Discovery of Dark Energy/Cosmological Constant — 3 Dec

- How do scientists make discoveries?
- Characteristics
  - New ideas
    - Einstein’s cosmological constant ca. 1920
  - New instruments
    - Large CCDs to search for SN
  - New wavelengths (NA)
  - Careful design
    - SN are clean, not messy.
  - Serendipity
    - Did not expect to find dark energy
  - Courage to make the measurement (NA)

In a fair sample with R=Moon’s orbit
Ordinary matter: 4%, 3oz
Dark matter: 27%, 1lb
Dark energy: 73%, 3 lb

Einstein’s General Relativity

- What causes gravity?
- Newton’s answer: mass.
  - Force of gravity between what’s in the sphere and test mass m
    \[ F = G \frac{M m}{R^2} \]
- Einstein’s answer: mass and pressure
  - Force of gravity between what’s in the sphere and test mass m
    \[ F = G \left( M + 3PV/c^2 \right) \frac{m}{R^2} \]

Grades

- Average on test 3: 24/40
  - Be certain to pick up both sheets of the answers.
- Provisional grades
  - Pick up sheet
  - Check that your grades have been recorded correctly.
  - A few late hwk will be graded by Fri.
  - I have a Hwk 8 and a Hwk 10 with no name.
  - Your grade may change significantly, because the Final Exam contributes 31% of the course grade.
  - You will be able to pull up missed homeworks.
  - Lowest 3 exercise and lowest homework grades have been dropped.
  - Average grade is 3.1.

Source of Gravity

- Einstein’s answer: mass and pressure
  \[ F = G \left( M + 3PV/c^2 \right) \frac{m}{R^2} \]
- Newton’s Law of gravity
  \[ F = G \frac{M m}{R^2} \]
- Einstein’s Law of gravity
  \[ T = \begin{pmatrix} M/V & 0 & 0 & 0 \\ 0 & P_x/c^2 & 0 & 0 \\ 0 & 0 & P_y/c^2 & 0 \\ 0 & 0 & 0 & P_z/c^2 \end{pmatrix} \]
- Ordinary matter has little pressure because speed is much smaller than c.
  \[ 3PV/c^2 = M (v/c)^2 \]
- Radiation has positive pressure
  \[ 3PV/c^2 = M \]
  \[ F = G 2M \frac{m}{R^2} \]
Cosmological Constant

• Einstein’s answer: mass and pressure
  Force: \[ F = G \left( M + \frac{3}{c^2} P V \right) \frac{m}{R^2} \]
  – If on average the material is at rest, then \( T \) has 4 components. \( M + \frac{3}{c^2} P V \) is sum of the 4 terms on the diagonal of \( T \).

• Einstein in 1920s: My equations of gravity allow a special tensor. I called it a “cosmological constant”
  – \( T_{cc} \) has same mathematical properties as \( T_{\text{matter}} \) and \( T_{\text{rad}} \).
  – “What is not forbidden is mandatory.”
  – Pauli: “What is not forbidden is mandatory.”
  – Pressure does not push; pressure sucks.

1. Write the force of gravity for the case of the cosmological constant. (Watch the signs.)
   A. \( F = G \frac{M}{R^2} \)
   B. \( F = G \left( 2M \right) \frac{m}{R^2} \)
   C. \( F = G \left( -2M \right) \frac{m}{R^2} \)

• Ideas:
  – 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.