Welcome back to 8.033!

George Gamow
1904-1968
(Ukrainian)

Summary of cosmology so far:

Key formula summary

Interpretation of **r**, t, a, comoving

- FRW metric:

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

- Hubble parameter:

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

- Dimensionless current Hubble parameter:

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

- Friedmann equation:

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

- Cosmological parameter measurements (2005):
  - $\Omega_b \approx 0.05$,
  - $\Omega_d \approx 0.25$,
  - $\Omega_\Lambda \approx 0.7$,
  - $\Omega_\mathrm{k} \approx 0$,
  - $h \approx 0.70$,
  - $\Omega_\mathrm{m} \equiv \Omega_b + \Omega_d \approx 0.3$,
- Age of the Universe at redshift z:

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

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- Cosmological parameter measurements (2006):
  - $\Omega_b \approx 0.04$,
  - $\Omega_d \approx 0.21$,
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- Age of the Universe at redshift z:

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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 receeding 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?

MIT Course 8.033, Fall 2006, Lecture 18

Max Tegmark

Today's topic: Cosmology 3/4

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

- Friedmann equation:

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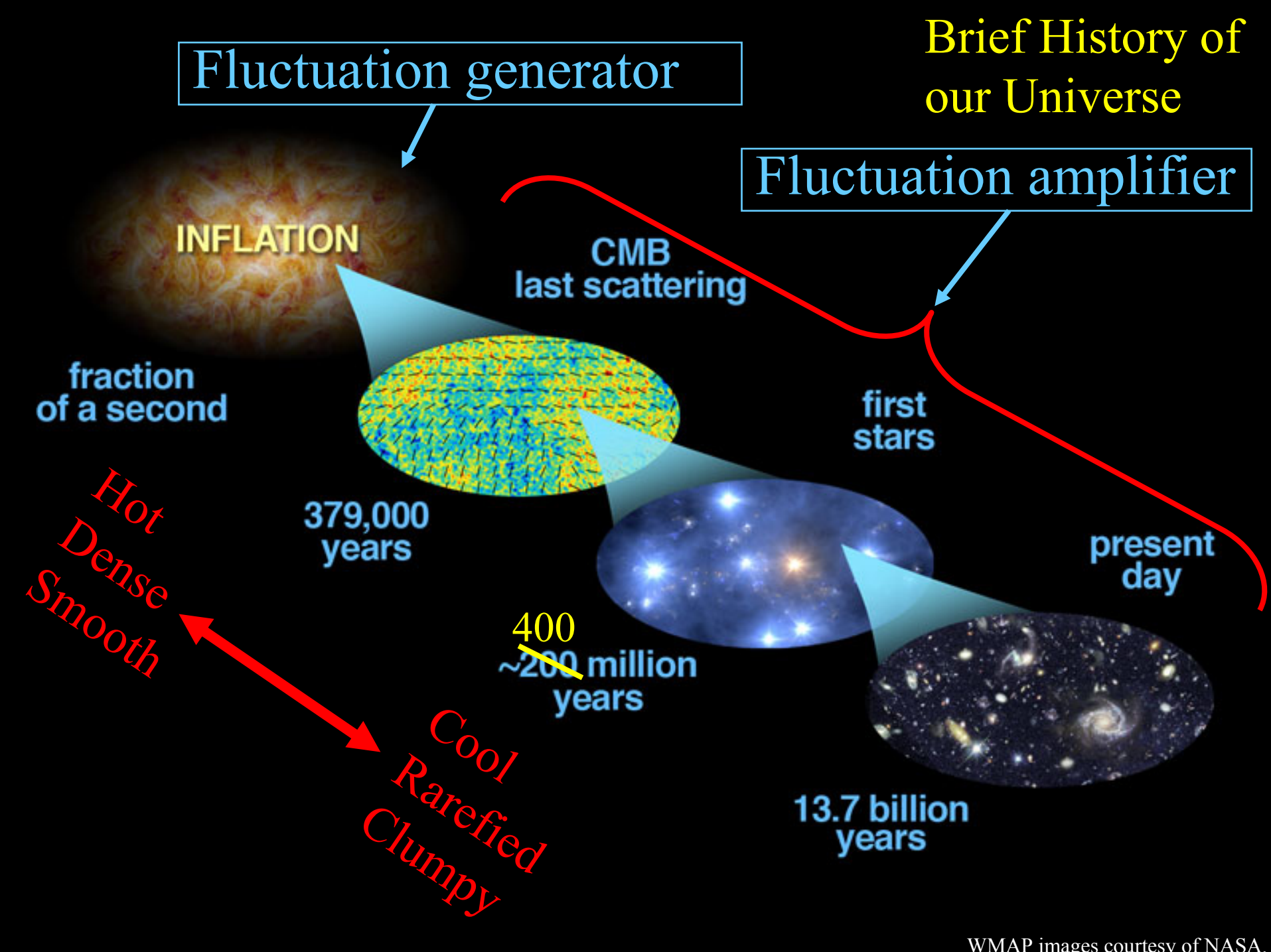
$$t(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')}$$

A brief history of our universe

Brief History of our Universe



WMAP images courtesy of NASA

Evidence for Big Bang:

- Observed galaxy recession (Hubble's law)
- Existence of CMB
- Correct predictions of big bang nucleosynthesis
- Darkness of night sky! (Olber)
- Distant objects look younger

Plenty enough bang for most people to call "big"…

Evidence for *what*, exactly?

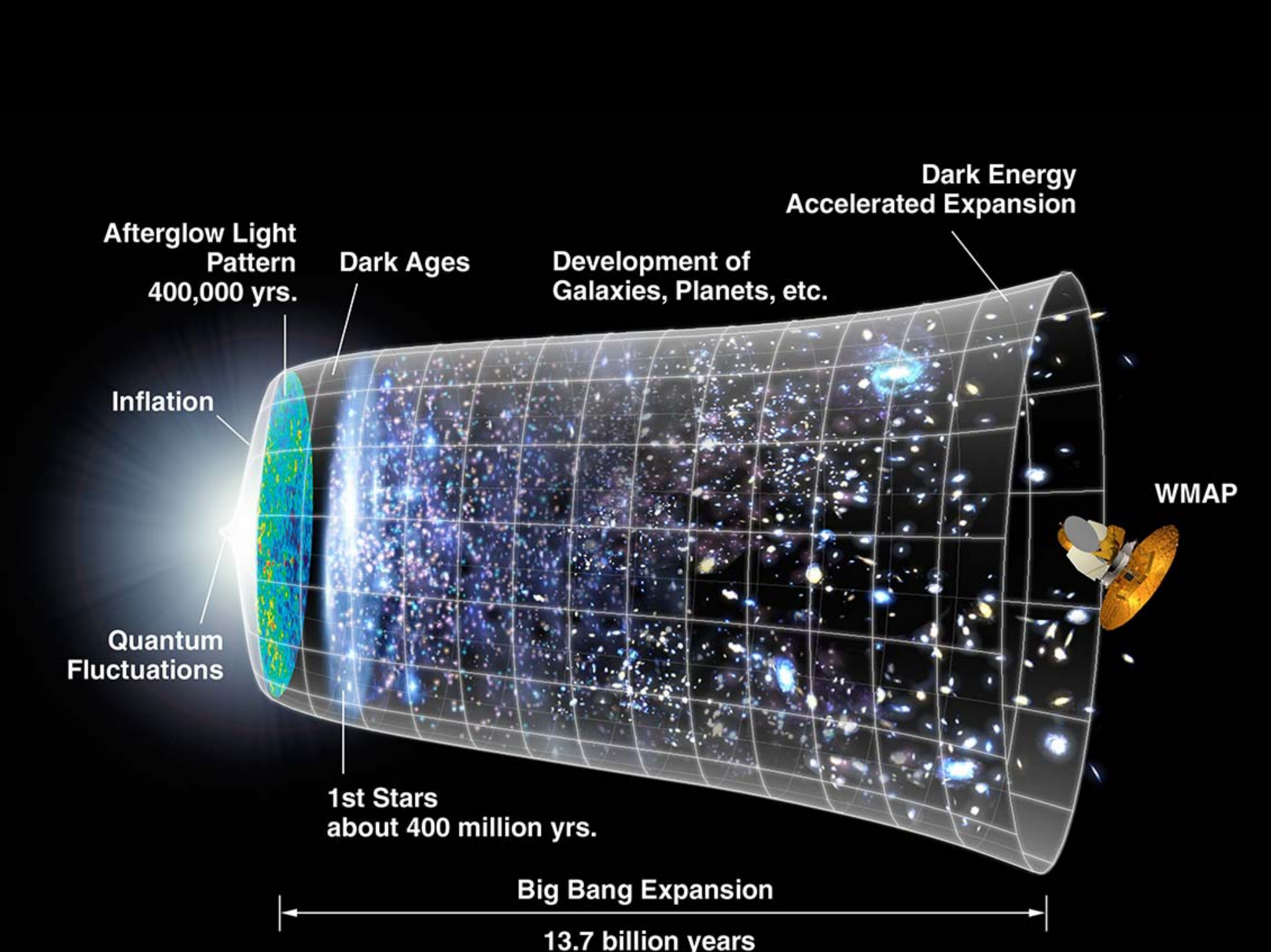
Our entire observable universe was once as hot as the core of the Sun, doubling its size in a under a second.

- *Not* evidence for a singularity

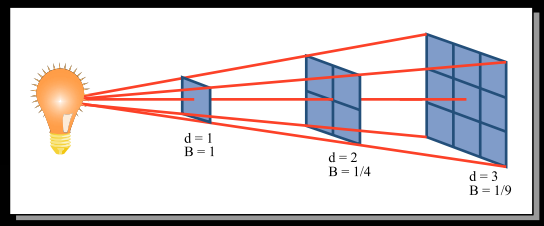
Evidence 1:

The Universe *is* expanding!

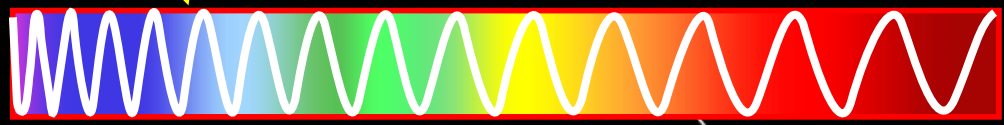
$v=Hr$


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Distant light is { -dimmed → -redshifted ↓



Figures by MIT OCW.



Afterglow Light Pattern 400,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Inflation

WMAP

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion

13.7 billion years

Distant light is { -dimmed
-redshifted

Redshift

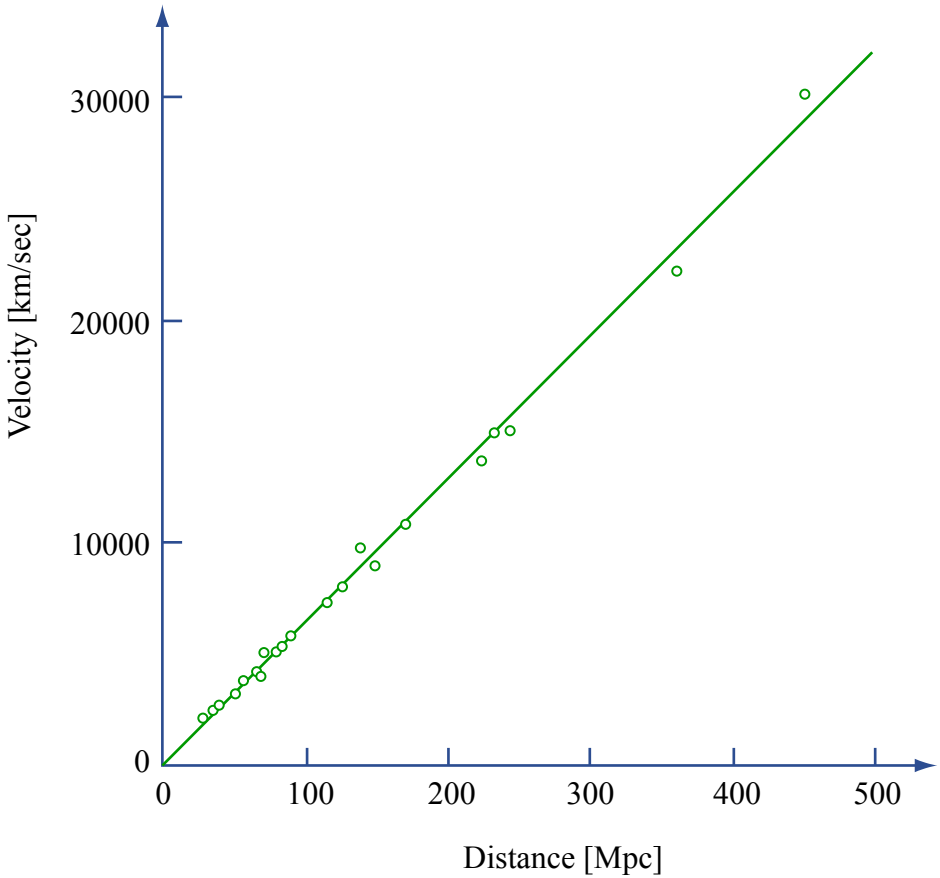


Figure by MIT OCW.

Dimming

Distant light is { -dimmed
-redshifted

Redshift

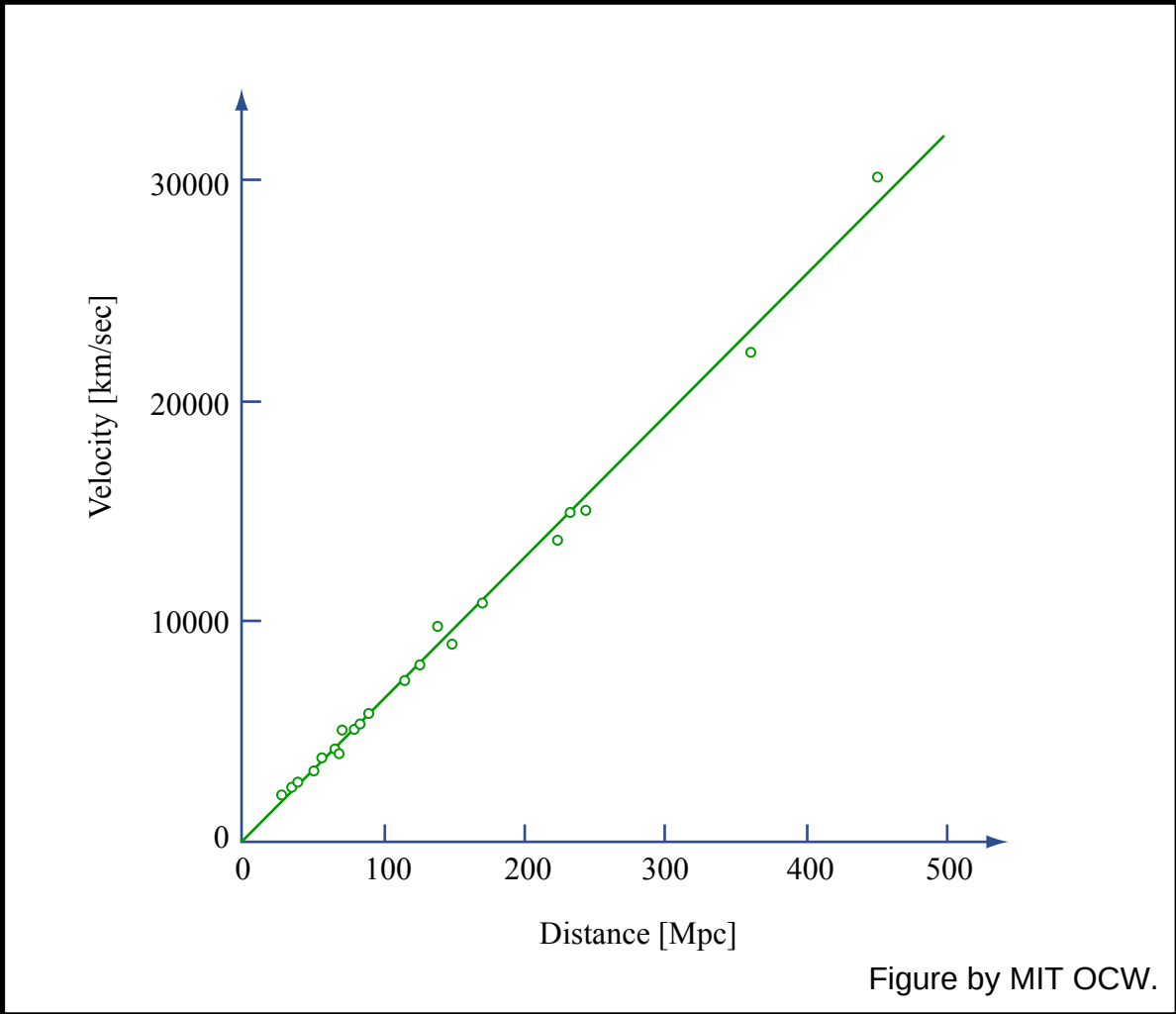


Figure by MIT OCW.

Standard candles, rulers or clocks → Dimming

Edwin Hubble 1889-

(American; 1930 paper)

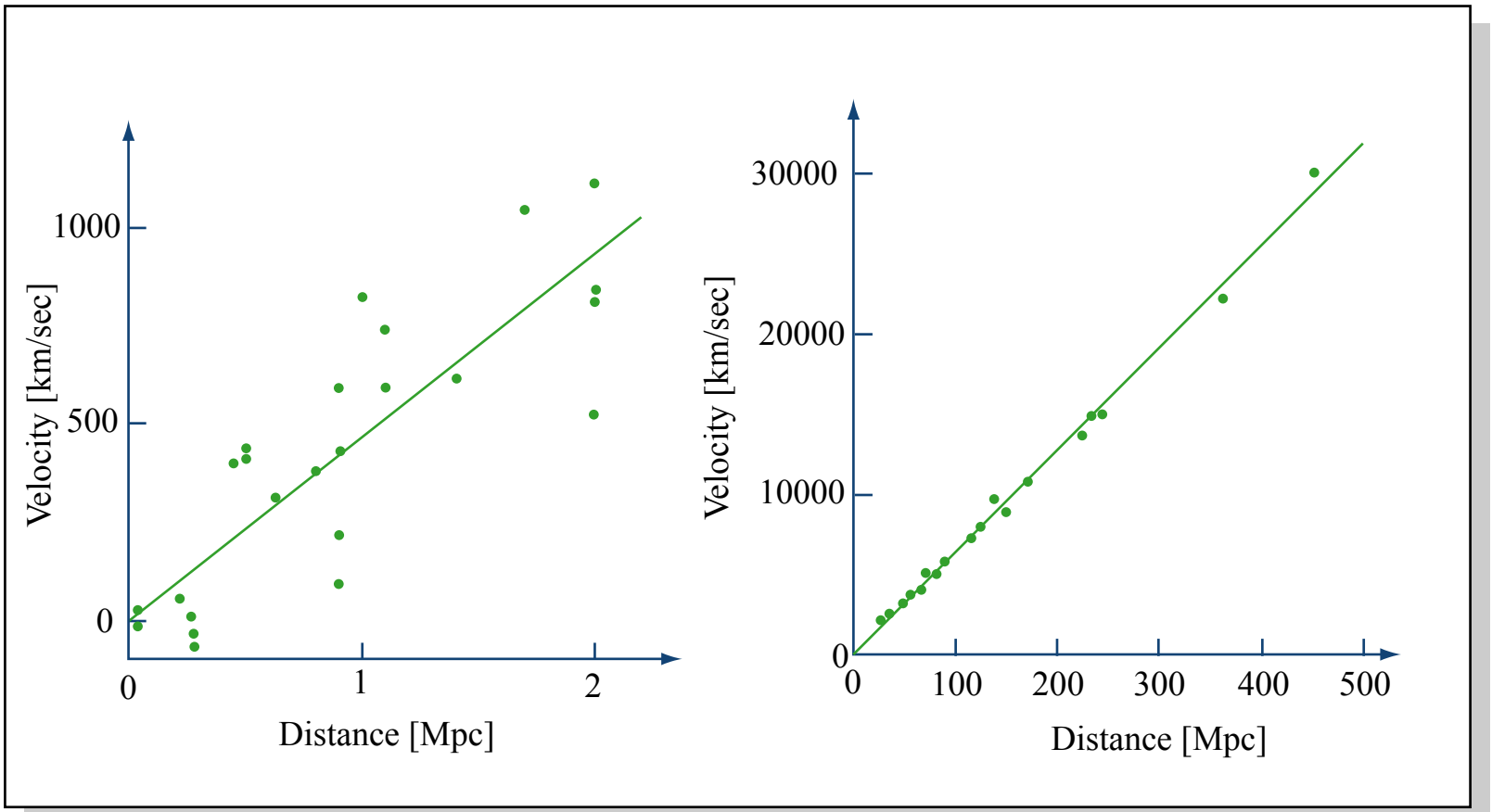
Mt. Wilson Observatory 1931

Hubble 1929:

H≈550 km/s/Mpc

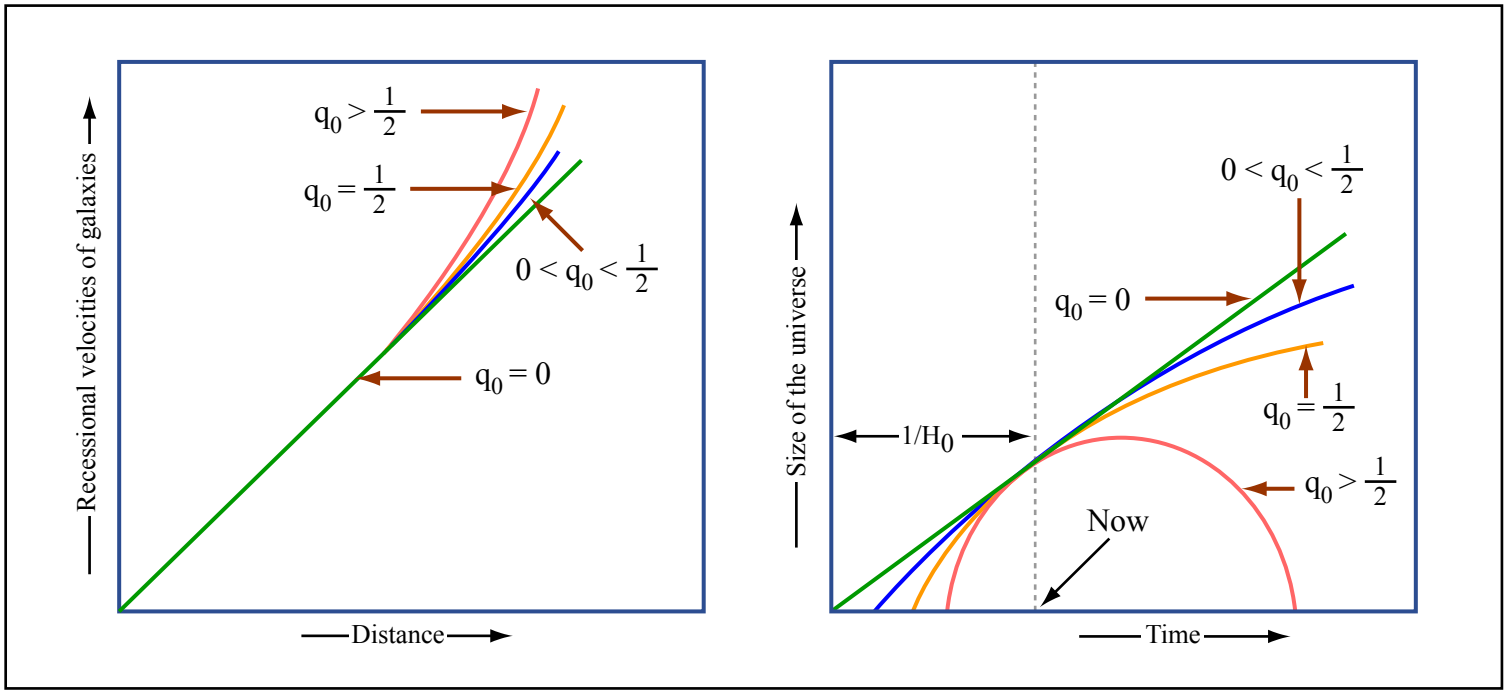
Riess et al 1996:

H≈70 km/s/Mpc



Figures by MIT OCW.

How measure distance & redshift?



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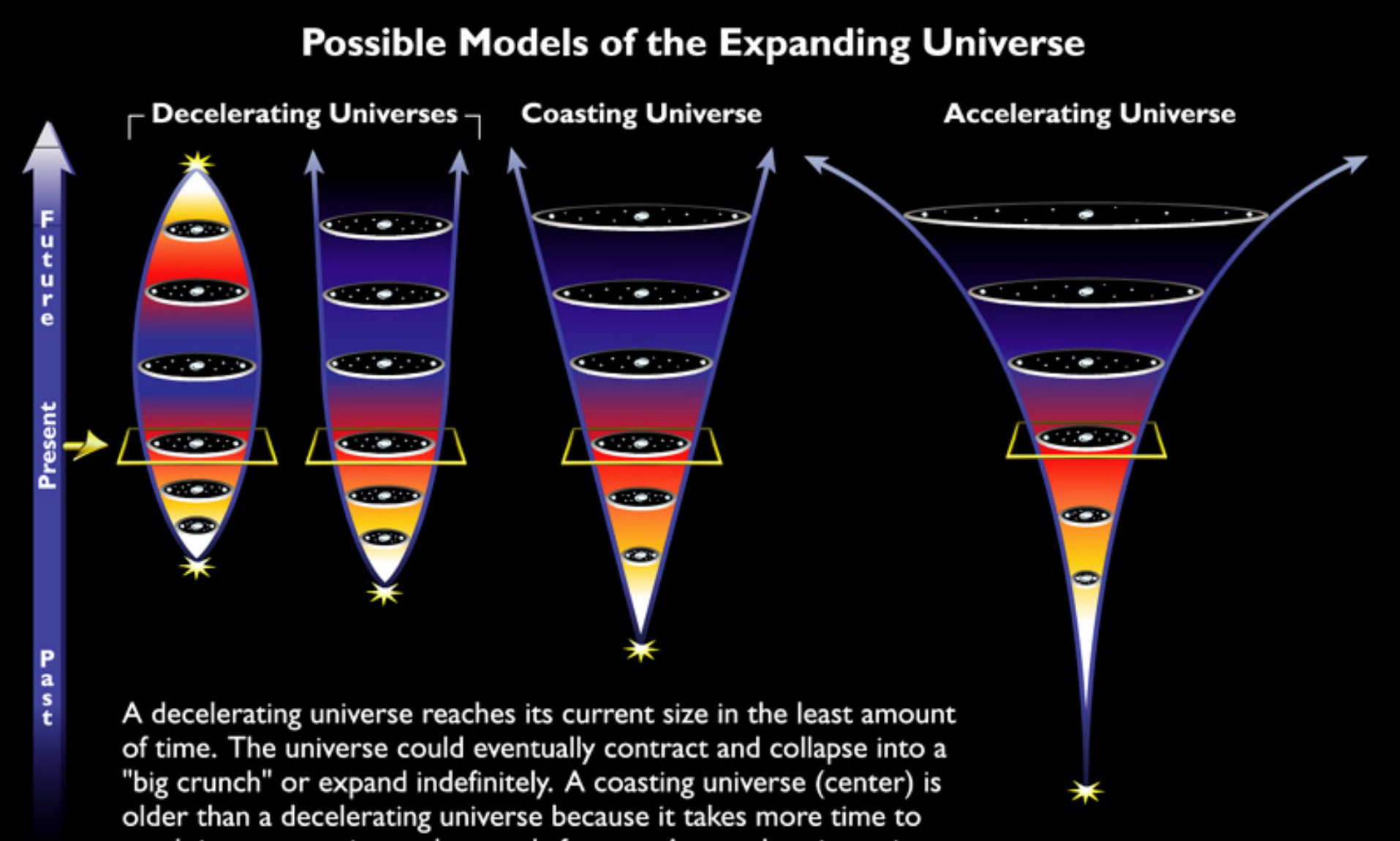


Figure from STScI/NASA

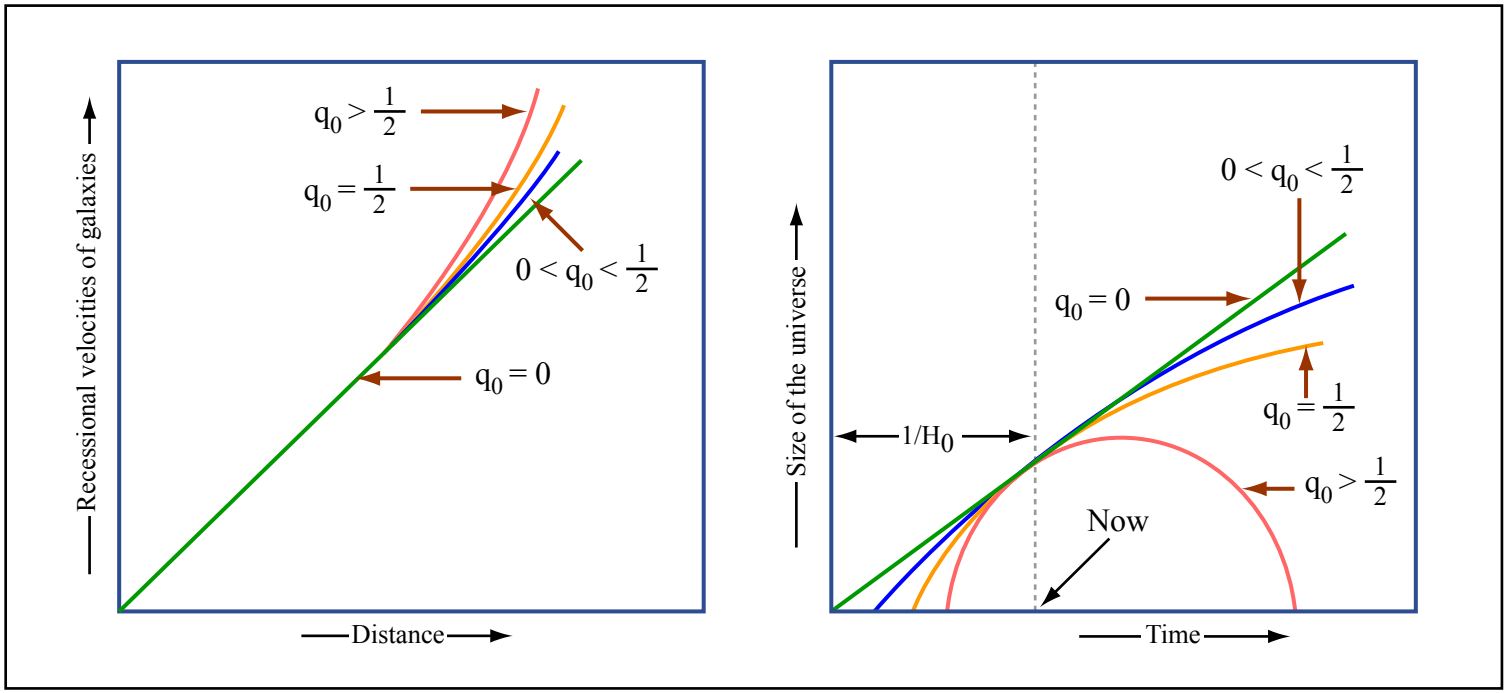


Figure by MIT OCW.

Figure 8 from "What is the Universe made of? How old is it?" by Charles Lineweaver.
http://arxiv.org/pdf/astro-ph/9911294

Evidence 2:

Cosmic microwave background exists

$T \approx 2.726K$

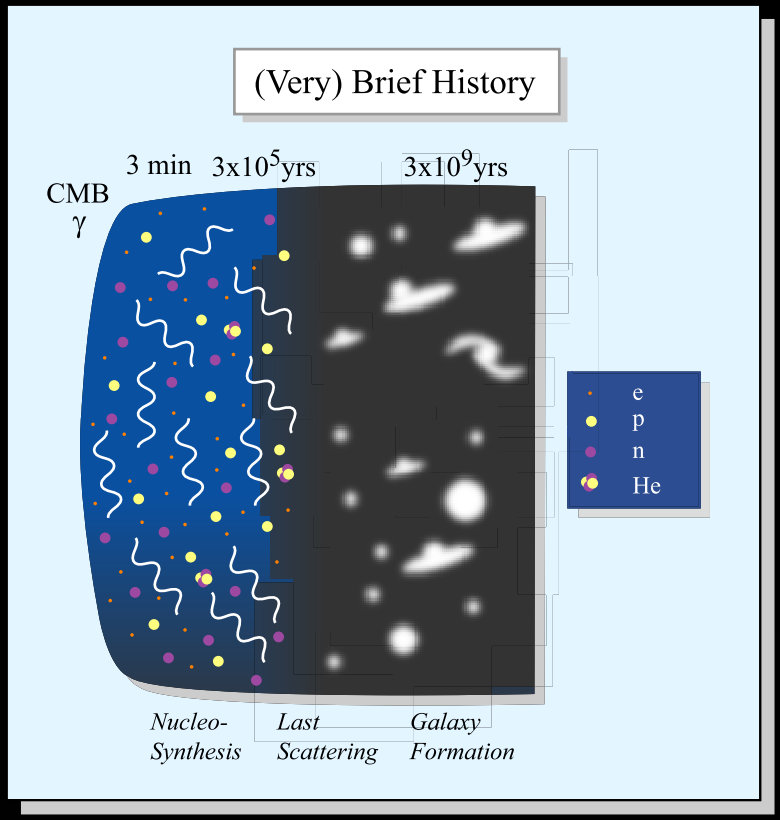


Figure by MIT OCW.

Image courtesy of WMAP/NASA.

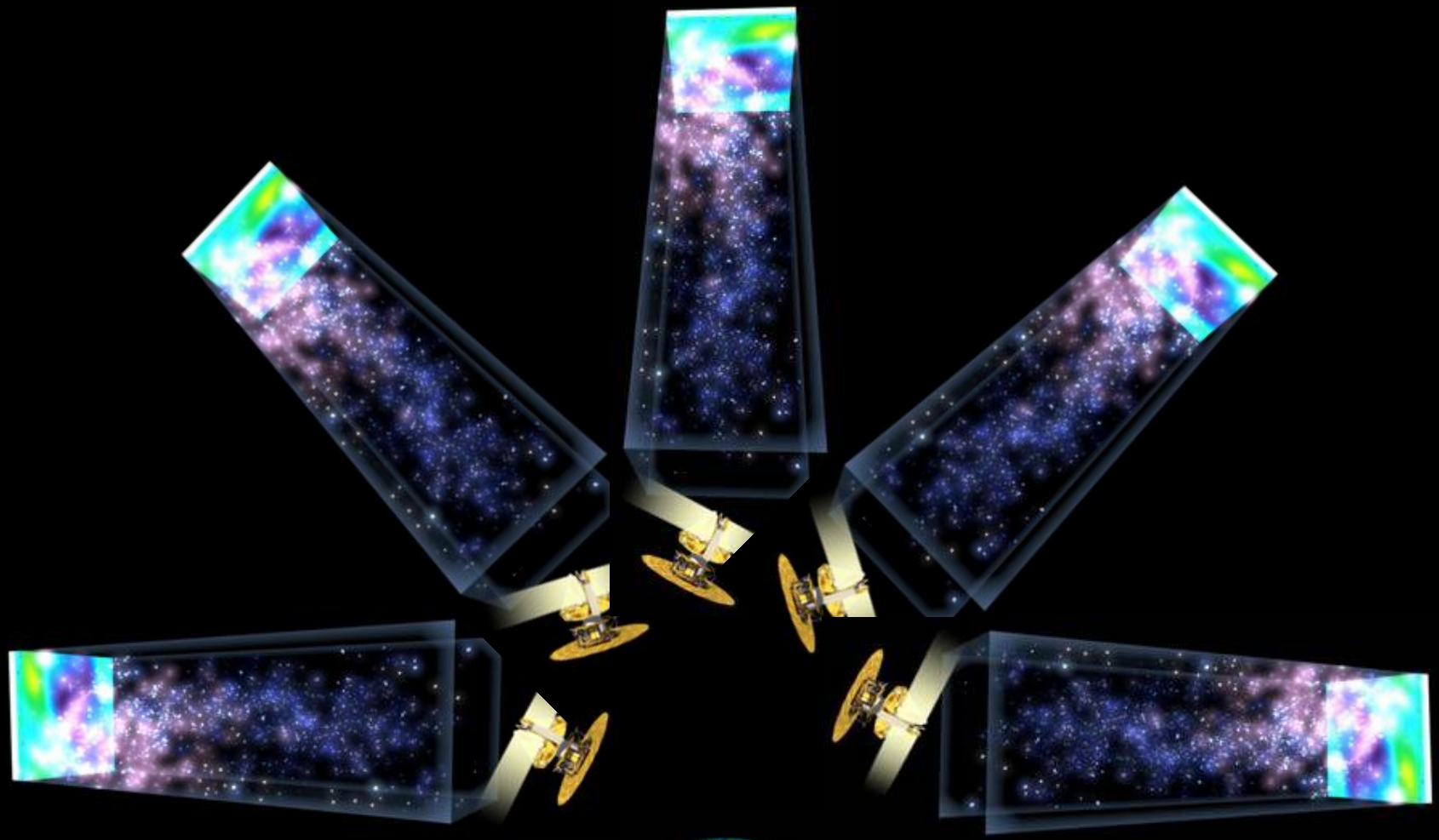


Image courtesy of WMAP/NASA.

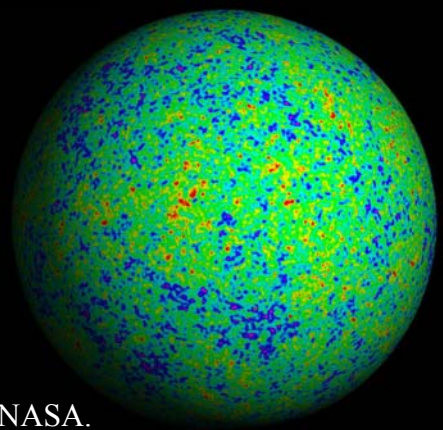


Image courtesy of NASA.

Figure 1 from Tegmark, de Oliveira-Costa & Hamilton, “A high resolution foreground cleaned CMB map from WMAP.”

http://arxiv.org/abs/astro-ph/0302496

Arno Penzias & Robert Wilson 1965

Arno Penzias 2005

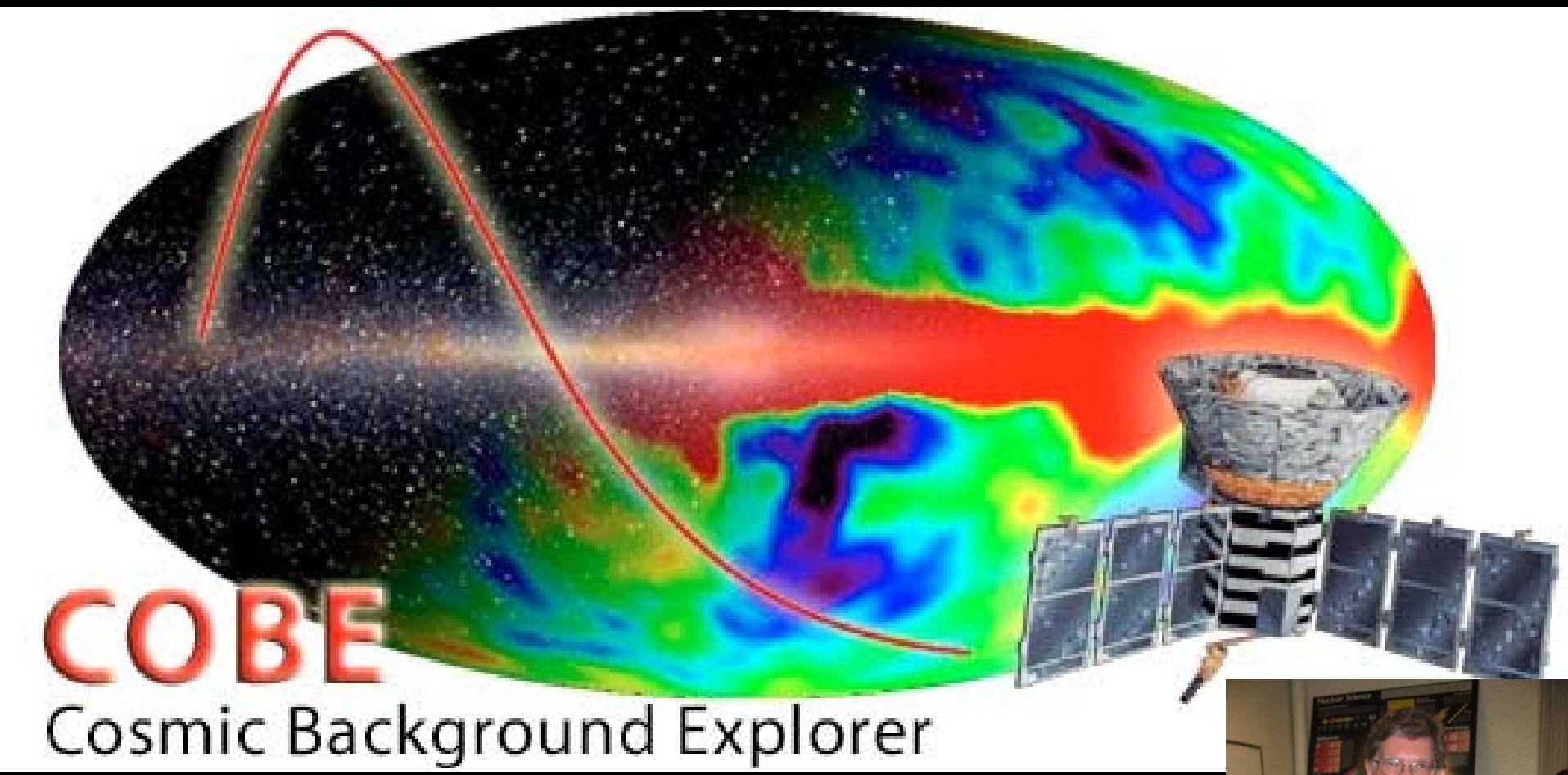
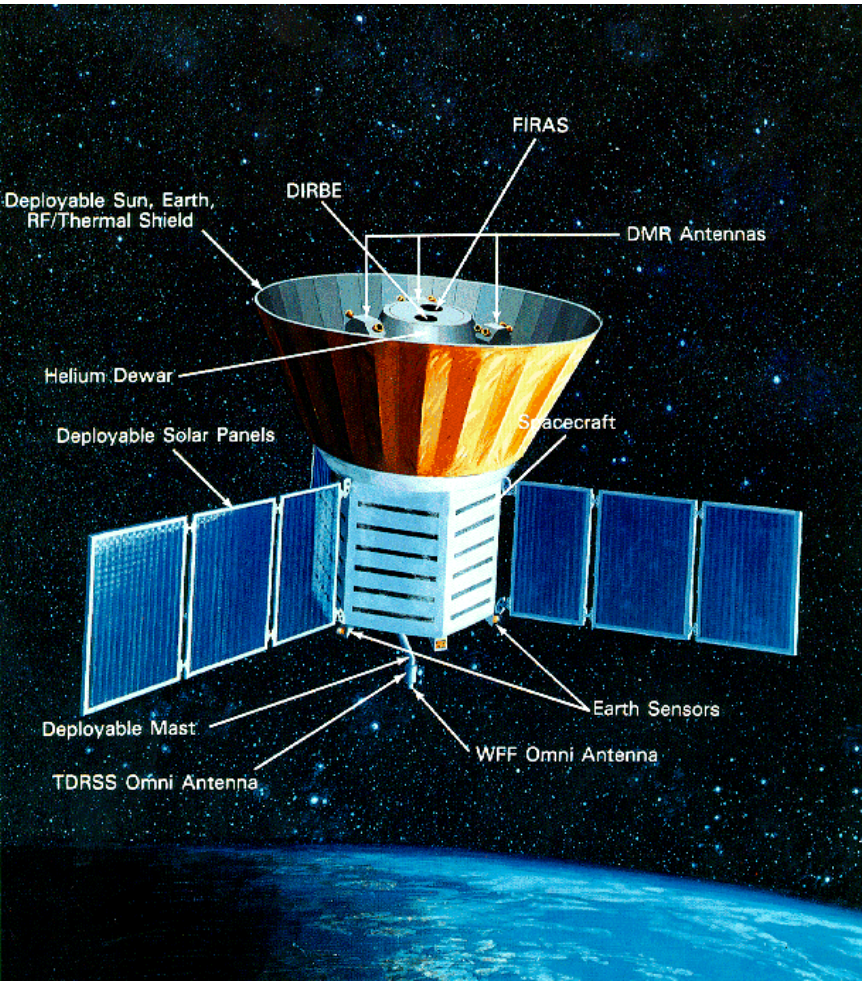


Image courtesy of NASA.

2006 Nobel Prize in Physics: George Smoot (pictured, graduated from MIT) and

Other people associated with MIT who worked on COBE:
Chuck Bennett, Ed Cheng, Steve Meyer, Rai Weiss & Ned Wright

Image courtesy of Wikipedia.



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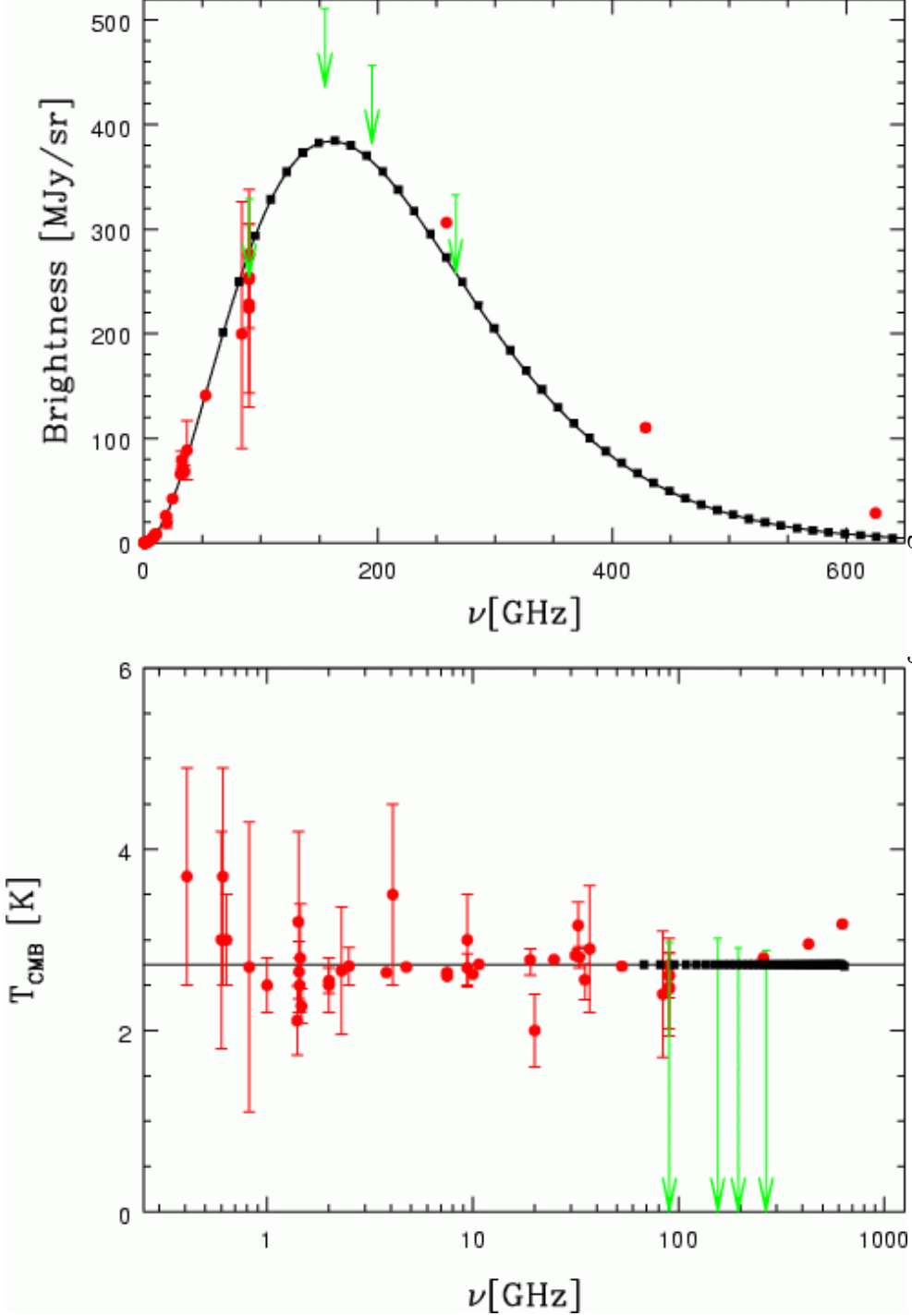

Image courtesy of NASA.

Evidence 3:

Big Bang Nucleosynthesis happened

(correctly predicts the abundance of light elements)

George Gamow
1904-1968
(Ukrainian)

CMB

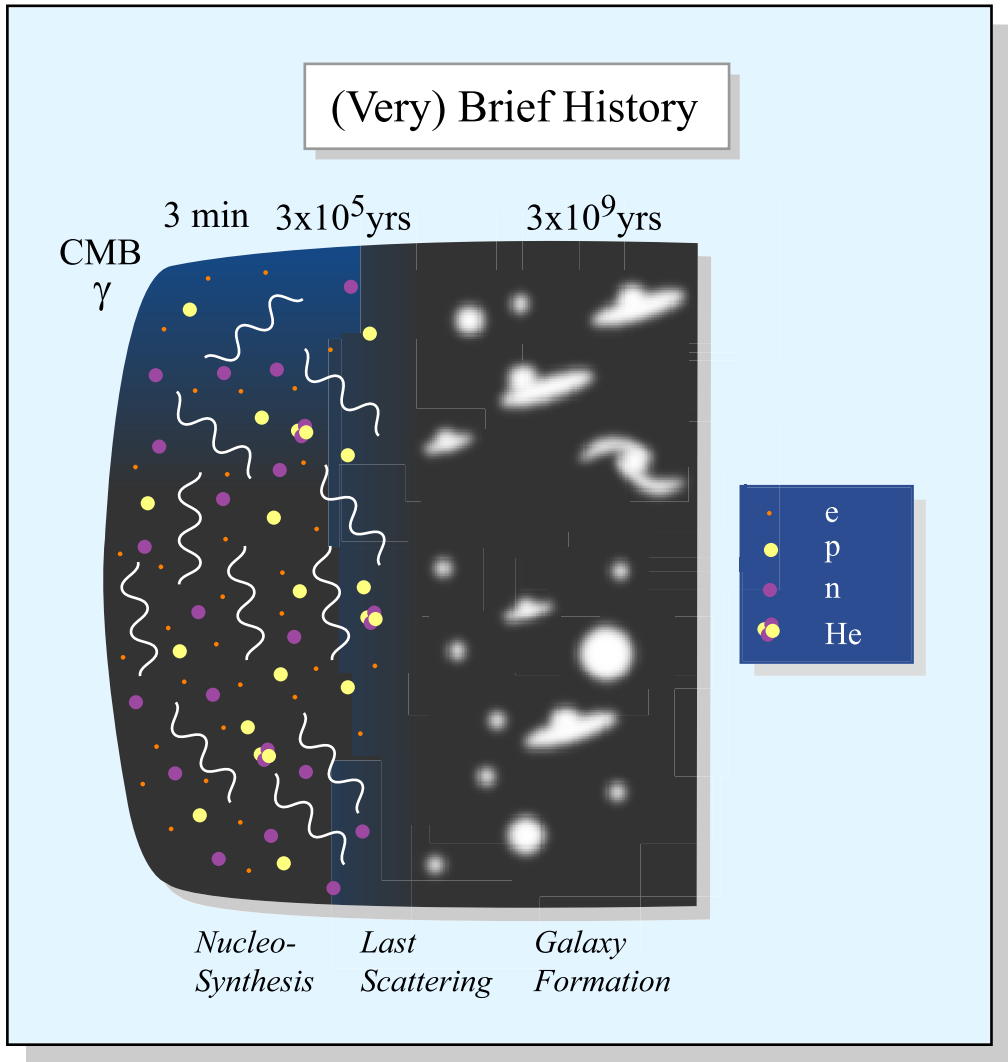

Figure by MIT OCW.

Figure 2 from Tytler et al 2000,
"Review of Big Bang Nucleosynthesis and Primordial Abundances"
http://arxiv.org/abs/astro-ph/0001318

Evidence 4:

The fine details of cosmic clumpiness