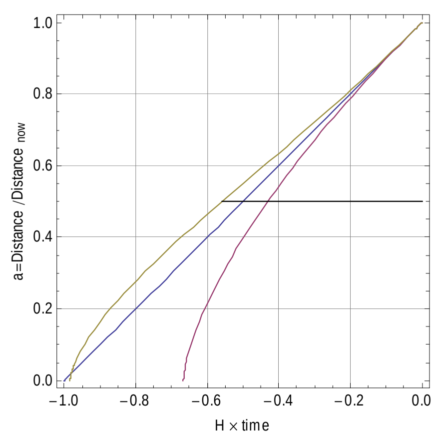

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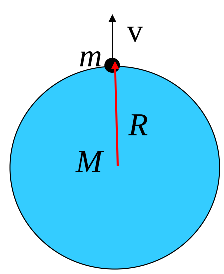
How did Einstein think of "cosmological constant," stuff that repels?

- 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.

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



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
  - Curvature of space = 8πG (Mass-Pressure tensor)
  - **G** = 8πG **T**
  - Object feels curvature of space and changes its momentum
  - **G** and **T** are tensors having 16 components
  - If on average the material is at rest, then **T** has 4 components. The source of gravity, $(M + 3PV/c^2)$, is the sum of the 4 terms on the diagonal of **T** V.
- Ordinary matter has little pressure because speed is much smaller than c.
  - $3PV/c^2 = M (v/c)^2$ is negligible compared with M.
- Radiation has positive pressure
  - $3PV/c^2 = M$.
  - $F = G\, 2M\, m/R^2$.

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

$$T_{\text{matter}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v_x/c)^2 & 0 & 0 \\ 0 & 0 & (v_y/c)^2 & 0 \\ 0 & 0 & 0 & (v_z/c)^2 \end{pmatrix}$$

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

Cosmological Constant

- Einstein's answer: mass and pressure
  - Force: $F = G (M + 3PV/c^2) m/R^2$.
  - If on average the material is at rest, then **T** has 4 components. source of gravity, $(M + 3PV/c^2)$, is the sum of the 4 terms on the diagonal of **T** V.
- 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

$$T_{\text{matter}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v_x/c)^2 & 0 & 0 \\ 0 & 0 & (v_y/c)^2 & 0 \\ 0 & 0 & 0 & (v_z/c)^2 \end{pmatrix}$$

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$$T_{\text{CC}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Cosmological Constant

- Einstein's answer: mass and pressure

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

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

$$T_{\text{matter}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v_x/c)^2 & 0 & 0 \\ 0 & 0 & (v_y/c)^2 & 0 \\ 0 & 0 & 0 & (v_z/c)^2 \end{pmatrix}$$

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

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Cosmological Constant

- Einstein's answer: mass and pressure

  Force: $F = G (M + 3PV/c^2)\, m/R^2$.
- Einstein's Law of gravity

  Curvature of space = 8πG Mass-Pressure

  $G = 8\pi G\, T$

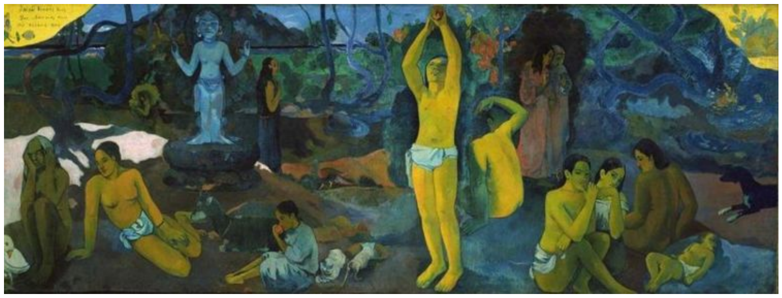
  – Object feels curvature of space and changes its momentum
- Einstein in 1920s: My equations of gravity allow "cosmological constant"
  – T_{cc} has same mathematical properties as T_{matter} and T_{rad}.
  – Pauli: "What is not forbidden is mandatory."
  – $F = G (M – 3M)\, m/R^2$

  $F = – G\, 2M\, m/R^2$.
  – 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.

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?

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

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?

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?