# Last time: general relativity, black holes, & gravitational waves

- Masses bend spacetime; other objects move along trajectory corresponding to shortest distance in curved space.

- Gravity bends light as well

- Black holes are collapsed stars from which light can no longer escape

- Accelerating masses emit very weak gravitational waves

- These waves were detected for 1st time last year by LIGO project (Caltech, MIT, Florida)
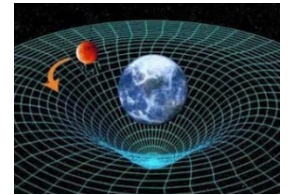
Eddington 1919 expt. confirms bending of light
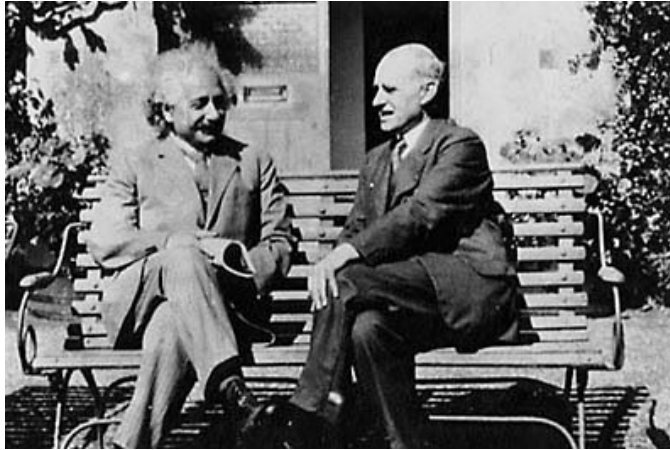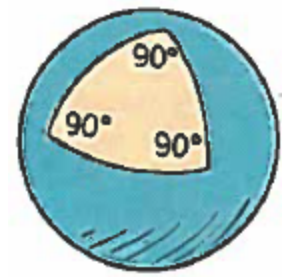
Einstein theory of general relativity says any mass curves spacetime around it:
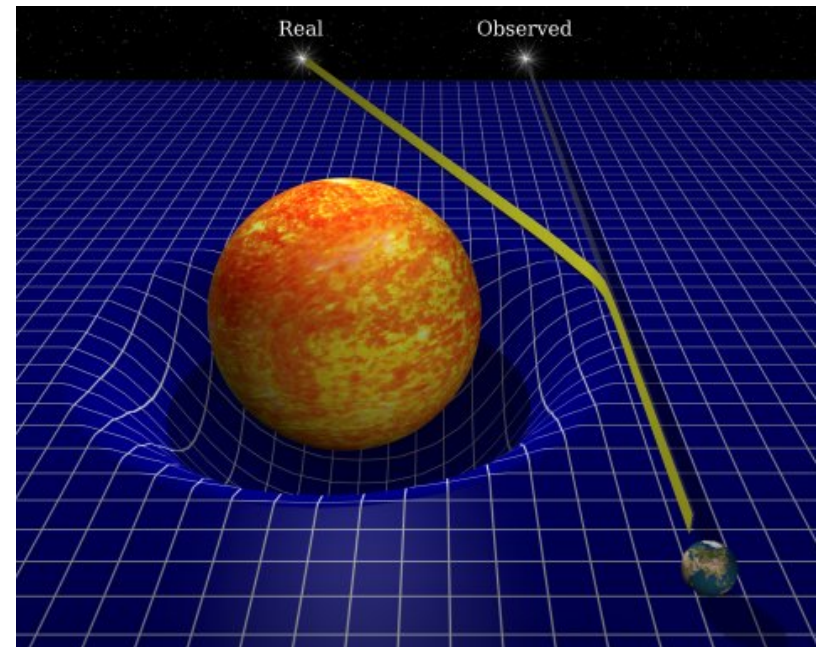
Light travels on a *geodesic* – the shortest path between 2 pts. on the curved surface

# Cosmology in 20th century

Measuring large distances

- Henrietta Leavitt: In 1908 studied Cepheid variables – stars that oscillate in brightness. She found intrinsic relation between brightness and period ☐ compare stars with same period. If they are dimmer, then further away because brightness ☐ $1/r^2$

Composition of Stars

- Cecelia Payne-Gaposchkin: Ph.D thesis (1925) showed that spectral lines observed in stars showed overwhelmingly evidence for hydrogen and helium, unlike Earth

- Hans Bethe 1939: shows energy of sun comes from nuclear fusion of hydrogen

Hydrogen-1

Hydrogen Burning

Hydrogen-1

$E=mc^2$

Energy

Hydrogen-1

Helium-4
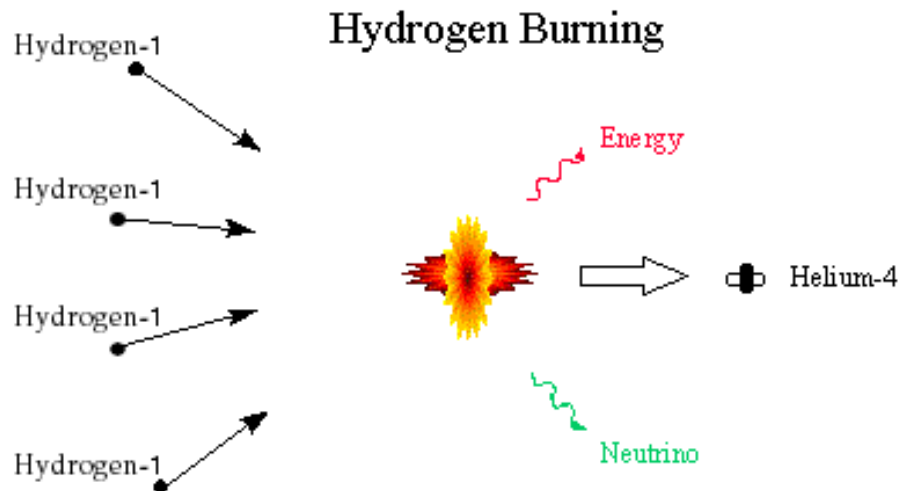
Mass of fusion products less than inputs
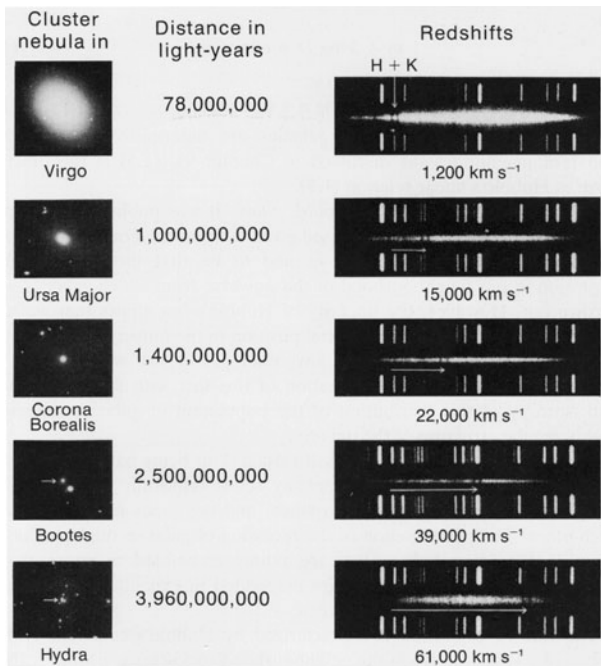
Hydrogen-1

Neutrino

Doppler shift/ Redshift

- Doppler shift (usually for sound) occurs when emmitter is moving with respect to the observer: change in apparent frequency

https://www.youtube.com/watch?v=h4OnBYrbCjY

- Redshift is Doppler shift for light

Hubble's Discovery

Cluster nebula in	Distance in light-years	Redshifts
Virgo	78,000,000	1,200 km s⁻¹
Ursa Major	1,000,000,000	15,000 km s⁻¹
Corona Borealis	1,400,000,000	22,000 km s⁻¹
Bootes	2,500,000,000	39,000 km s⁻¹
Hydra	3,960,000,000	61,000 km s⁻¹

- Edwin Hubble's observations of remote galaxies, and the redshift of their spectral lines (1924).

- Hubble noticed that the further away the galaxy, the greater the redshift of its spectral lines.
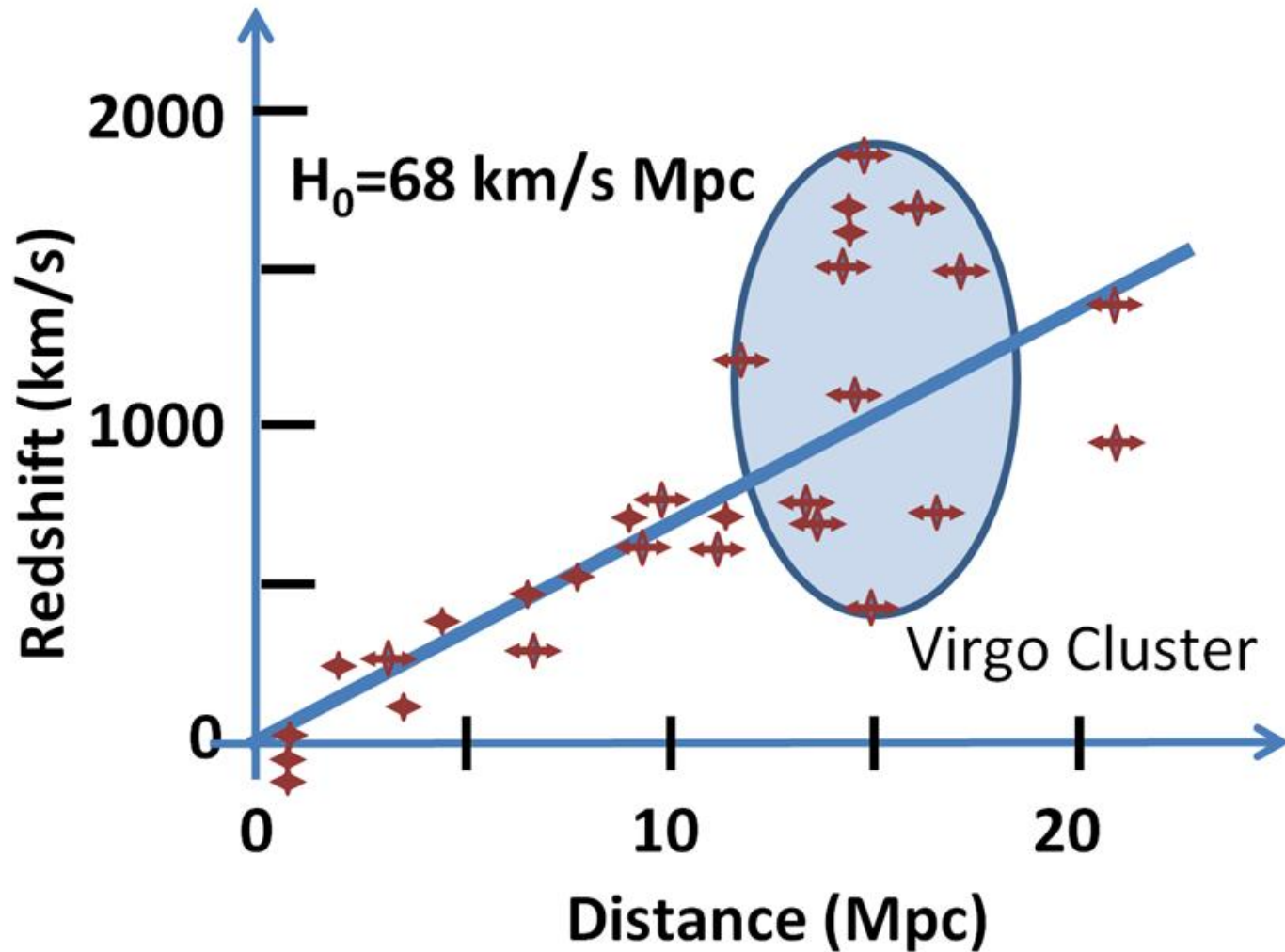
- This linear relationship is called Hubble's Law.

Hubble's Law

- $v = H_0 d$

- v = recessional velocity of the galaxy

- H_0 = Hubble constant*

- d = distance of galaxy to earth

- Galaxies are getting farther apart as time progresses, therefore the universe is expanding.

Note $1/H_0$ is a time –meaning?

Hubble's law: data

$H_0 = 68$ km/s Mpc

Redshift (km/s)

2000

1000

0

Virgo Cluster

0   10   20

Distance (Mpc)

Hubble's Constant

- Expansion rate measured using Type 1A Supernovae.

- The age of the universe can be derived from Hubble's constant by working backwards d❓0

    - $T_0 = 1/H_0$

  – Current measurements $H_0 = 73$ km/s*Mpc, then

     $T_0 = 13.4$ billion years old (age of universe)

Einstein doesn't like it.
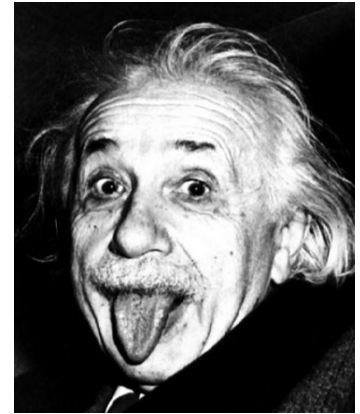
- All the solutions to E's equations which give Hubble's law have singularities

- Einstein thought that singularities such as these indicated that there were important physical effects not accounted for in his equations. He also thought that the *right* answer would involve **static** behavior: large-scale structure should not change with time.

- He also saw how he could "fix" the field equation to eliminate singular and dynamic solutions: introduce an additional constant term, which became known as the **cosmological constant**, to represent the missing, unknown, physical effects.

Einstein gives up.

- The Universe is observed to be expanding; it is not static.
    - Thus the real Universe may be described by one of the **dynamic** solutions to the original Einstein field equation.
    - Thus there appeared to be no point in Einstein's cosmological constant, so he let it drop, calling it **"my greatest blunder."**
    - Thereafter he began trying to show that the singularities in the dynamic solutions simply wouldn't be realized. His effort resulted in the **steady-state** model of the Universe, which we'll describe later.
- Cosmological constant, will come back, though.

How the Universe Expands

- The space between galaxies expands, not the galaxies themselves

- Example: raisins in a loaf of bread.
    - As the dough rises, the overall loaf of bread expands; the space between raisins increases but the raisins themselves do not expand.

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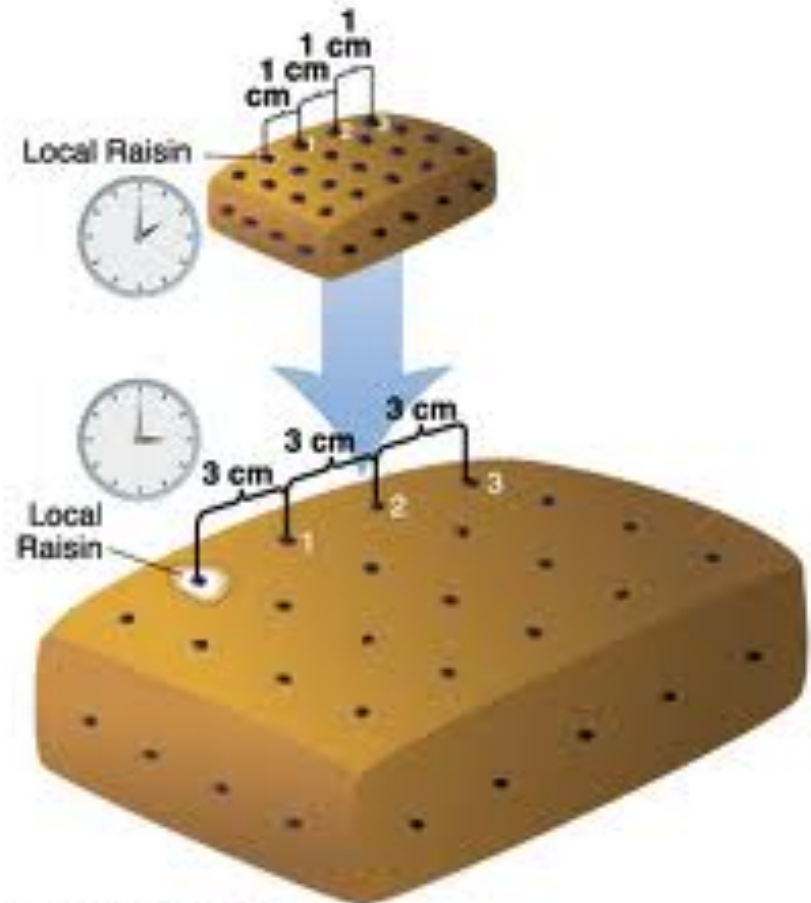
Center of Universe?

- There is NO CENTER to the universe
  - Expansion looks the same regardless of where you are in the universe.
  - Every point appears to be the center of the expansion, therefore no point is the center.
  - The universe is infinite.

Evidence for Expansion

- The light from remote galaxies and other objects is redshifted.

- This redshift is called cosmological redshift because it is caused by the expansion of the universe, not by the actual movement of the object (Doppler redshift).

Origins of the Big Bang Theory

- Georges Lemaître (1927) considered idea of expanding universe, realizing that the universe was smaller yesterday than today, and so on until a "day that would not have had a yesterday": the moment of creation.

- This idea wasn't widely accepted at first: Fred Hoyle dismissed "this hot Big Bang", noting that there wasn't any record or remnants. He argued for a "steady state" universe.

Origins of the Big Bang Theory

- George Gamow (1948) suggested that if the universe was created with a "hot Big Bang", then:
  - Various elements, such as H and He, would be produced for a few minutes immediately after the Big Bang due to the extremely high temperatures and density of the universe at this time.
  - The high density would cause rapid expansion.
  - As the universe expanded, H and He would cool and condense into stars and galaxies.
  - Today, due to continued cooling, radiation left over from the epoch of recombination, when neutral atoms formed (~380,000 years after Big Bang) should be about 3K (he said 10K!).

Evidence for the Big Bang Theory

- Gamow's theory was revisted in the 1960's by Bob Dicke and Jim Peebles of Princeton University.
  - Believed that this cooled radiation would be redshifted to the microwave region of the electromagnetic spectrum.
  - Dicke made a receiver to detect this radiation, but was unsuccessful.

Evidence for the Big Bang Theory

- The radiation, so far undetected by the Princeton team, was posing a problem for NJ Bell Telephone Labs, where Arno Penzias and Robert Wilson were developing a new microwave-satellite technology for phone calls.

  - Puzzled by steady hiss that they received no matter where in the sky they pointed their antenna.

  - This faint background noise they were trying to get rid of was exactly what the Princeton team was trying to detect: evidence of the Big Bang.
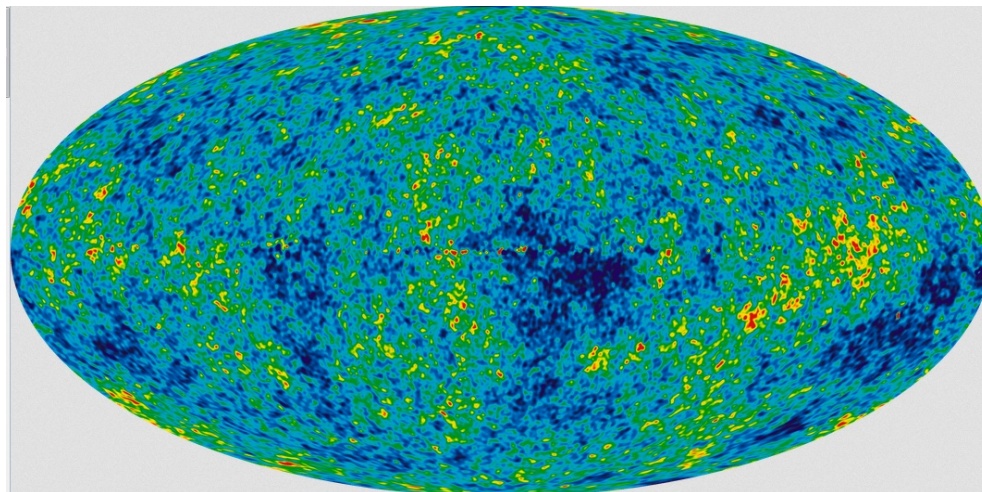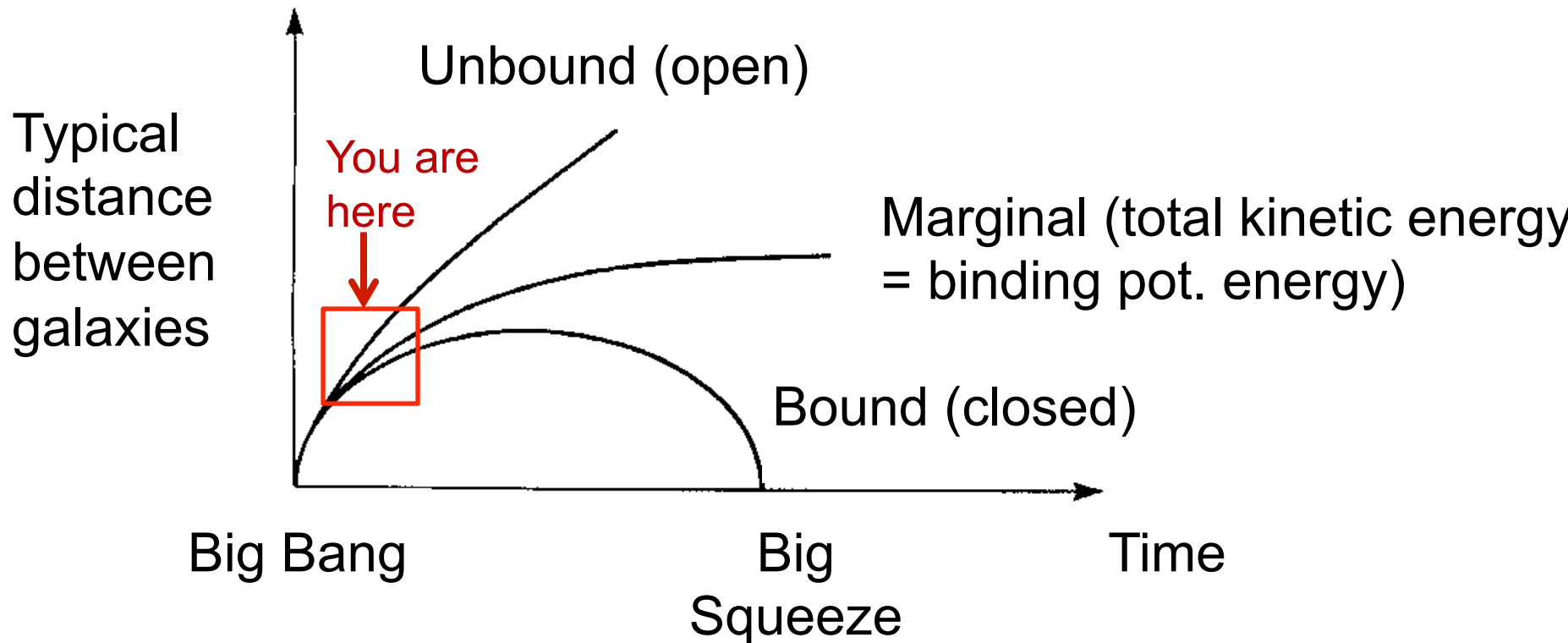
Cosmic microwave background radiation

- Detection of this Cosmic Microwave Background radiation, won Penzias and Wilson the Nobel Prize for Physics in 1978.

- CMB radiation can be detected by your TV as well - 1% of static seen on a channel that your TV doesn't receive is from the birth of the universe.

CMB Radiation

- COBE (Cosmic Background Explorer) 1989: detector outside the atmosphere:

  – Measured the blackbody spectrum of CMB radiation to be at T = 2.725 K - consistent with theory.

  – CMB radiation almost entirely isotropic

- WMAP (Wilkinson Microwave Anisotropy Probe) (2002) improved picture of CMB Radiation.

Homogeneous solutions to Einstein equations: the structure of the expanding Universe

Typical distance between galaxies

Unbound (open)

You are here

Marginal (total kinetic energy = binding pot. energy)

Bound (closed)

Big Bang

Big Squeeze

Time

All three expanding solutions predict that the matter in the universe was concentrated at earlier times, and that the expansion started as an explosion of this concentration.

The latest: dark matter and dark energy

- https://www.youtube.com/watch?v=QAa2O_8wBUQ

Questions unanswered or unasked

- What was there before the big bang?

- What caused the big bang?

- Is the universe open or closed or marginal?

- What is the meaning of life?

- What is the airspeed of an unladen swallow?

And there are many more but…

"The more I learn, the more I realize how much I don't know."
--- A. Einstein