Week 15 Tuesday

Today's Agenda
- Extragalactic distances
- Large Scale Structure (LSS)
- Evolution
- Early Universe

Announcements / Reminders
- HW 10 due this Friday @11:59pm
  - HW 11 also available, due next week
- Read Chapters 20 & 23.0-3 (& 24)

- HEAP TODAY @ 4pm
  - LSS / Cosmology probed through weak lensing!
- Colloquium Friday @ 2pm
  - Intercellular Communication & Drug Delivery

Project Presentations

- ~20 groups, need to get through 10+ per day
- Aim for ~5 min presentations
- 10% of your course grade is based on class participation (attendance / asking questions / group work)
  - Asking questions after presentations counts toward your participation!
  - Completing Feedback forms also counts (but less)
- Project is 20% of your course grade (3/4 project, 1/5 prez, 1/20 paragraph description)

Your Name: ______________

Interpreting & Communicating Science: Peer Feedback

Provide constructive criticism on your peers' projects. Feedback will be distributed anonymously.

Presenter Name(s): ___________________________

Did the project and presentation improve your understanding of the concept?

____

Which aspect did you feel was most instructive?

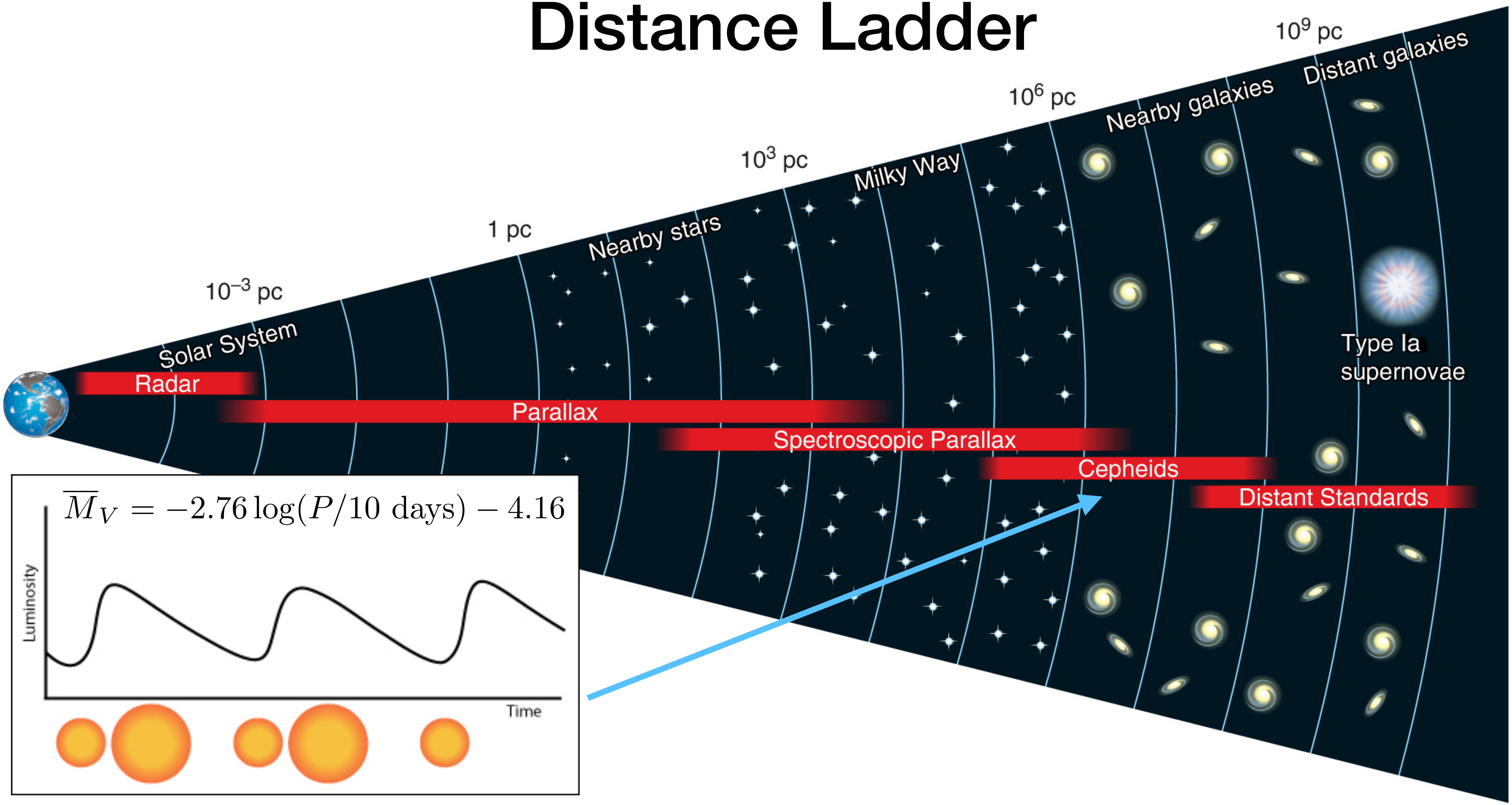
Project Presentation Both were equally useful Neither were useful

Any suggestions for how the final copy could be improved before it is submitted:

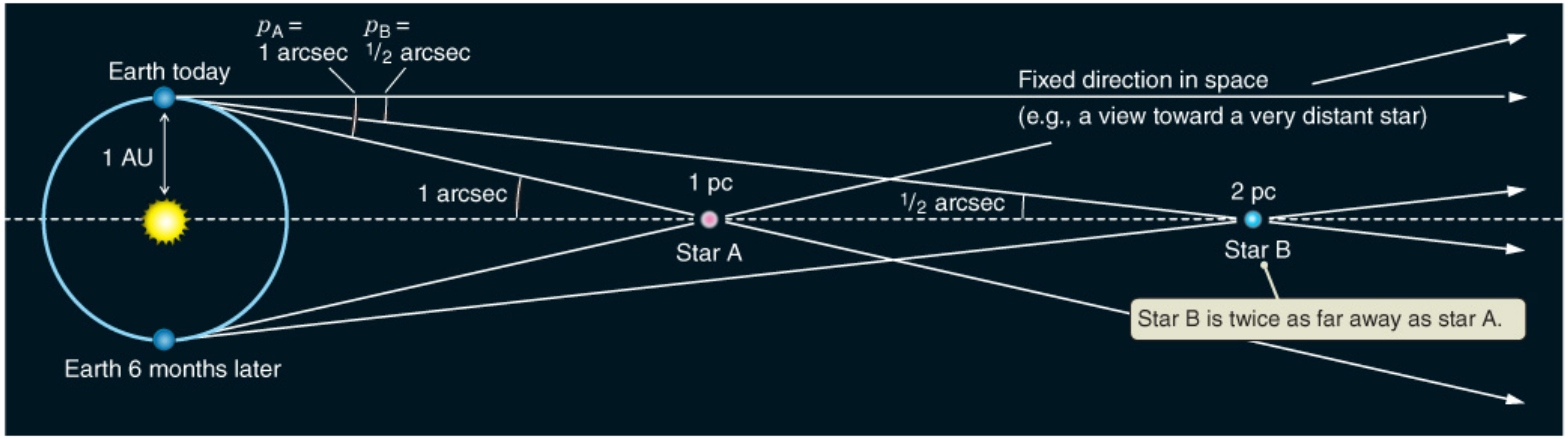
December 15th:
Archival Copy of Project Due

December 17th:
Final Exam

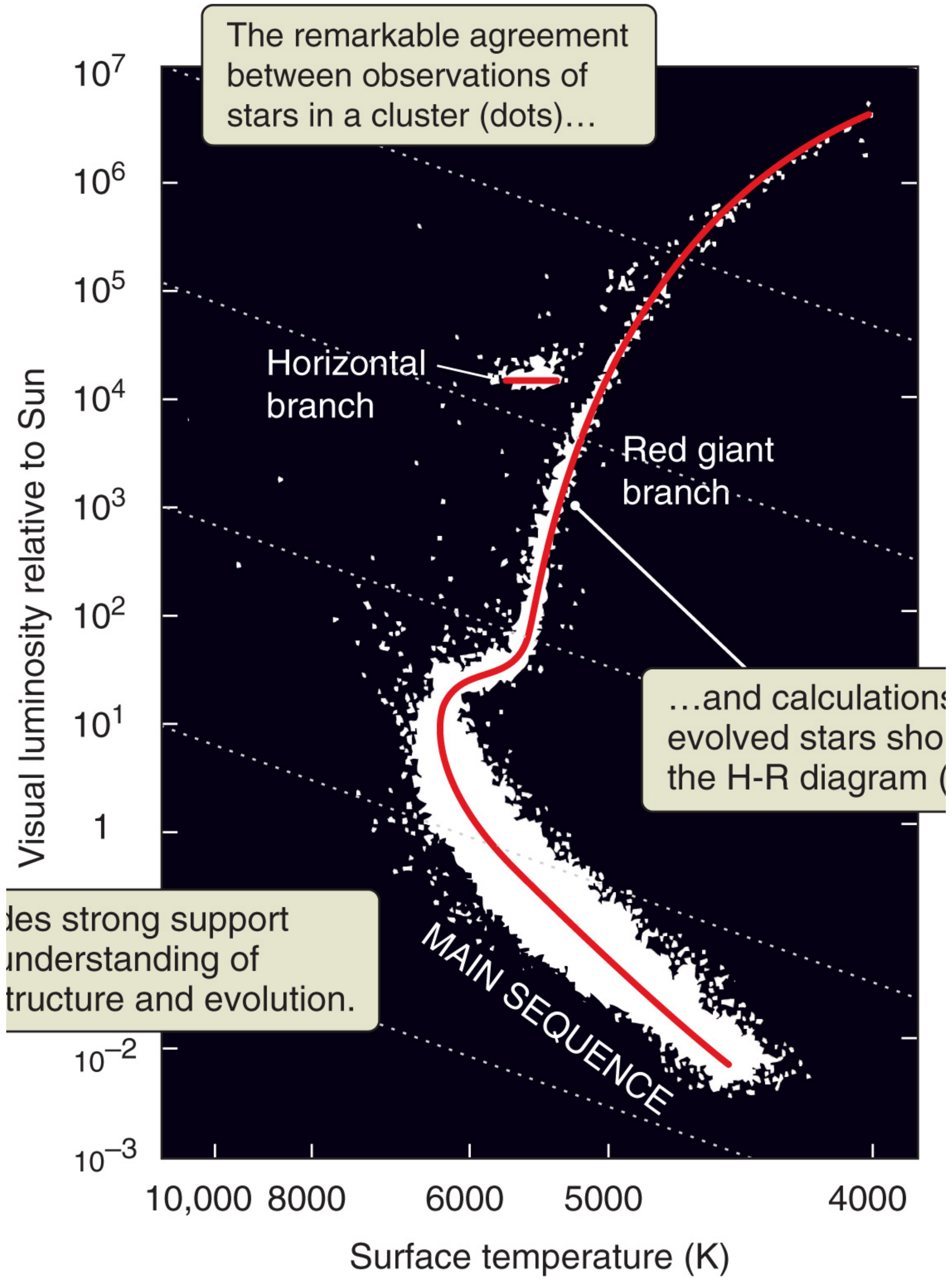
Distance Ladder



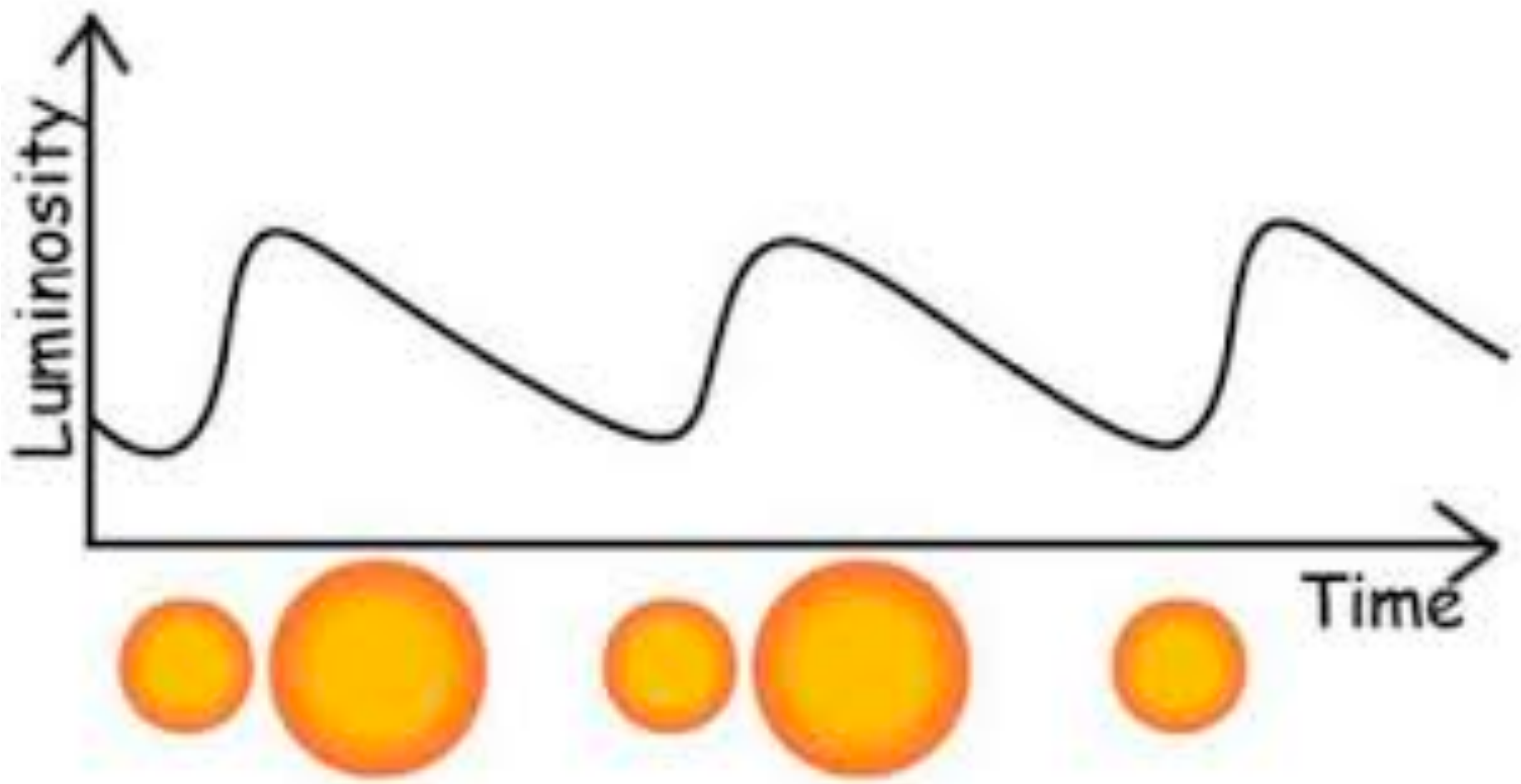
Parallax



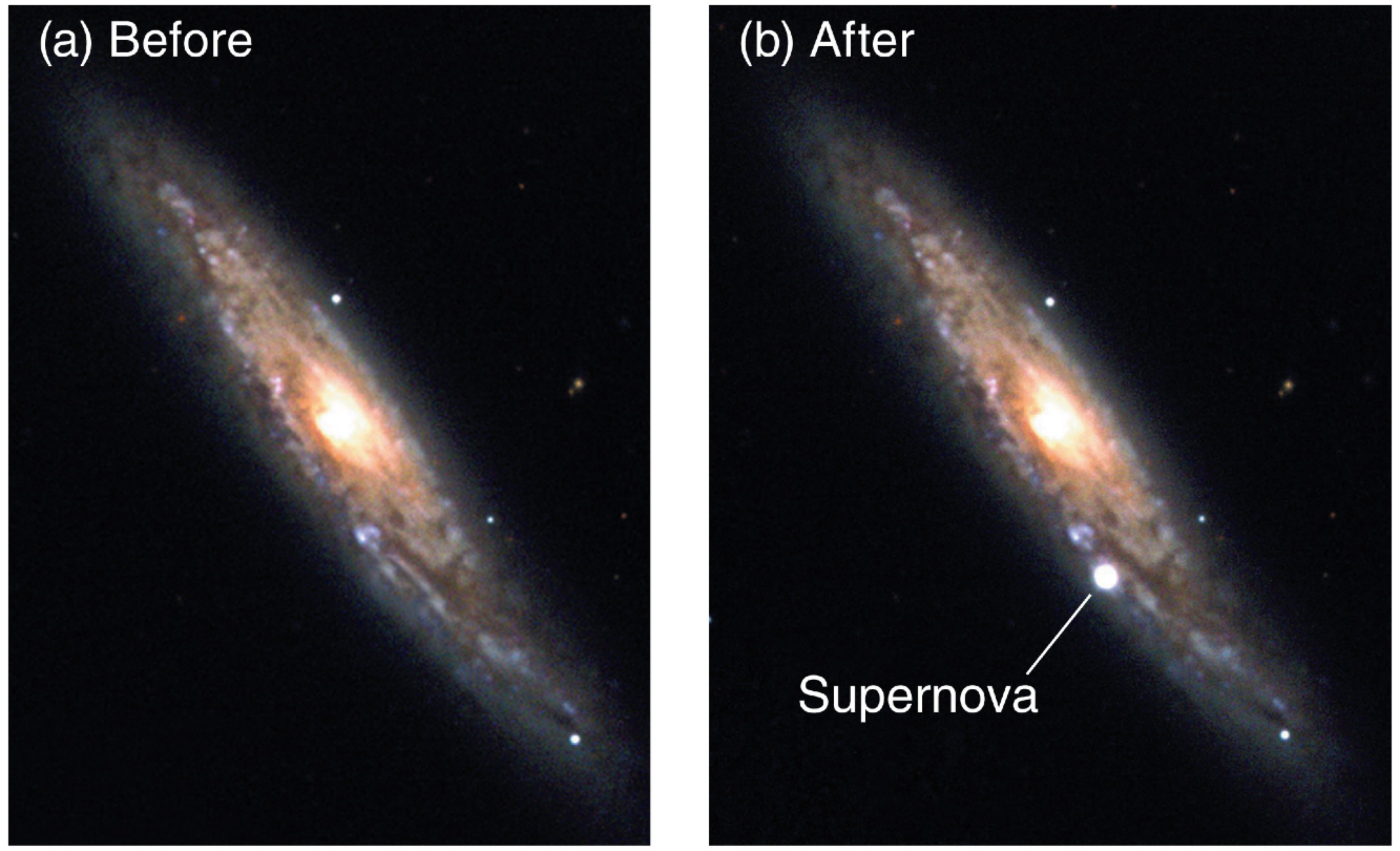
Spectroscopic Parallax



Cepheid Variables

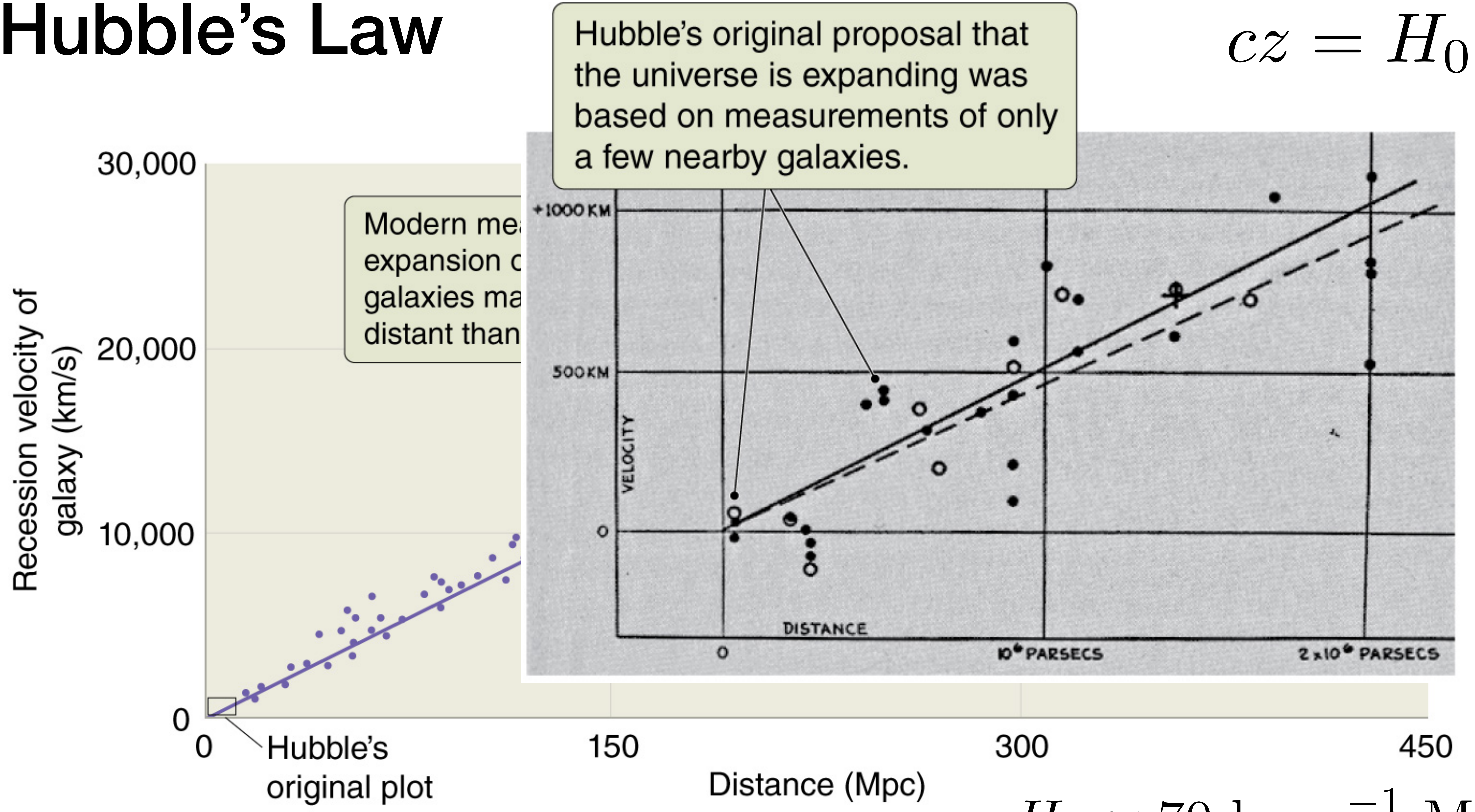


Type Ia SNe



Hubble's Law

$$cz = H_0 d$$



cz

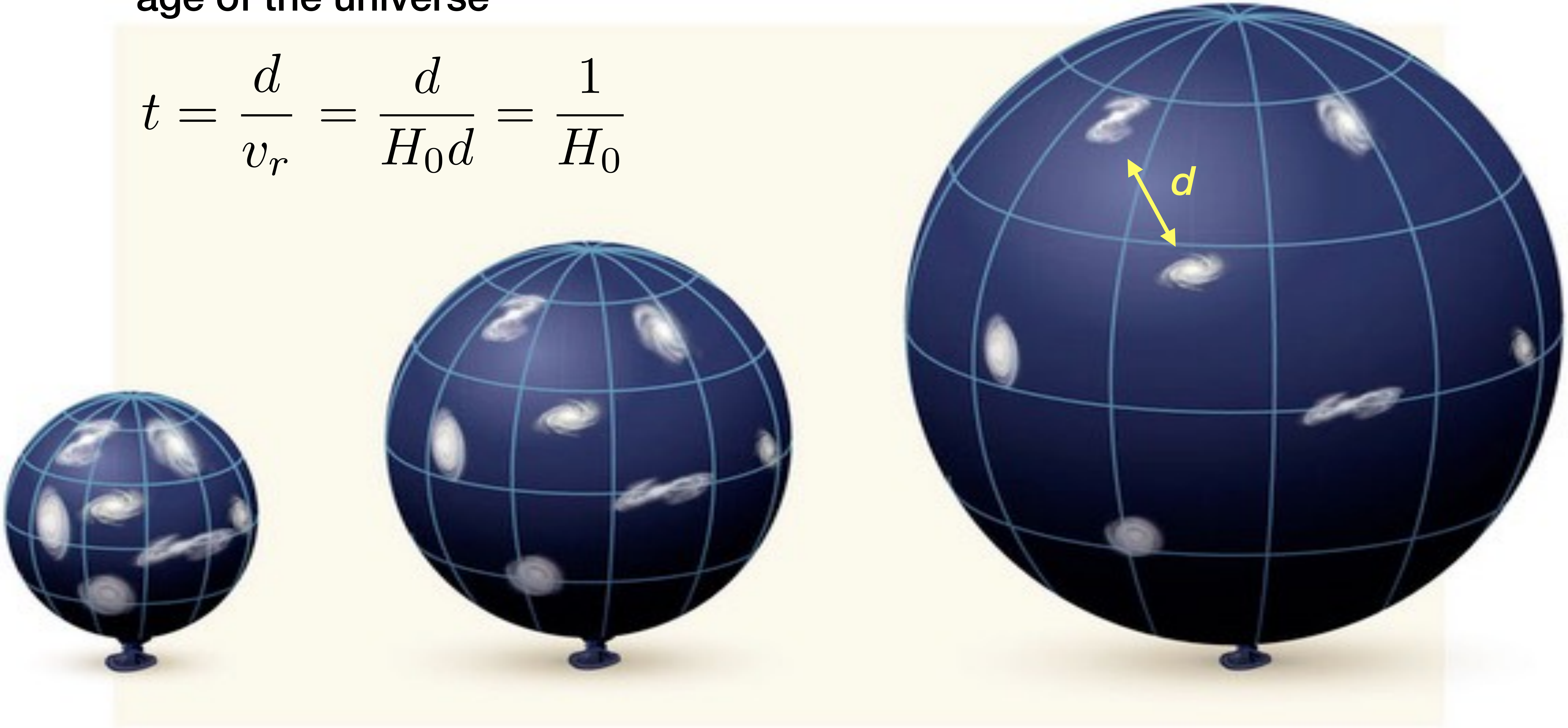
d

$$H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

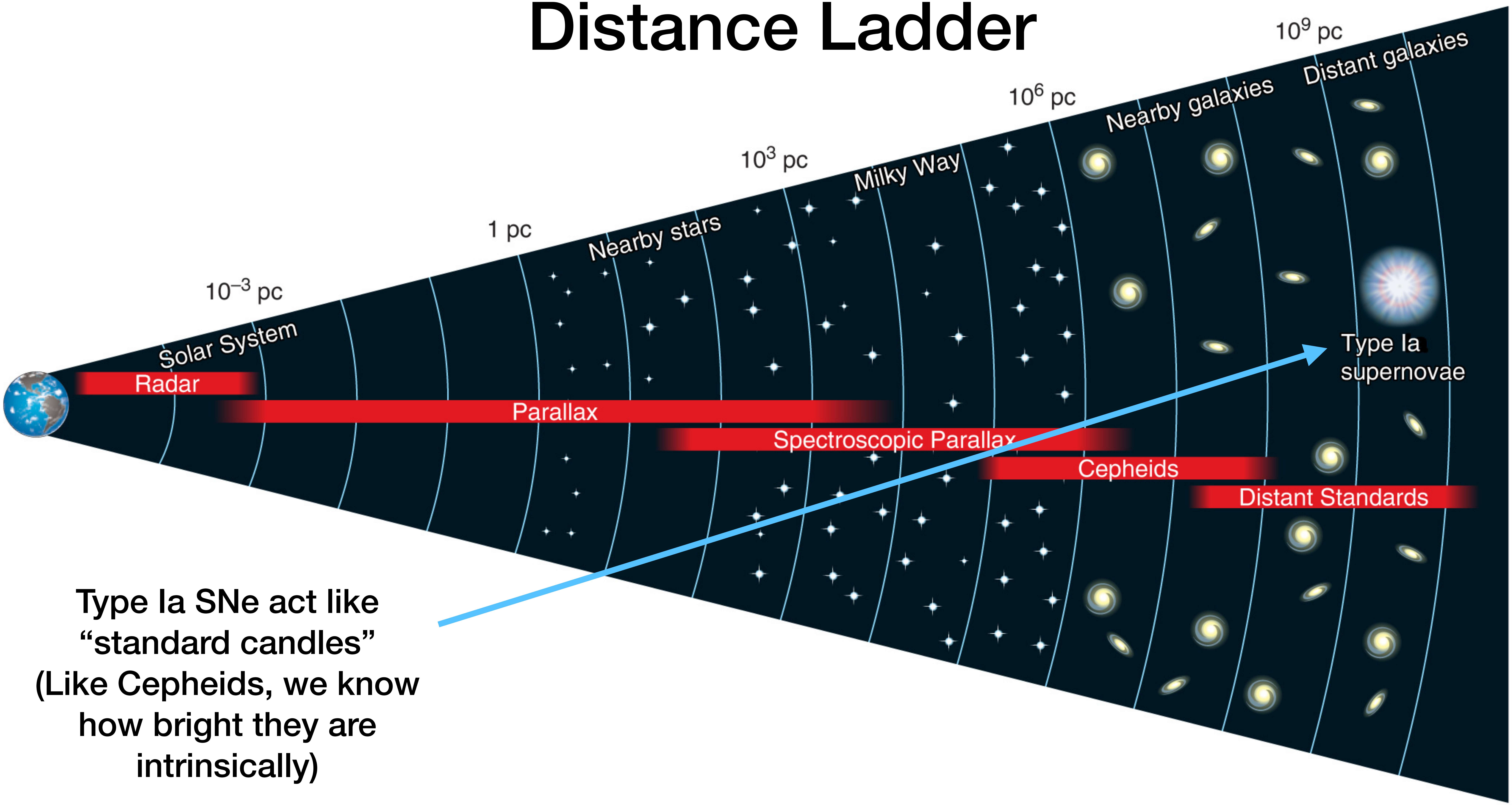
We live in an expanding “balloon universe”

If expansion constant, then can estimate the age of the universe

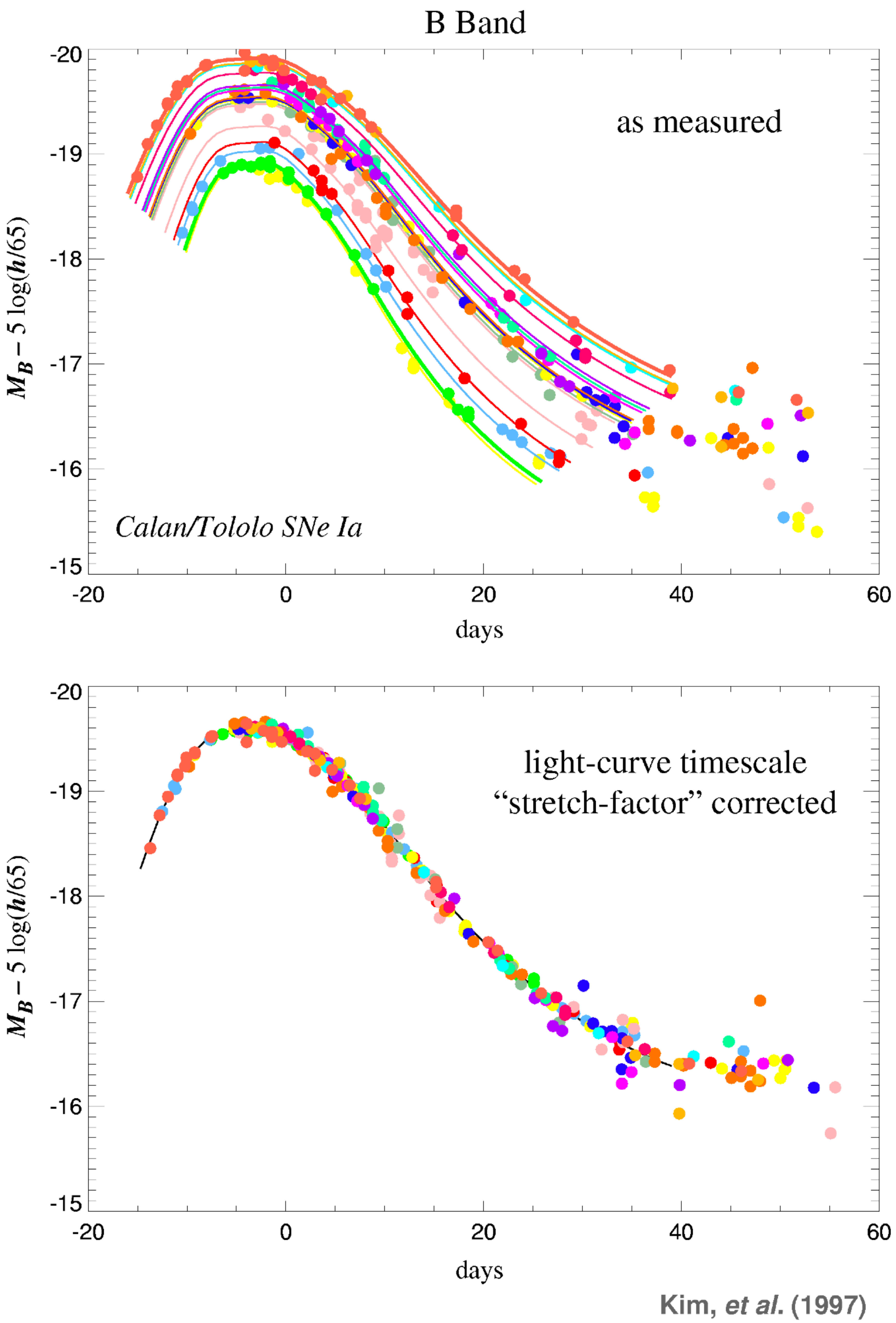
$$t = \frac{d}{v_r} = \frac{d}{H_0 d} = \frac{1}{H_0}$$

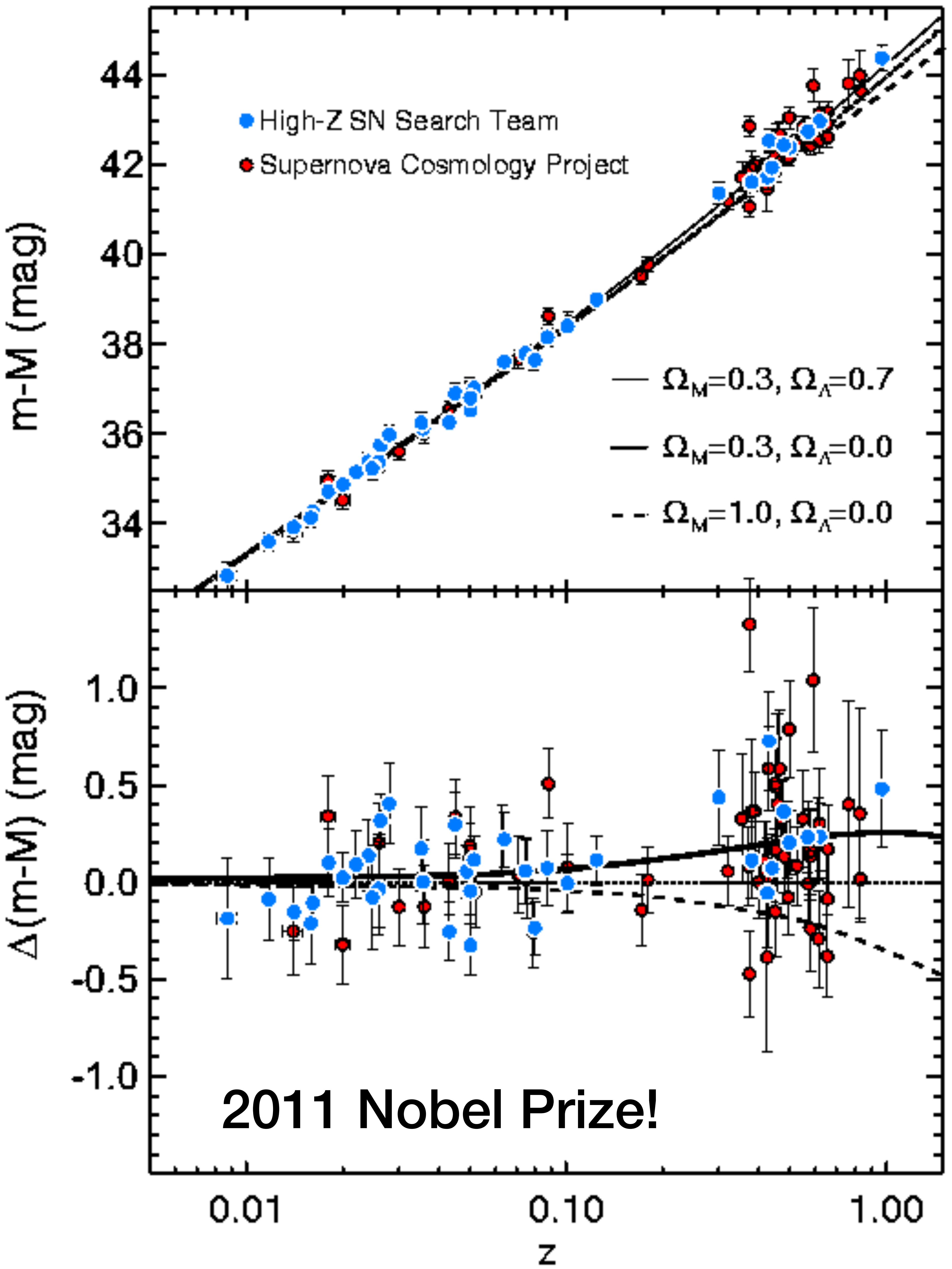


Distance Ladder

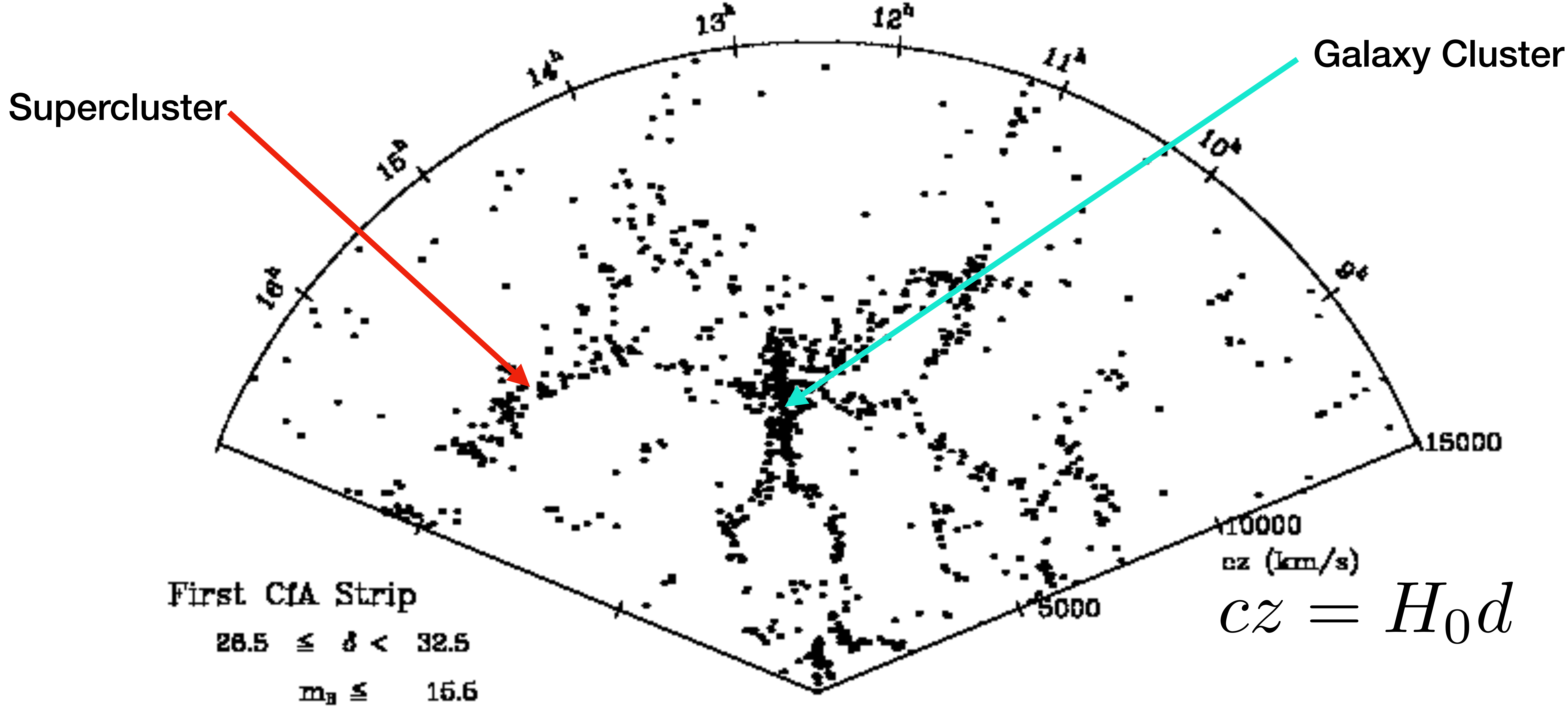


Type Ia SNe act like "standard candles" (Like Cepheids, we know how bright they are intrinsically)


B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
light-curve timescale
"stretch-factor" corrected
Kim, et al. (1997)


High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
2011 Nobel Prize!
z

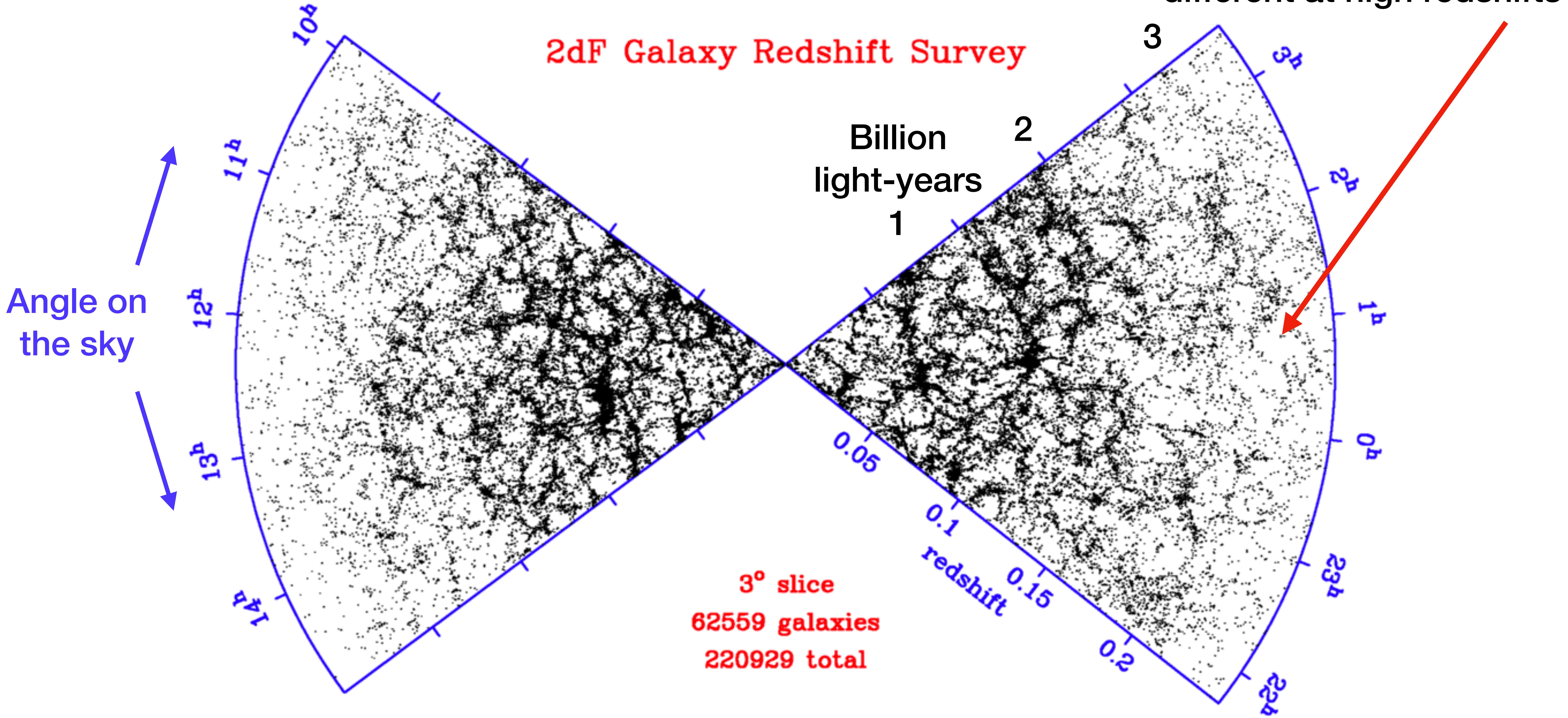
Finger of God: the Coma Cluster



$$cz = H_0 d$$

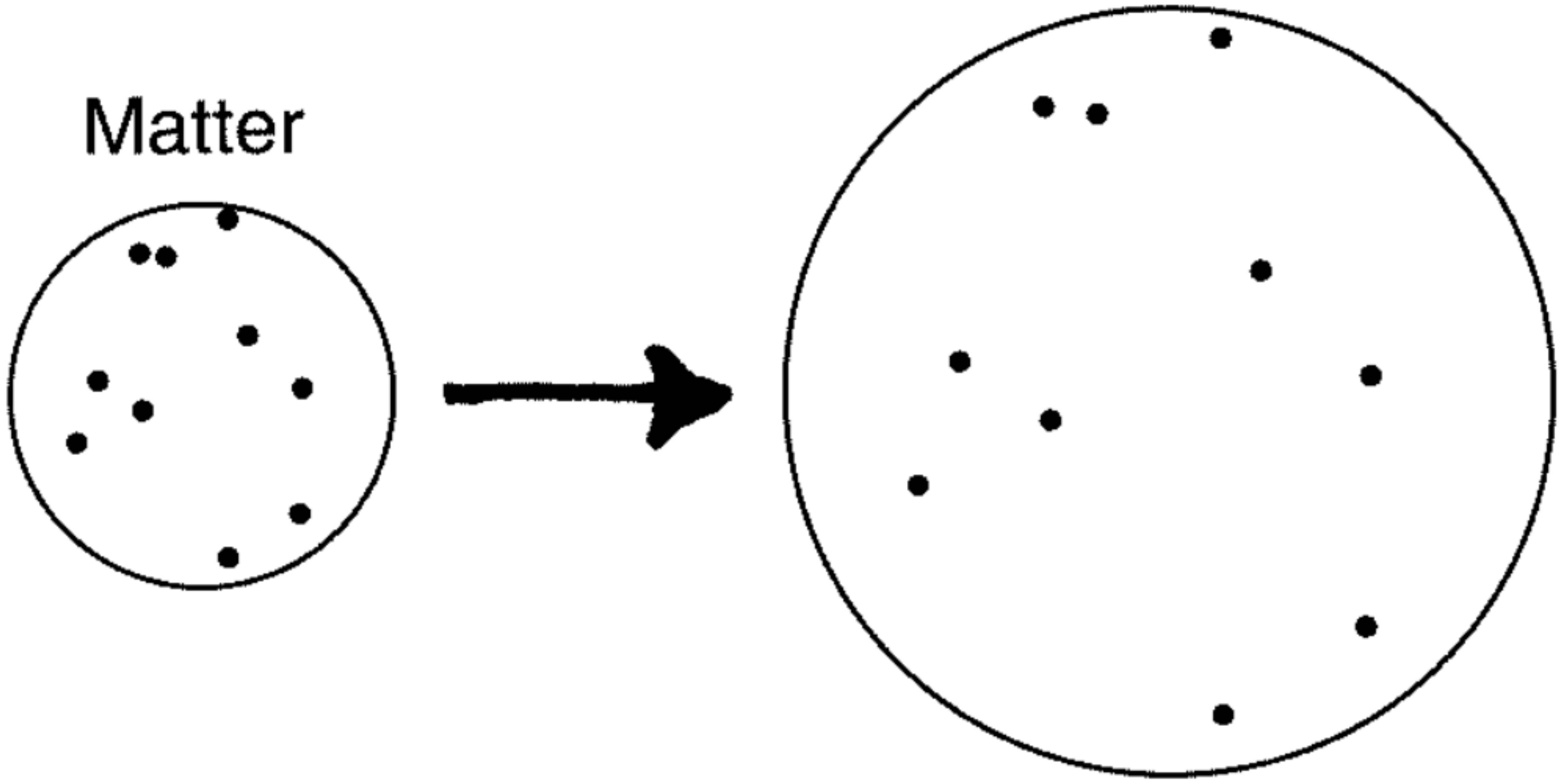
Galaxy Surveys

Why does the pattern look different at high redshifts?



Cosmology

How does the expansion speed change with time?



When dense, the gravitational force is stronger
(But also the expansion speed was higher)

Like shooting a cannonball straight up:

1) $v < v_{esc}$: go up and come back down
2) $v = v_{esc}$: stop when infinitely far away
3) $v > v_{esc}$: reach coasting velocity

Same is true if all particles exploding away from each other

Friedmann Equation

Master equation of the universe

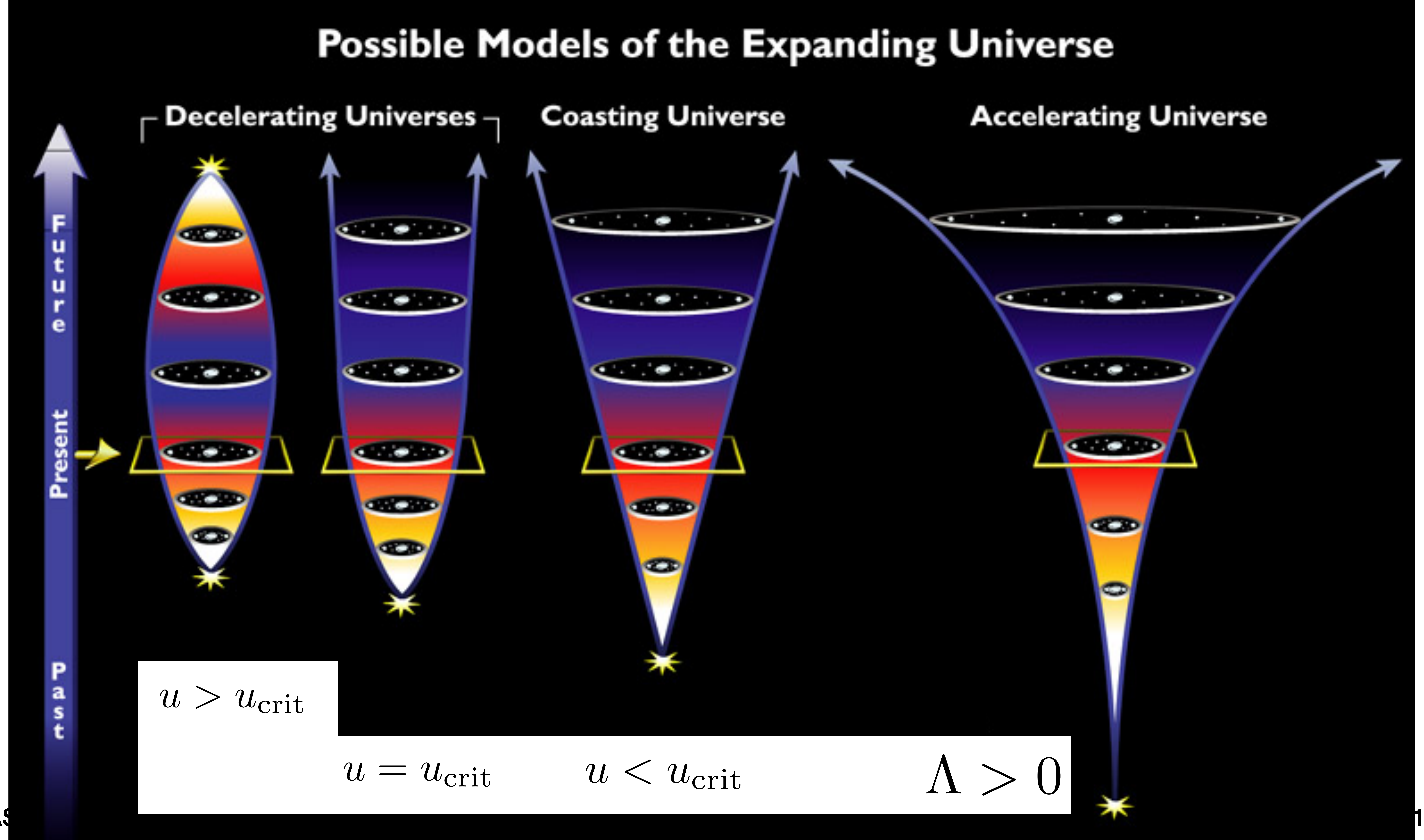
Curvature of space
(Flat =0, spherical <0, or hyperbolic >0 geometry?)

Cosmological constant
(Dark energy)

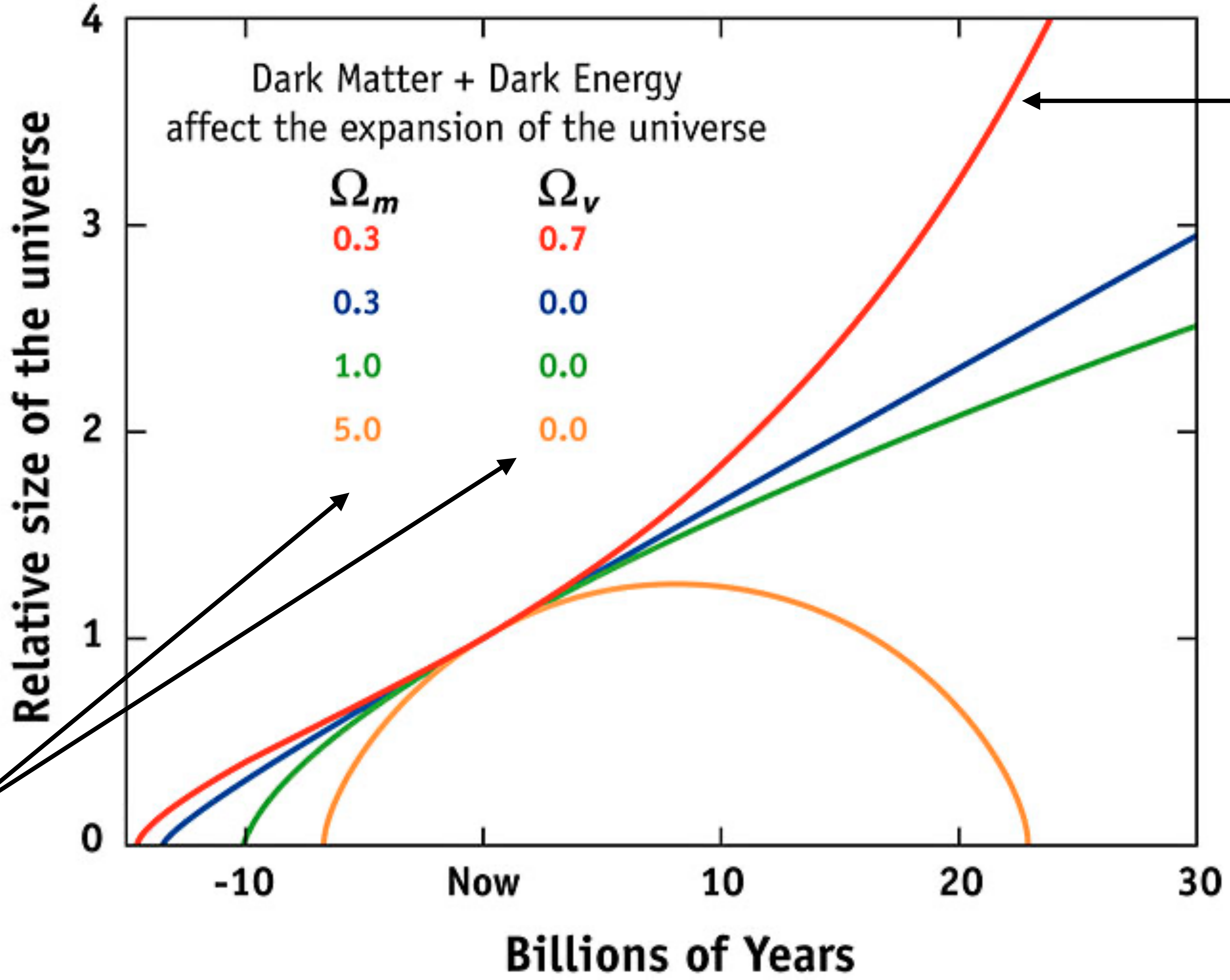
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}u(t) + \frac{\kappa c^2}{r_{c,0}^2}\frac{1}{a(t)^2} + \frac{\Lambda}{3}$$

Hubble parameter
(Speed of expansion)

“Energy density”
(Sum of rest mass & KE of all particles + radiation)


Possible Models of the Expanding Universe
Decelerating Universes
Coasting Universe
Accelerating Universe
Future
Present
Past
$u > u_{\text{crit}}$
$u = u_{\text{crit}}$
$u < u_{\text{crit}}$
$\Lambda > 0$

Expansion of the Universe

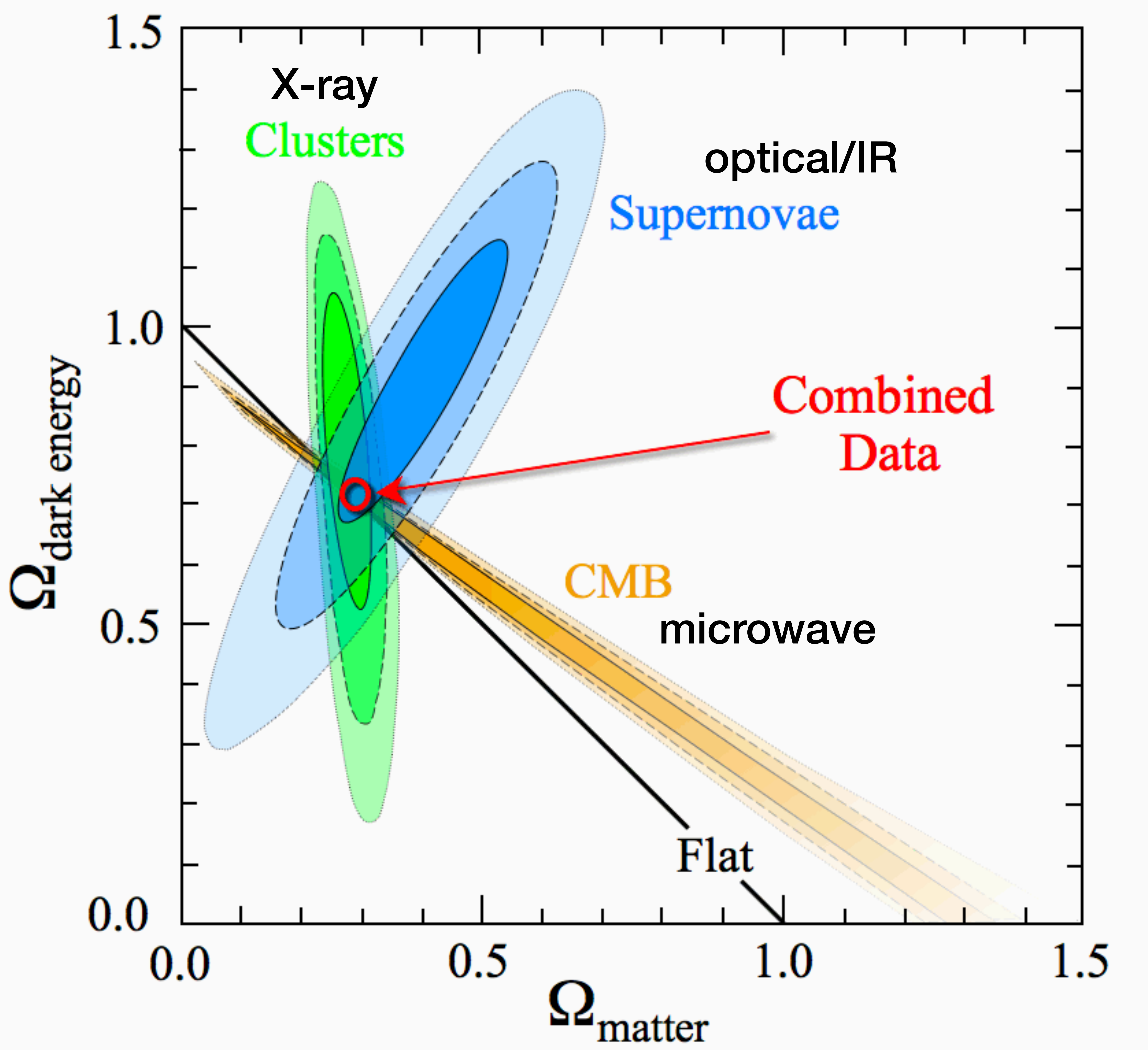


$a(t)$

Our universe (we think)

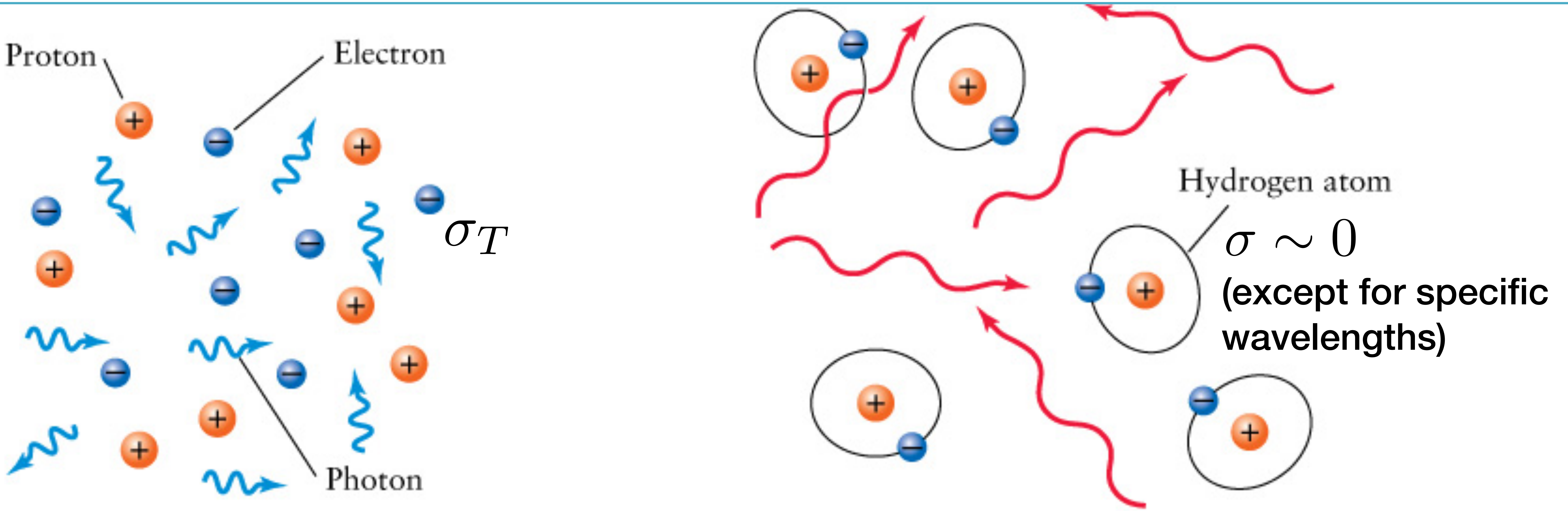
Fractions relative to the critical density

Many different kinds of observations agree



What happens if we roll back the clock to the early universe?

At some point in the past, universe so hot it is ionized —> opaque



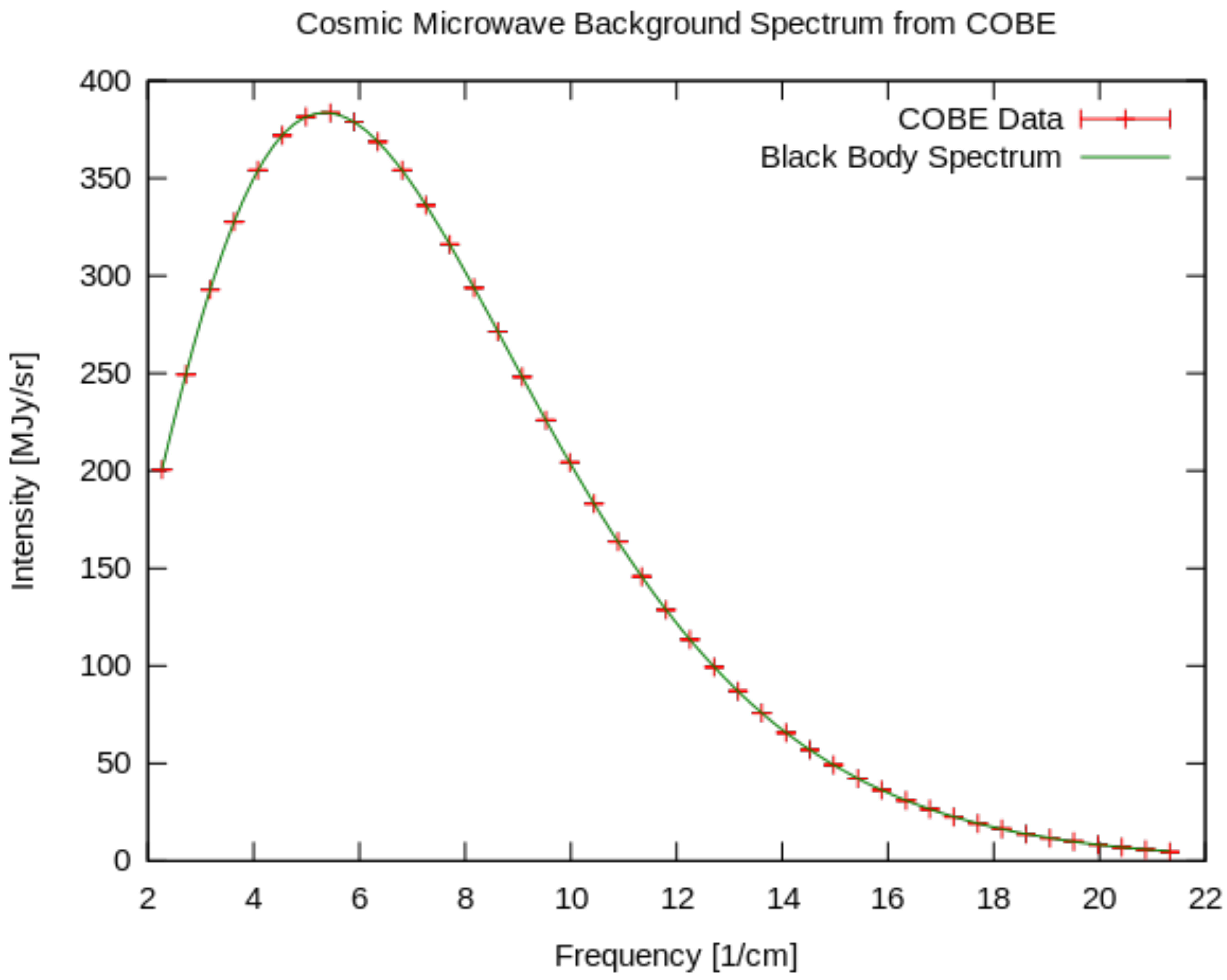
(a) Before recombination:

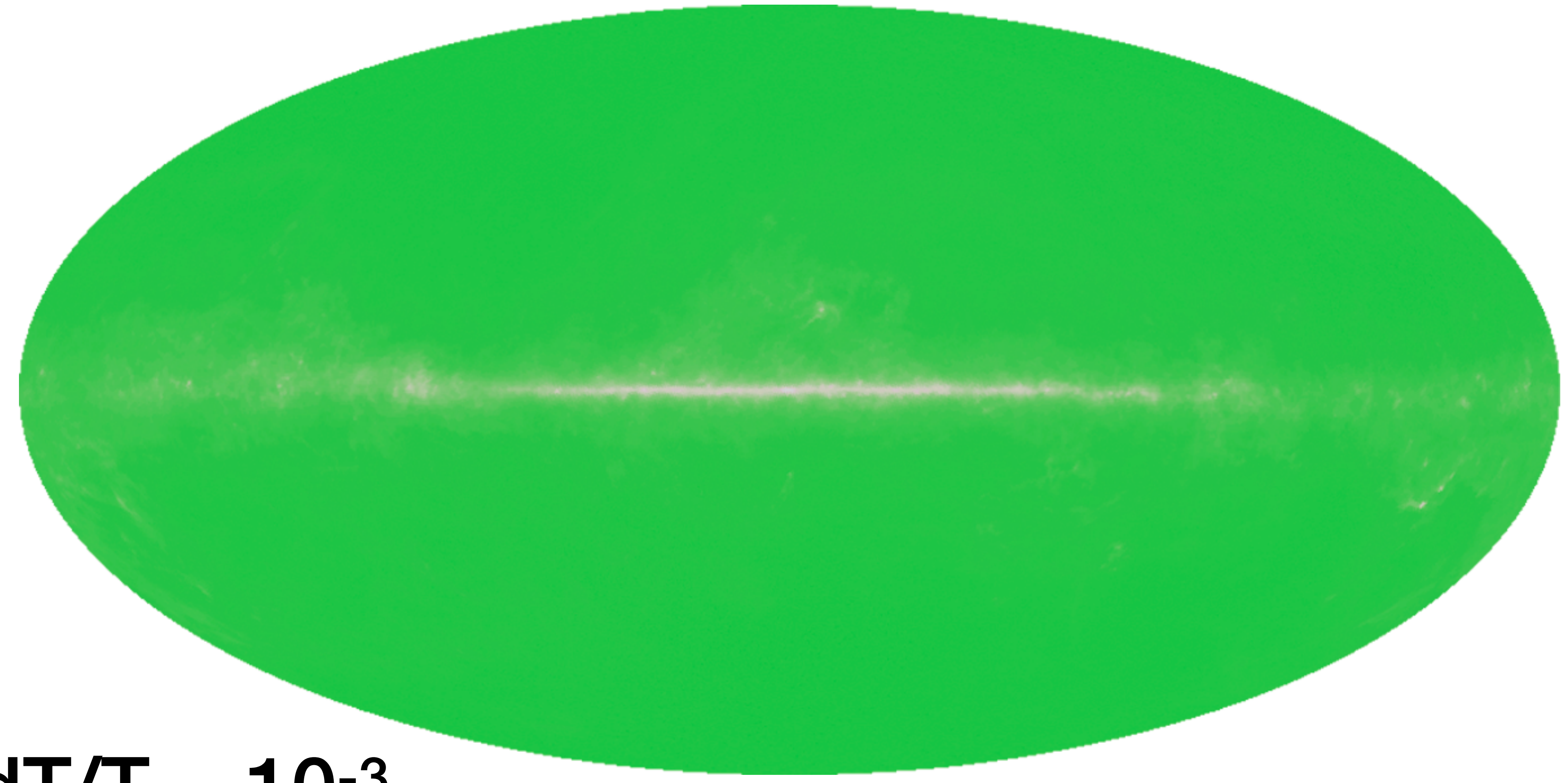
- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.

(b) After recombination:

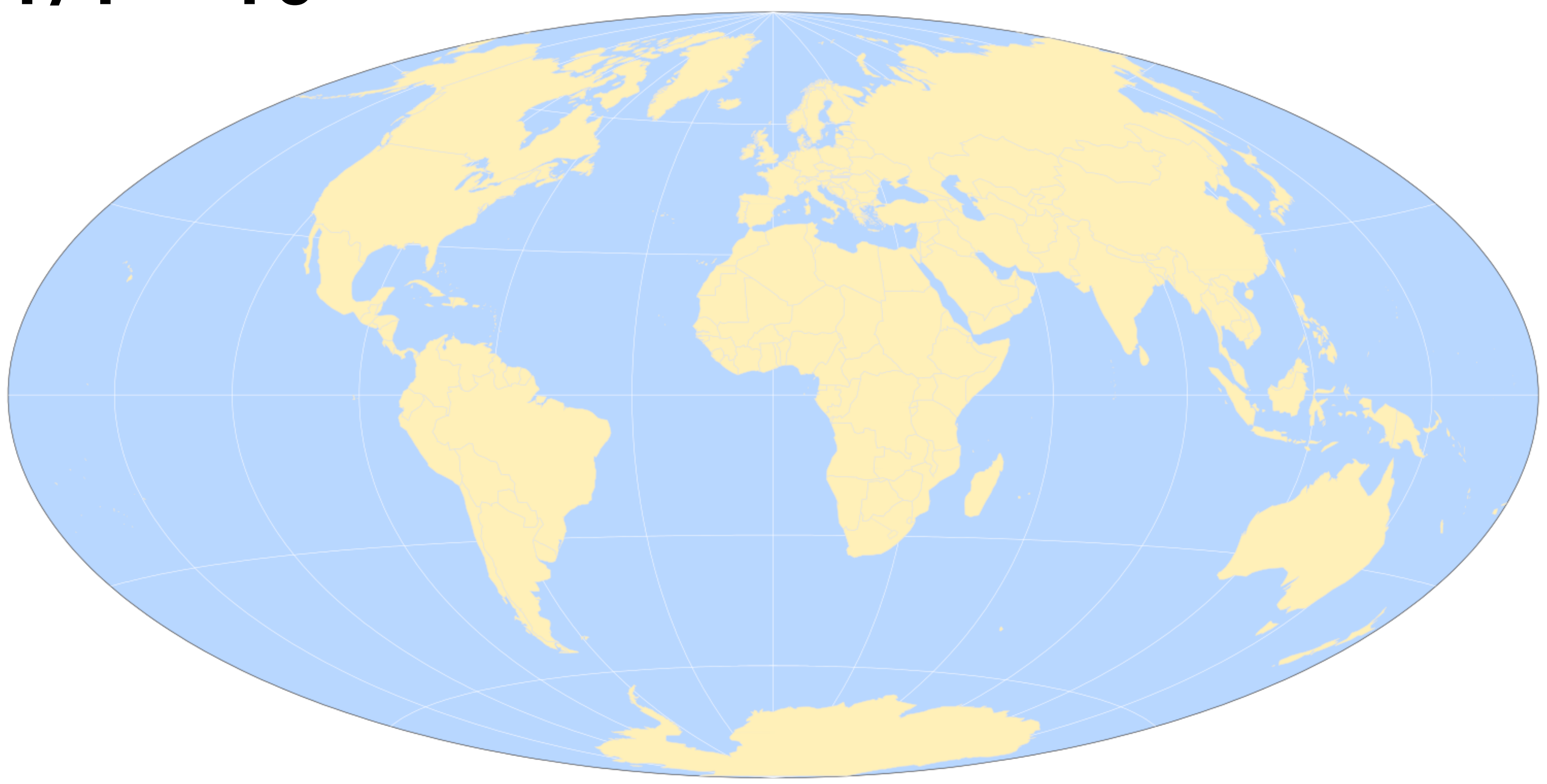
- Temperatures became low enough for hydrogen atoms to form.
- The universe became transparent: Collisions between photons and atoms became infrequent.
- Matter and radiation were no longer at the same temperature.

Near perfect BB everywhere on the sky





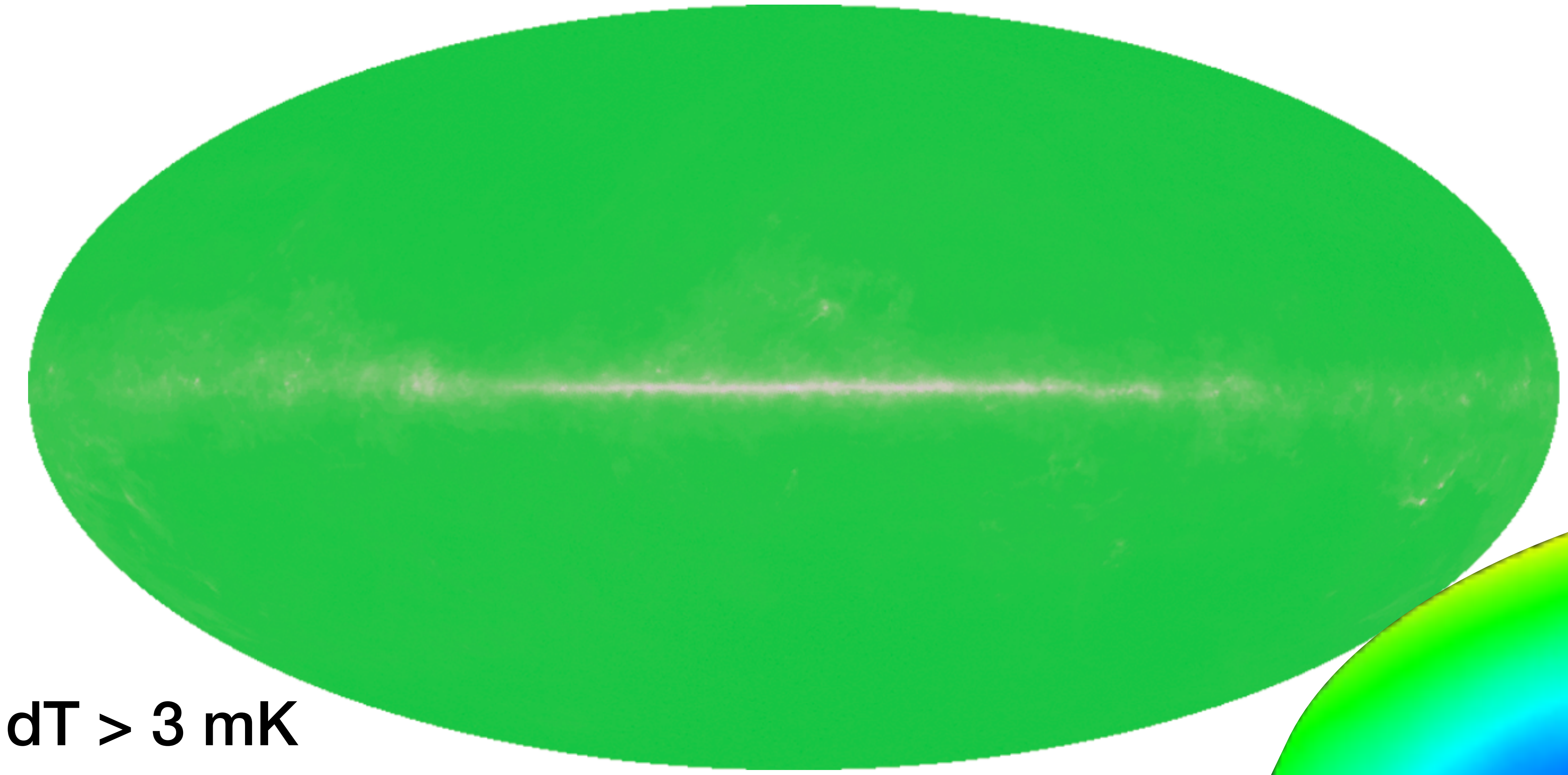
$dT/T \sim 10^{-3}$



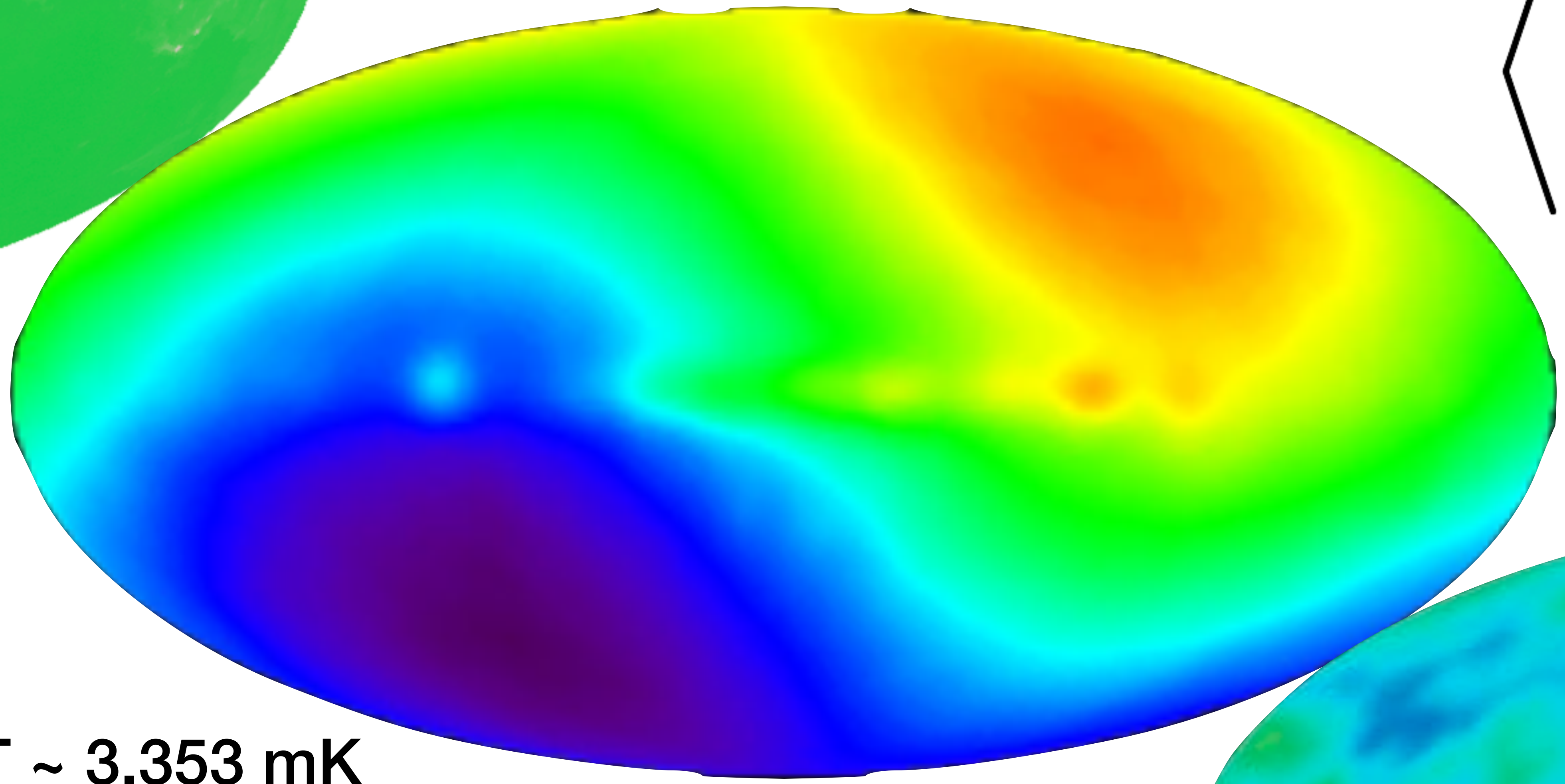
Spatial variations on different scales

$$\frac{\delta T}{T}(\theta, \phi) \equiv \frac{T(\theta, \phi) - \langle T \rangle}{T}$$

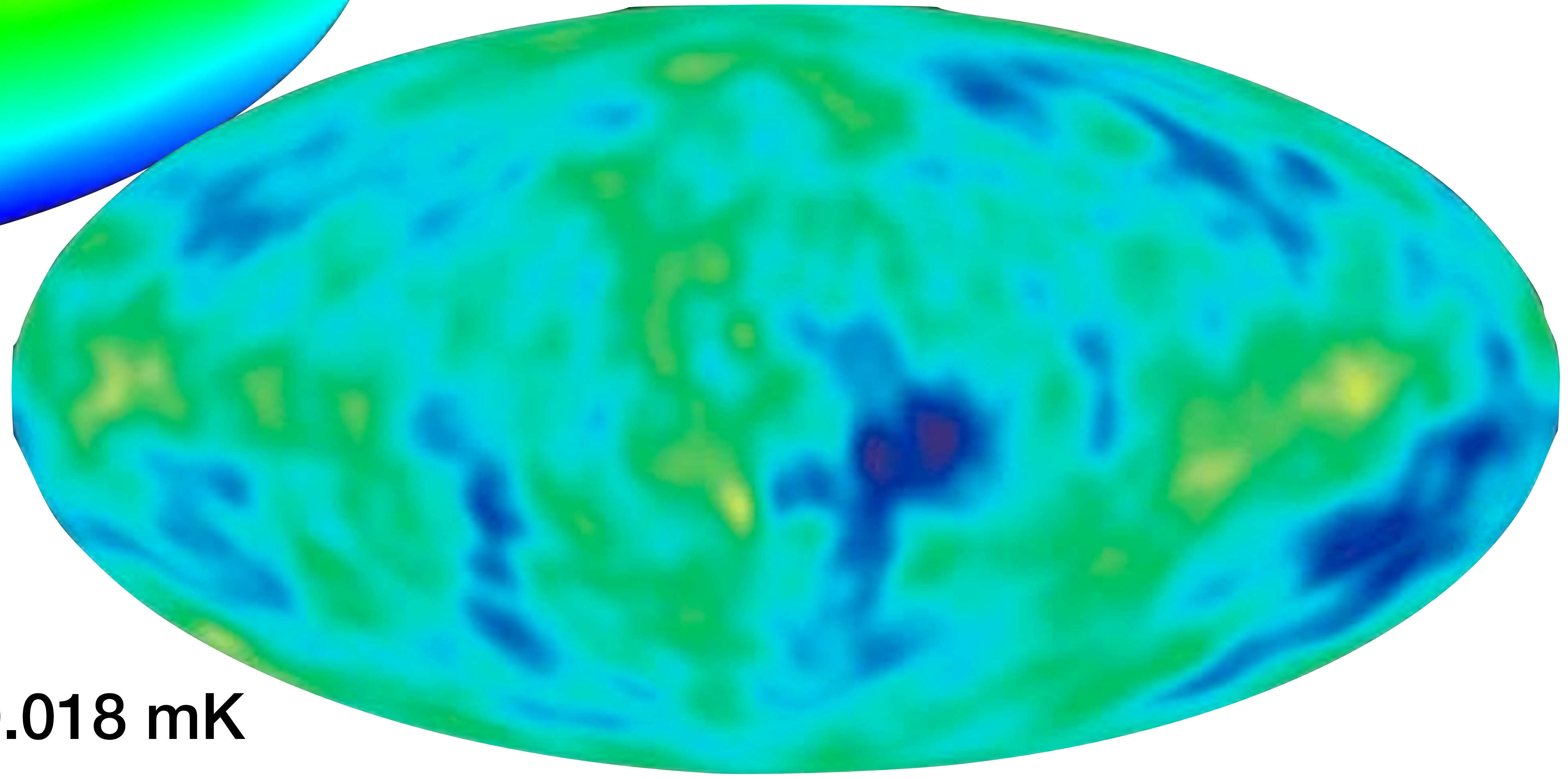
$$\left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle^{1/2} = 1.1 \times 10^{-5}$$



dT > 3 mK

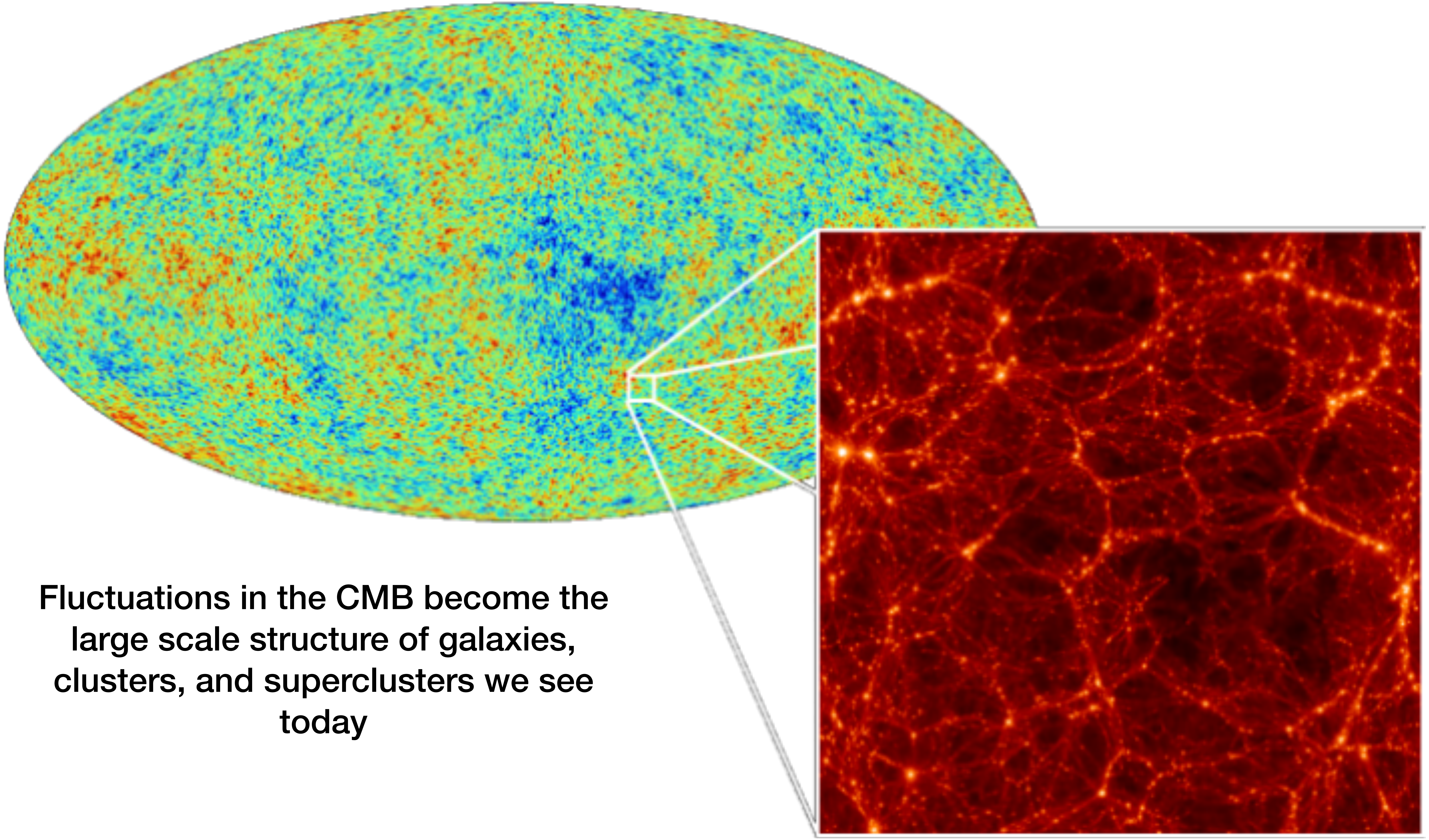


dT ~ 3.353 mK



dT ~ 0.018 mK

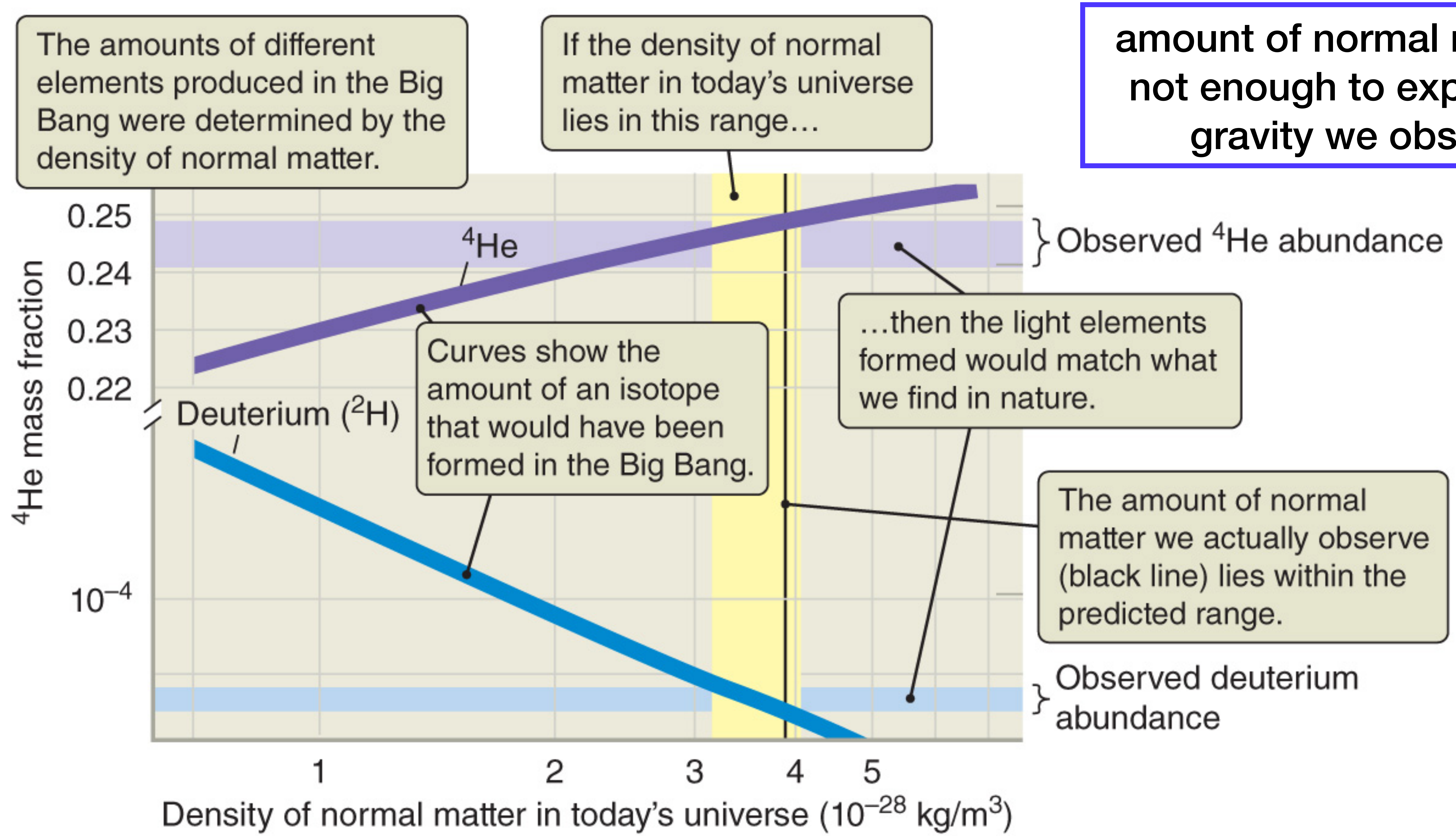

Cobe 1992
WMAP 2003
Planck 2013



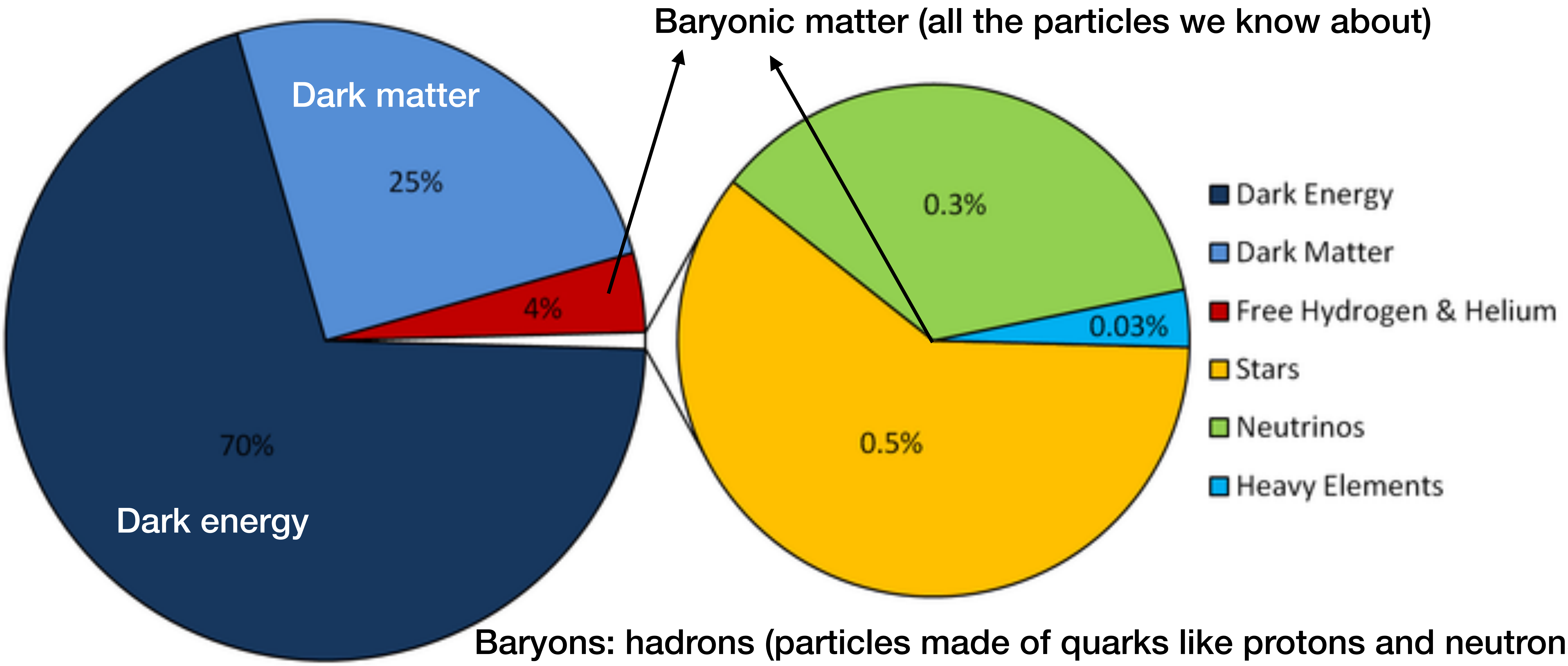
Fluctuations in the CMB become the large scale structure of galaxies, clusters, and superclusters we see today

Go further back, hot enough for H—>He fusion

amount of normal matter is not enough to explain the gravity we observe

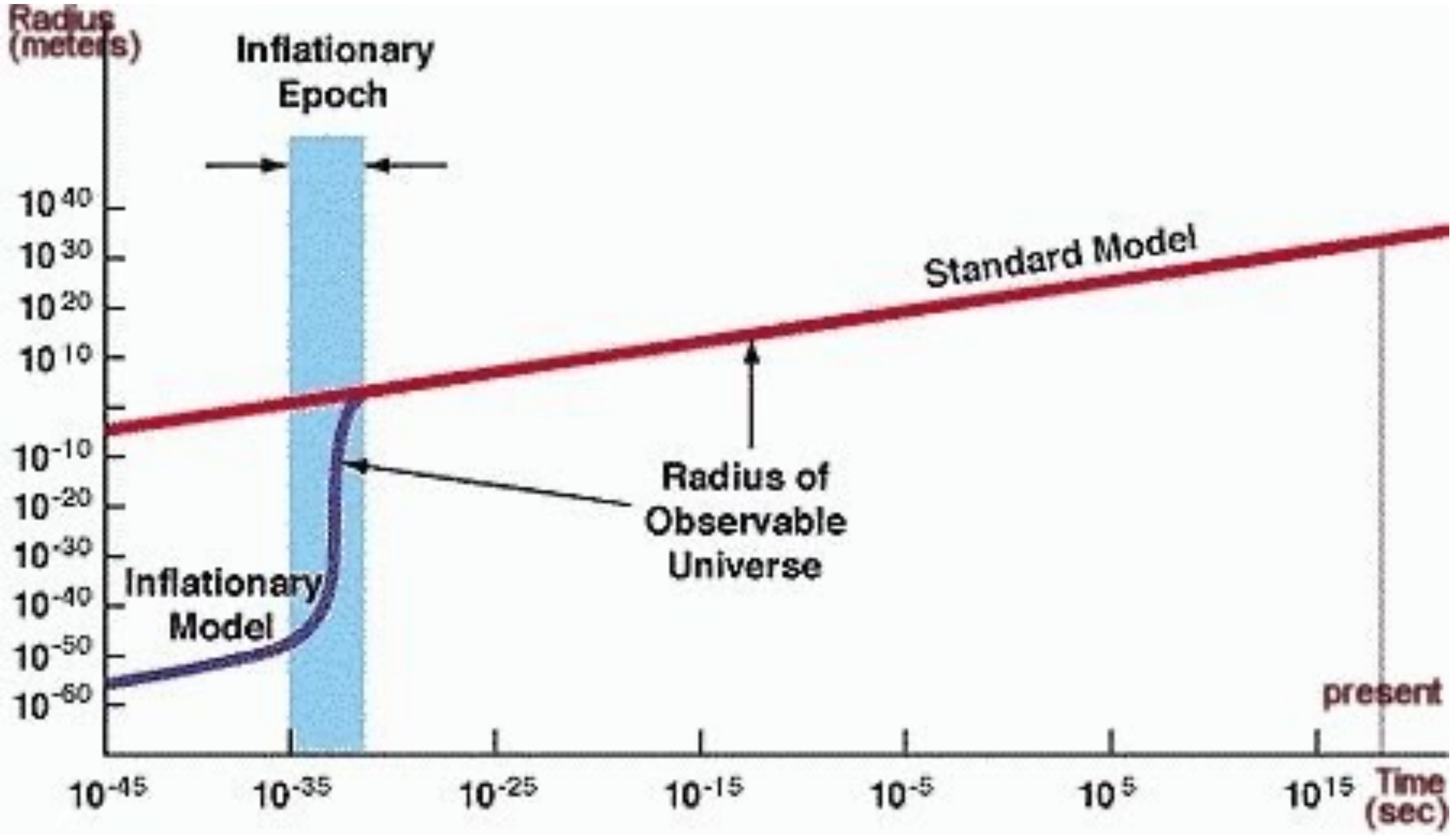


Relative Contents of the Universe

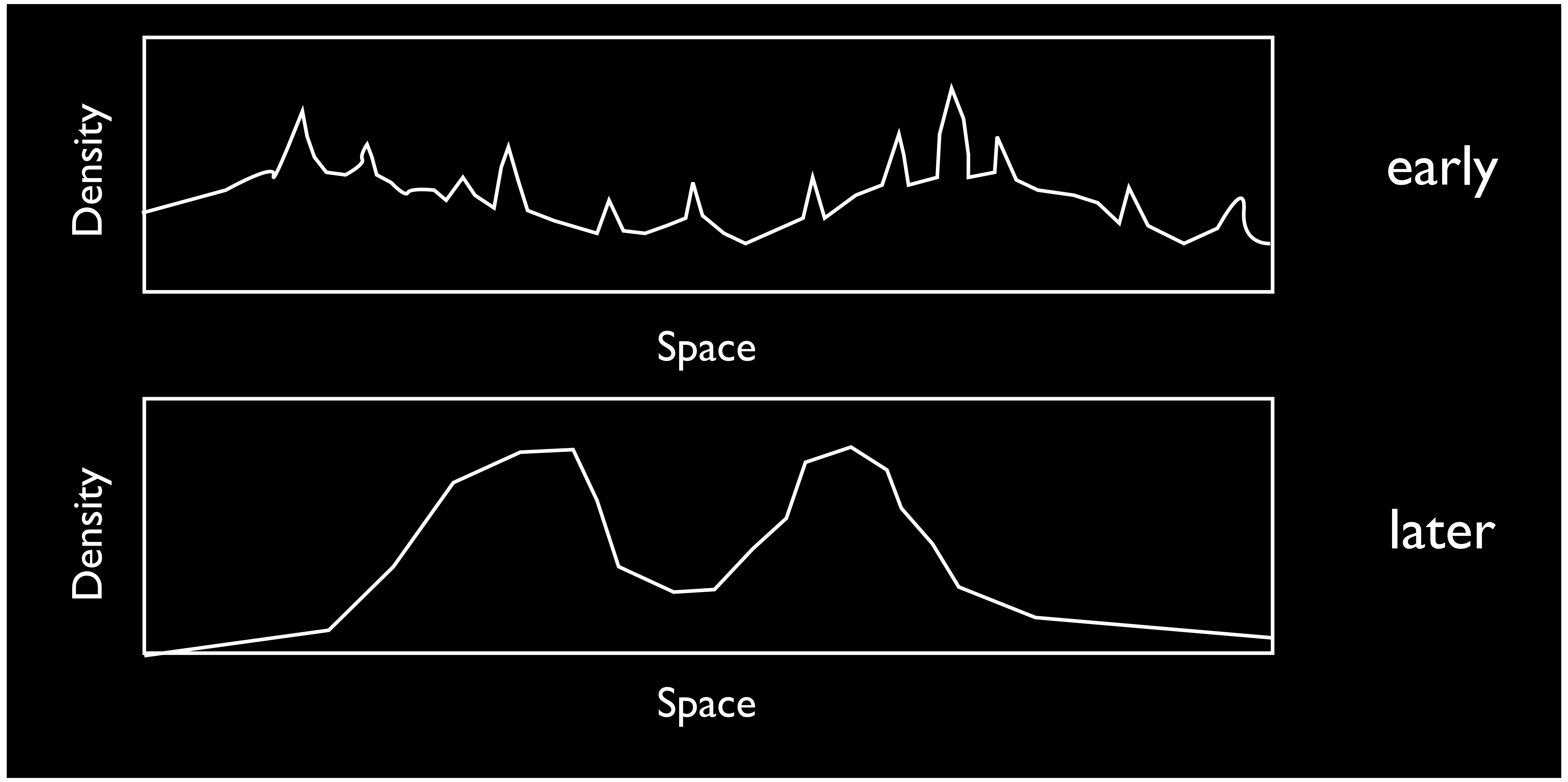


Baryons: hadrons (particles made of quarks like protons and neutrons)
Leptons: lighter particles not made of quarks, including electrons

Way further back: origin of structure (inflation?)



Initial quantum density perturbations amplified by Inflation after the Big Bang.

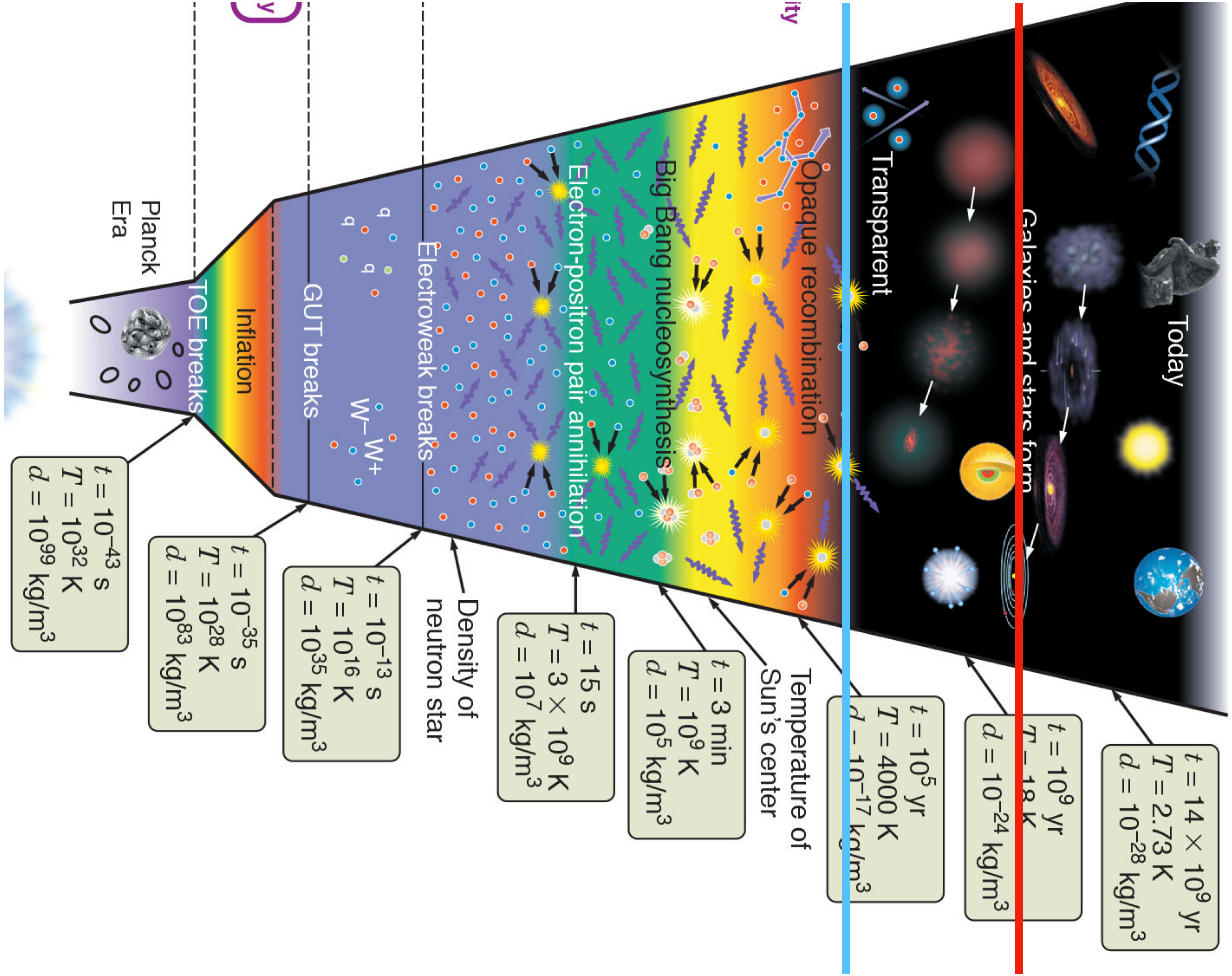


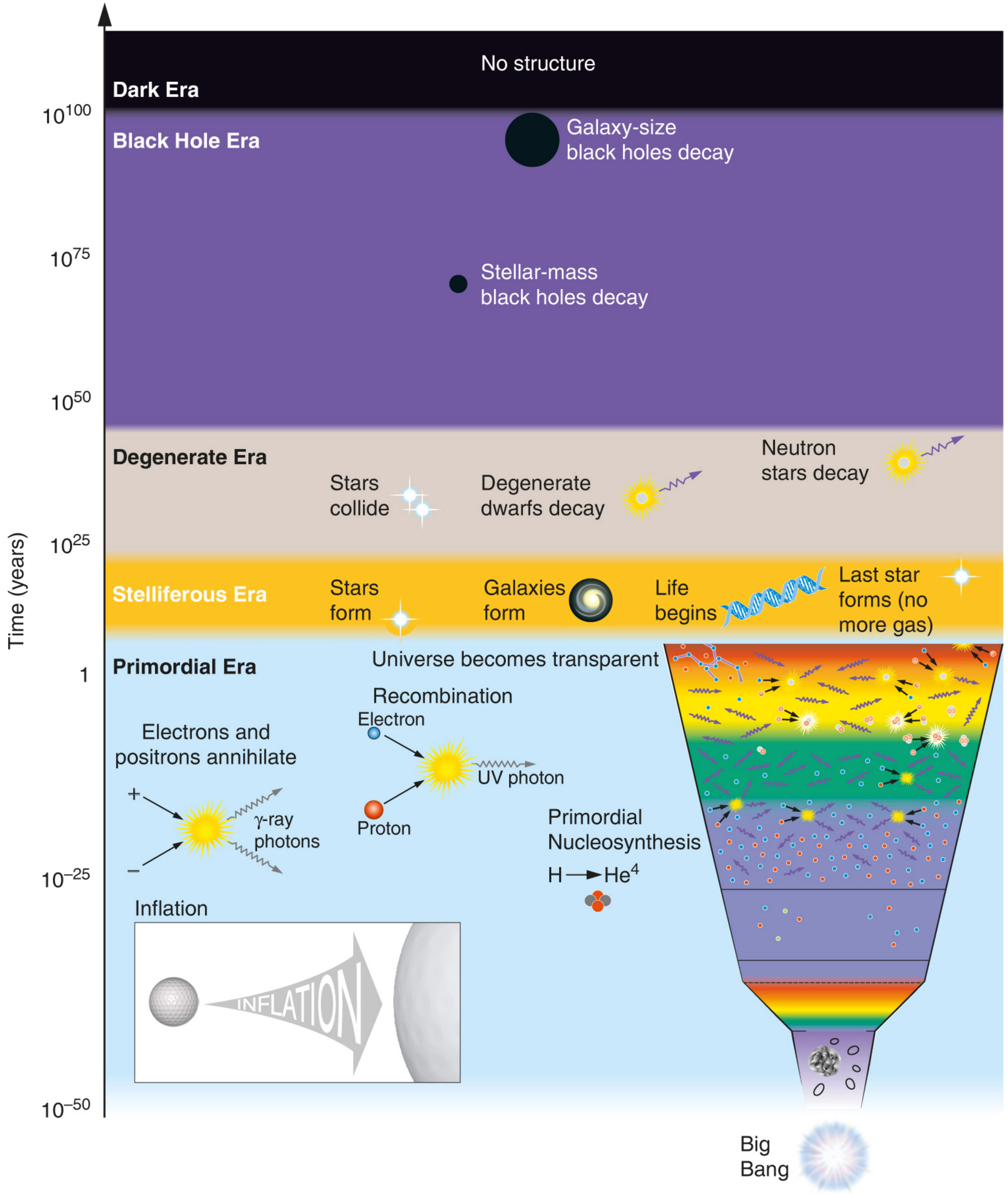
Called Hierarchical Structure Formation

Universe is opaque

Electrons & ions combine (recombination)

Universe gets ionized again (reionization)





The Deep Future (maybe?)

((This scenario assumes protons decay))

Primordial Era	10^5 yr
Stelliferous Era	10^{14} yr
Degenerate Era	10^{39} yr
Black Hole Era	10^{100} yr
Dark Era	infinity?