Weighing the Universe with Supernovae. Discovery of Dark Energy/ Cosmological Constant—8 Dec

- Homework 11 will be due on the last day of classes (Fri, 10th). Answers will be posted after class. No late papers.
- 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
- Please fill out http://rateyourclass.msu.edu
  - Closes when grades are submitted.

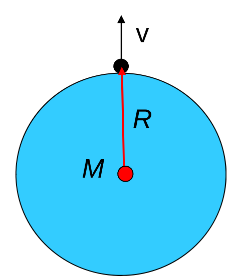
- Weighing the universe means to find mass density
- What we will find: Expansion of universe speeds up!
  - "Dark energy" is dominant. Dark energy repulses whereas matter and radiation attract.

Effect of gravity on expansion of the universe

- Analyze the effect of gravity on the motion of the one galaxy to find the effect of gravity on the expansion of the universe.

- Newton says: The galaxy feels the pull only of the mass inside the sphere.
- If there is much mass, the galaxy will slow down, and the expansion of the U will slow down too.

1. Consider H's constant H=v/D. If there is little mass in the sphere, v was constant and D was smaller in the past. If there is more mass, Hubble's constant in the past would be ___.
   A. even bigger
   B. same as with little mass
   C. not as big



Do this at home.

Hint: Consider change in v due to acceleration. Ignore change in D due to acceleration, since that is the sum of the changes in v, which is smaller than the change in v itself.

Density parameter

- The density parameter Ω is a quantity that compares gravity and motion.
- Compare potential energy and kinetic energy.
- Ω=(potential energy)/ (kinetic energy)

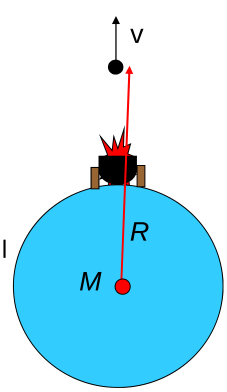
Density parameter of cannon Ball

- Cannonball is shot out of cannon at speed v.
  - Kinetic energy is ½ v^2.
- Gravity pulls on cannonball to slow the motion.
  - Potential energy is G M /R
- Cannonball will escape if shot fast enough so that

  KE $\geq$ PE
- Define "Density parameter of the cannonball"

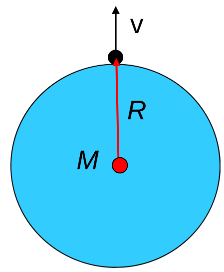
  Ω = PE / KE = 2 G M / (R v^2)

1. A cannonball is shot with Ω=0.7. Will the cannonball escape? Same question for Ω=1.1.
   A. YY
   B. YN
   C. NY
   D. NN



Density parameter of universe

- Sphere expands and galaxy moves because universe expands.
- Galaxy is moving at speed v.
  - Kinetic energy is ½ v^2.
- Hubble's Law connects v and R.
  KE= ½ $(H R)^2$
- Gravity pulls on galaxy to slow the motion.
  - Potential energy is G M /R
- Galaxy will escape and <u>Universe will expand forever</u> if moving fast enough
  Ω=PE/KE $\leq$ 1



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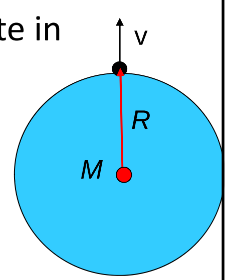
Does universe expand forever?

- Density parameter should not depend on which galaxy and on size of sphere. Write in terms of the mass density ρ.
  $\Omega = PE/KE = 8\pi G\rho / (3H^2)$

2. If the density parameter Ω=0.2, will the universe expand forever?
   A. Y
   B. N



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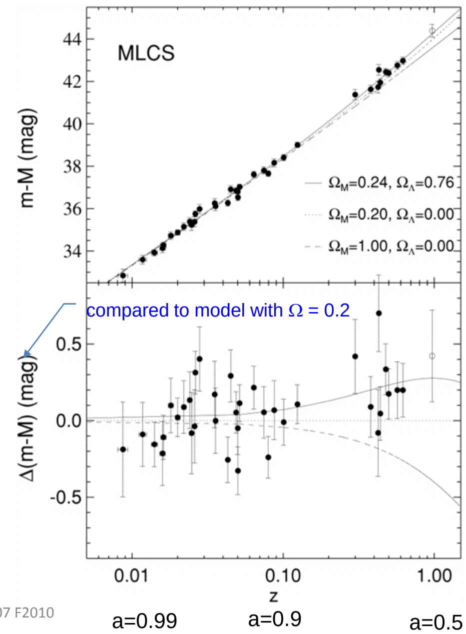
Observations

- Distant SN from Riess et al, 1998, ApJ 116, 1009. Nearby SN from several surveys.

3. On upper plot, nearest SN is at
   a. upper right.
   b. lower left.
4. For the most distant SN, the wavelength of light has increased by a factor of ___ since the SN emitted it.
   A. 1.00
   B. 0.5
   C. 0.99
   D. 0.01
   E. 2

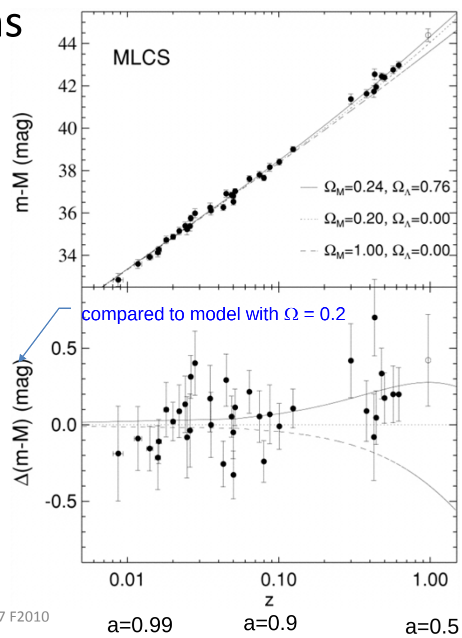
- Ideas
  - Magnitudes are more positive for fainter SN.
  - Expansion parameter
    $a = D/D_{now}$
  - Redshift $a=1/(1+z)$
    $z = (\lambda - \lambda_{lab})/\lambda_{lab}$.



Models & Observations

- The dotted line shows a model with density parameter Ω=0.2 (PE/KE=0.2)
  - Model is adjusted to fit observations of nearby SN.

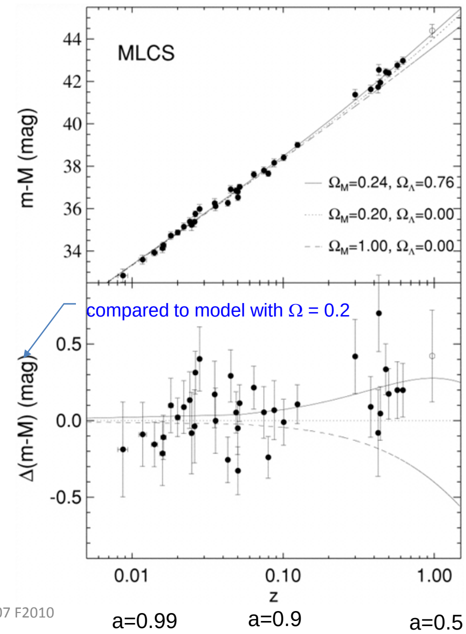
5. The distant SNare ___ compared with the model.
   a. Too bright
   b. Too faint



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.

6. The model with Ω = 0.2 does not agree with the observations. The model must put the SN at (1)__ distance to make it agree with the observations. The universe took a (2)__ time to expand than the model, and therefore the universe has (3)__ mass than the model.
   A. Greater for (1) and (3)
   B. Smaller for (1) and less for (3)
   C. Smaller for (1) and greater for (3)
   D. Greater for (1) and less for (3)



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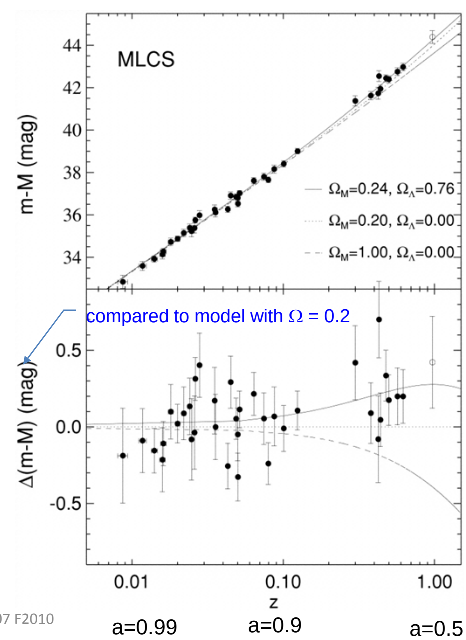
Observations

- 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."



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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
  - $\Omega_{dark\ energy} = 73\%$
- $\Omega_{matter} + \Omega_{dark\ matter} + \Omega_{dark\ energy} = 1$