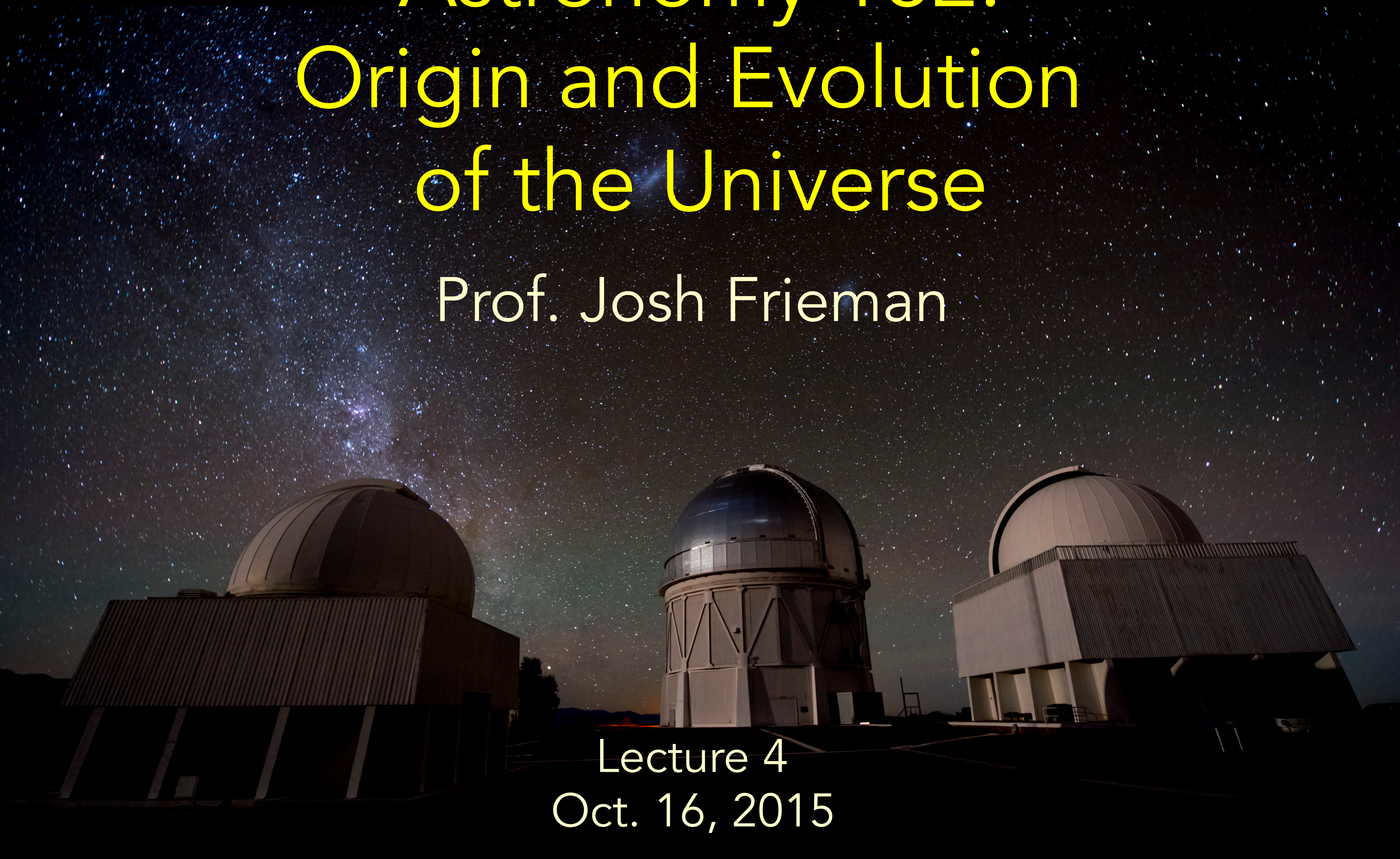
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 4
Oct. 16, 2015

Today

- Newtonian Cosmology and the Fate of the Universe
- Einstein’s Special Relativity

Assignment

- This week: read Hawley and Holcomb, Chapters 3 and 10.
- Assignment for next Wed., Oct. 21: Hawley and Holcomb Chapter 10: write ~3 page essay plus ~1 page of questions

The Expanding Universe

Distance between galaxies given by universal scale factor: $d(t)=d_0a(t)$

Dynamics of Cosmic Expansion

- Separation between any pair of galaxies is increasing due to expansion: $d(t)=d_0a(t)$, where $a(t)$ is a universal function. This is consistent with Hubble's law.

- What determines the time-dependence of the cosmic scale factor $a(t)$?

Dynamics of Cosmic Expansion

- One way to address this:

- Consider a galaxy at present distance d from the Milky Way. It is receding from us with current speed $v=H_0d$.
- Tomorrow, it will be slightly further away (due to expansion). Will it be receding faster or slower than it is today?

Expansion and Gravity

- The gravity of the Milky Way is pulling on that galaxy.
- The force on that galaxy (from Milky Way) should cause it to *decelerate* (slow down).
- Newton: a force F on a body of mass m causes it to accelerate in the direction of the force:

$$F=ma$$

where a is the resulting acceleration.

Expansion and Gravity

- Gravitational pull of the Milky Way accelerates that galaxy toward us. Since acceleration is the change in speed per unit time, we expect Milky Way's gravity to *slow down* that receding galaxy: recession speed v should *decrease* over time.

- Since $v=Hd$ and d is increasing with time due to expansion, in order for speed v to decrease the expansion rate H must decrease *faster* than d grows.

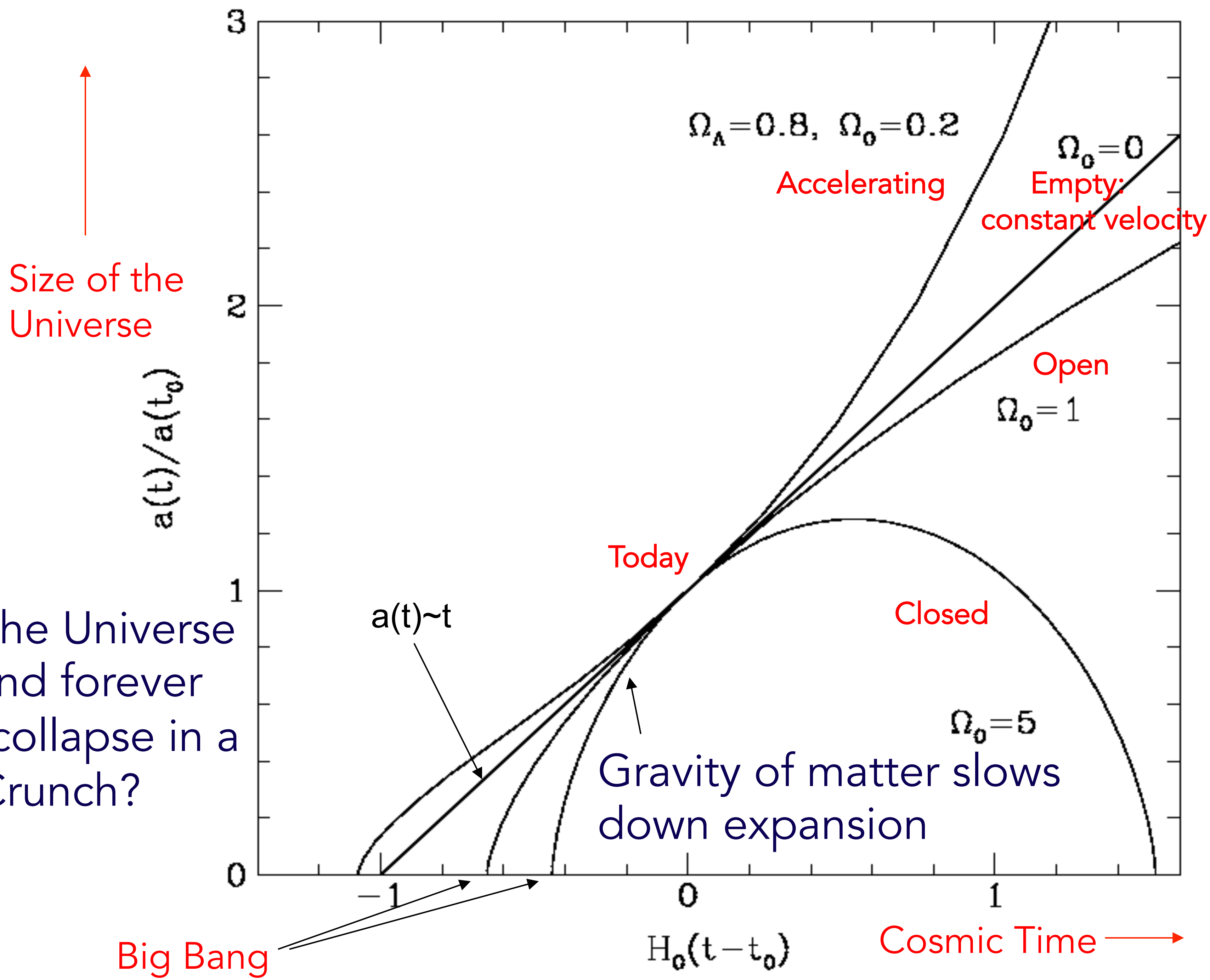
Expansion and Gravity

- Recall the separation between Milky Way and that galaxy is $d=d_0a(t)$.
- If it were receding at *constant* speed v, then its distance would grow linearly with time: $d=vt$.
- Due to gravity, we expect its recession speed v to *decrease* with time.
- This implies its distance d should grow more slowly than t.

Expansion and Gravity

- However, since d~a, this implies that the cosmic scale factor a(t) should grow more slowly than t due to gravity.
- If the mass (gravity) of the Milky Way is large enough, the recession speed could slow so much that it eventually reverses and starts approaching us. Expansion would turn into contraction.

Will the Universe Expand forever or recollapse in a Big Crunch?



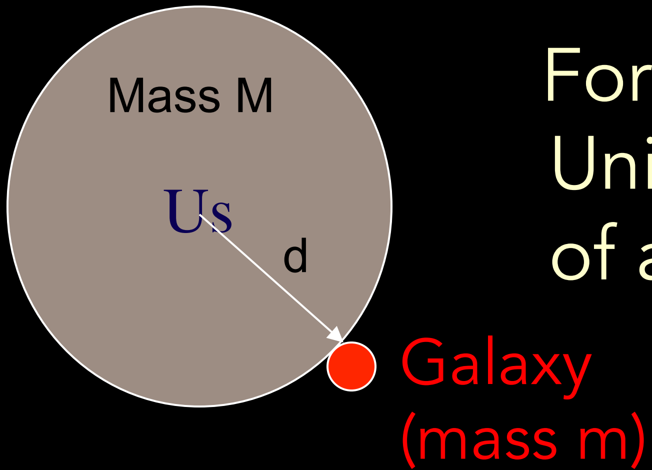
Deceleration and Age of the Universe

- Due to gravity we expect scale factor $a(t)$ to grow more slowly than t.
- Previous figure shows that, in that case, the age of the Universe t_0 would be less than the Hubble time:

$$t_0 < 1/H_0 = 14 \text{ billion years}$$

Expansion and Gravity

- Wait a minute: isn't that galaxy being pulled *away* from us by other galaxies on the other side of it?
- Yes, but it's also being pulled *toward* us by other galaxies on this side.
- For gravity, for a homogeneous Universe, we can ignore the effects of all bodies outside a sphere of radius d centered on us (Newton showed this).

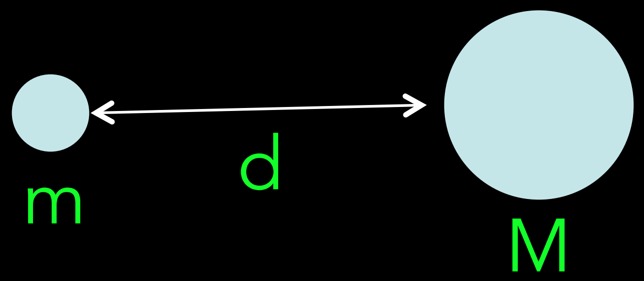


- Can consider galaxy moving in the gravitational field of a spherical body of mass $M=(4\pi/3)\rho d^3$

Newton's Universal Law of Gravity

- The force of gravity between two massive bodies is proportional to the product of their masses and inversely proportional to the square of their distance.
- Explains the observed motions of the planets around the Sun (Kepler's empirical laws).

$$F_g = \frac{GMm}{d^2}$$



where G is Newton's constant of gravitation

Newtonian Gravity

- Your weight on the surface of the Earth is just the force of Earth's gravity on you:

$$W = \frac{GM_E m}{R_E^2}$$

- If you release a body near the surface of the Earth, it accelerates downward with:

$$a = \frac{F}{m} = \frac{GM_E m}{R_E^2 m} = \frac{GM_E}{R_E^2}$$

independent of the mass m of the body (Galileo)

Orbits

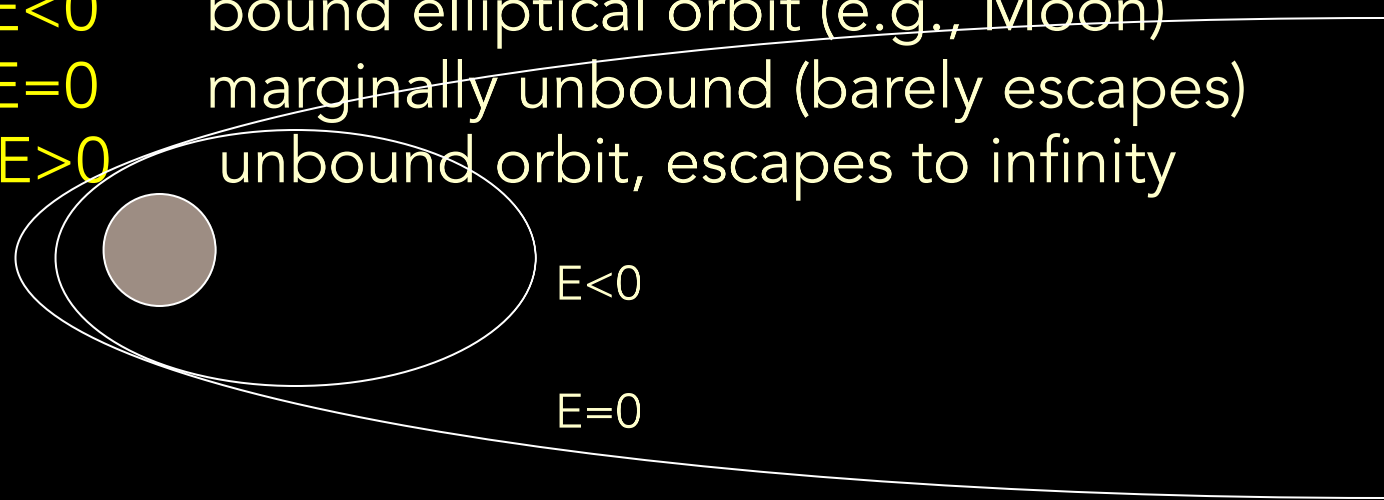
- Galaxy motion determined by same equation that governs orbits of satellites around the Earth.
- Conservation of Energy:

Kinetic energy + Potential Energy = Total Energy E = constant

$$\frac{1}{2}m\mathrm{v}^2 - \frac{GMm}{d} = E$$

$$\mathrm{v}_{esc} = \sqrt{\frac{2GM}{d}} = d\sqrt{\frac{8\pi G\rho}{3}}$$

$v < v_{escape}$	E<0	bound elliptical orbit (e.g., Moon)
$v = v_{escape}$	E=0	marginally unbound (barely escapes)
$v > v_{escape}$	E>0	unbound orbit, escapes to infinity



Orbits

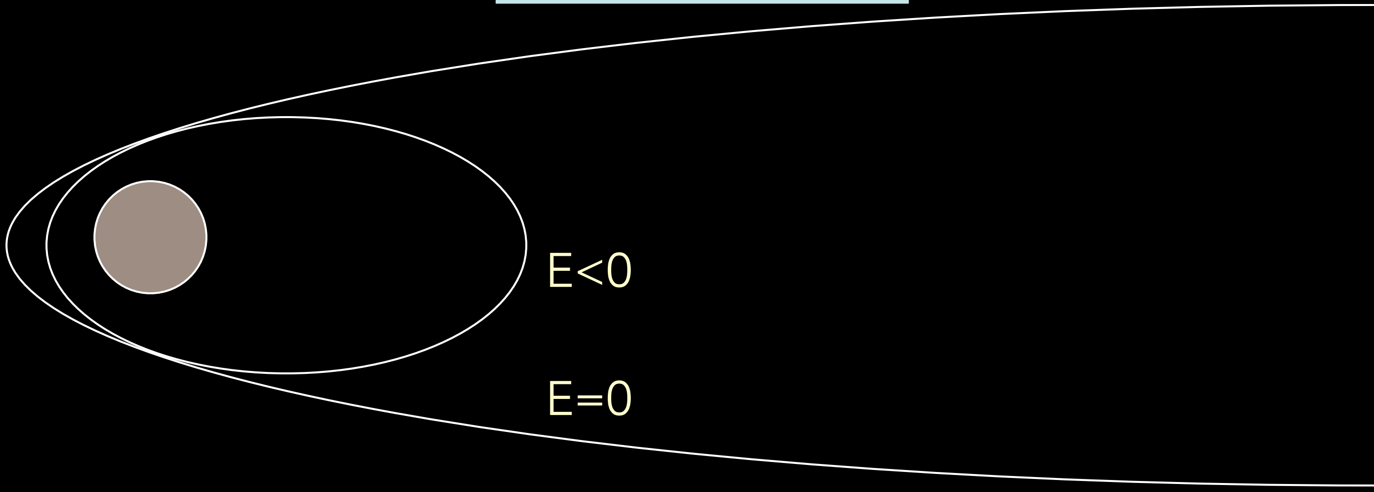
- Galaxy motion determined by same equation that governs orbits of satellites around the Earth.

$$v = H_0 d$$

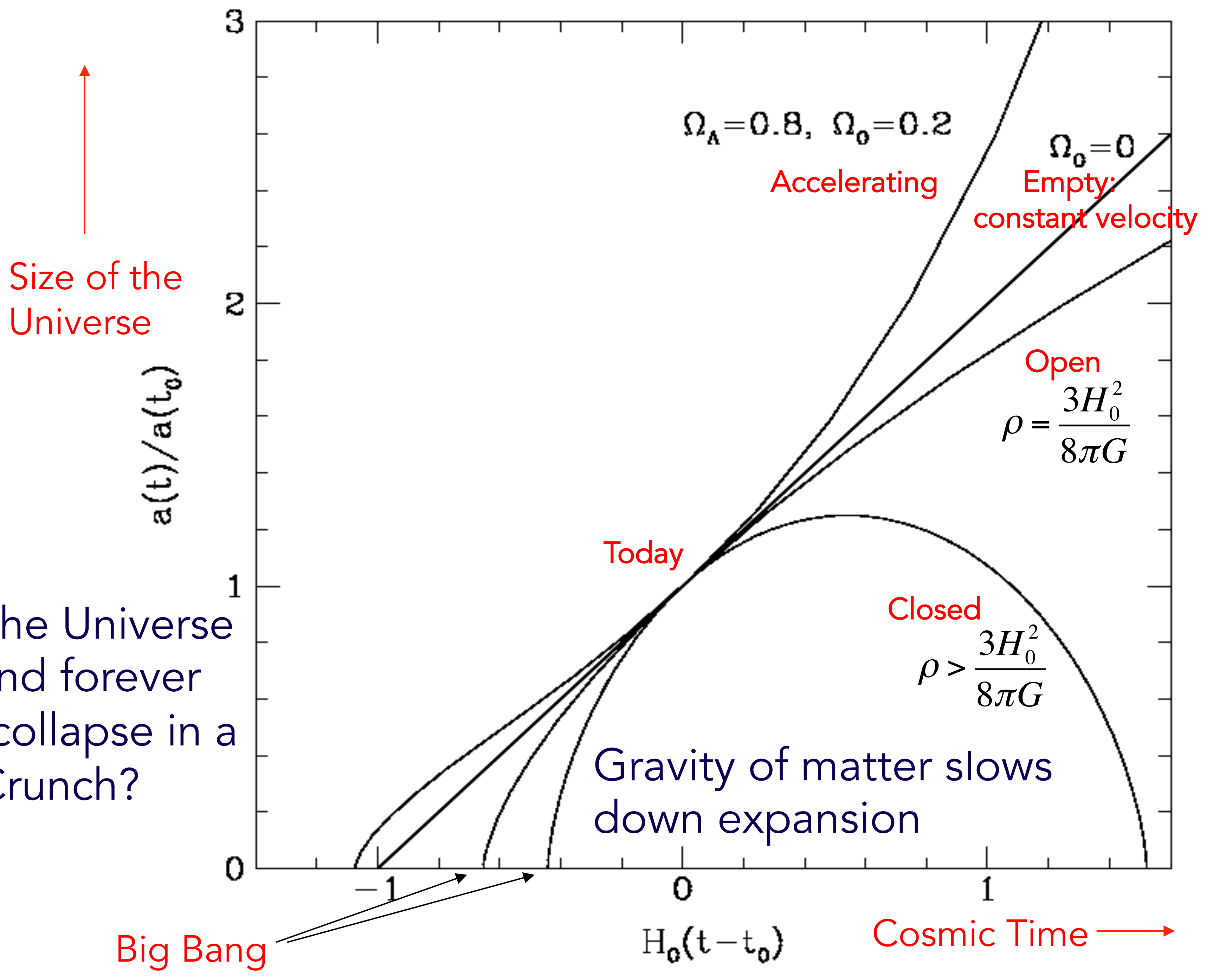
$$v_{esc} = \sqrt{\frac{2GM}{d}} = d\sqrt{\frac{8\pi G\rho}{3}}$$

- For $v = v_{escape}$, $E=0$, and

$$H_0^2 = \frac{8\pi G\rho}{3}$$



Will the Universe Expand forever or recollapse in a Big Crunch?



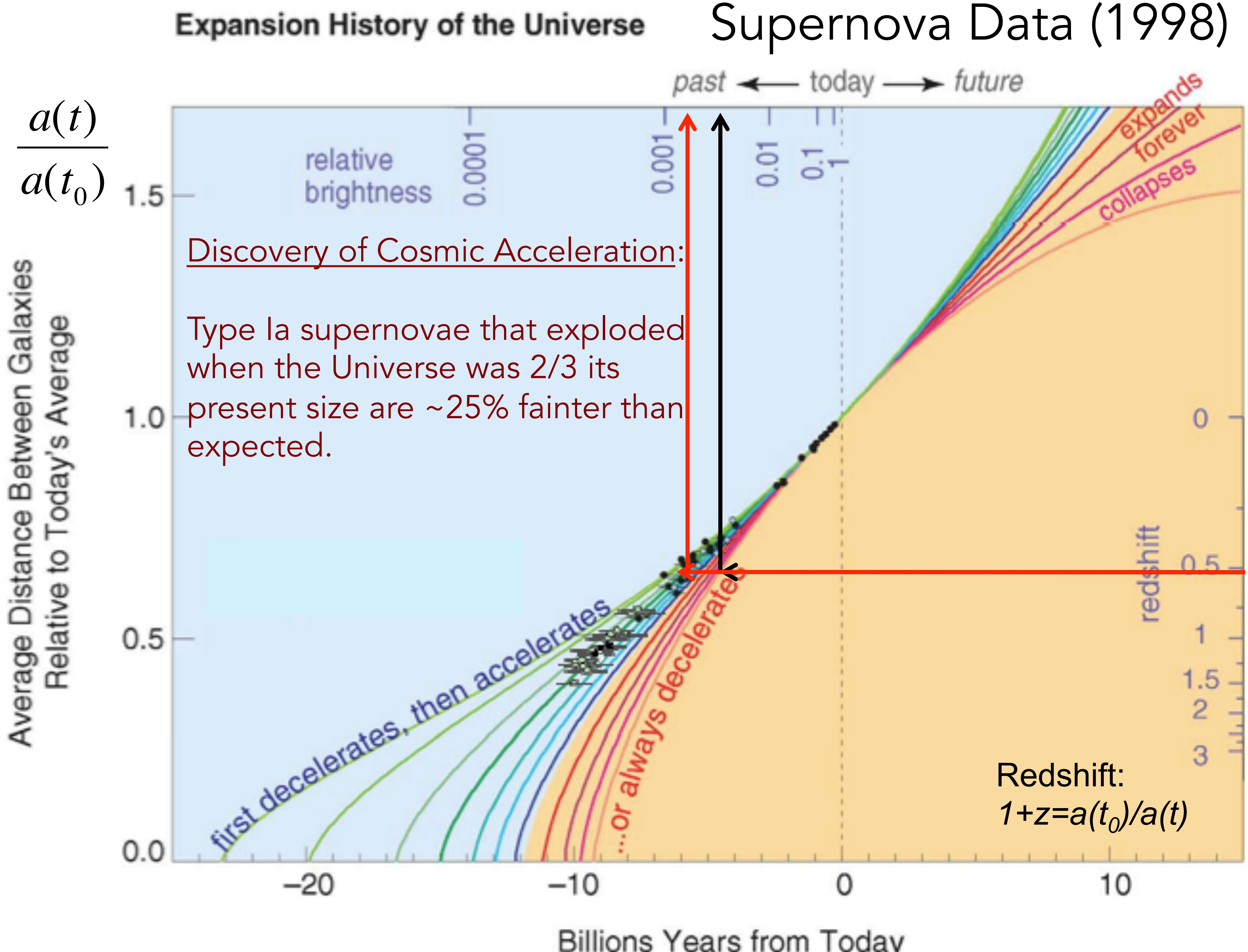
Fate of the Universe

- Will the Universe expand forever or recontract to a Big Crunch?
- Is recession speed larger or smaller than escape speed?
- Is the mass density of the Universe smaller or larger than the critical value,

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} = 2 \times 10^{-29}\,\mathrm{gm/cm^3}$$

- Density of atoms is well below this. But how much unseen—dark---matter is there? This question dominated discourse through the 1980's.
- Discovery of cosmic acceleration in 1998 changed the dynamics from this picture, as we will see.

Supernova Data (1998)



$\frac{a(t)}{a(t_0)}$

Discovery of Cosmic Acceleration:

Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected.

Redshift:
$1+z=a(t_0)/a(t)$

Cosmic Acceleration

- Throughout the 20th Century, cosmologists attempted to measure the deceleration (slowing) of the expansion due to gravity, but the measurements were inconclusive.
- 1998: Two teams of astronomers, using type Ia supernovae as standard candles, found that instead the expansion is *speeding up* (Nobel Prize 2011).
- To explain this, we either need to modify our understanding of how gravity works on cosmological scales or else invoke a dominant, new component of the Universe---dark energy---that has very different properties from ordinary matter.

Einstein's Relativities

- 1800's: Maxwell's Theory of Electromagnetism and the measured constancy of the speed of light appeared to be at odds with Newtonian physics. The aim to resolve this conflict led Einstein to his Theory of Special Relativity (1905).
- Also, according to Newton, if I suddenly change the mass of an object, then the gravitational force it exerts on bodies at very great distances changes instantaneously, in violation of Special Relativity, which states that nothing can travel faster than light. This (among other reasons) led Einstein to formulate a new theory of gravity to replace Newton's: General Relativity (1916).

Special Relativity (1905)

Maxwell's Theory of Electromagnetism (mid-1800's):

- Unified description of Electricity and Magnetism.
- Light is an electromagnetic wave that always travels at fixed speed: $c = 3 \times 10^{10}$ cm/sec = 670 million mph
- Light never stops or slows down.

Einstein, age 16: What happens if you chase after a light beam?
Newton: Go faster & faster (accelerate) until you catch up to it, at which point the light will appear to stand still. But according to Maxwell's theory, there's no such thing as `stationary' light: it always travels at speed c.

Einstein's resolution: the Theory of Special Relativity

Hawley and Holcomb: Chapter 7

"When the Special Theory of
Relativity began to germinate
in me, I was visited by all
sorts of nervous conflicts... I
used to go away for weeks in
a state of confusion."

"A storm broke loose in
my mind."

Principle of Relativity

- The concept of constant-velocity, aka inertial motion is relative. The motion (velocity) of an object is defined only in comparison to other objects. There is no `absolute' notion of motion.

- Example: train pulling out of a station next to another train… are we moving or are they?

- Key point: you don't `feel' motion at constant velocity, but you do feel accelerated motion (due to a force).

Einstein: in a closed compartment (with no reference to outside objects) moving at constant velocity, you cannot perform an experiment to determine if you are moving or not. The Laws of physics must be identical for all observers undergoing relative constant-velocity motion (i.e., for all inertial observers).

Constancy of Speed of Light

- Despite Principle of Relativity, all observers agree that light travels at speed c regardless of benchmarks for comparison (experimentally established by Michelson & Morley 1880's).

- If you run away from a speeding bullet, the faster you move, the slower its relative approach to you will be. In principle, you could outrun it (Superman did not violate the Laws of Physics)

- Now suppose I briefly shine a flashlight or laser beam at you, sending out a packet of light (photons) at 670 million mph. If you blast away from me in a spaceship at, say, 100 million mph and measure the speed of approach of the photons, Newton and Galileo say you'll measure it to be 570 million mph, but experiment indicates you'll measure it to be 670 million mph.

Einstein's Paradox

- No matter how hard you chase after (or away from) a light beam, it always retreats from (or approaches) you at light speed. You can't catch up to (or outrun) light and make it appear stationary. This clearly requires an abandonment of Newton & Galileo.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

Hence speed connects our notions of space and time.

- Einstein:

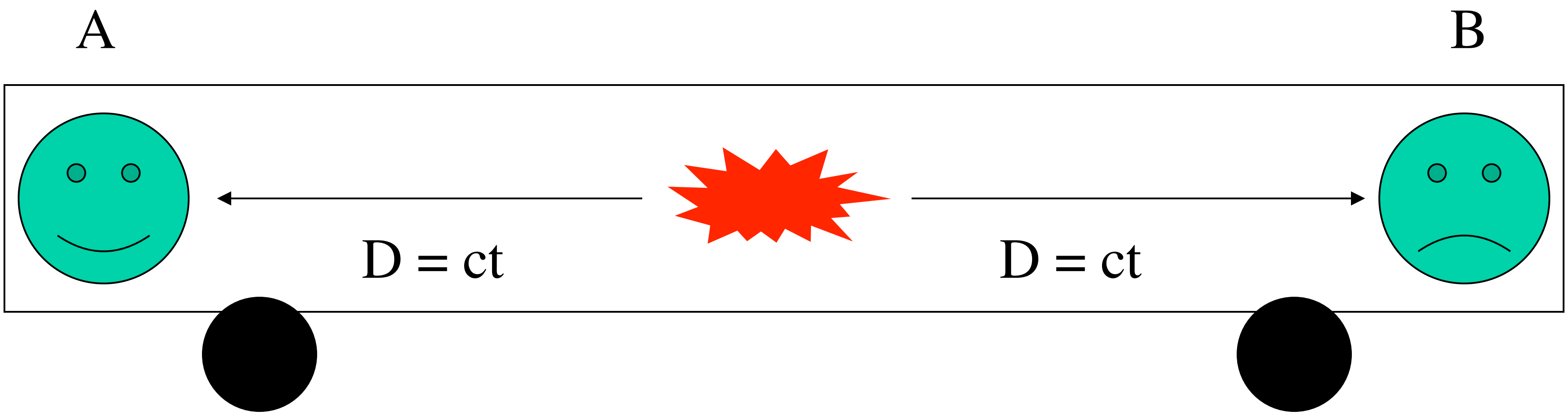
Constancy of speed of light ⟷ must alter our conceptions of Space & Time

Time: relativity of simultaneity

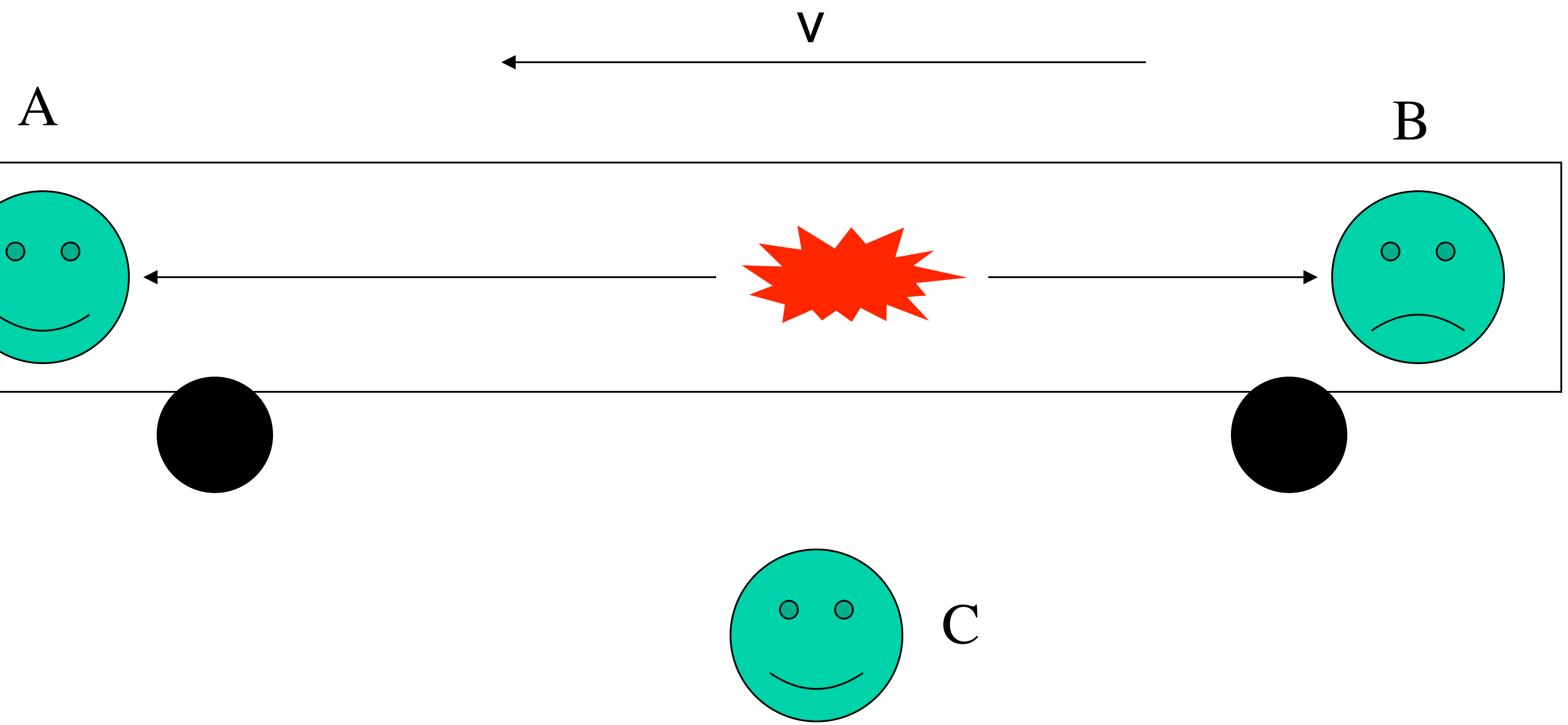
Consider a long train moving at (constant) high speed past a platform. In the middle of the train car, turn on a light bulb. Observer A at the front of the car and observer B at the back of the car, equidistant from the bulb, see it turn on at exactly the same time.

However, observers on the platform disagree: they see observer B approach the light bulb and A recede from it, so the light has less distance to travel to reach B than A. So they see the light reach B before it reaches A.

As seen by observers on the train, light takes same amount of time to reach each end of the car.



As seen by observer C at rest on the platform, light takes more time to reach A than B, since it travels a longer distance



Time: relativity of simultaneity

- Who's right, those on the train or on the ground?
- According to the Principle of Relativity, they both are:

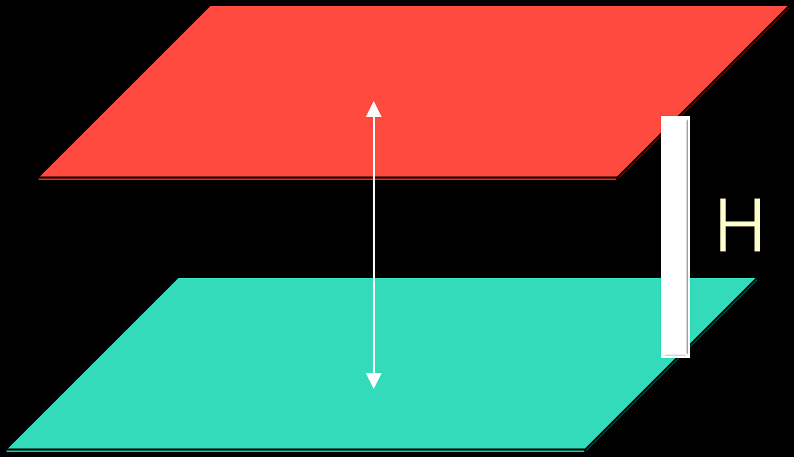
- Simultaneity is relative. Observers in relative motion do not agree on which events occur at the same time.

- Einstein: this means their conceptions of time must differ.
- How do we measure time?

Clocks & Time

Define Time operationally as that which is measured by clocks, via some regular, cyclic mechanism.

Illustration: Light Clock

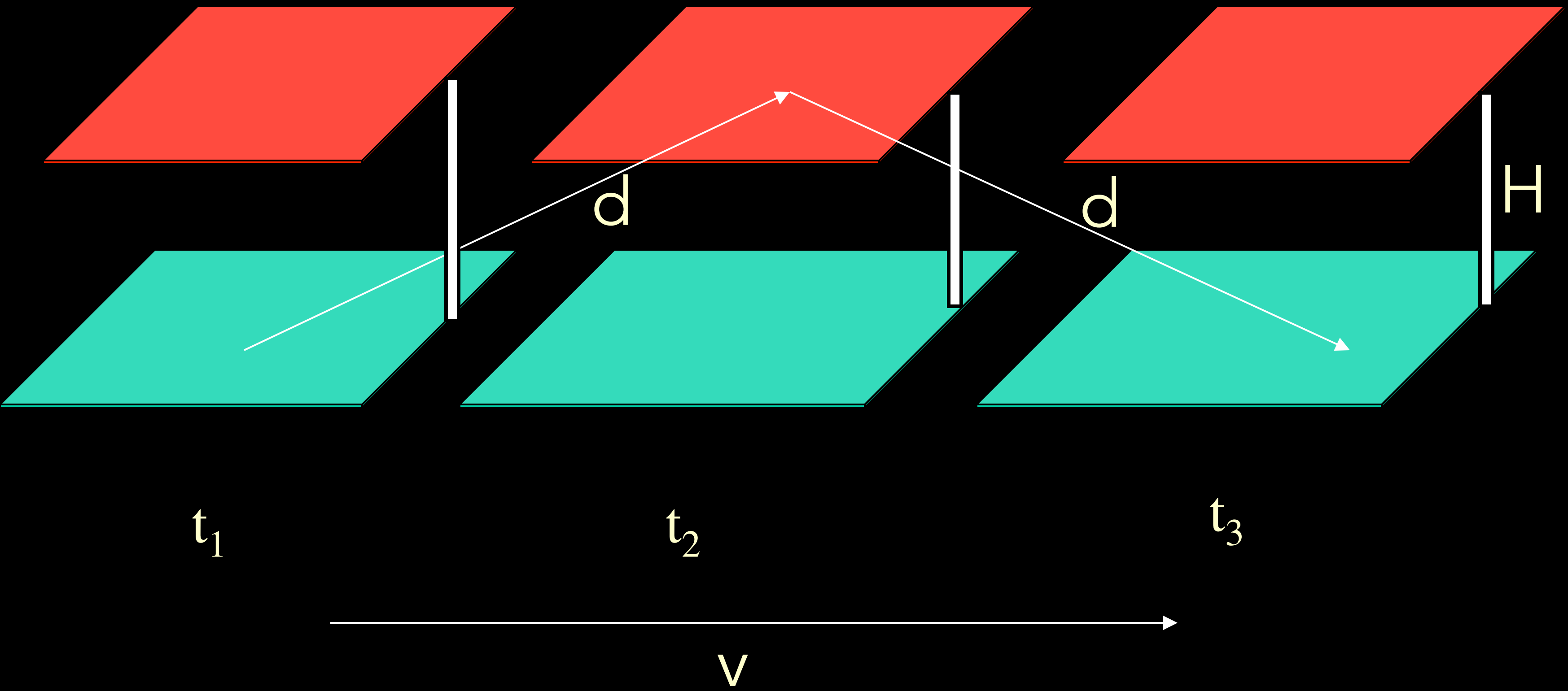


Light Clock: ticks every time a light particle (photon) bouncing between the fixed walls makes one complete vertical circuit. It ticks when $ct=2H, 4H, 6H, \ldots$, so the time between ticks is $\Delta t=2H/c$

Let's assume observers A, B, and C have such clocks.

Now consider the light clock held by observer A on the train, moving past stationary observer C: according to C, the photon in the moving clock travels a longer round-trip path. Since speed of light is constant, it takes longer between ticks:

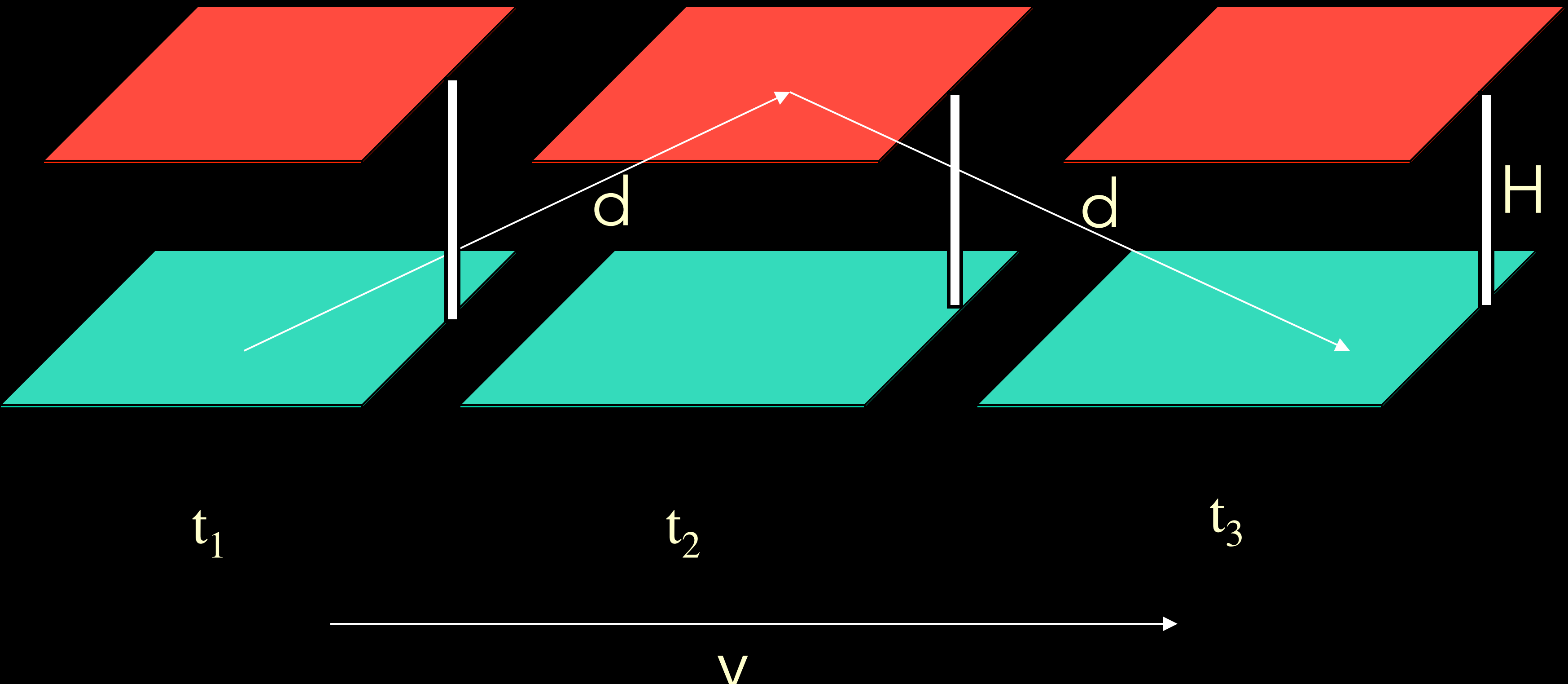
<u>the moving clock slows down according to the stationary observer (and vice versa according to Principle of Relativity)</u>



According to Observer C on the platform, the time between ticks of A's clock has increased to

$$\Delta t_A = 2d/c > 2H/c$$

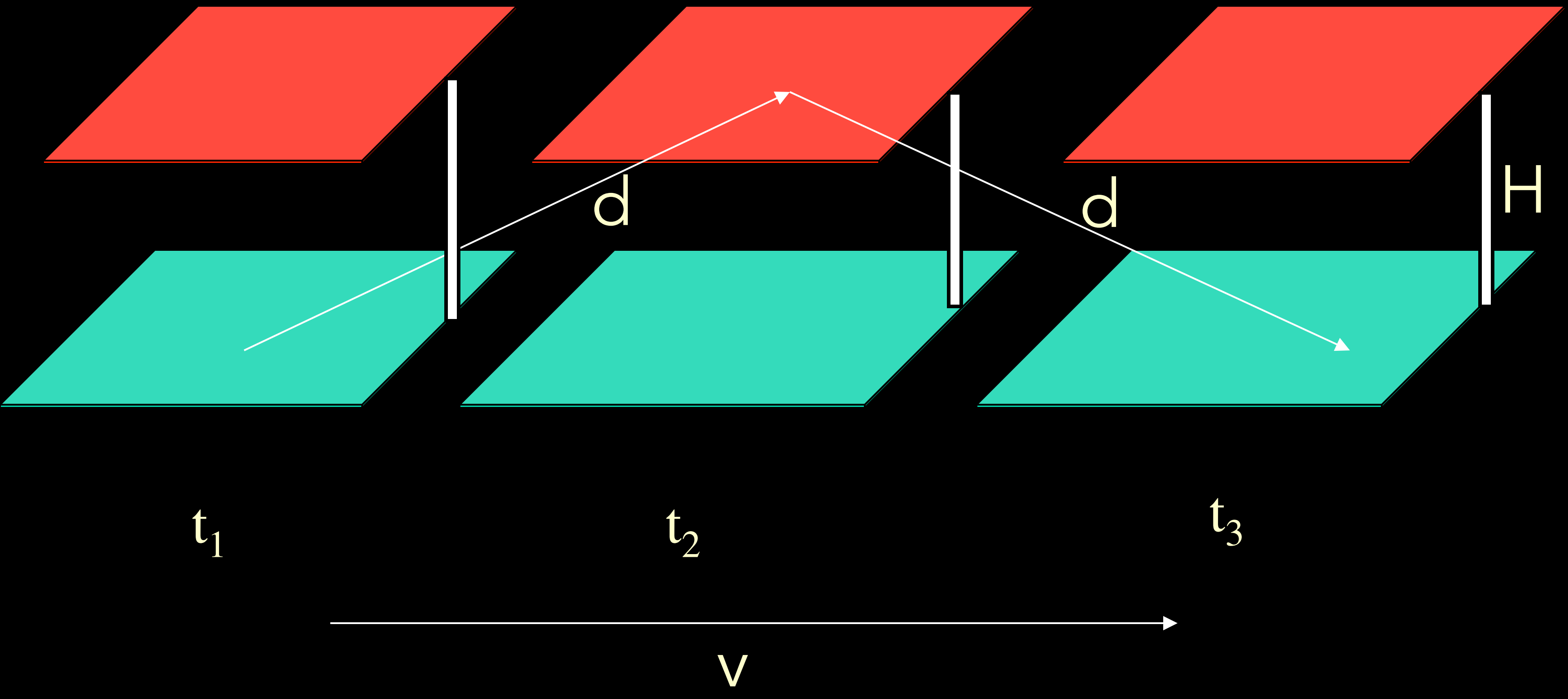
the moving clock slows down according to the stationary observer (and vice versa according to Principle of Relativity)



According to Observer C on the platform, the time between ticks of A's clock has increased to

$$\Delta t_A = 2d/c > 2H/c$$

$$d^2 = H^2 + (v\Delta t_A/2)^2$$



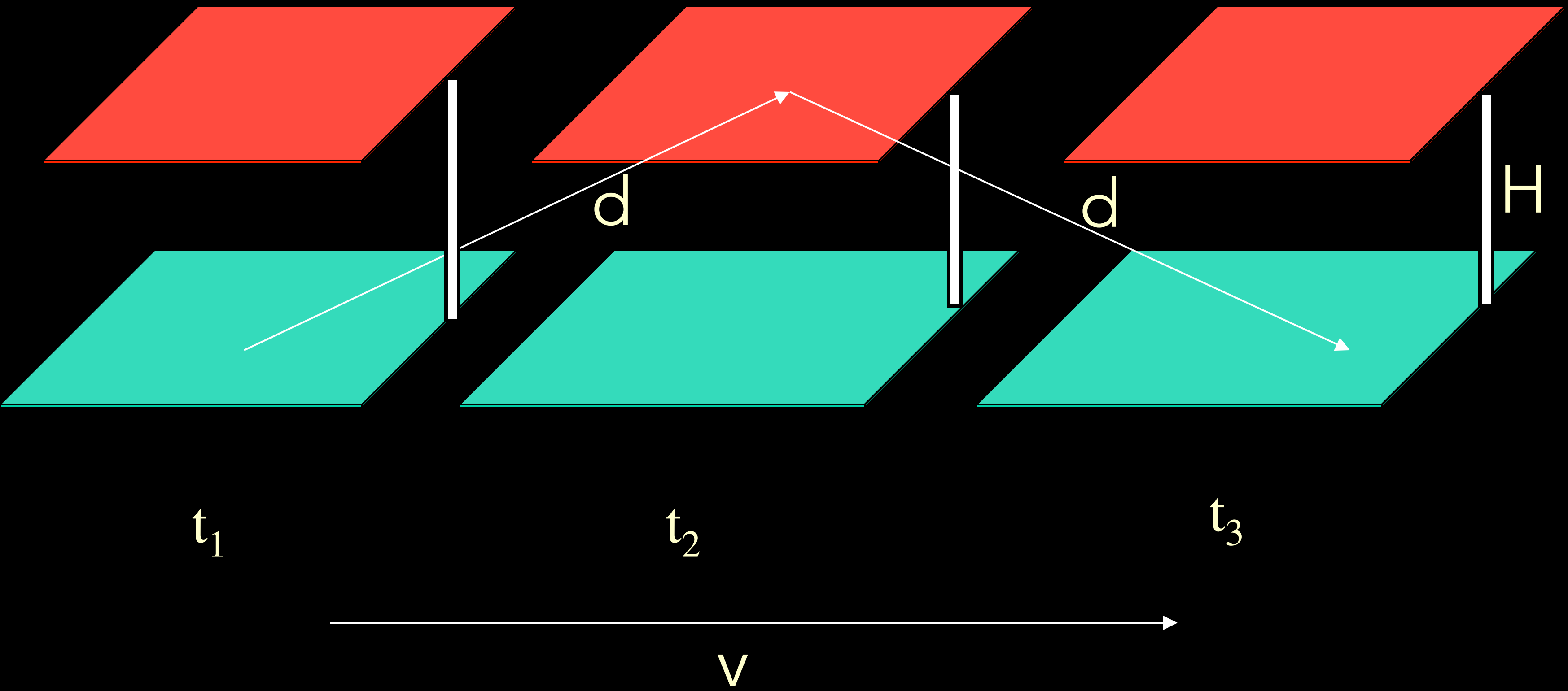
$$\Delta t_A = 2d/c > 2H/c = \Delta t_C$$

$$d^2 = H^2 + (v\Delta t_A/2)^2$$

$$(c\Delta t_A/2)^2 = (c\Delta t_C/2)^2 + (v\Delta t_A/2)^2$$

Time between ticks of A's clock according to C:

$$\Delta t_A = \Delta t_C /(1-v^2/c^2)^{1/2}$$



$$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Einstein:

- By the Principle of Relativity, this behavior applies to all clocks: this is a feature of Time itself.

- A moving clock ticks more slowly than a stationary clock. The faster a clock moves relative to us, the slower it appears to tick to us. As the clock approaches light speed, it appears to almost stop ticking.

- If time elapses more slowly for bodies in motion, can we live longer by moving quickly?

- No: for we observe that the moving individual does everything more slowly, i.e., appears to be living in `slow-motion', so their net `amount of life' (what they accomplish) is the same. Also, they see *our* clocks slow down as well.