

Welcome  
back  
to 8.033!



Edwin Hubble 1889-1953  
(American; 1930 paper)

Image courtesy of Wikipedia.

# KEY FACT 1:

The (observable) Universe  
is homogeneous &  
isotropic (on large scales)

## Summary of last lecture:

# Key formula summary

- FRW metric:

Interpretation of  $\mathbf{r}$ ,  $t$ ,  $a$ , comoving

$$d\tau^2 = dt^2 - a(t)^2 \left( \frac{dr^2}{1 - \kappa r^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2 \right)$$

- Hubble parameter:

$$H \equiv \frac{\dot{a}}{a}$$

- Dimensionless current Hubble parameter:

$$h \equiv H_0 / (100 \text{ km s}^{-1} \text{ Mpc}^{-1}) \approx H_0 \times 9.7846 \text{ Gyr}$$

# KEY FACT 2:

The Universe *is*  
expanding!

$$v=Hr$$

# MIT Course 8.033, Fall 2006, Lecture 18

Max Tegmark

## Today's topic: Cosmology 2/4

- Friedmann equation and its solutions
- Age of the Universe
- Brief history of the Universe

- Friedmann equation:

$$\begin{aligned} H^2 &= \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2} \\ &= H_0^2 [\Omega_\gamma(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda] \end{aligned}$$

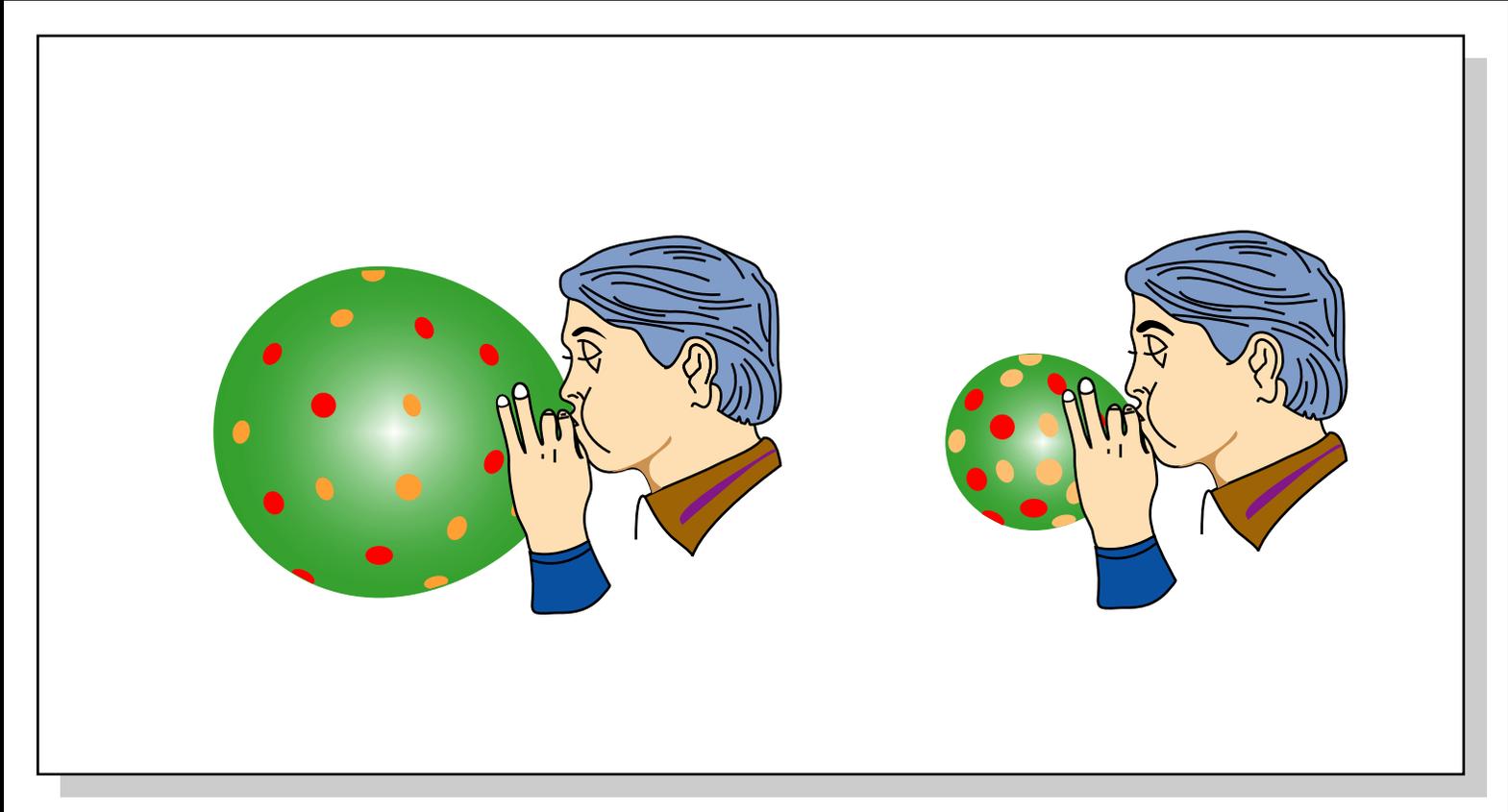
- Cosmological parameter measurements (2006):

- $\Omega_b \approx 0.04$ ,
- $\Omega_d \approx 0.21$ ,
- $\Omega_\Lambda \approx 0.75$ ,
- $\Omega_k \approx 0$ ,
- $h \approx 0.7$ ,
- $\Omega_m \equiv \Omega_b + \Omega_d \approx 0.25$ ,

- Age of the Universe at redshift  $z$ :

$$t(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')}$$

# What does it *mean* that “the universe is expanding”?



Figures by MIT OCW.



(Bunjee cord)

## DO ANY OF THESE QUESTIONS CONFUSE YOU?

1. What is the Universe expanding into?
2. How can stuff be more than 14 billion light years away when the Universe is only 14 billion light years old?
3. Where in space did the Big Bang explosion happen?
4. Did the Big Bang happen at a single point?
5. How could a the Big Bang create an infinite space in a finite time?
6. How could space not be infinite?
7. If the Universe is only 10 billion years old, how can we see objects that are now 30 billion light years away?
8. Don't galaxies receding faster than  $c$  violate relativity theory?
9. Are galaxies really moving away from us, or is space just expanding?
10. Is the Milky Way expanding?
11. Do we have evidence for a Big Bang singularity?
12. What came before the Big Bang?
13. Should I feel insignificant?



(Bunjee cord)

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# A brief history of our universe

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Fluctuation generator

Fluctuation amplifier

INFLATION

CMB last scattering

first stars

present day

fraction of a second

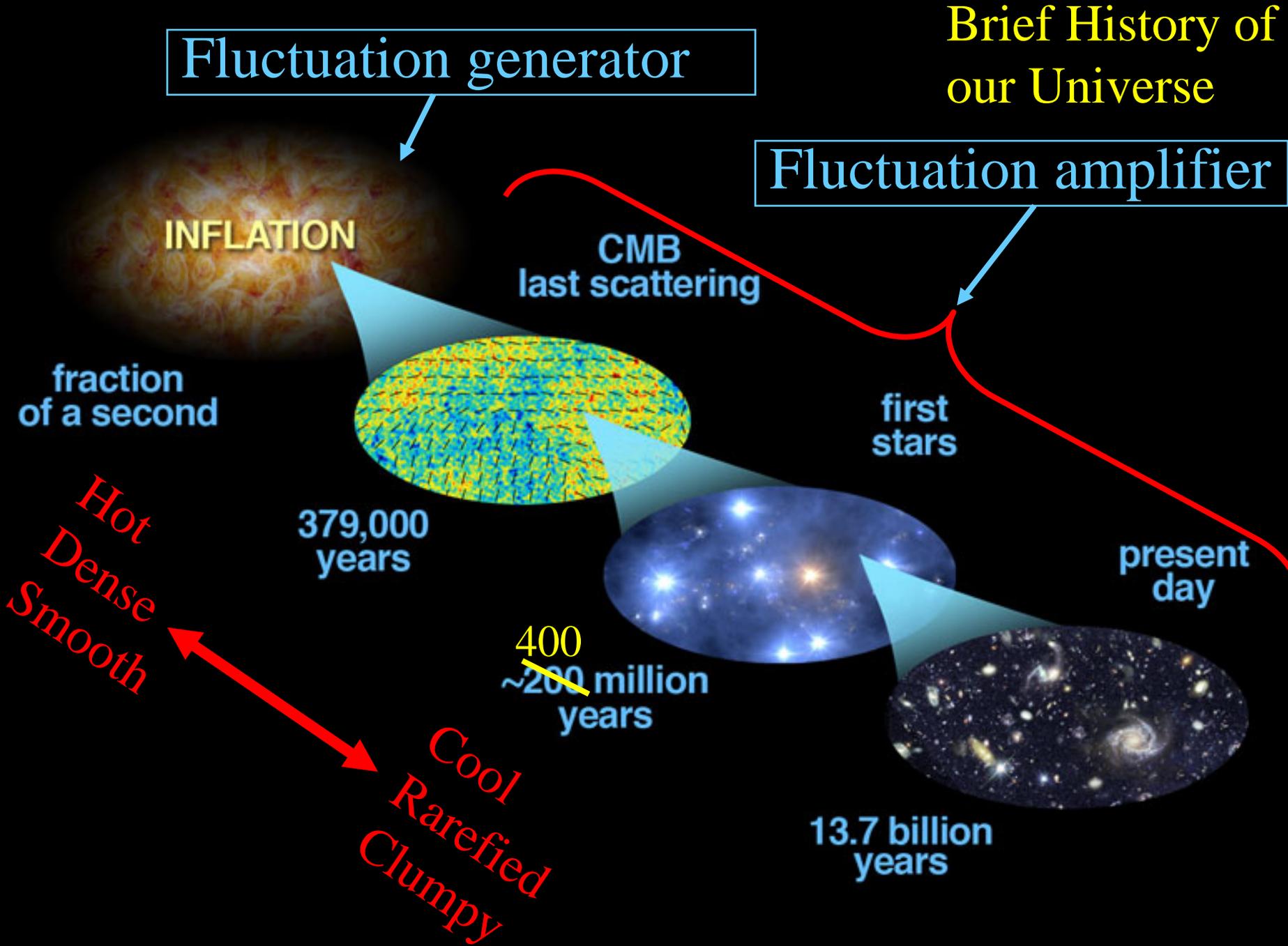
379,000 years

400 million years

13.7 billion years

Hot  
Dense  
Smooth

Cool  
Rarefied  
Clumpy





Formation movies



SDSS movie