What is the universe made of?
Discovery of Dark Energy

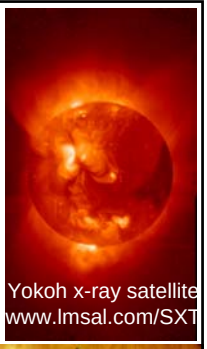
- What is the universe made of?
  - 4% ordinary matter
  - 27% dark matter
  - 73% dark energy
- Einstein: What causes gravity
- Discovery of dark energy

- Please rate your class at
  - rateyourclass.msu.edu
  - Closes on May 8th.
- Open house at MSU Telescope
  - Friday and Saturday, May 1 and 2, from 9:30pm - 11pm, weather permitting
  - Observatory is on Farm Lane & Forest Rd (south of campus)
- Final Exam
  - Wed, May 6th, 3:00-5:00
  - Room 1410 (our classroom)
  - One 8½ ×11 cheat sheet.
  - Covers entire course with more emphasis on galaxies & cosmology.
  - Study guide will be ready on Fri.

What is dark matter?

- Ordinary matter
  - Protons, neutrons, & electrons
  - We, the earth, the sun are made of ordinary matter
- Ordinary matter interacts with light
  - We can see ordinary matter
  - Ordinary matter can emit light.
    - » The hot sun emits light, which is visible to the eye. Hotter gas around the sun emits X-ray light.
- Dark matter
  - Does not interact with light
  - Interacts with matter very weakly
  - Gravity has same effect on ordinary & dark matter.

1. What would happen to the peppers if a wizard turned them into dark matter? S1: We could not see them. S2: They would stay on the plate. S1 and S2 are
   A. TT
   B. TF
   C. FT
   D. FF


Yokoh x-ray satellite
www.lmsal.com/SXT


Nolan Loh

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  - Gravity has same effect on ordinary & dark matter.

1. What would happen to the earth if a wizard turned the sun into dark matter? S1: The Earth would turn cold. S2: The Earth would not orbit the sun. S1 and S2 are
   A. TT
   B. TF
   C. FT
   D. FF


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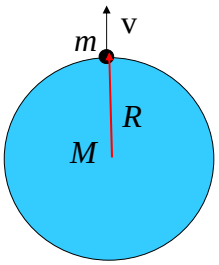
Nolan Loh

Einstein's theory of gravity

- What causes gravity?
- Newton's answer: mass.
  - Force of gravity between what's in the sphere and test mass m

    $F = G\ M\ m/R^2$.
- Einstein's answer: mass and pressure
  - Force of gravity between what's in the sphere and test 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 = $8\pi G$ (Mass-Pressure tensor)

  $\mathbf{G} = 8\pi G\ \mathbf{T}$
  - 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. $(M + 3PV/c^2)$ is sum of the 4 terms on the diagonal of **T** V.

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

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

1. Ordinary and dark matter have little pressure because speed is much smaller than c. For ordinary and dark matter, the force of gravity is
   A. $F = G\ M\ m/R^2$.
   B. $F = 2\ G\ M\ m/R^2$.
   C. $F = -\ G\ M\ m/R^2$.
   D. $F = -\ 2G\ M\ m/R^2$.

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

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. (M + 3PV/c^2) is sum of the 4 terms on the diagonal of **T** V.

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

1. For radiation, the force of gravity is
   A. F = G M m/R^2.
   B. F = 2 G M m/R^2.
   C. F = – G M m/R^2.
   D. F = – 2G M 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. (M + 3PV/c^2) is sum of the 4 terms on the diagonal of **T** V.

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

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

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

- Pressure of the cosmological constant does not push; it sucks.

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

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. (M + 3PV/c^2) is sum of the 4 terms on the diagonal of **T** V.

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

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=2 G M m/R^2

   C. F = – G M m/R^2.

   D. F= –2G M m/R^2

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

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

Dark Energy/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.
- Cosmological constant is a specific for of dark energy.

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

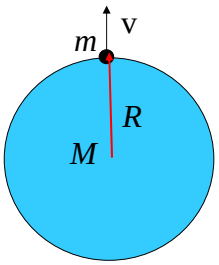
$$T_{\text{rad}} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix}$$

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

1. What would happen to the earth if a wizard turned the sun into dark energy? S1: The Earth would turn cold. S2: The Earth would continue to orbit the sun. S1 and S2 are
   A. TT
   B. TF
   C. FT
   D. FF

Weighing the Universe

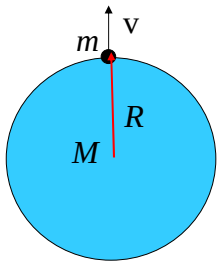
1. I throw a ball (labeled *m*) up. The mass within the sphere (labeled *M*) pulls on the ball. The mass inside is the mass of Earth. The ball should ___.
   A. slow down
   B. speed up
   C. move at the same speed



- The Big Bang caused a galaxy *m* to move at speed *v*. The mass within the sphere (labeled *M*) pulls on the galaxy. Sphere contains many galaxies and other stuff. The galaxy should ___.
  A. slow down
  B. speed up
  C. move at the same speed

Weighing the Universe

- I throw a ball (labeled *m*) up. The mass within the sphere (labeled *M*) pulls on the ball. The ball should slow down because of the pull of gravity.



3. The Big Bang caused a galaxy *m* to move at speed *v*. The mass within the sphere (labeled *M*) pulls on the galaxy. Surprise: The galaxy <u>speeds up</u>. Therefore the mass within the sphere is mostly
   A. dark energy.
   B. dark matter.
   C. ordinary matter.
   D. radiation from the Big Bang.