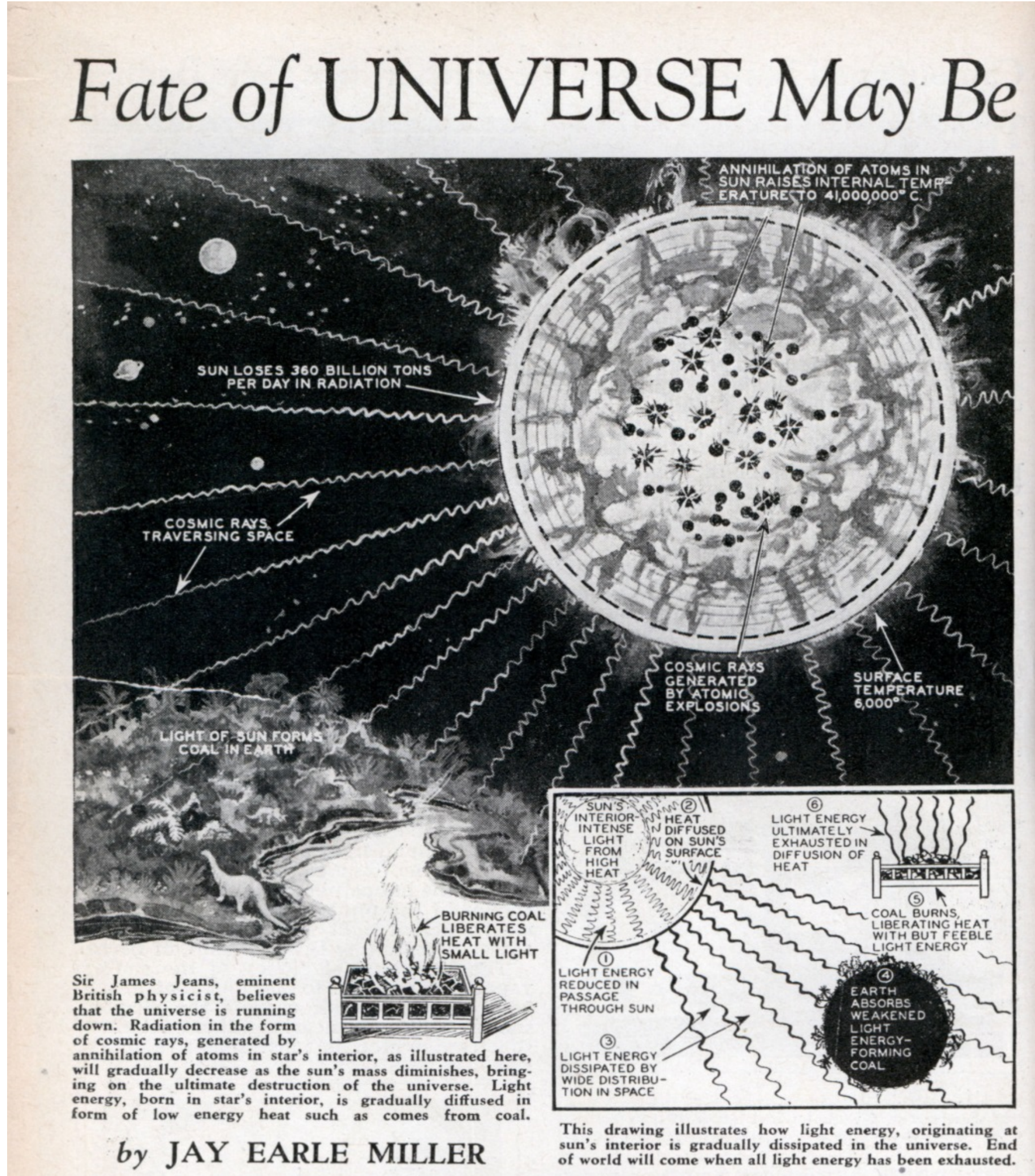
Astronomy 120

The Age & Fate of the Universe



Fate of UNIVERSE May Be

Sir James Jeans, eminent British physicist, believes that the universe is running down. Radiation in the form of cosmic rays, generated by annihilation of atoms in star's interior, as illustrated here, will gradually decrease as the sun's mass diminishes, bringing on the ultimate destruction of the universe. Light energy, born in star's interior, is gradually diffused in form of low energy heat such as comes from coal.

by JAY EARLE MILLER

This drawing illustrates how light energy, originating at sun's interior is gradually dissipated in the universe. End of world will come when all light energy has been exhausted.

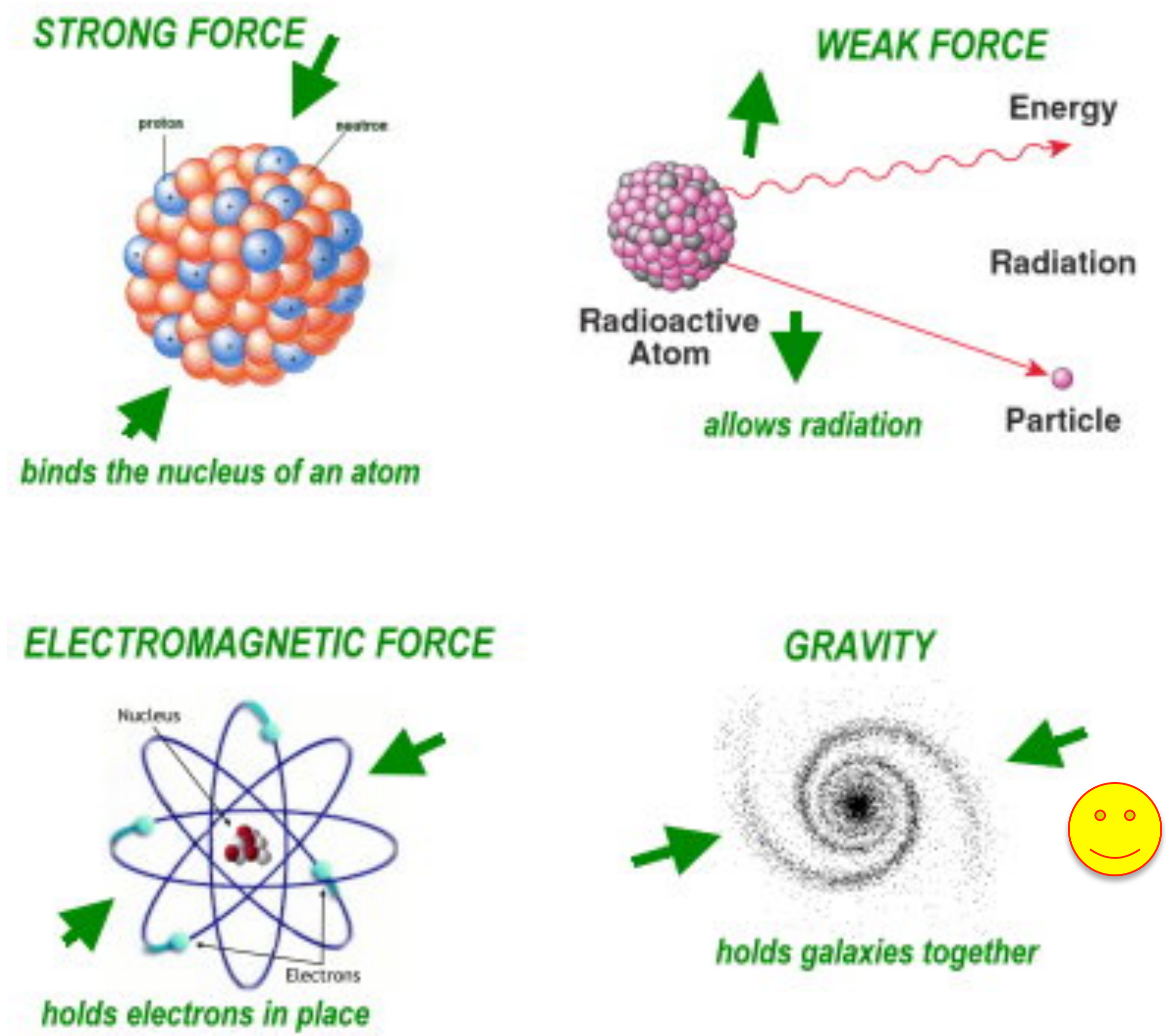
Class 20

Prof J. Kenney

November 14, 2016

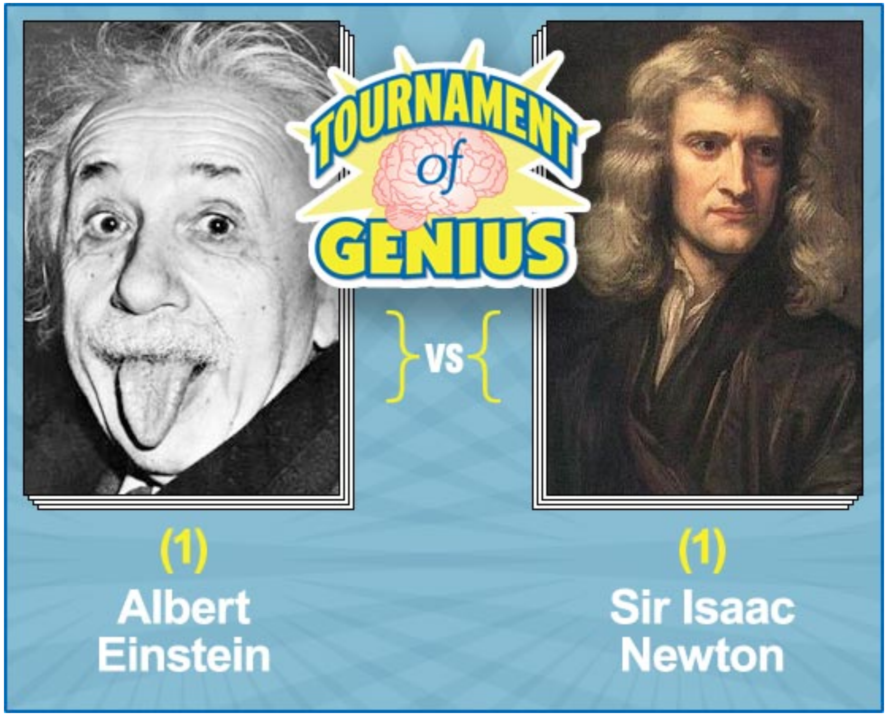
Why Einstein's General Relativity (1915) is relevant for cosmology

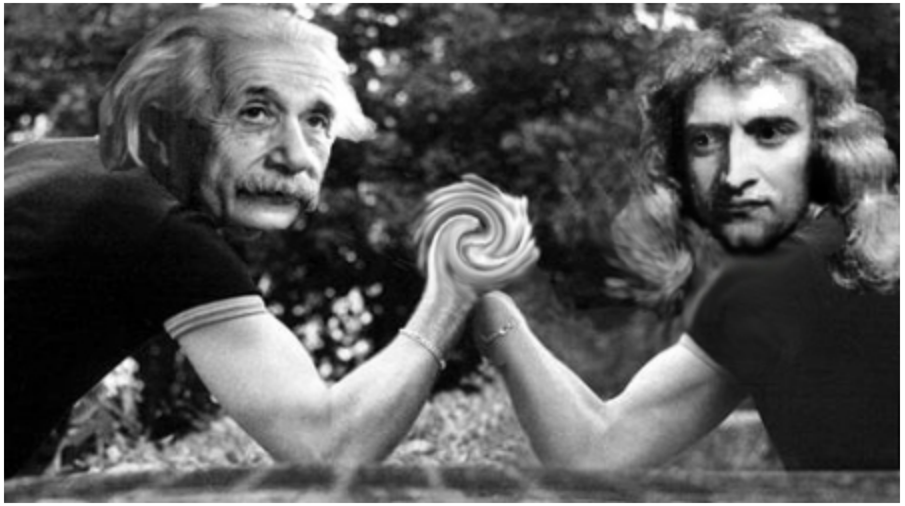
Gravity dominates other known fundamental forces on largest scales



Why Einstein's General Relativity (1915) is relevant for cosmology

- Gravity dominates other known fundamental forces on largest scales
- GR is best theory of gravity

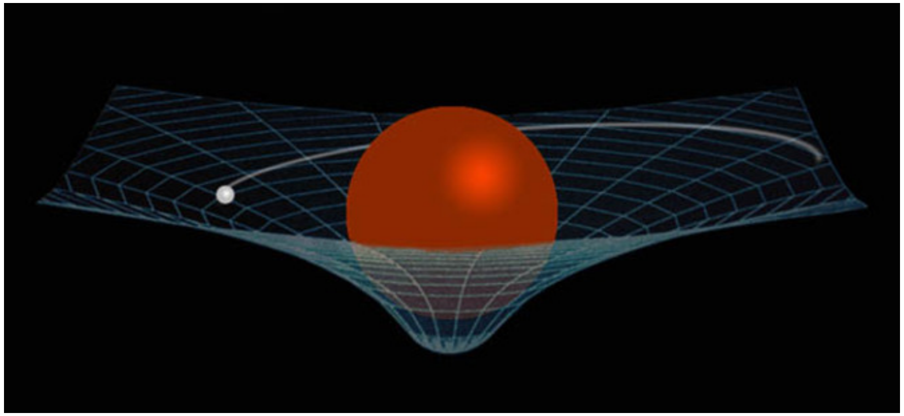




Einstein is boss !

Why Einstein’s General Relativity (1915) is relevant for cosmology

- Gravity dominates other known fundamental forces on largest scales
- GR is best theory of gravity
- GR describes gravity as “curved space-time”, so space and time as well as gravity are natural parts of GR



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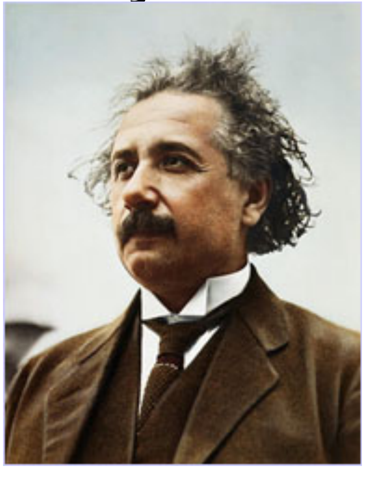
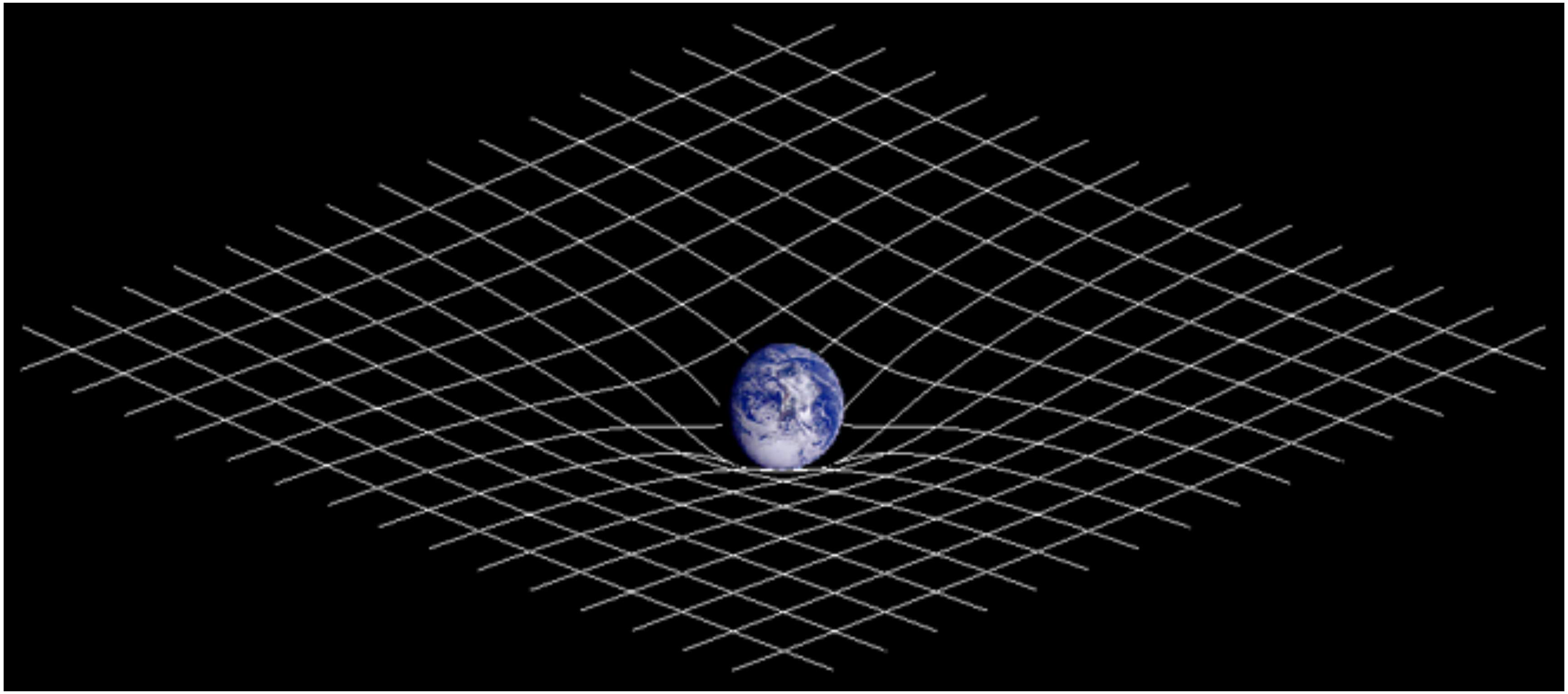
-> **GR may describe universe on largest scales of space and time**

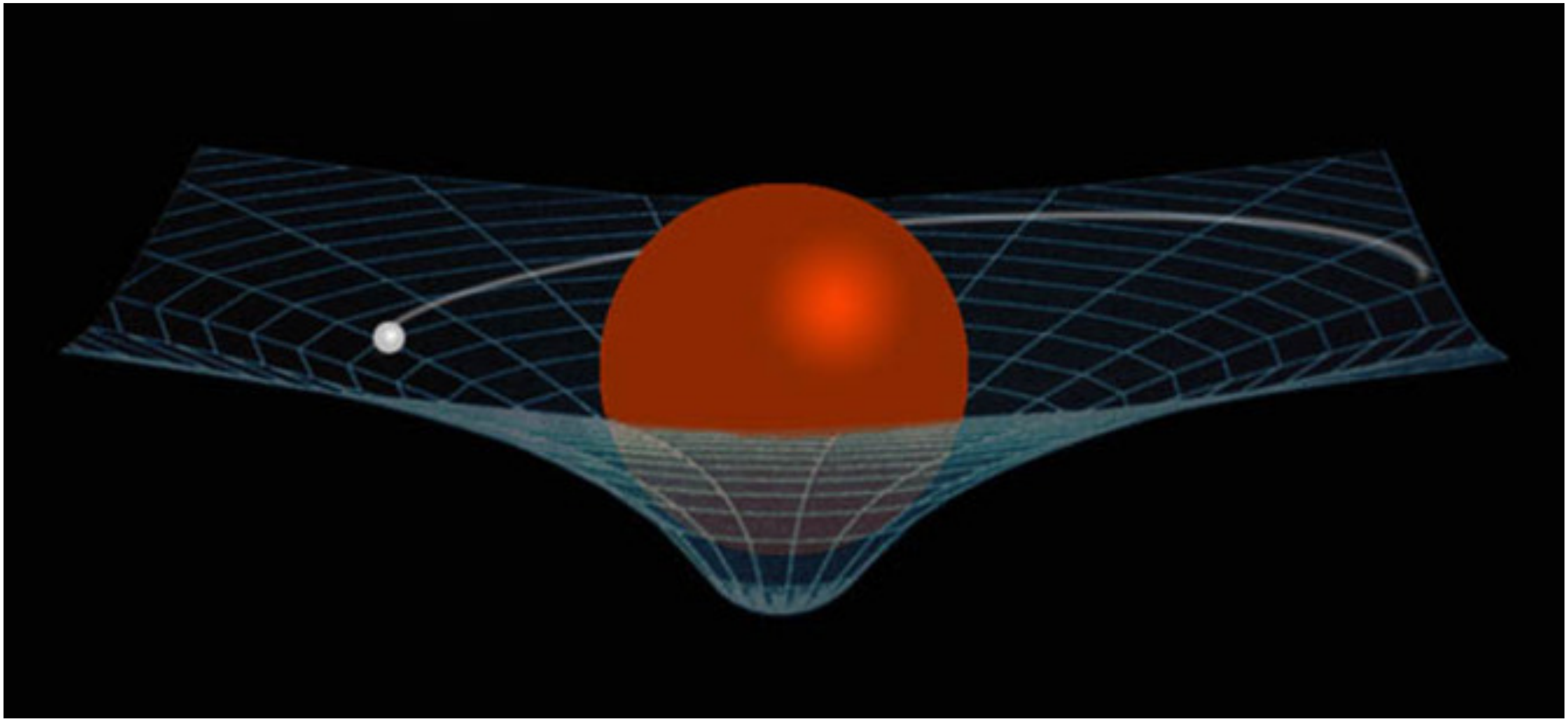


"boss"

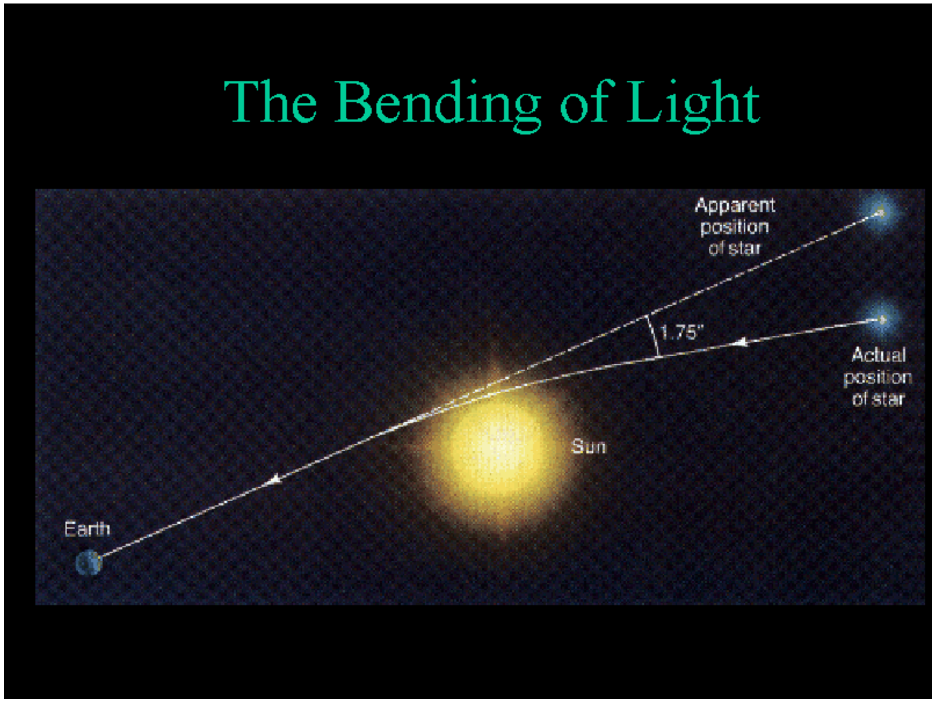
Curved space of General Relativity

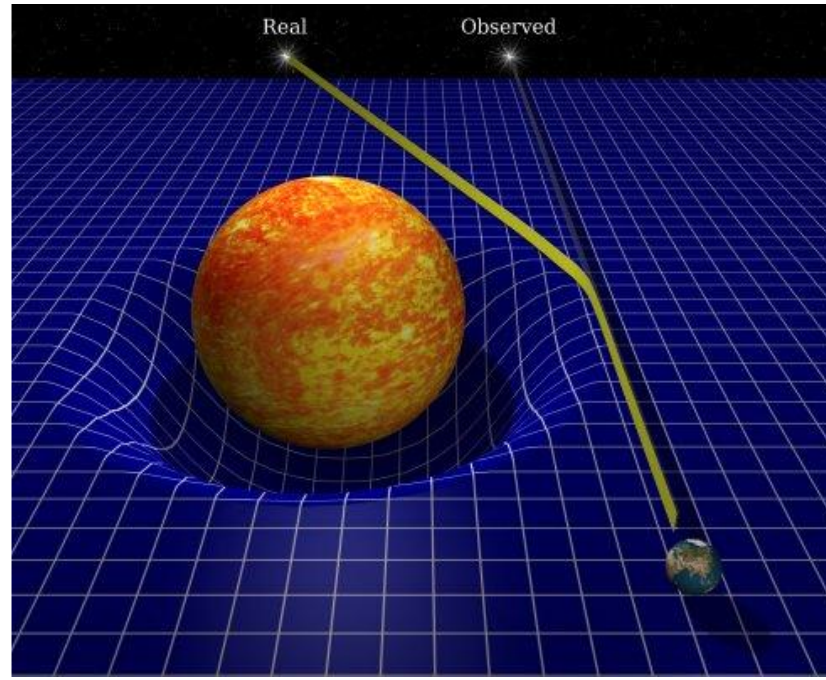


General Relativity (GR) and orbits

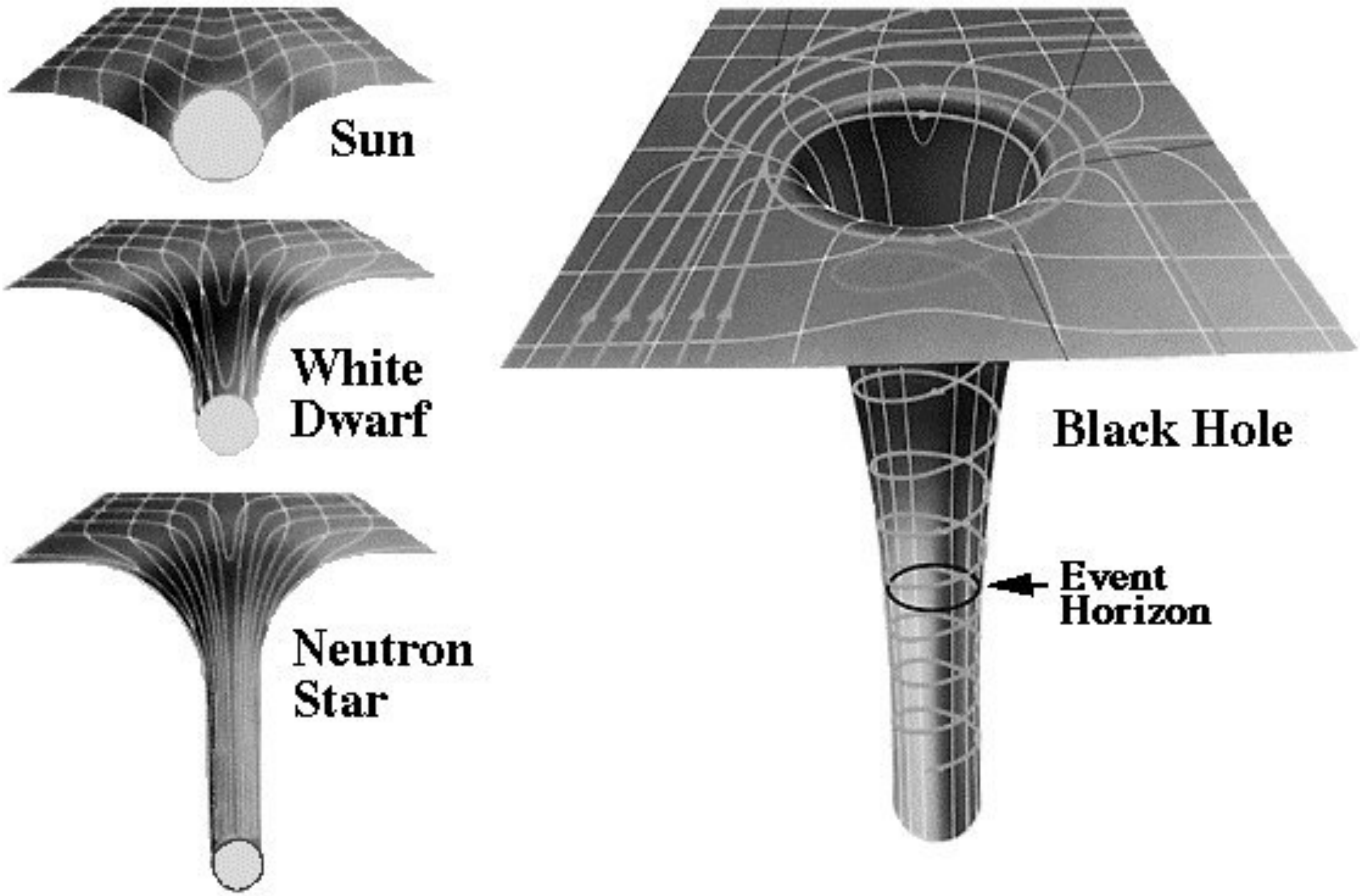


GR and bending of light



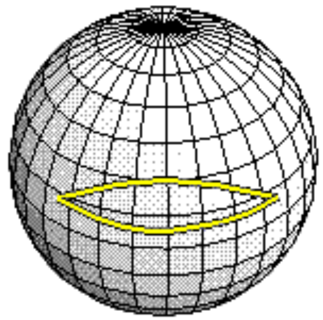


Formation of White Dwarf, Neutron Star, Black Hole in GR

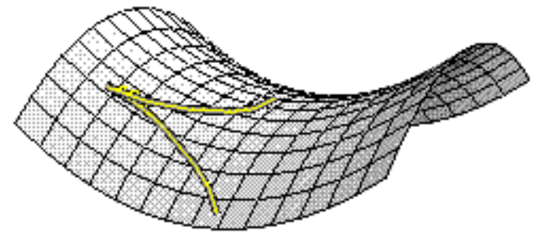


Types of possible curvatures for universe in General Relativity

Positive (spherical)

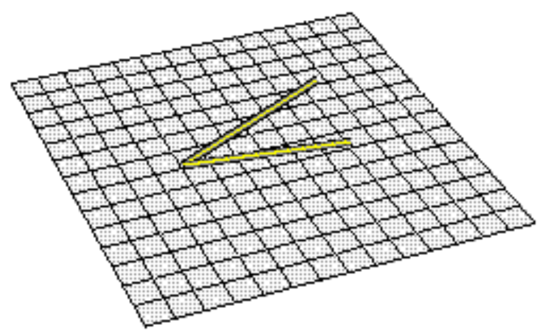


A *closed* universe curves "back on itself". Lines that were diverging apart come back together. Density > critical density.



An *open* universe curves "away from itself". Diverging lines curve at increasing angles away from each other. Density < critical density.

Negative (saddle)



Zero curvature (flat)

A *flat* universe has no curvature. Diverging lines remain at a constant angle with respect to each other. Density = critical density.

Relativity in Calvin & Hobbes

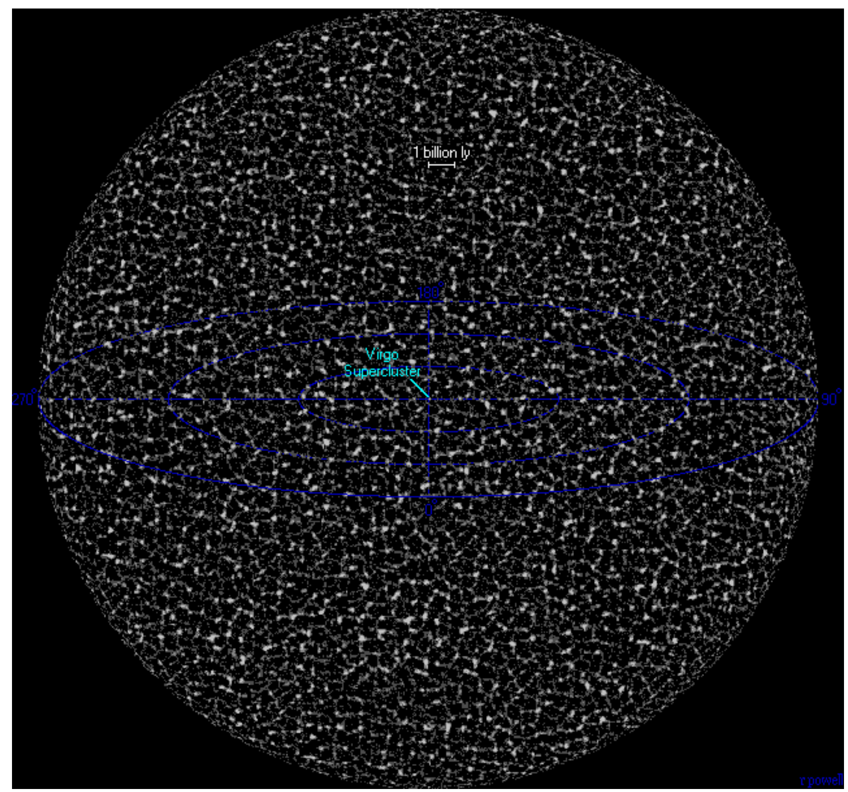
After Einstein completed his theory of gravity, GR, in 1915, he & others applied it to the grandest example of spacetime: *the universe as a whole.*

This was the birth of modern cosmology.

How Einstein applied his General Relativity to cosmology in 1915

- Assumes universe homogenous & isotropic (cosmological principle)…

this seems OK!



Professional artist sketch of galaxy distribution on scale of 10 billion light years

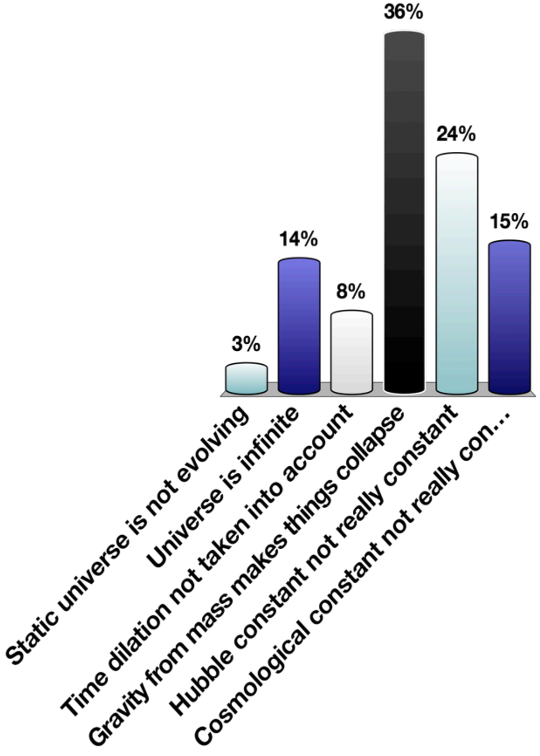
How Einstein applied his General Relativity to cosmology in 1915

- Assumes universe homogenous & isotropic (cosmological principle)…

  this seems OK!
- Assumes universe static in time…

Why didn't Einstein's equations have a simple solution for a static universe?

A. Static universe is not evolving
B. Universe is infinite
C. Time dilation not taken into account
D. Gravity from mass makes things collapse
E. Hubble constant not really constant
F. Cosmological constant not really constant



How Einstein applied his General Relativity to cosmology in 1915

- Assumes universe homogenous & isotropic (cosmological principle)…

  this seems OK!

- Assumes universe static in time…

  whoops! His biggest blunder!

  (this was before expansion was discovered in 1929)

Why did Einstein think something had to balance gravity?

Why did Einstein think something had to balance gravity?

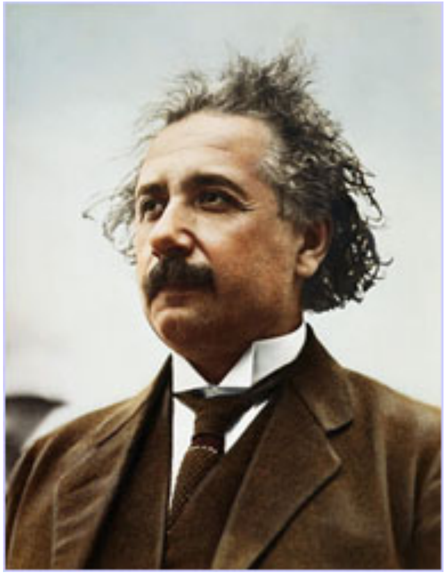
- A universe with only gravity would collapse, since the gravity would pull everything together
- SO! To have static universe there would have to be something to balance gravity. Einstein assumed there was *some mysterious unknown repulsive force* to do this.
- Einstein called it "the cosmological constant" (represented by symbol Λ), and assumed it perfectly balanced gravity to maintain a static universe

BUT! Then in 1929 *expansion was discovered* by Hubble, so Einstein realized the universe Was obviously NOT STATIC. So no need to invent something to balance gravity, since it is obviously not balanced!

Hubble to Einstein:
"See what I'm talking 'bout?"

BUT! Then in 1929 *expansion was discovered* and Einstein realized the universe was obviously NOT STATIC. So no need to invent something to balance gravity, since it is obviously not balanced!

Einstein says: "My biggest blunder!" "I guess there was no need for me to invent the cosmological constant. Can we just forget I ever mentioned it?"

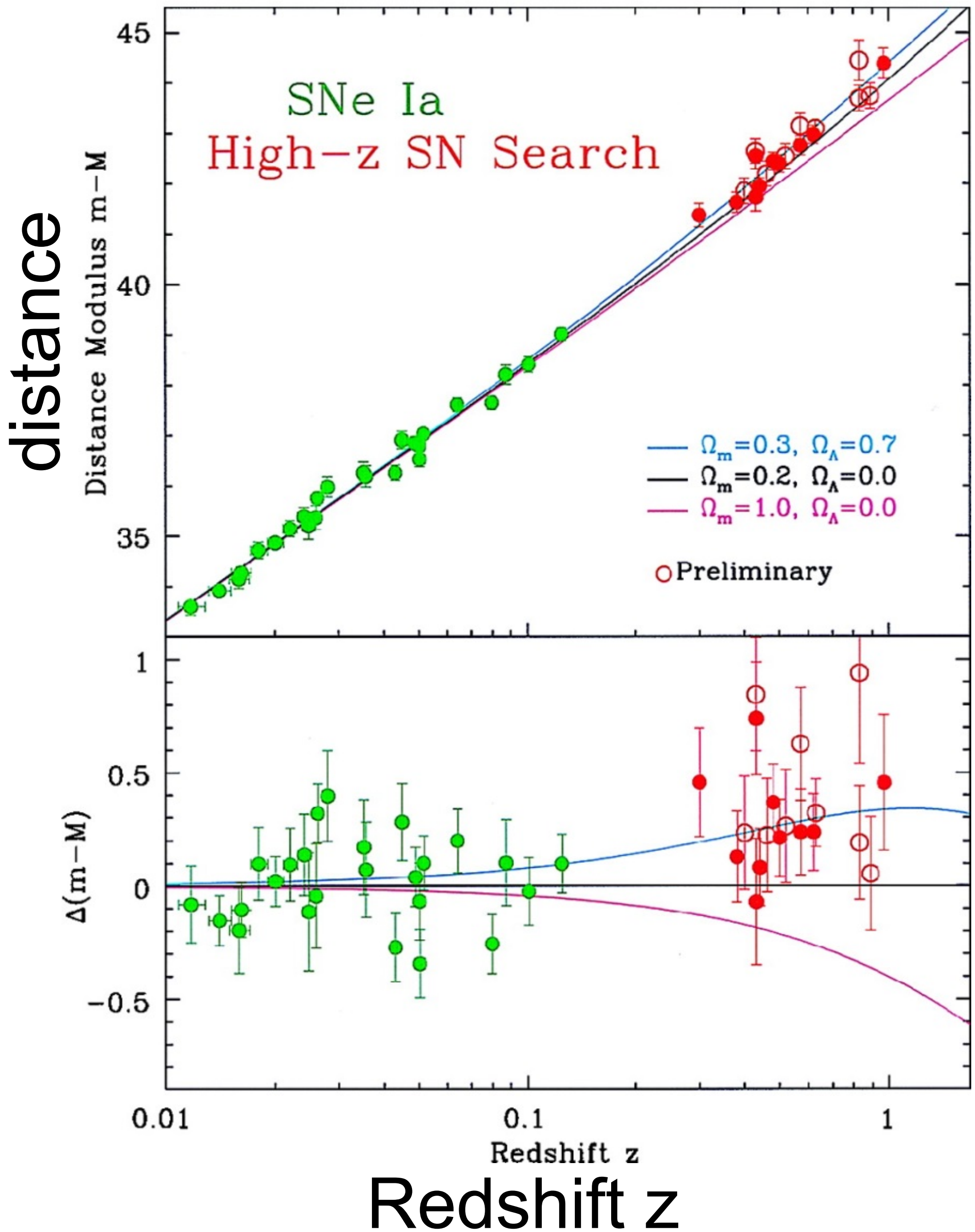


"boss" or "boso"?

But then!

- In 1998 astronomers unexpectedly discover that the expansion is ACCELERATING!!

Evidence for *acceleration* in expansion of universe



Distant supernovae at a given distance have smaller redshifts than they would if expansion was constant or slowing down (decelerating)

This wins Nobel Prize in Physics in 2011 !!

But then!

- In 1998 astronomers unexpectedly discover that the expansion is ACCELERATING!!
- This can only happen if something is acting to make the universe expansion speed up. This thing acts sort of like Λ in Einstein's equations, i.e., acts opposite gravity but not equal strength so not balanced (so not the same as the "cosmological constant").
- We call the thing causing the expansion to accelerate DARK ENERGY (or Λ).

What is **Fate of Universe**?

Will universe expand forever?

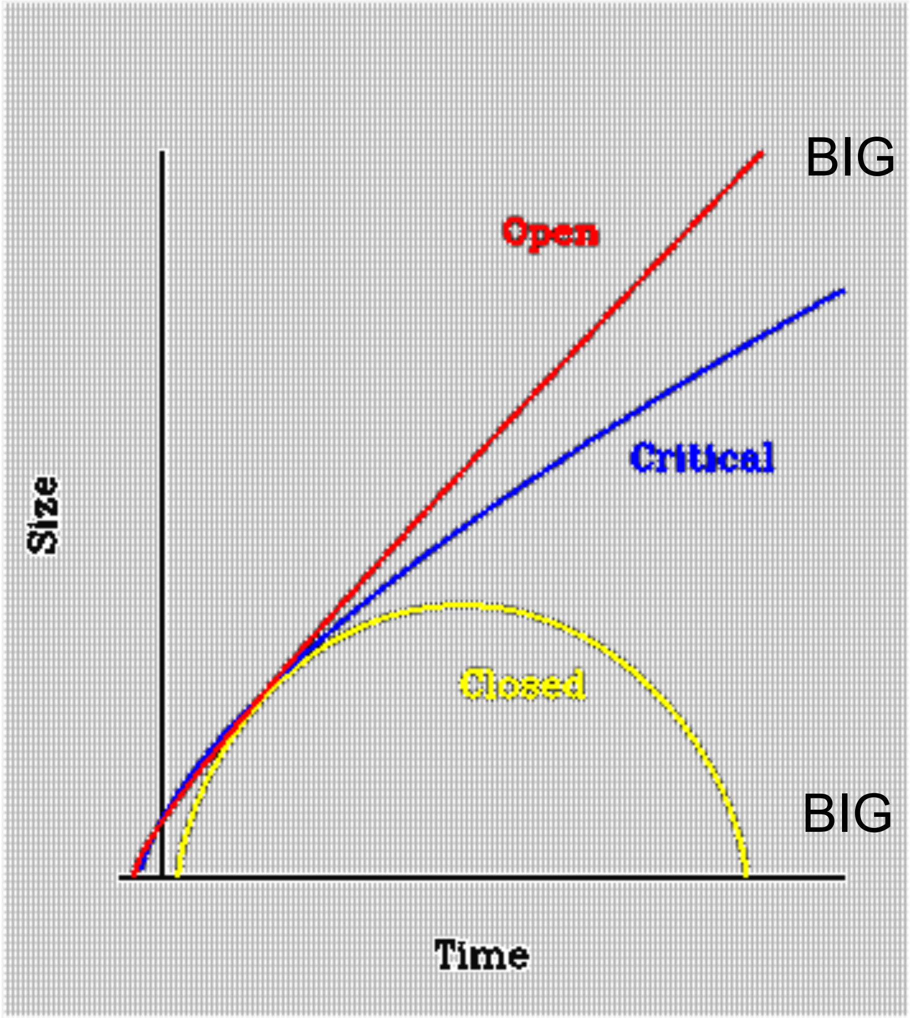
(BIG FREEZE)

or….

Will expansion ultimately stop so that the universe contracts and collapses?

(BIG HOT CRUNCH)

Expansion vs. time if only gravity (no dark energy)

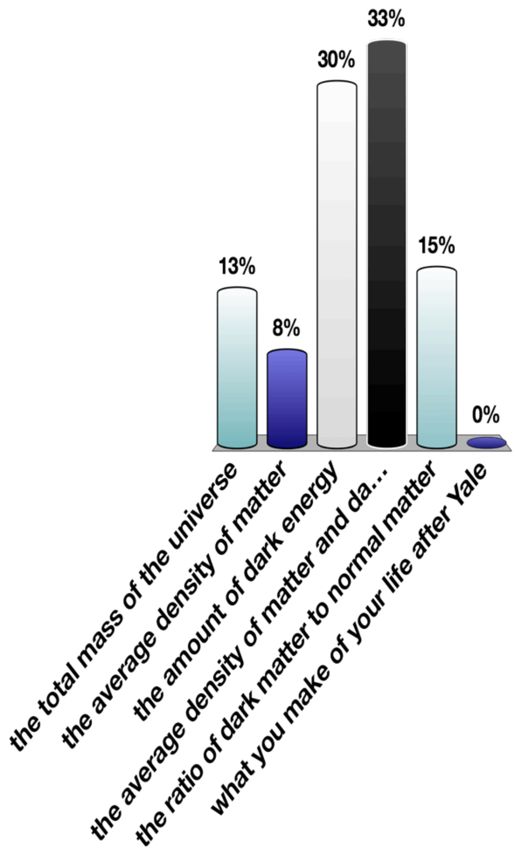


BIG FREEZE

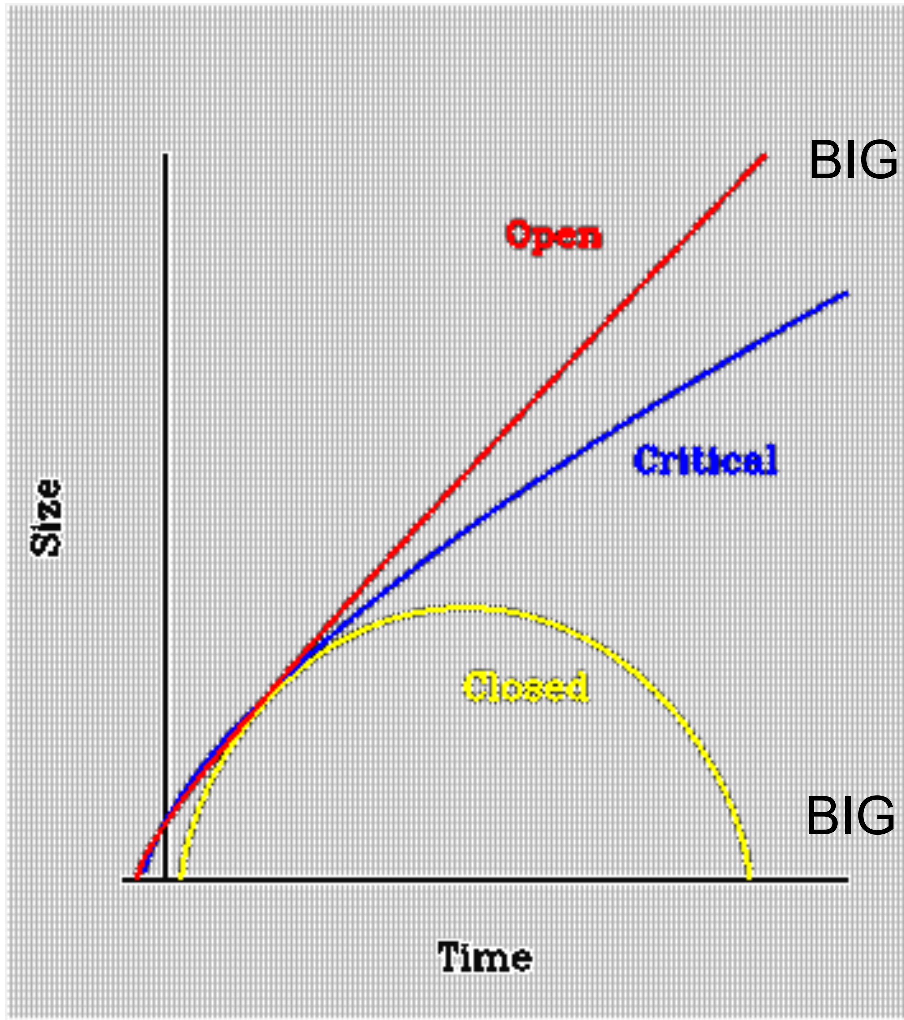
BIG HOT CRUNCH

What determines the Fate of the Universe?

1. the total mass of the universe
2. the average density of matter
3. the amount of dark energy
4. the average density of matter and dark energy
5. the ratio of dark matter to normal matter
6. what you make of your life after Yale



Expansion vs. time if only gravity (no dark energy)



BIG FREEZE

BIG HOT CRUNCH

Assume infinite Newtonian universe filled with galaxies.
What is net gravitational effect on any galaxy in infinite universe?

LET'S ASSUME (PRETEND) THAT VELOCITY V OF ANY GALAXY AS SEEN BY OBSERVER AT DISTANCE R IS AFFECTED ONLY BY GRAVITY OF ALL MASS M INSIDE OF RADIUS R

In other words, assume gravitational force of everything outside of sphere cancels to zero. This is a highly dubious assumption but it happens to work.

Calculate total energy

If $E<0$ bound (no escape, will collapse)

If $E>0$ unbound (escape, expand forever)

If $E=0$ just barely bound/or just escape

E= KE + PE (and E is conserved)

$E = \frac{1}{2} mv^2 - GMm/r$

Where $M = \rho_m V = \rho_m \times 4\pi r^3/3$

M = total mass in sphere

ρ_m = mass density

$v = H_o r$ Hubble Law

$E = \frac{1}{2}\, m(H_0 r)^2 - Gm/r \times (4\pi r^3/3)\, \rho_m$

Explore critical case of E=0 (just barely escape, just barely bound).

The density corresponding to this critical E=0 case is defined to the be critical density ρ_c

If $\rho_m = \rho_c$ then E=0

$0 = \frac{1}{2}\, m(H_0 r)^2 - Gm/r \times (4\pi r^3/3)\, \rho_c$

$0 = \frac{1}{2}\, H_0^2 - (4\pi G/3)\rho_c$

$\rho_c = 3H_0^2 / 8\pi G$ CRITICAL DENSITY the ratio of actual mass density to critical density is a convenient dimensionless number

$\Omega_m = \rho_m / \rho_c = 8\pi G\rho_m / 3H_0^2$

Ω_m = cosmological mass density parameter (dimensionless)

if $\Omega_m > 1$ (or $\rho_m > \rho_c$) and $\Lambda = 0$ universe is bound

if $\Omega_m < 1$ (or $\rho_m < \rho_c$) and $\Lambda = 0$ universe is unbound so what are ρ_m ,ρ_c ?

$\rho_c = 3 H_0^2 / 8\pi G$

$\rho_c = 1.0 \times 10^{-26}$ kg m^{-3} if $H_0 = 73$ km s^{-1} Mpc^{-1}

this is equivalent to 6 atom m^{-3} not very much…!

Air in room $\rho_{air} = 5 \times 10^{25}$ atoms m^{-3}

How does this compare this with true mass density?

How does this compare this with true mass density?

From measurements of clusters and superclusters [Q: how do we measure this?]

$\rho_m = 2.4 \times 10^{-27}$ kg m^{-3}

of this mass,

~15% is luminous mass (baryons: stars, gas, dust)

~85% is dark matter

so what are ρ_m , ρ_c ?

$\rho_c = 1.0 \times 10^{-26}$ kg m^{-3} if $H_0 = 73$ km s^{-1} Mpc^{-1}

$\rho_m = 2.4 \times 10^{-27}$ kg m^{-3}

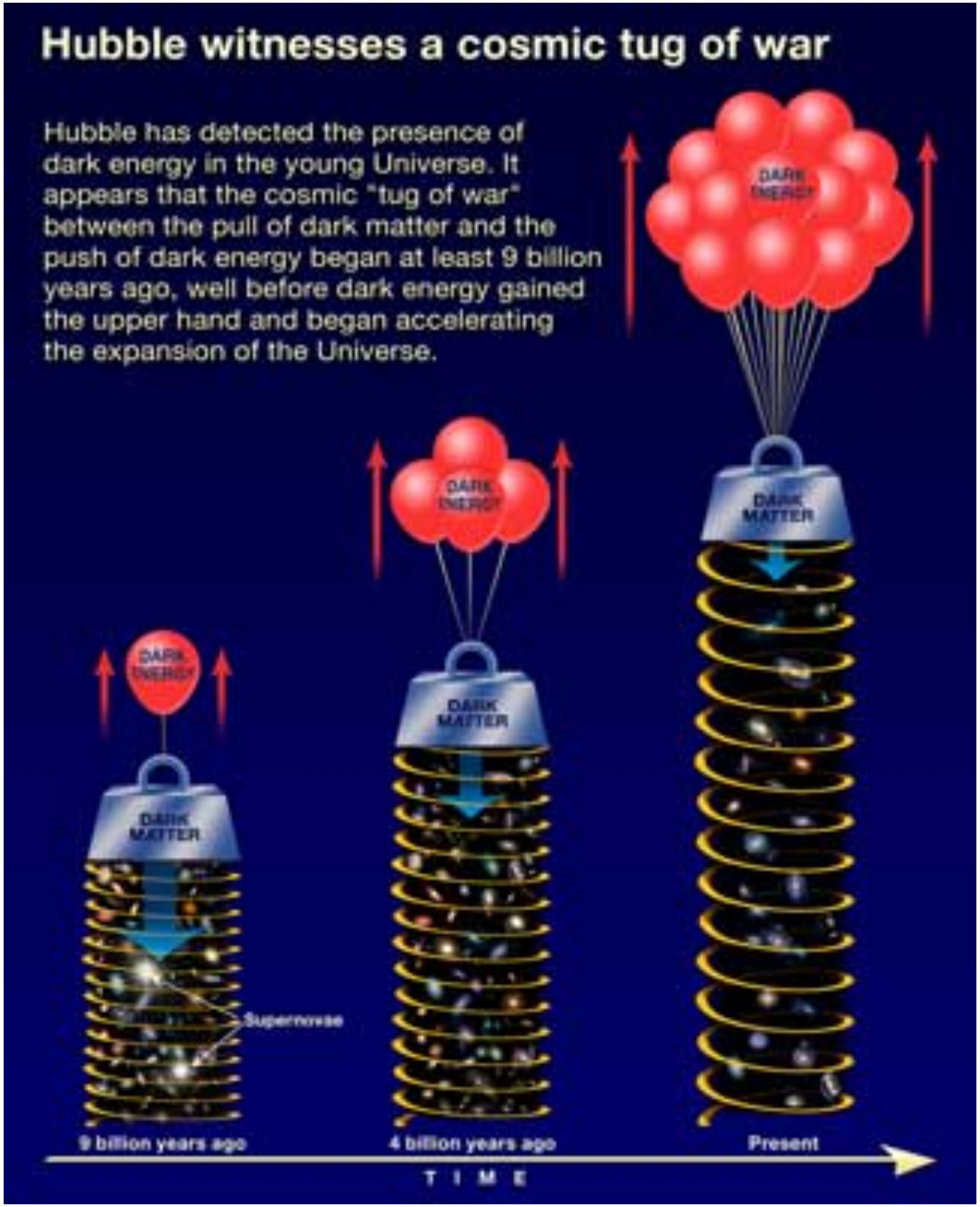
$\Omega_m = \rho_m / \rho_c = 0.24 \pm 0.04$ (i.e. $\Omega_m < 1$)

thus there is not enough mass to cause the universe to recollapse, since $\Omega_m < 1$

similar to saying that Big Bang threw stuff outwards with speed greater than escape speed

But what about Λ?

Fate depends on Λ as well as gravity …



Opposing forces: gravity (from matter) versus dark energy

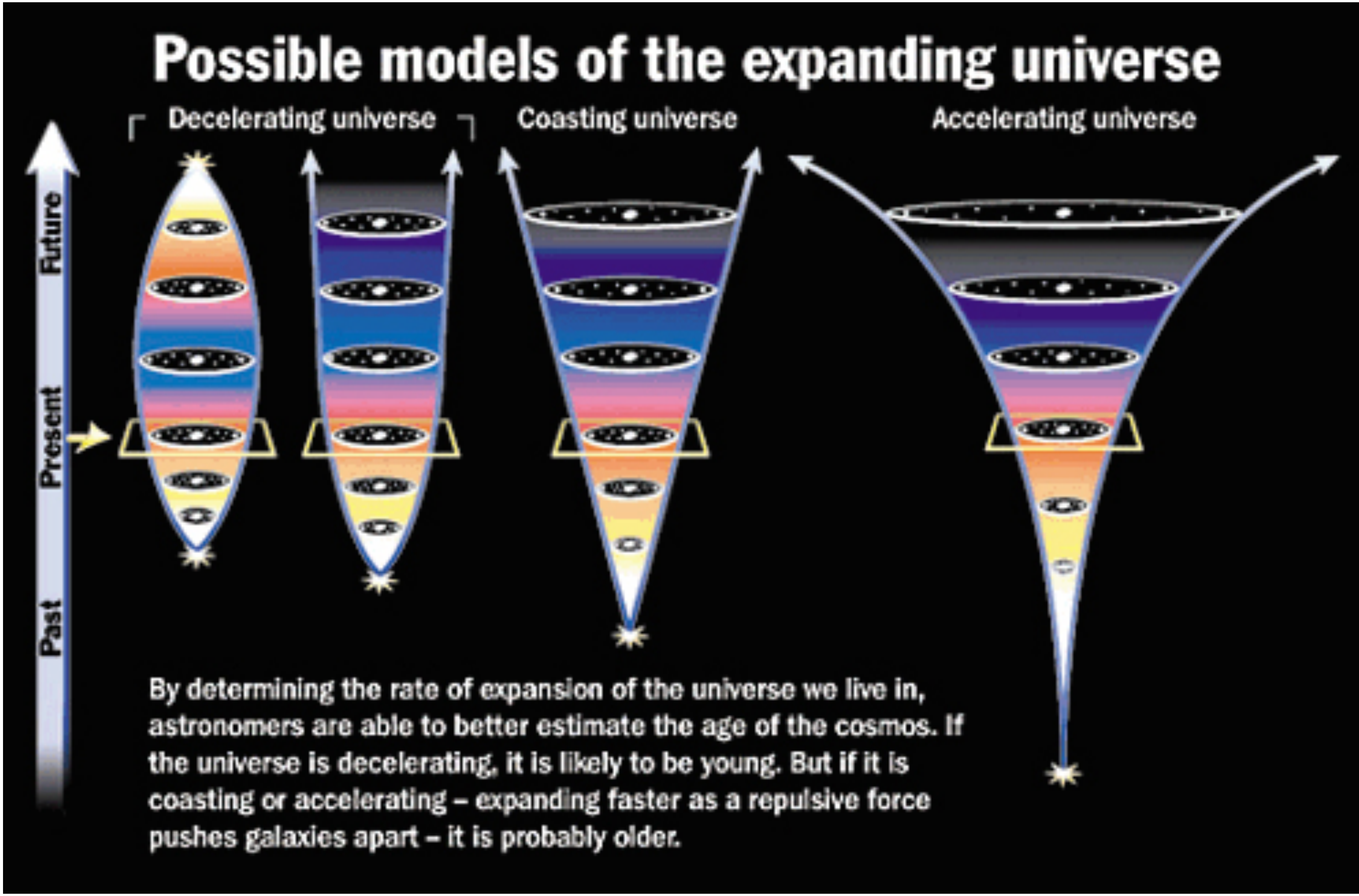
But what about Λ?

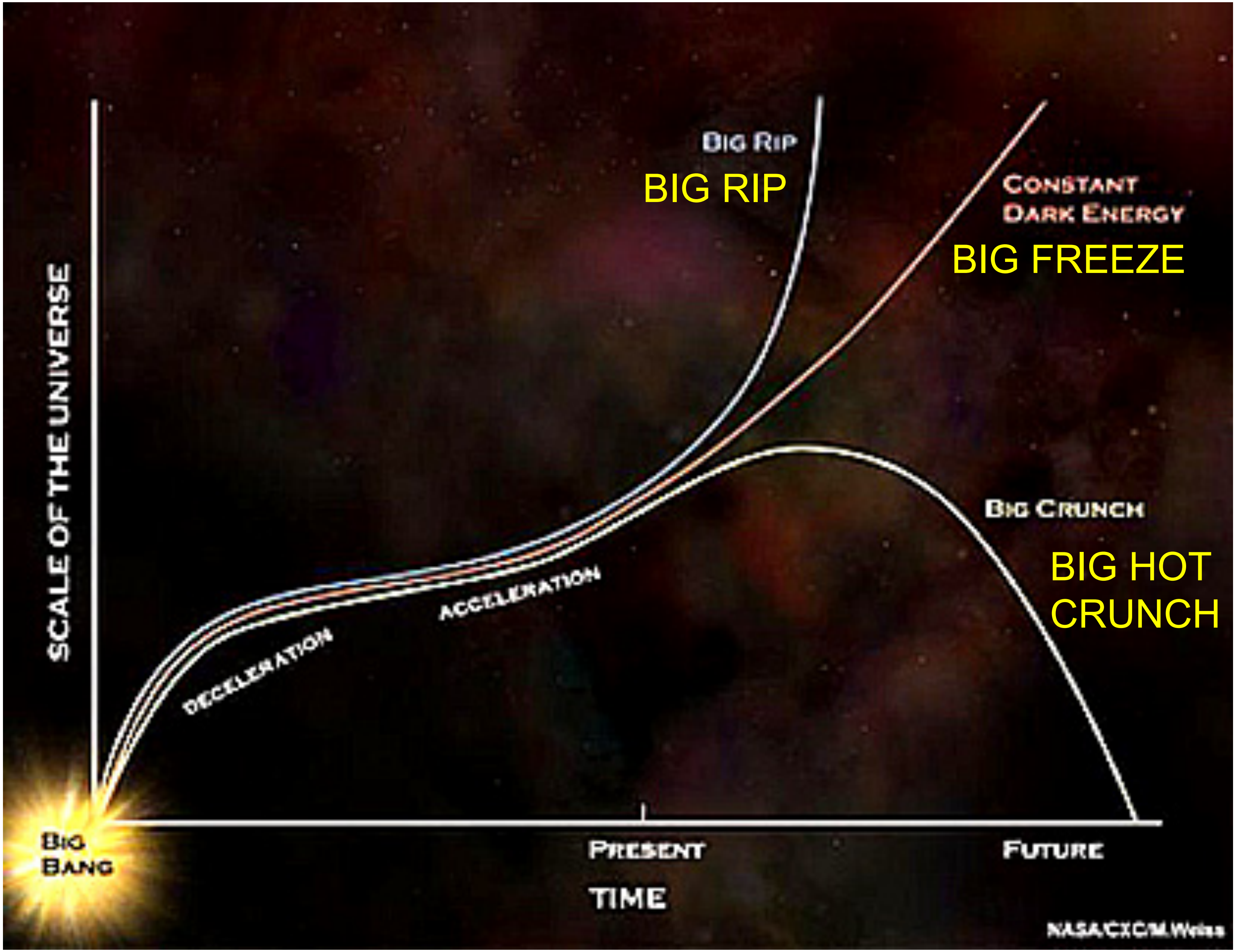
Fate depends on Λ as well as gravity …

Dark Energy causes expansion to accelerate so there is definitely not enough mass for universe to contract (Λ makes things "worse")

With our present estimates:

Since $\Omega_m < 1$ and $\Lambda > 0$ → universe will expand forever


Possible models of the expanding universe
Decelerating universe
Coasting universe
Accelerating universe
Future
Present
Past
By determining the rate of expansion of the universe we live in, astronomers are able to better estimate the age of the cosmos. If the universe is decelerating, it is likely to be young. But if it is coasting or accelerating – expanding faster as a repulsive force pushes galaxies apart – it is probably older.

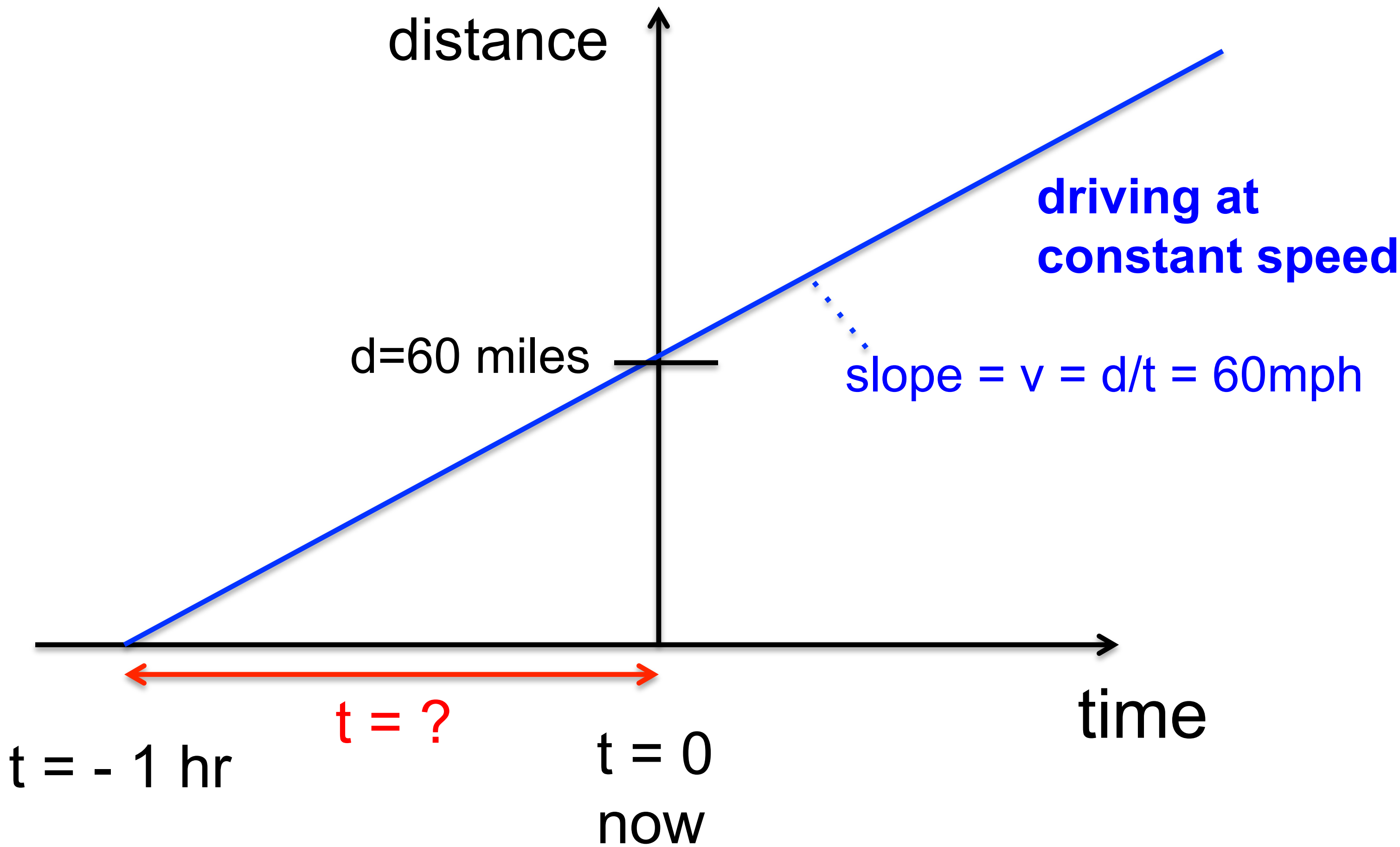


BIG RIP
BIG RIP
CONSTANT
DARK ENERGY
BIG FREEZE
BIG CRUNCH
BIG HOT
CRUNCH
SCALE OF THE UNIVERSE
DECELERATION
ACCELERATION
BIG
BANG
PRESENT
FUTURE
TIME
NASA/CXC/M.Weiss

What major problem would arise if Hubble's constant turned out to be 100 km s^{-1} Mpc^{-1}

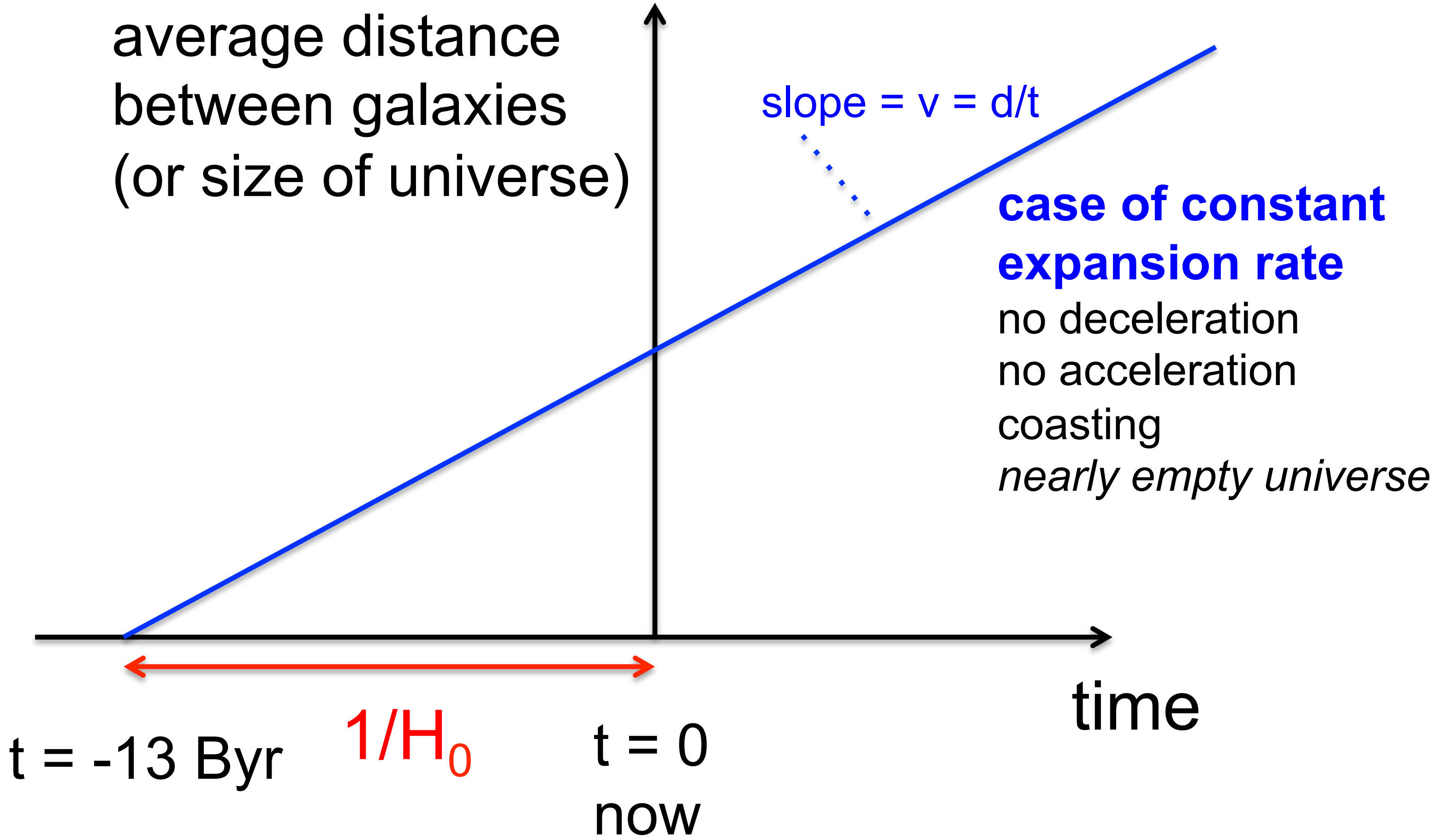
1. Some galaxies would be beyond the cosmic light horizon.
2. Some galaxies would have had to have traveled faster than our observations indicate.
3. The age of the universe would be less than the ages of some of the stars in it.
4. The age of the universe would be greater than the ages of some of the stars in it.
5. Some galaxies would be traveling too fast for the universe to remain gravitationally bound.

suppose you are 60 miles from new haven and driving at 60 mph – when did you leave new haven?



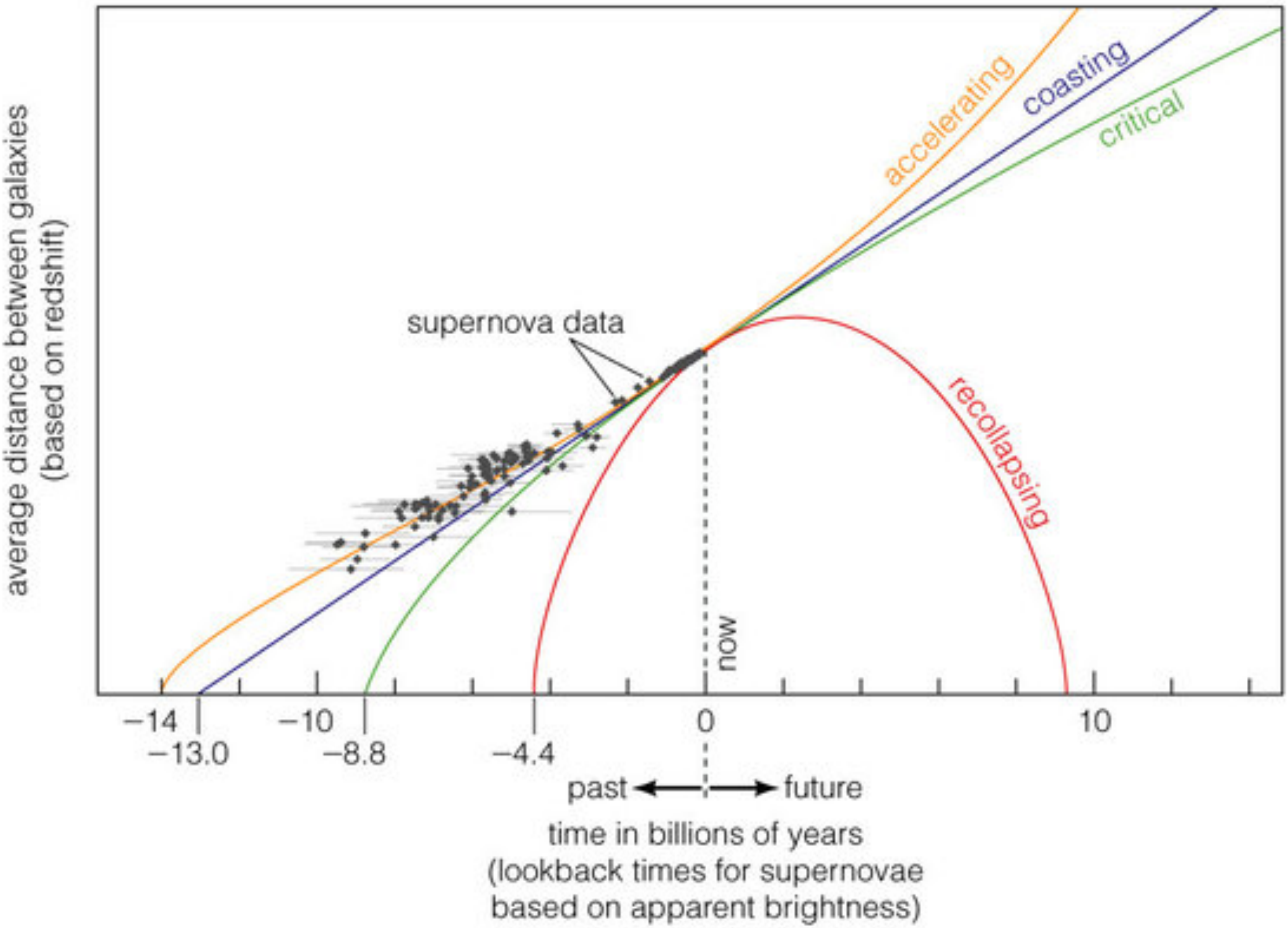
$t = d/v$ = 60 miles/60 mph = 1 hour

extrapolating expansion back in time

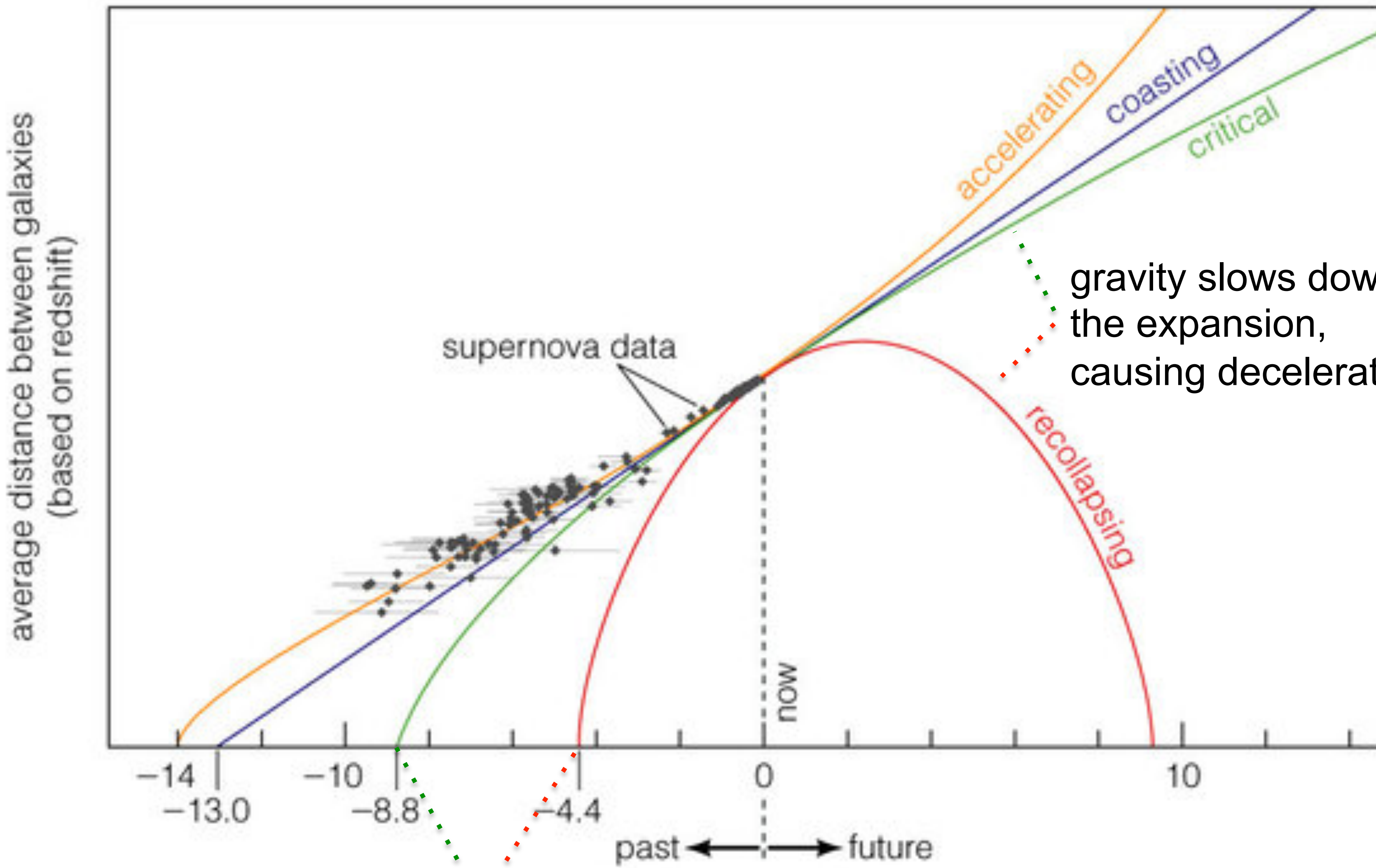


$t = d/v = d/H_o d = 1/H_0 = 13$ Byr

if expansion rate were constant, $1/H_0$ would give age of universe need to know how expansion rate has changed over time to know age of universe



mass in the universe causes expansion to decelerate

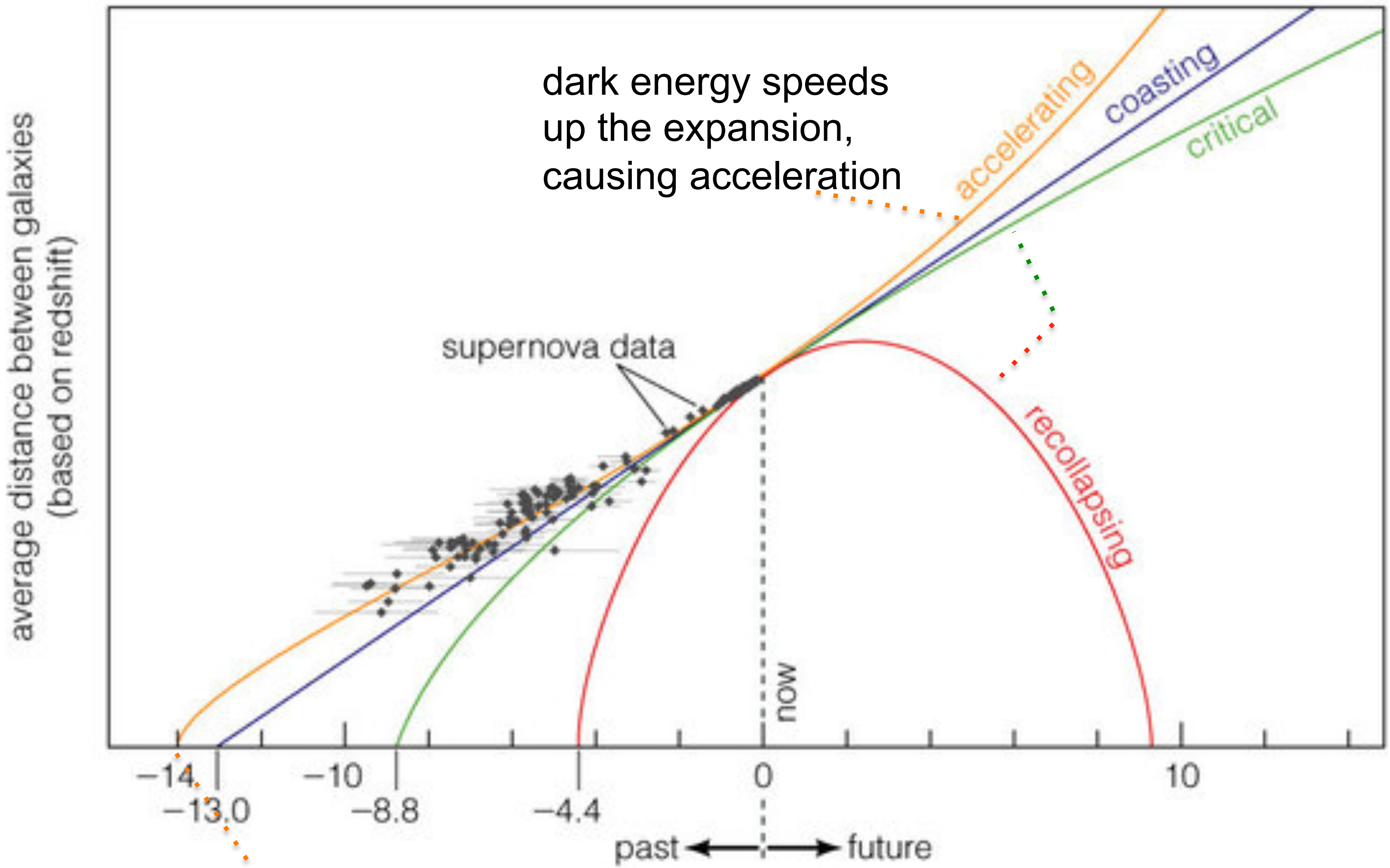


gravity slows down the expansion, causing deceleration

in this case, the age of the universe is less than the inverse of the Hubble constant $T_o < H_o^{-1}$

“dark energy” in the universe causes expansion to accelerate

dark energy speeds up the expansion, causing acceleration



in this case, the age of the universe is more than the inverse of the Hubble constant $T_o > H_o^{-1}$

relation between H_0 and Age of Universe

a.) if gravity and dark energy insignificant

then H(t) is nearly constant and universe always expands at same rate

in this case 1/Ho would give age of universe $T_0 = 1 / H_0$

for $H_0 = 73$ km s^{-1} Mpc^{-1} $1 / H_0 = 13.4$ Byr

b.) gravity slows down expansion, causing deceleration

in this case age $T_0 < H_0^{-1}$

c.) dark energy speeds up expansion, causing acceleration

in this case age $T_0 > H_0^{-1}$

d.) both gravity and dark energy (actual case)

Age T_o could be more or less than H_0^{-1} depending of relative strengths of gravity and dark energy

our current best estimate: $T_0 = 13.7 \pm 0.2$ Byr

we get consistent value for ages of oldest stars: 13 Byr.

Observing Sessions:

none tonight (Mon) or Tues

some chance Wed or Thurs night