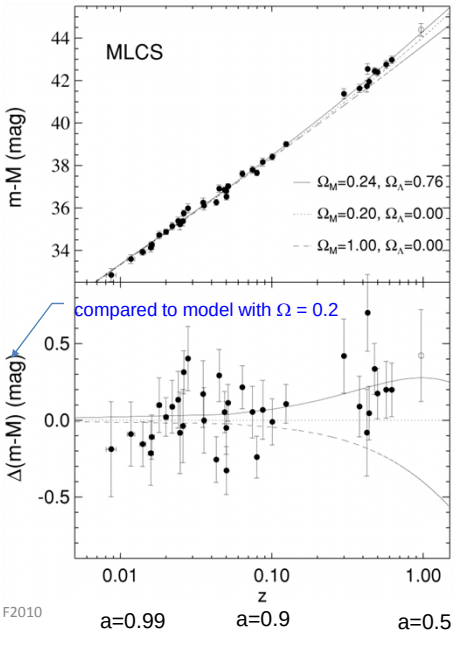
What is Dark Energy/ Cosmological Constant—10 Dec

- Homework has not been graded. Look at answers on Angel.
- Final exam
  - Covers the entire term with more emphasis on 20th century cosmology
  - Wed, 15th, 3:00-5:00 in 1415
  - Missouri Club: BPS-1420 on Mon, 12/13, 11:30am - 12:30pm
  - You cannot borrow a calculator from another student during the exam.
- Please fill out http://rateyourclass.msu.edu
  - Closes when grades are submitted.

- General Relativity. Einstein's law of gravity.
- Cosmological constant has negative pressure.
- Gravity of Cosmological constant is repulsive.

Observations

- Lower plot compares data to a model with density parameter
  Ω = PE/KE = 0.2
- Distant SN are 20% fainter than model with Ω = 0.2.
- Distant SN are 15% fainter than model with no mass (Ω =0)!
  - Longer time to expand than for a universe having no mass at all!
  - Shorter time means expansion slowed down; longer time means expansion sped up.
- Einstein (about 1920, 70 years earlier) thought of "cosmological constant," a kind of stuff where gravity repels.
  - The cosmological constant would make expansion speed up.
  - Modern name for cosmological constant is "dark energy."



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.
  - Key lesson: Physics must use mathematical object with the right transformation properties.
  - Space looks the same in all directions. Therefore physics equations must rotate. Therefor the mathematical objects must rotate.
  - Rotation is an example. There are other transformations.
- Figure out the consequences of the theory.

Einstein's path

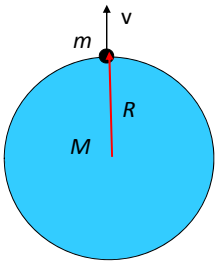
- Einstein's happiest thought: "A man falling from a roof does not feel gravity" (until he hits the ground).
  - Remaining steps took 9 years of thought.
  - Realization that tensors describe gravity.
  - Figure out the required transformations.
    - Key one is that gravity can be eliminated by choosing the right frame of reference.
  - Write a tensor equation that has the required transformations.

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 Law of gravity uses tensors.

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

  G = $8\pi G$ **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 nonzero components.
  - The source of gravity, $(M + 3PV/c^2)$, is the sum of the 4 terms on the diagonal of **T** V.

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

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

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

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

- Radiation has positive pressure

  $3PV/c^2 = M$.

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

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

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

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

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

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

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

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

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

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

Cosmological Constant

- Einstein 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.

What is the universe made of?

- Spherical sample of universe. R=moon's orbit. Sample has
  - 3 oz of ordinary matter
  - 1 lb of dark matter
  - 3 lb of dark energy
- Ordinary matter—protons, neutrons, electrons
  - Stars, gas, dust, planets, us
  - $\Omega_{matter} = 4\%$
- Dark matter—not detected except through gravity
  - $\Omega_{dark\ matter} = 23\%$
- Light
  - Mass density is small now. Dominant before universe was 1 Million years old
- Dark energy
  - Repulsive
  - $\Omega_{dark\ energy} = 73\%$
- $\Omega_{matter} + \Omega_{dark\ matter} + \Omega_{dark\ energy} = 1$