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UNIVERSITY OF NEW HAMPSHIRE

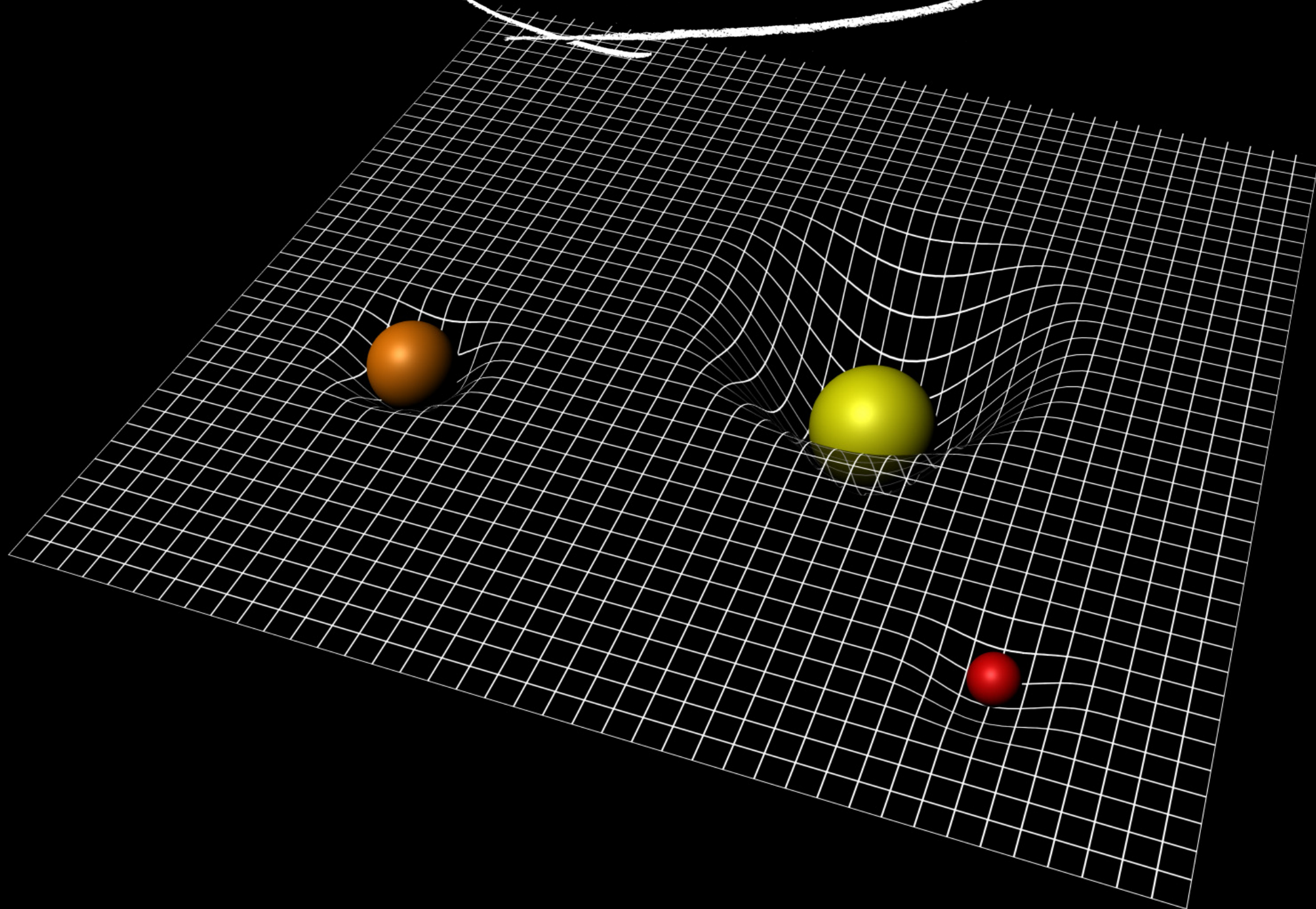
INTRODUCTION TO COSMOLOGY

Outline as Questions

- What do we know about the evolution of spacetime?
- What do we know about the contents of spacetime?
- How do we know dark matter exists?
- What is the evidence for cosmic acceleration?

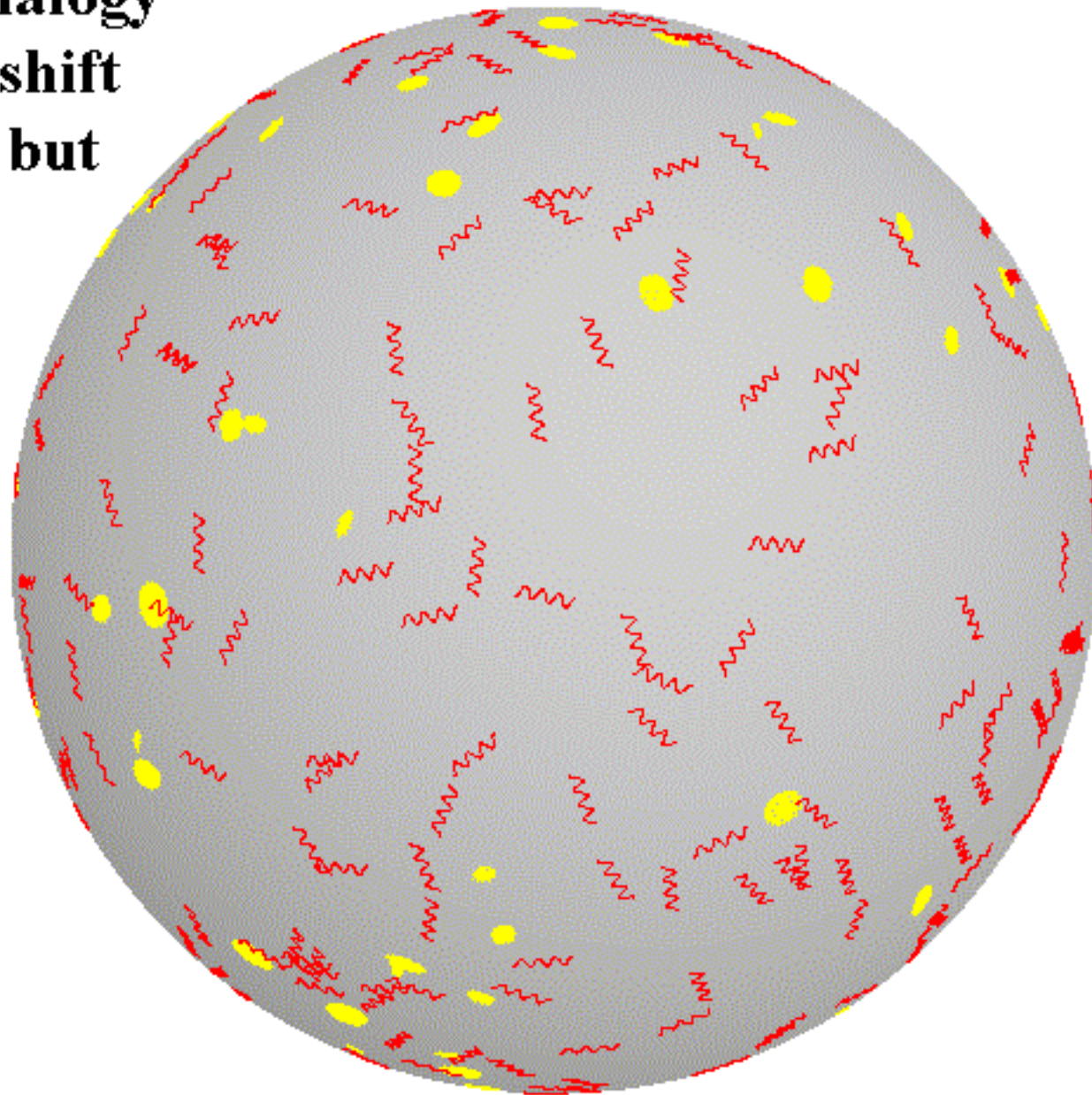
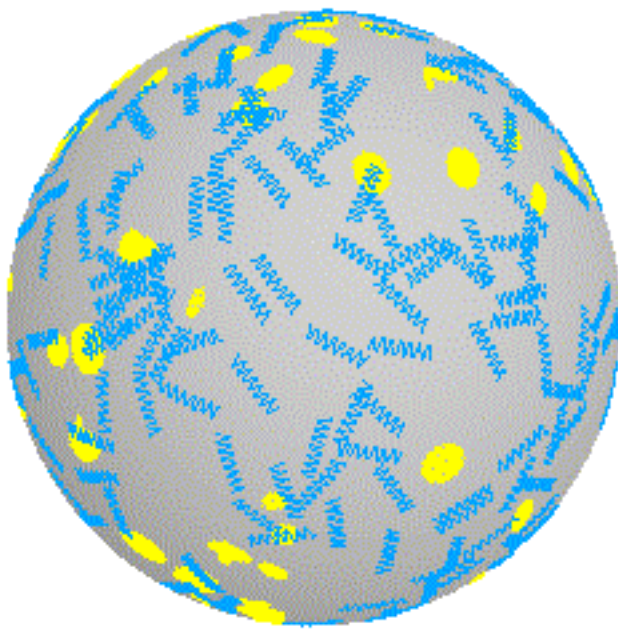
spacetime can curve

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu}$$



The Expanding Universe

Expanding Balloon Analogy
Photons move and redshift
Galaxies spread apart but
stay the same size



Cosmic Distances

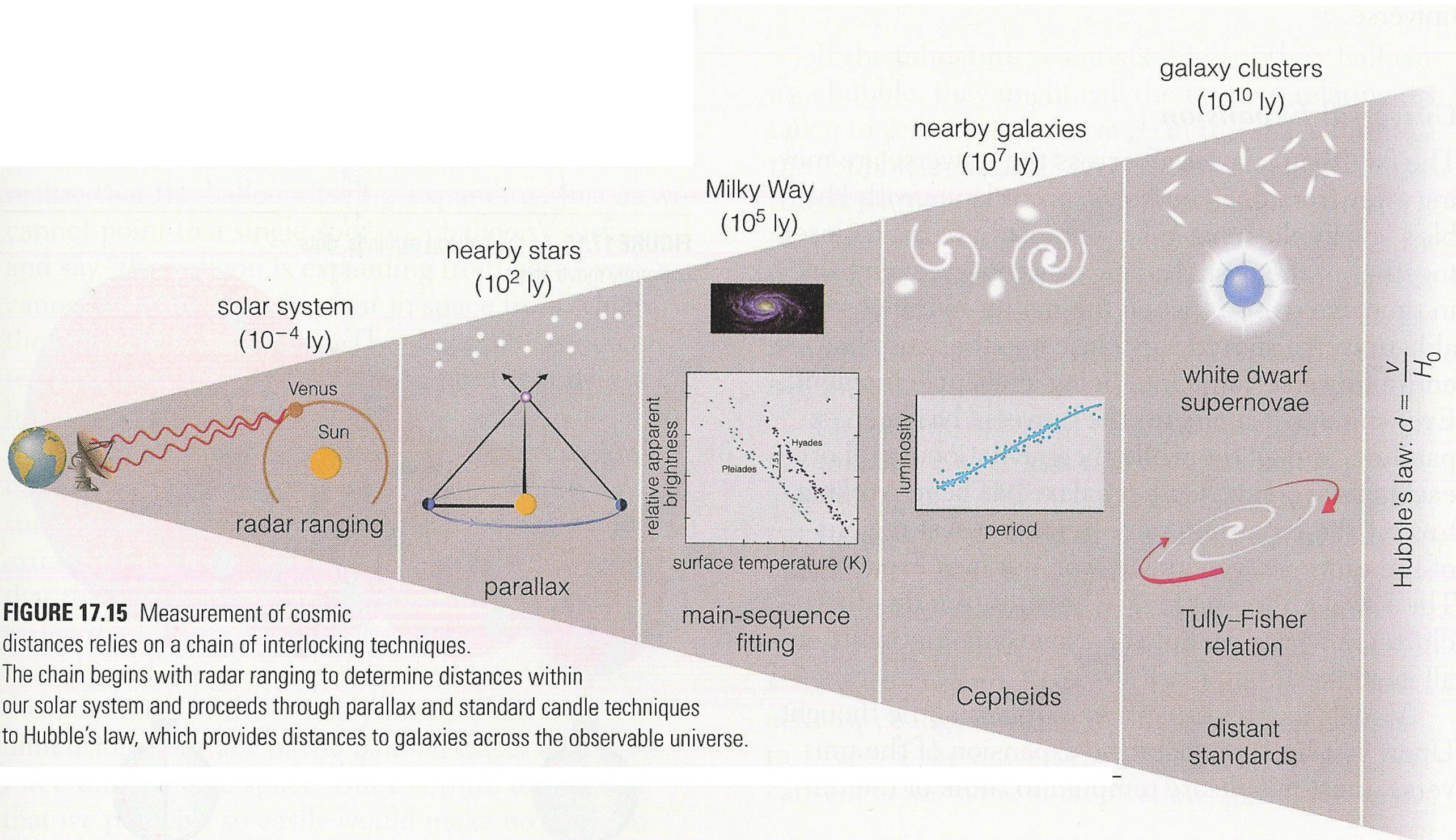


FIGURE 17.15 Measurement of cosmic distances relies on a chain of interlocking techniques. The chain begins with radar ranging to determine distances within our solar system and proceeds through parallax and standard candle techniques to Hubble's law, which provides distances to galaxies across the observable universe.

The Expanding Universe

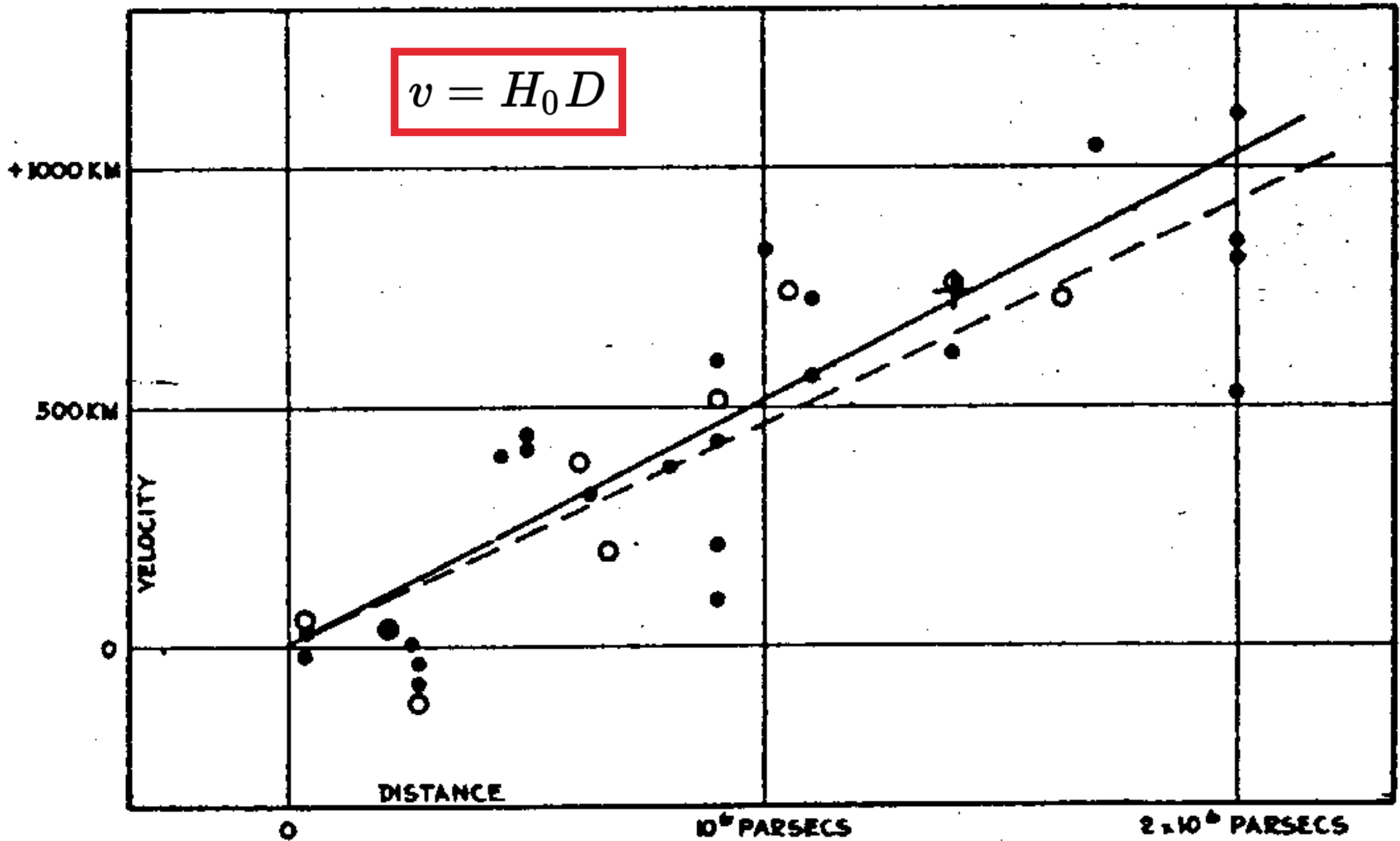
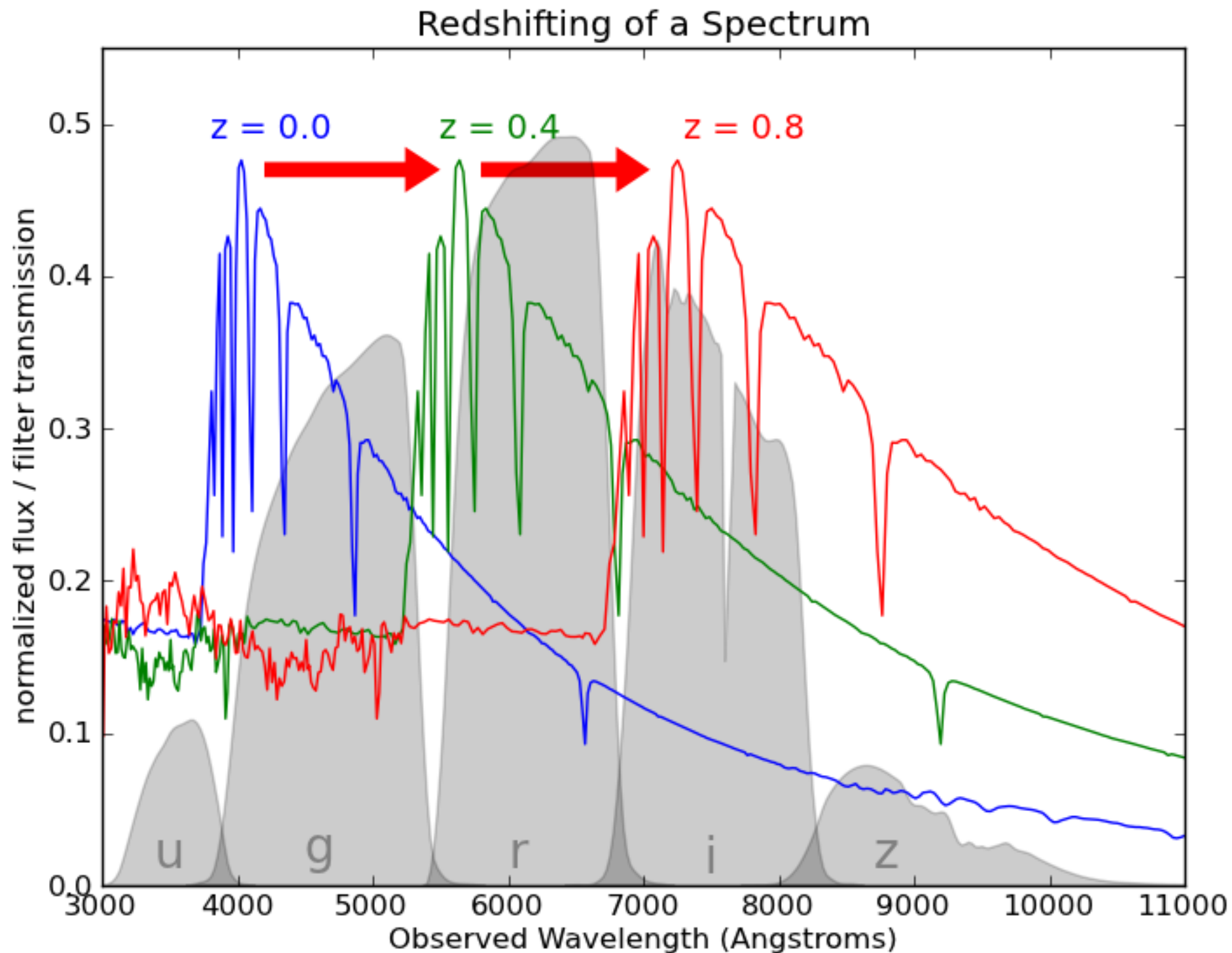


FIGURE 1

The Expanding Universe



The Expanding Universe

Friedmann-Lemaître-Robertson-Walker Metric

$$ds^2 = (c \, dt)^2 - R^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right]$$

scale factor

Redshift

$$v = H_0 D$$

$$z = \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1$$

Hubble constant

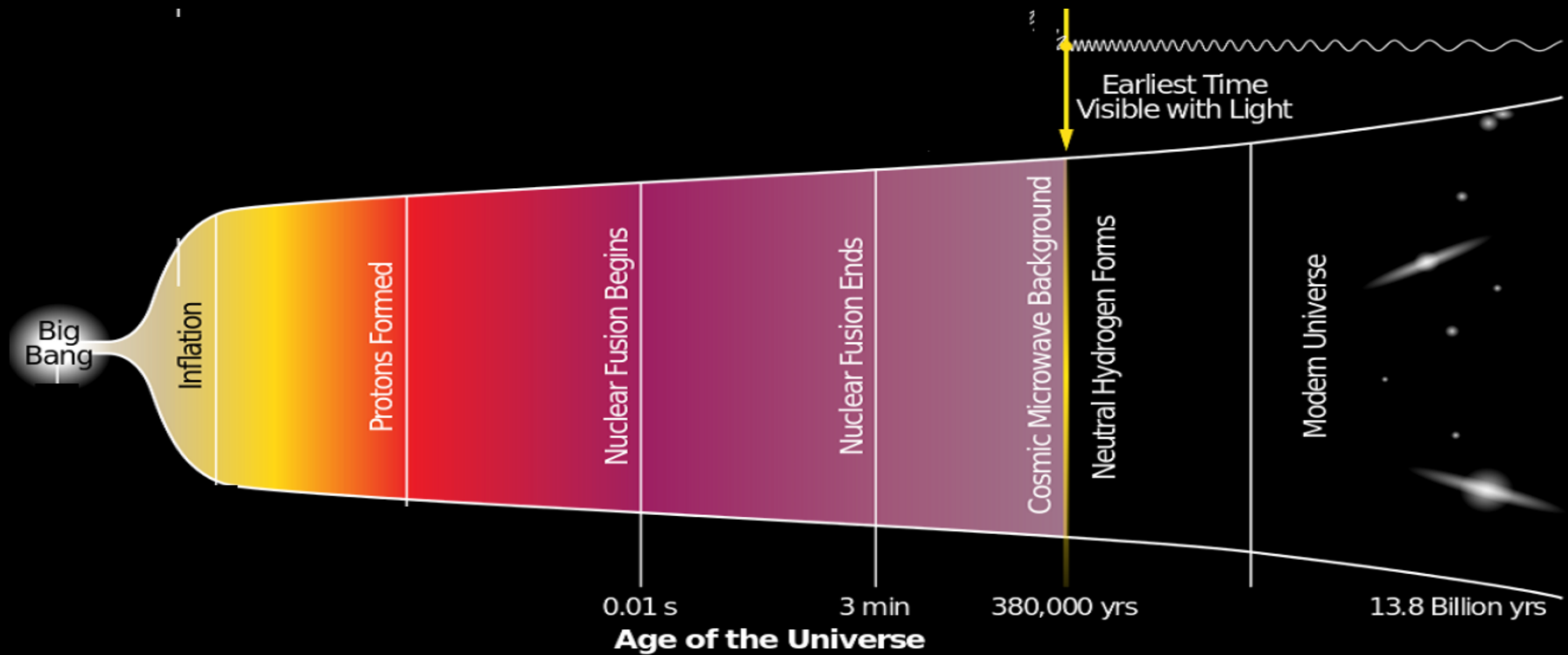
Friedmann Equations

Redshift

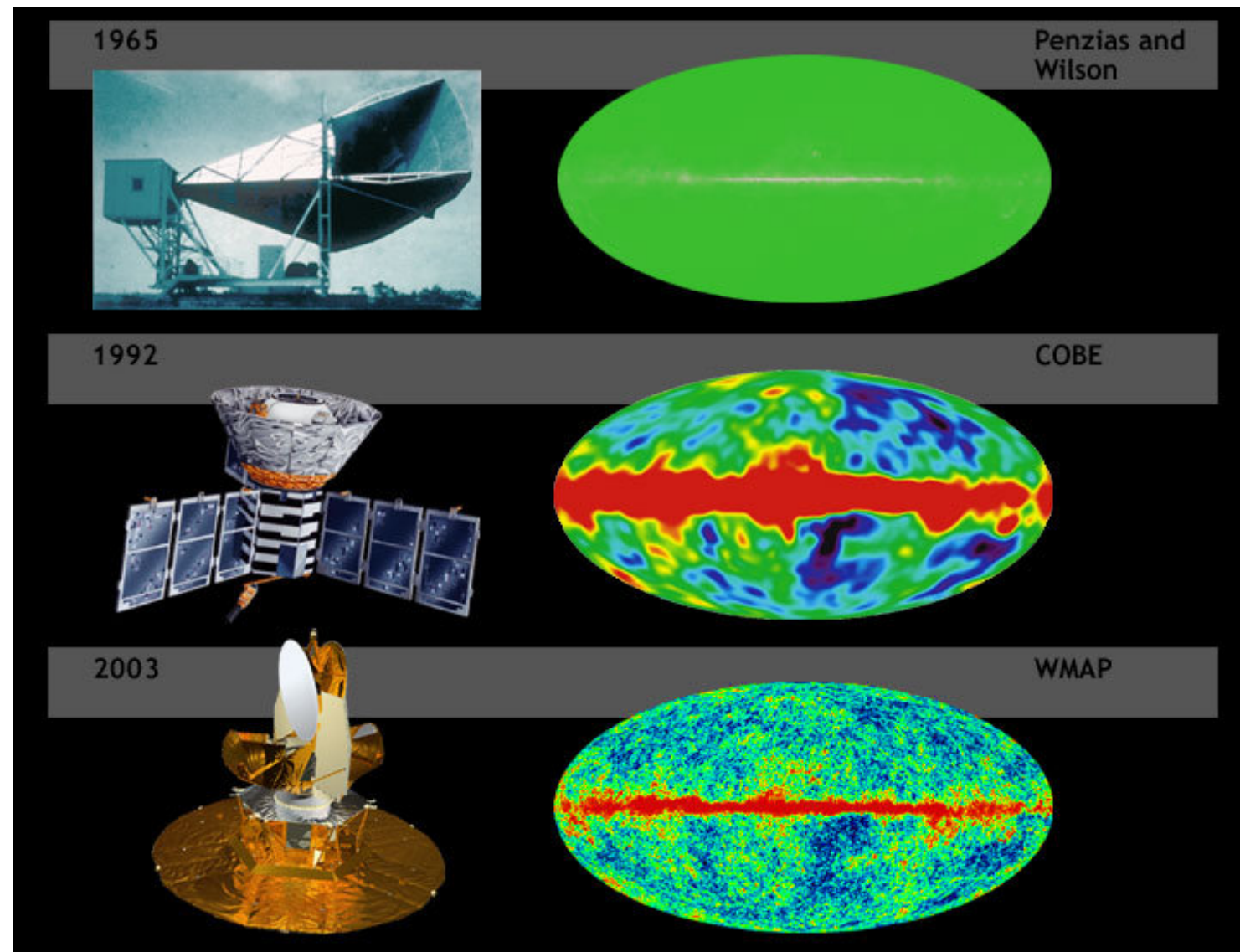
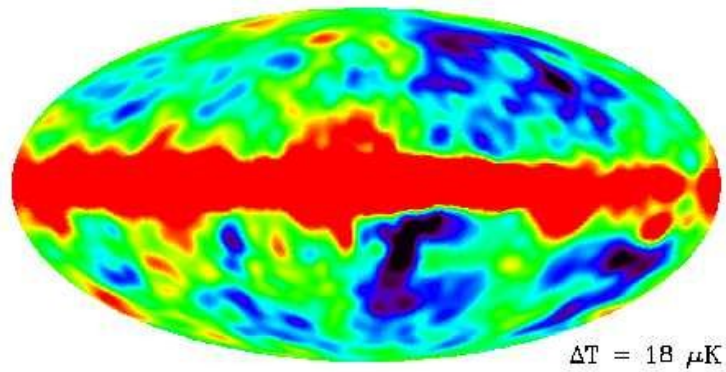
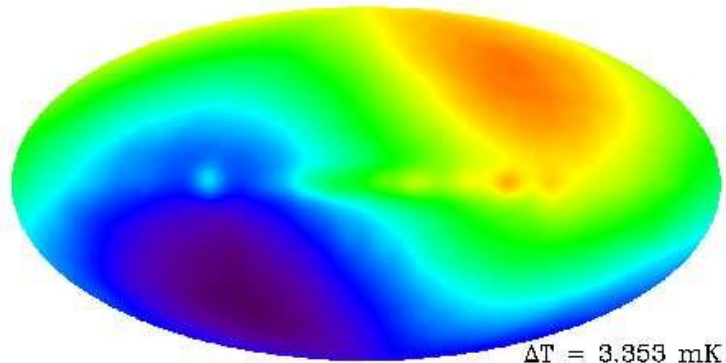
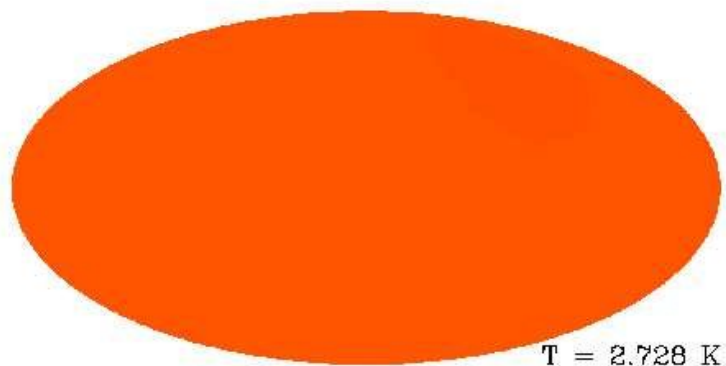
$$\left(H^2 - \frac{8}{3} \pi G \rho \right) R^2 = -kc^2$$

$$\left[\left(\frac{1}{R} \frac{dR}{dt} \right)^2 - \frac{8}{3} \pi G \rho \right] R^2 = -kc^2$$

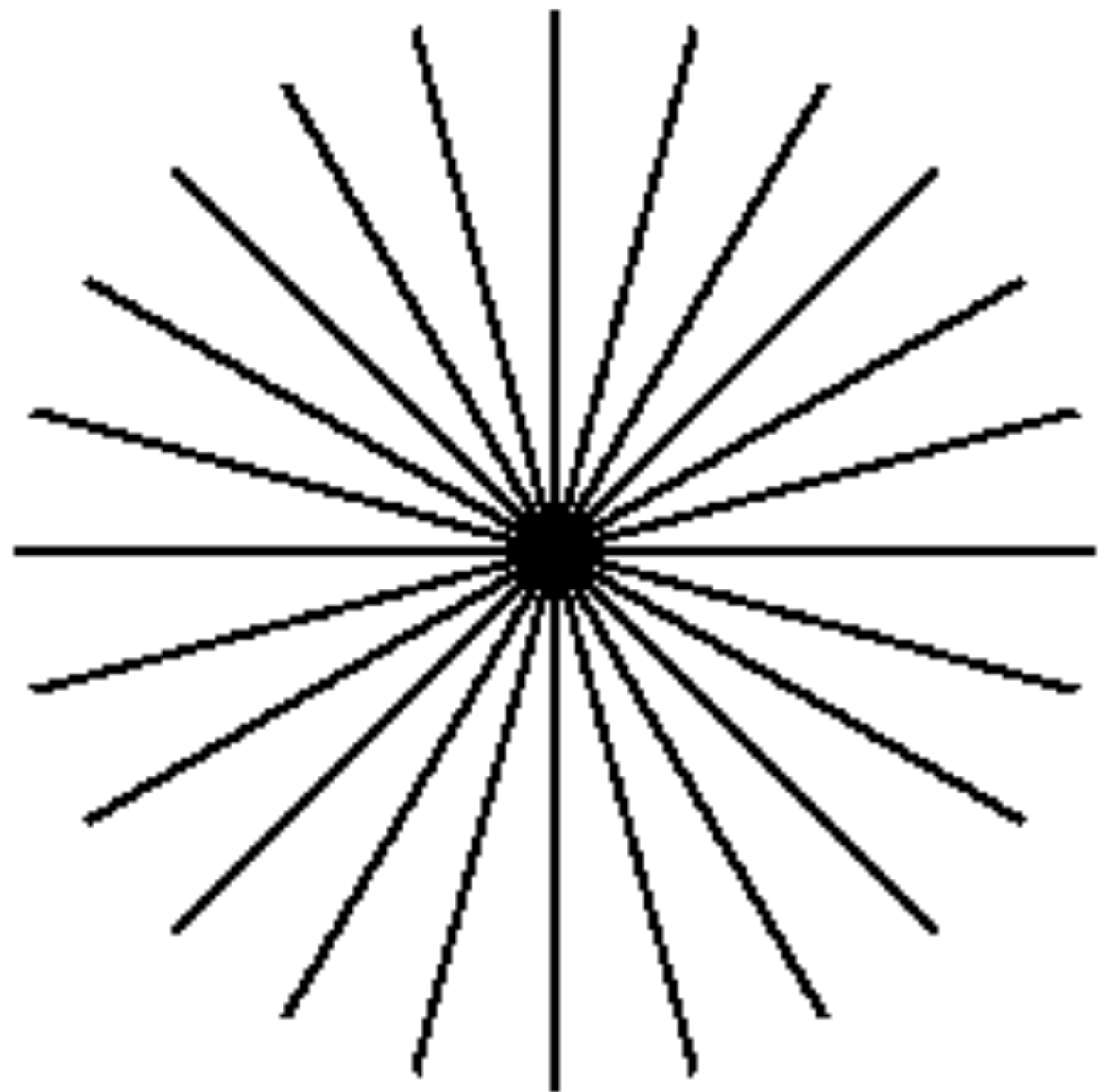
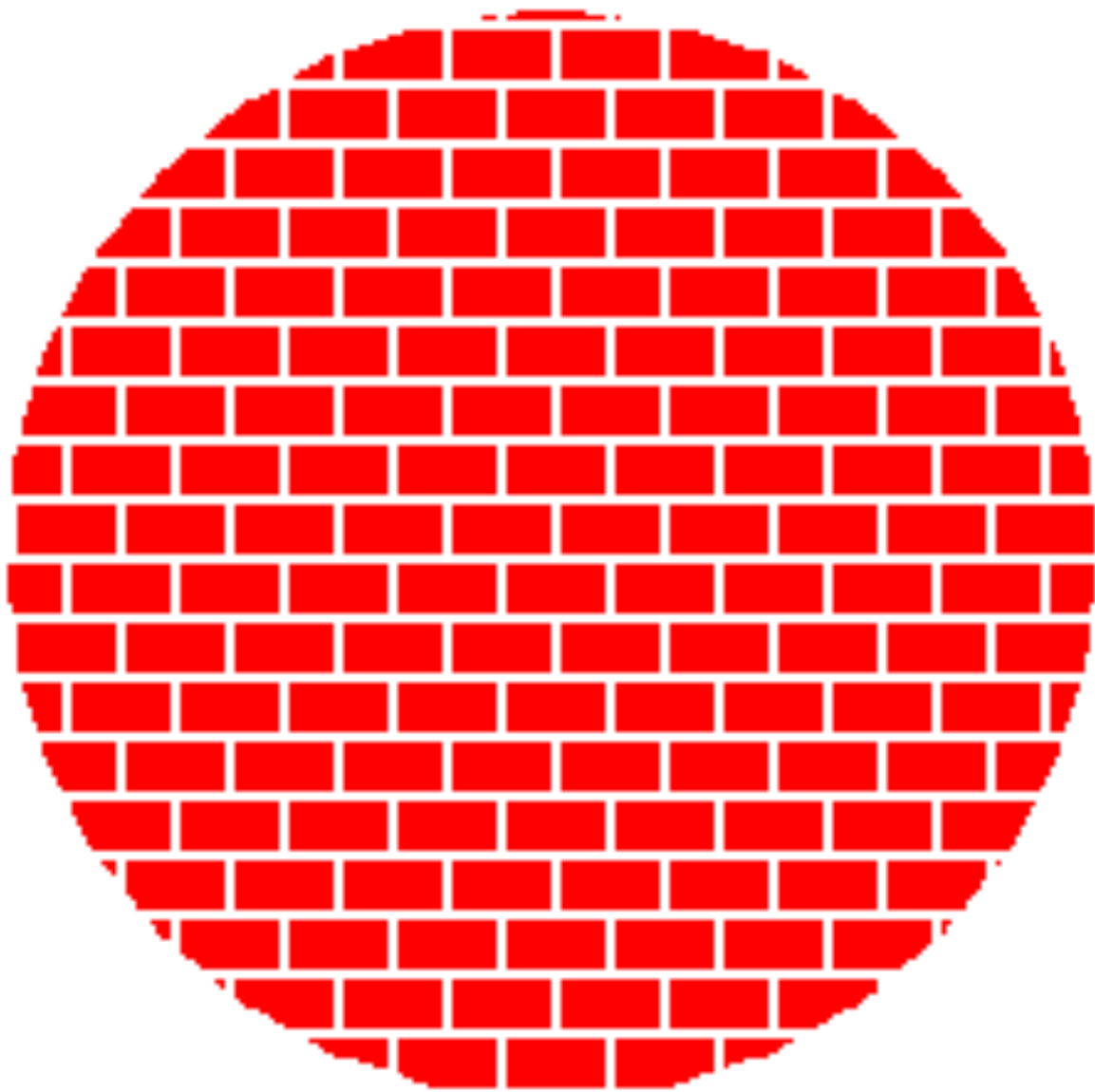
Tale As Old As Time



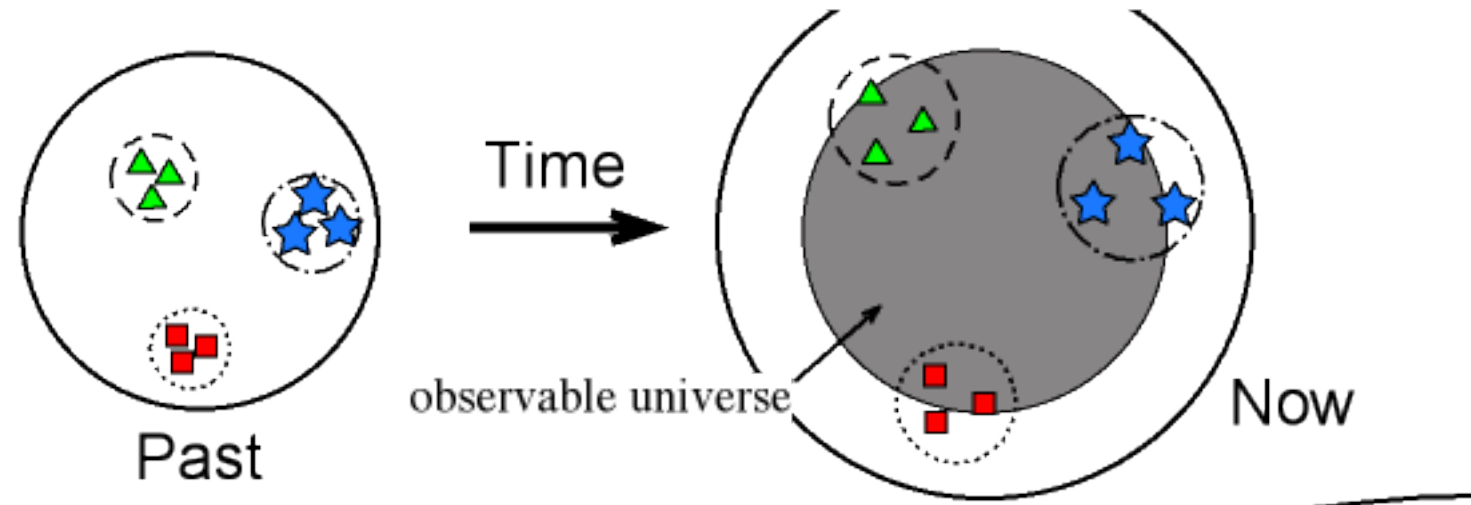
Cosmic Microwave Background Radiation



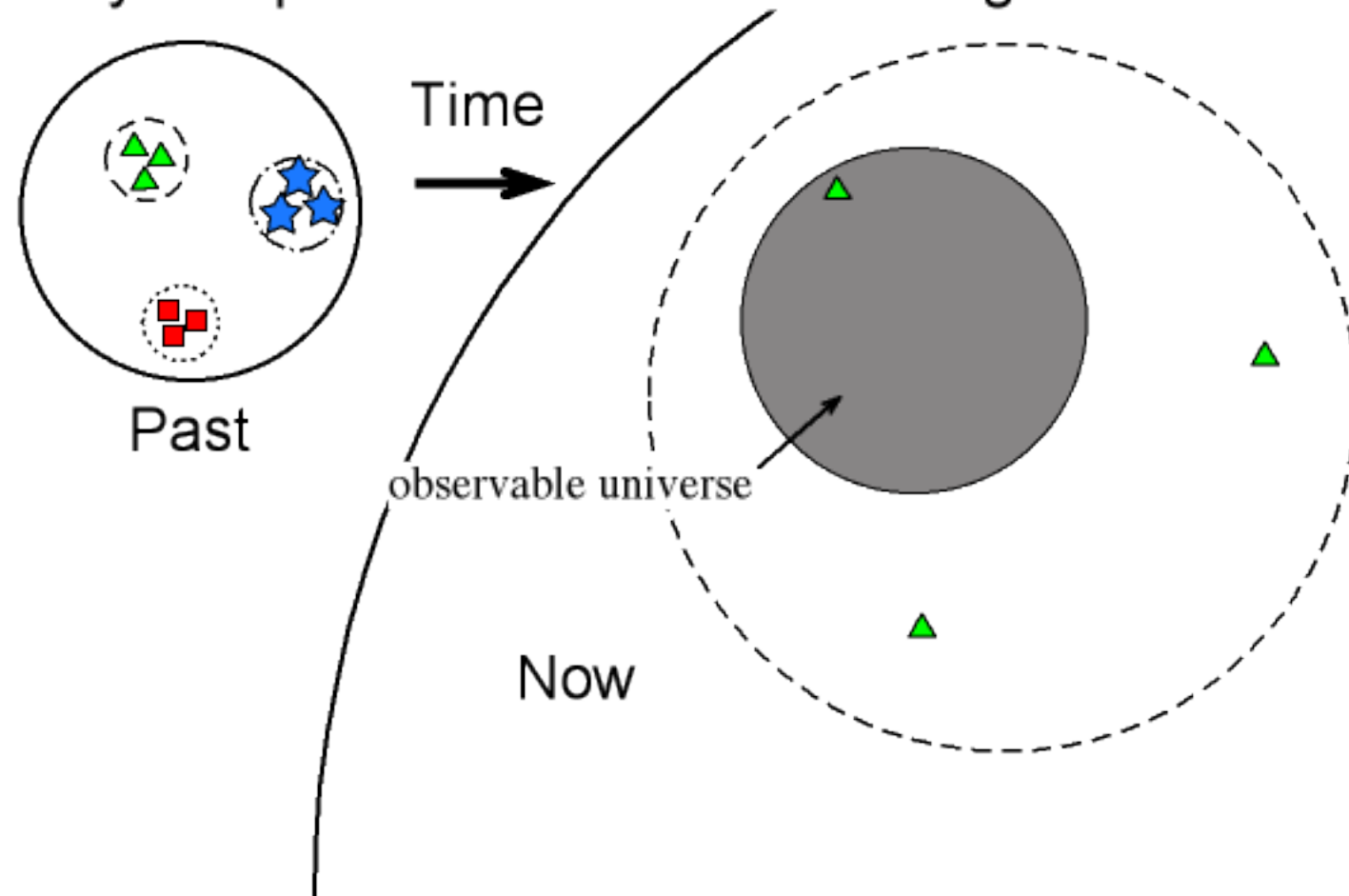
Cosmological Principle: Homogeneity and Isotropy



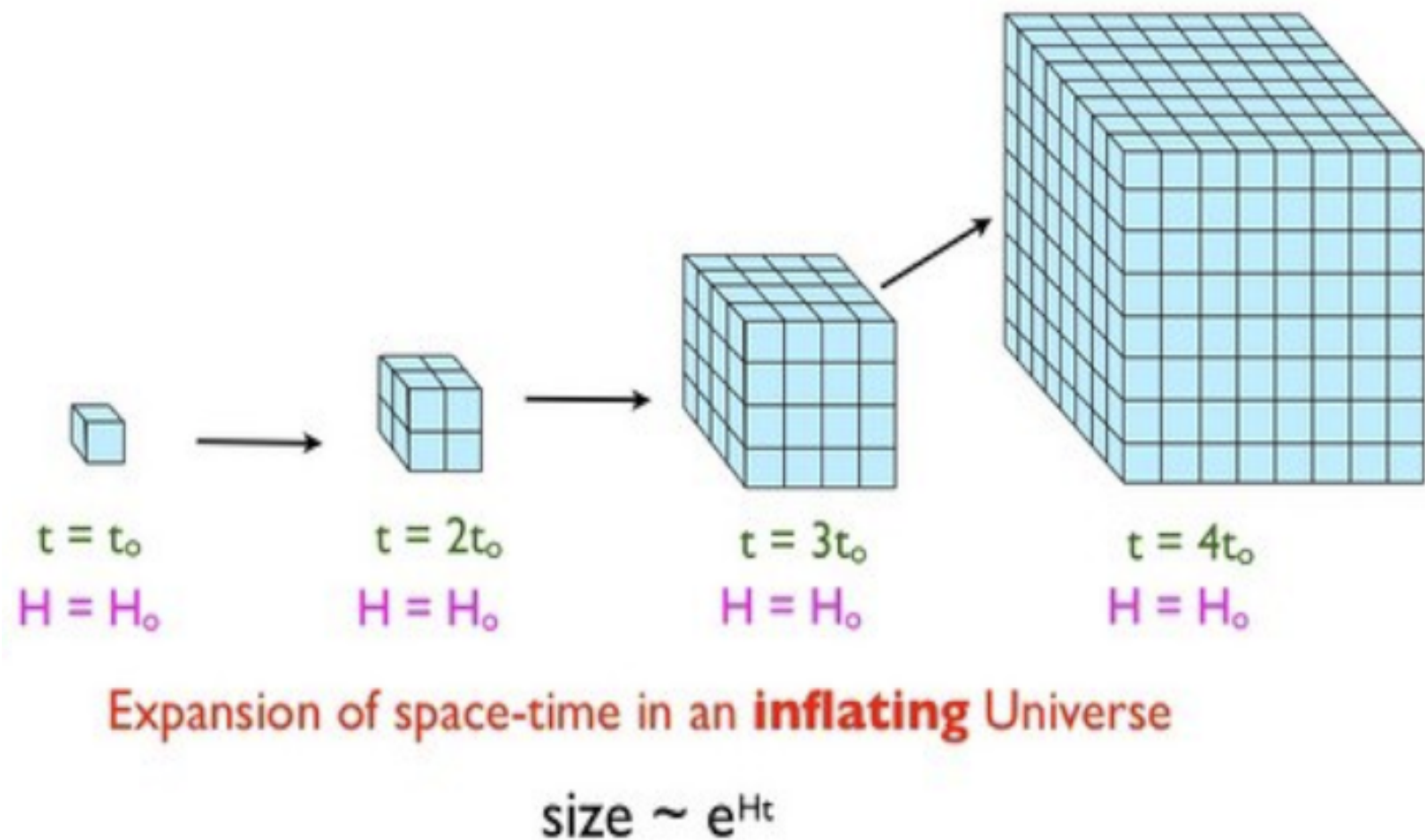
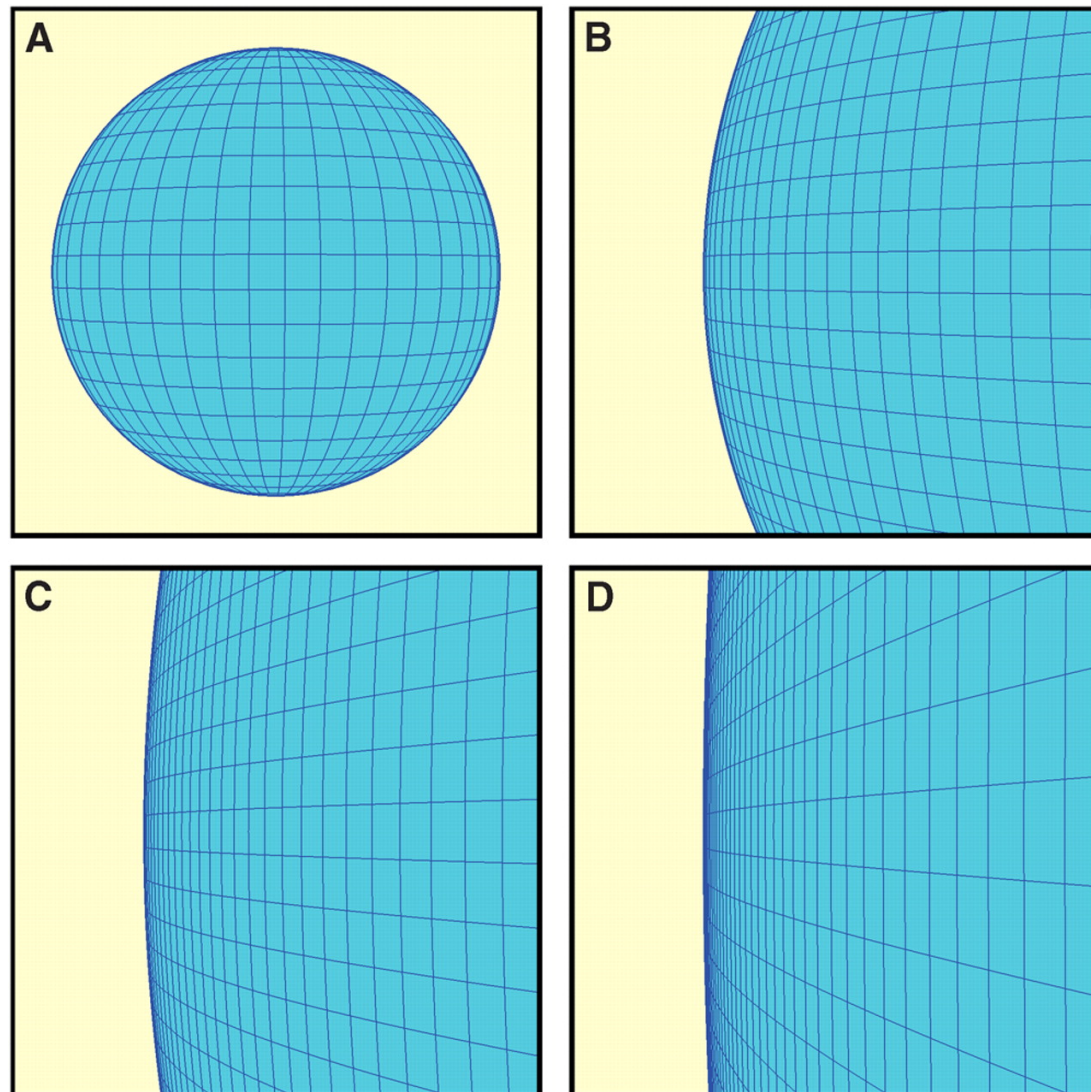
NO inflation: observable universe (shaded) includes parts that are different from each other



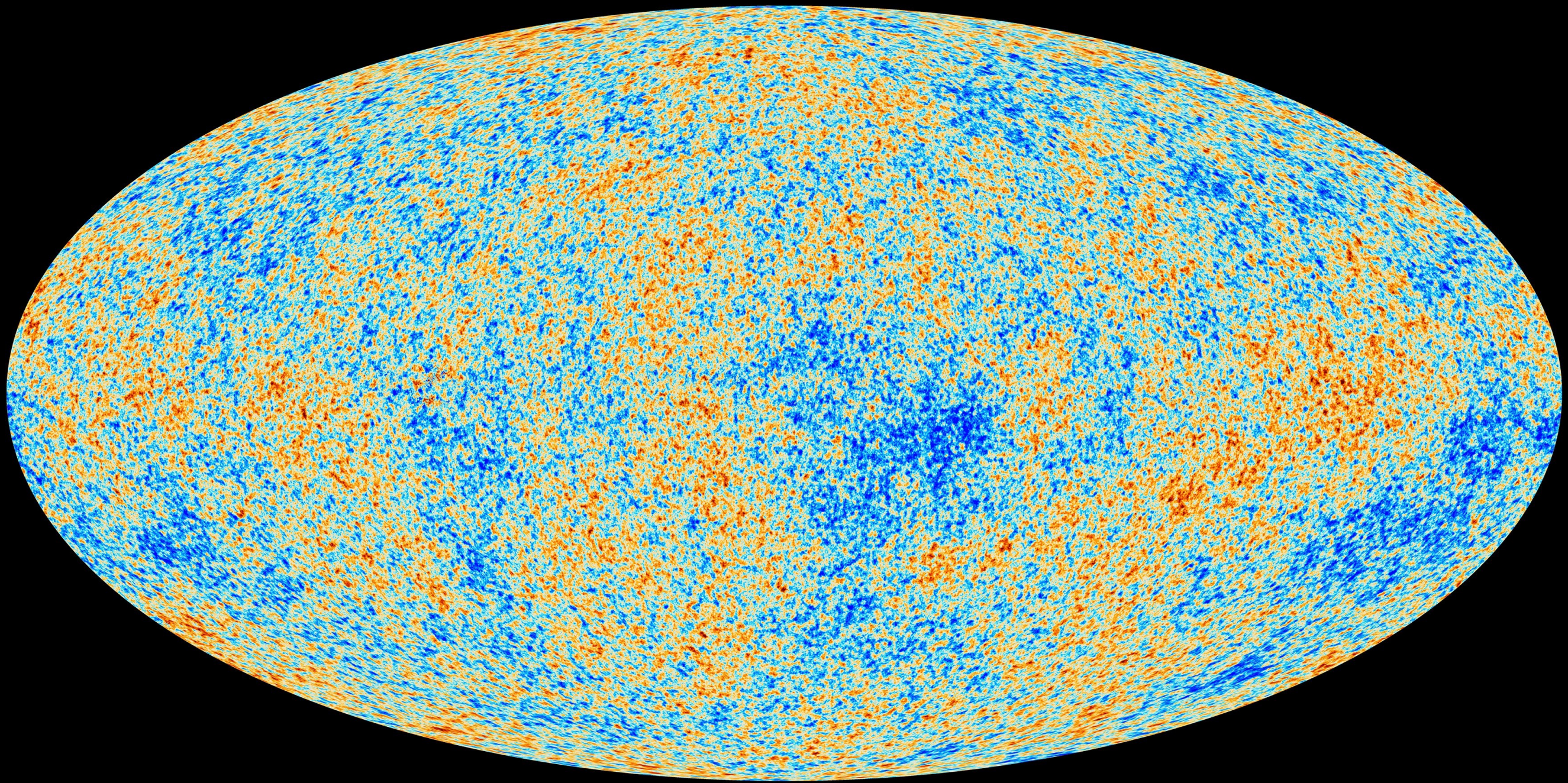
Inflation: observable universe (shaded) includes only one part that is the same throughout

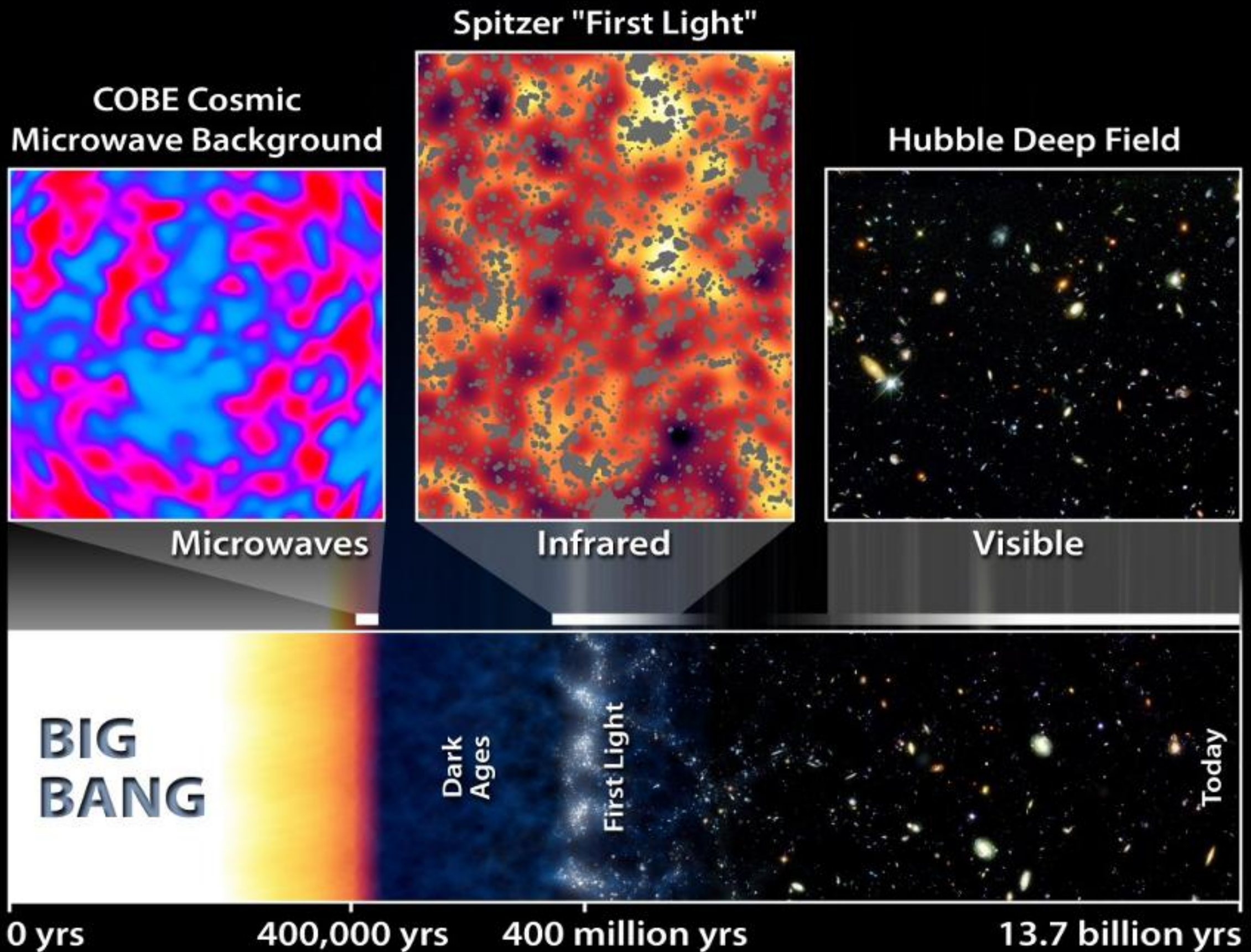


Spacetime During Inflation



Seeds of Structure Formation





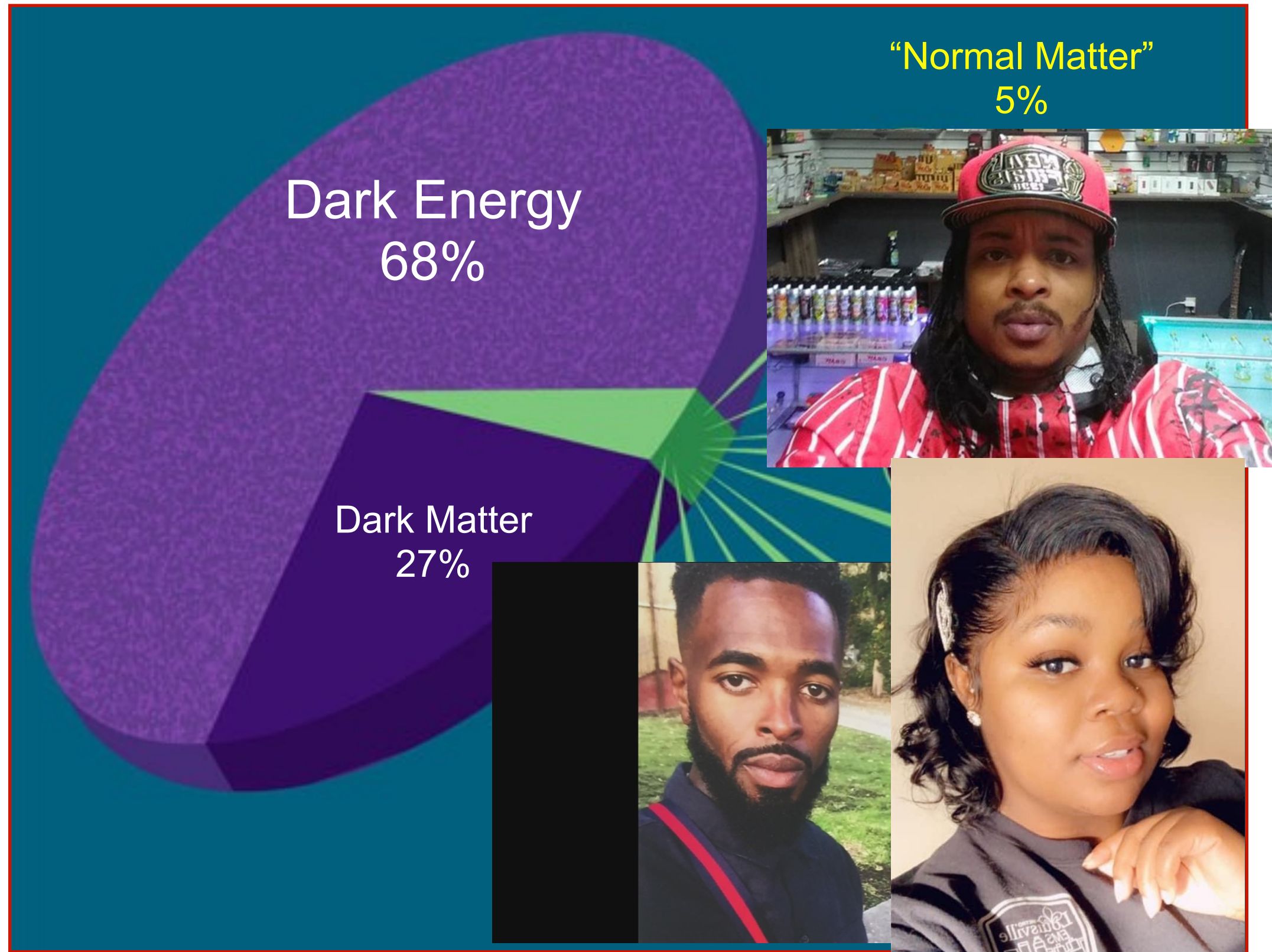
Timeline of the Universe

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / A. Kashlinsky (Goddard Space Flight Center)

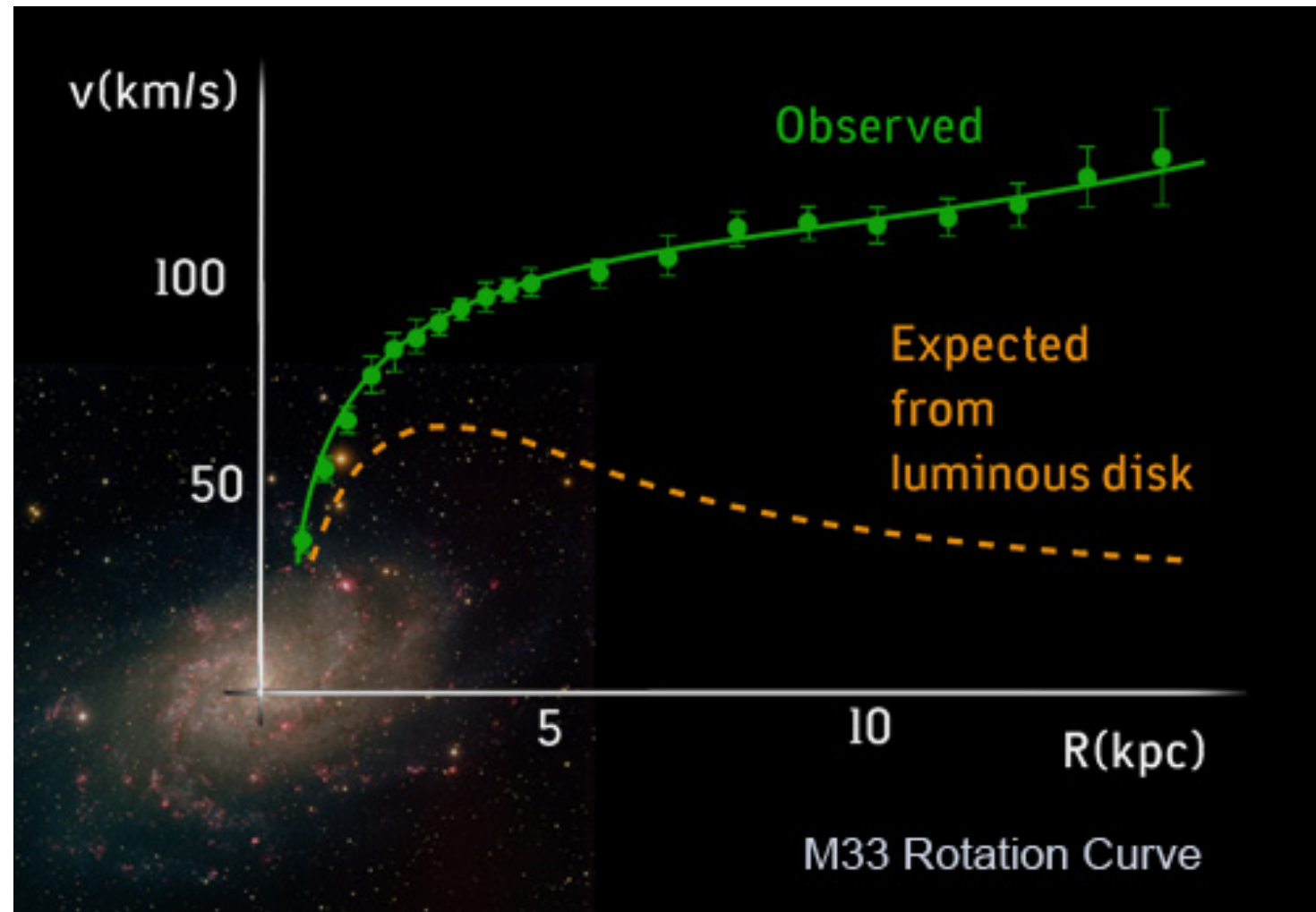
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What is the universe made of?



The Case for Dark Matter

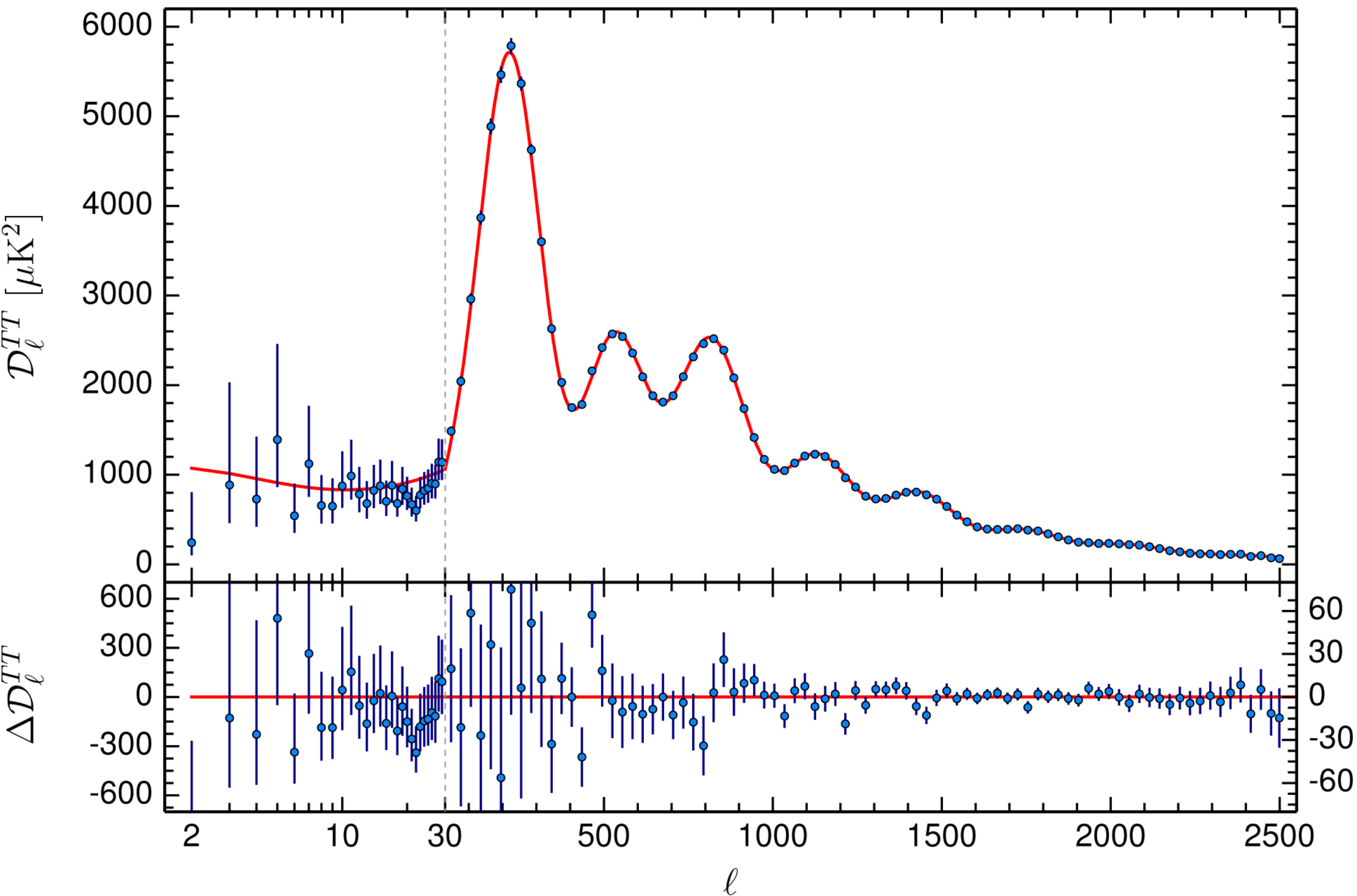
- Apparently need more mass than we can see
- Modified gravity?
- Produces no light!
- “**Dark matter**” -> only significant interaction is gravity
- Should be called **invisible matter**



The Case for Dark Matter



The Case for Dark Matter



Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

Dark Photon

Light Force Carriers

Sterile Neutrinos

Warm DM

Asymmetric DM

Dirac DM

mSUGRA

pMSSM

R-parity Conserving

Gravitino DM

Q-balls

Soliton DM

Quark Nuggets

UED DM

6d

5d

RS DM

Extra Dimensions

Warped Extra Dimensions

Axion DM

QCD Axions

Axion-like Particles

T-odd DM

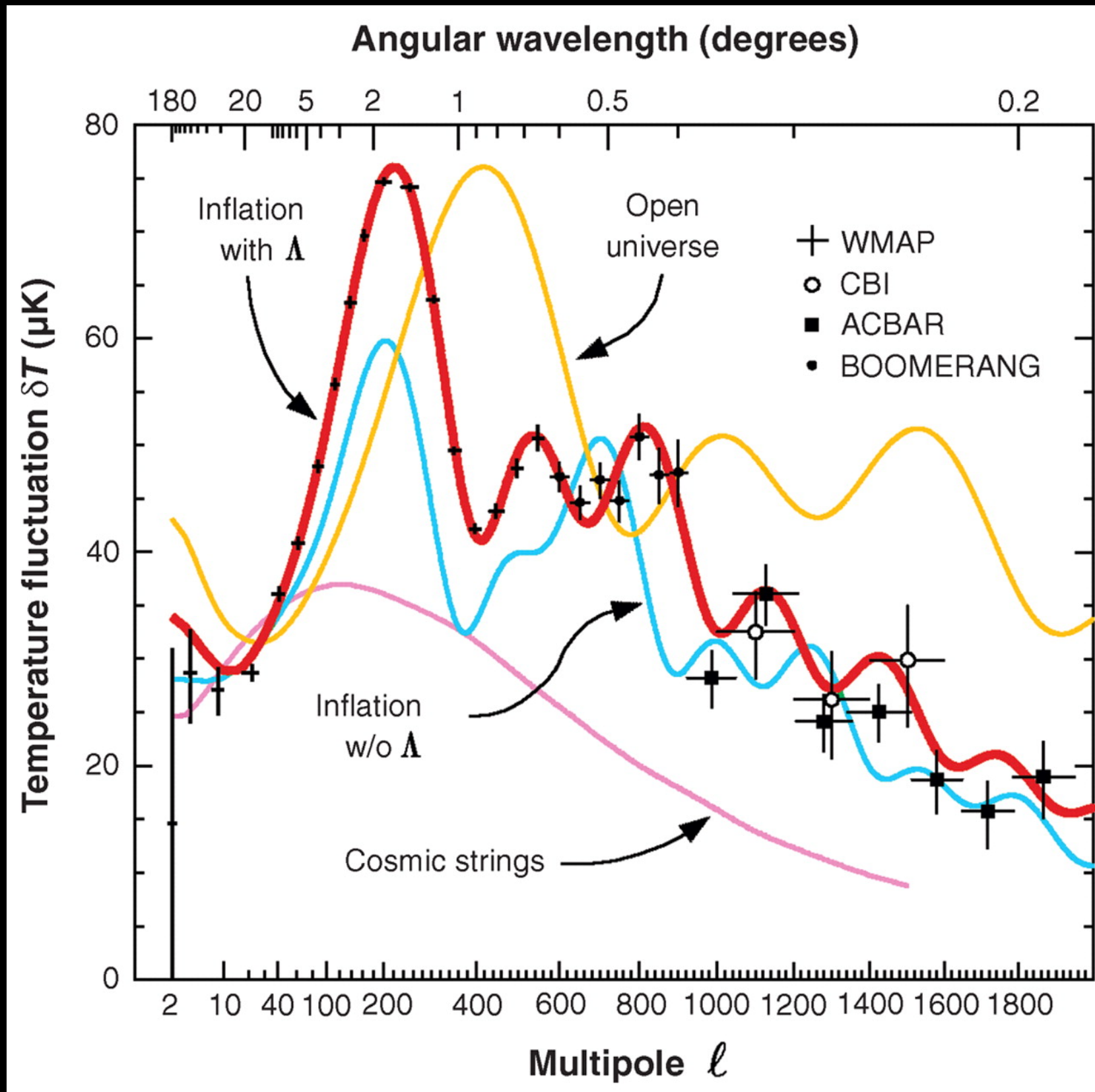
Little Higgs

Littlest Higgs

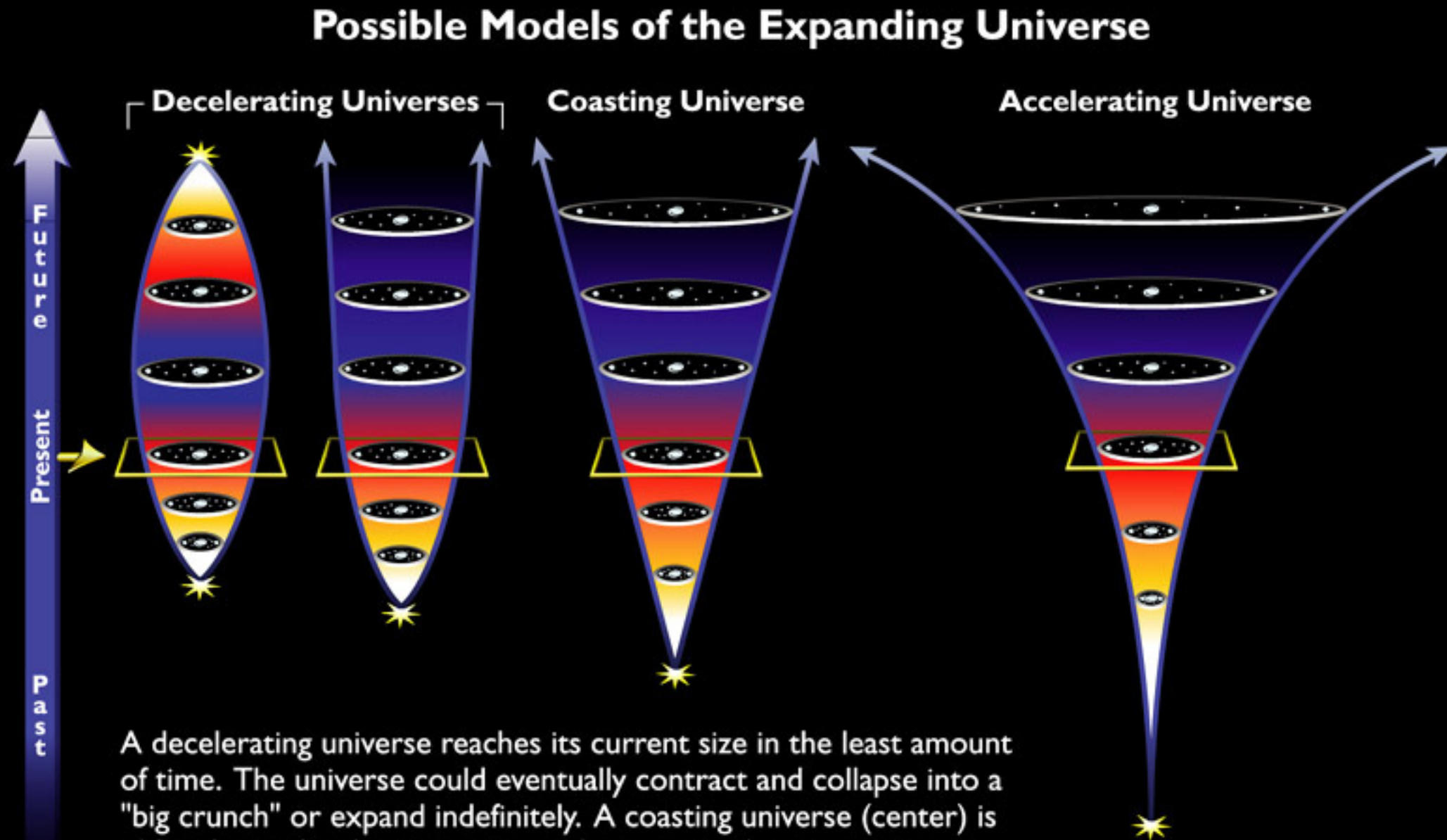
What else does CMB tell us?

- Expansion rate, Hubble constant
- The shape of spacetime is flat
- Measurement of the cosmological constant

A Flat Universe

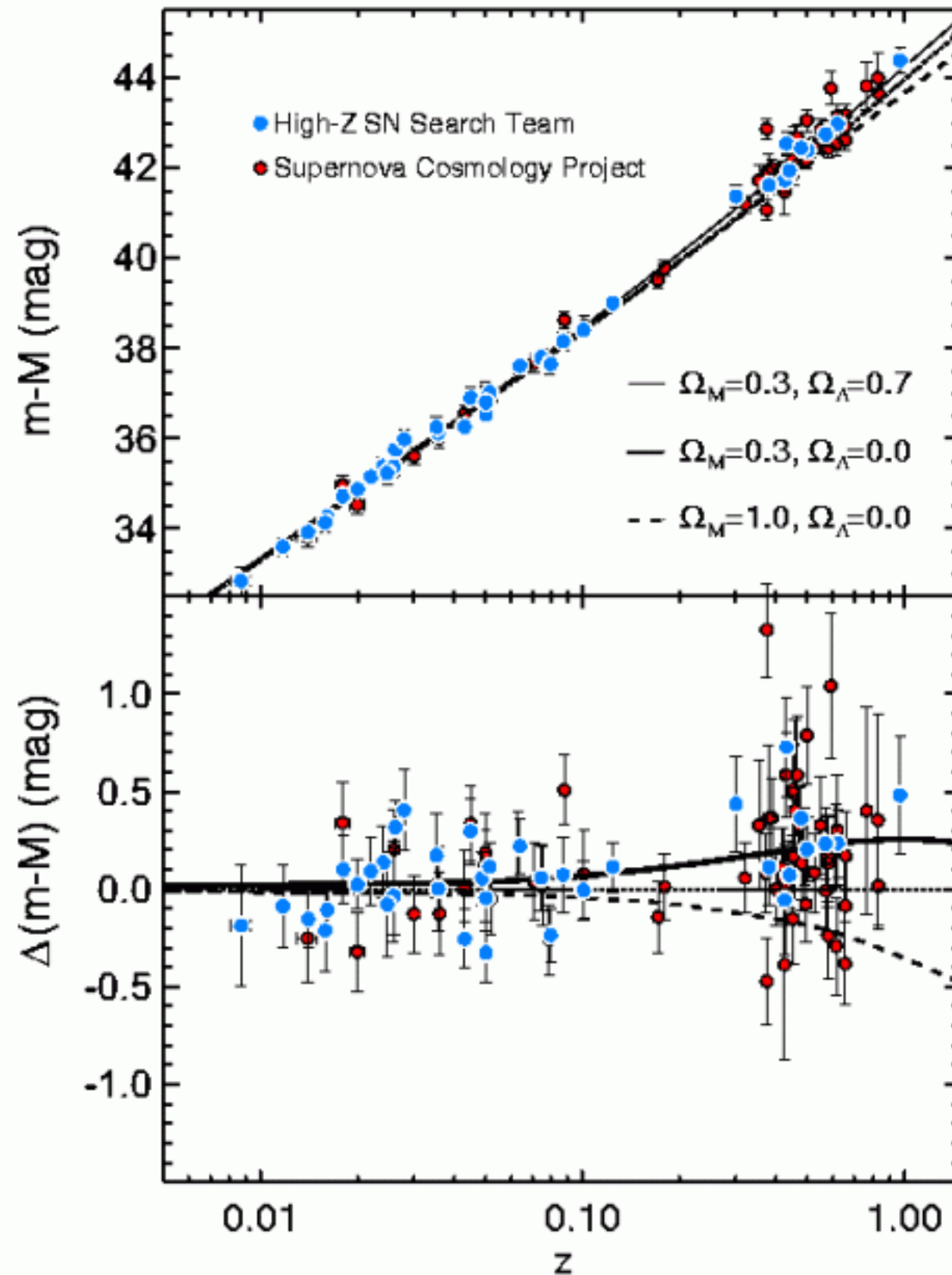


Possible Expansion Futures



A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

The Case for Dark Energy



Λ CDM Cosmology

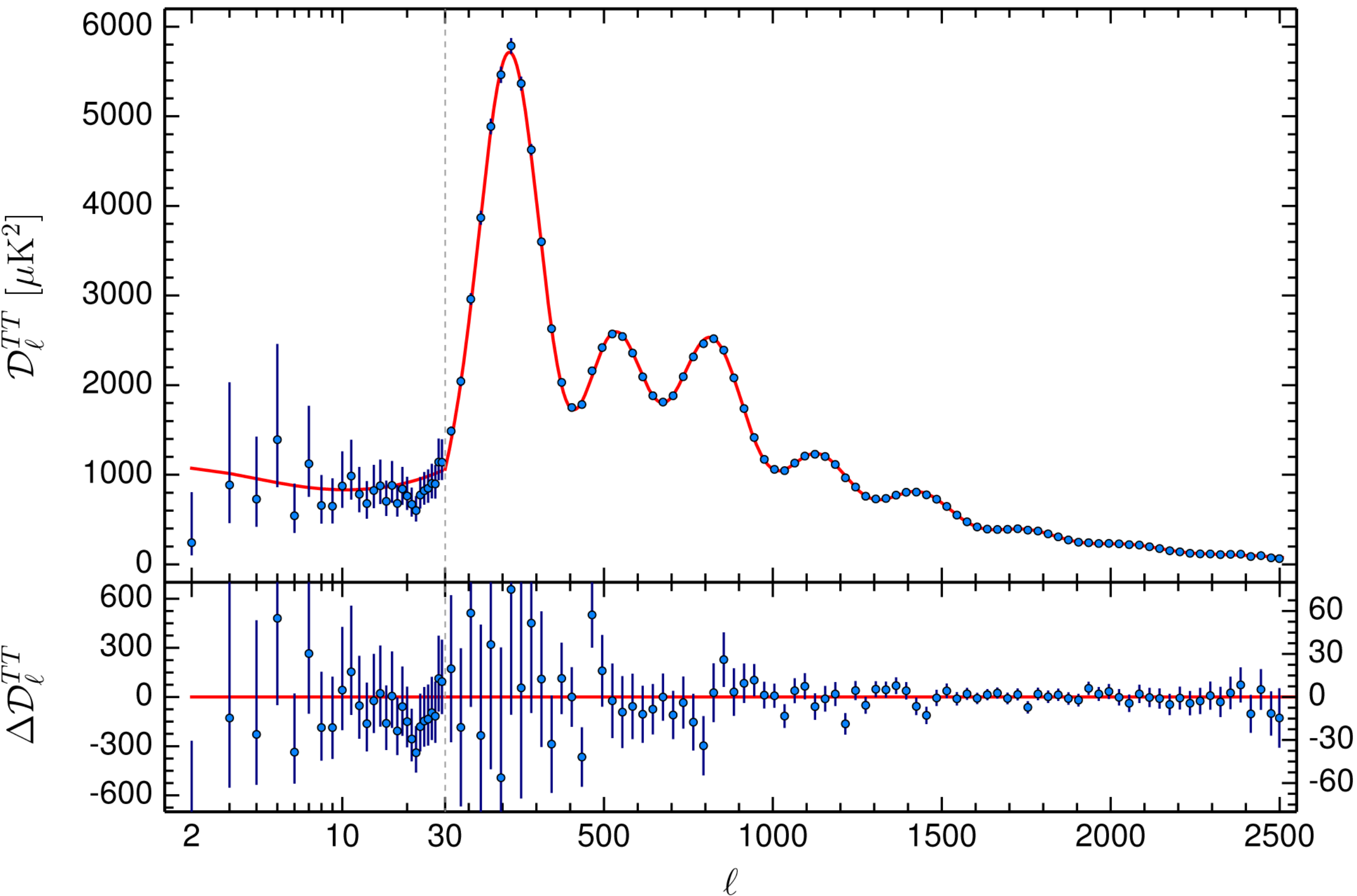
Einstein's Equation

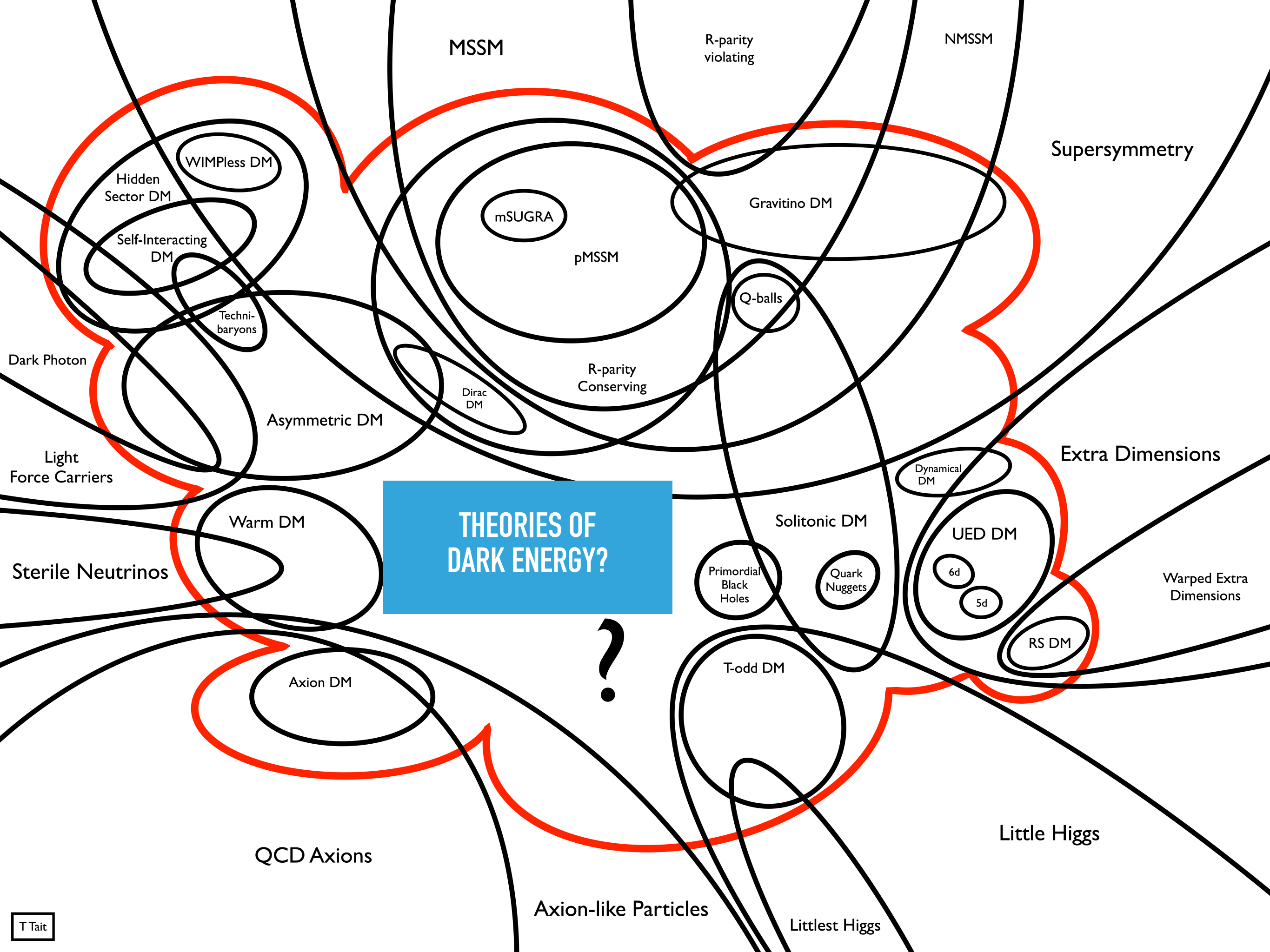
$$G_{\alpha\beta} - \Lambda g_{\alpha\beta} = 8\pi T_{\alpha\beta}$$

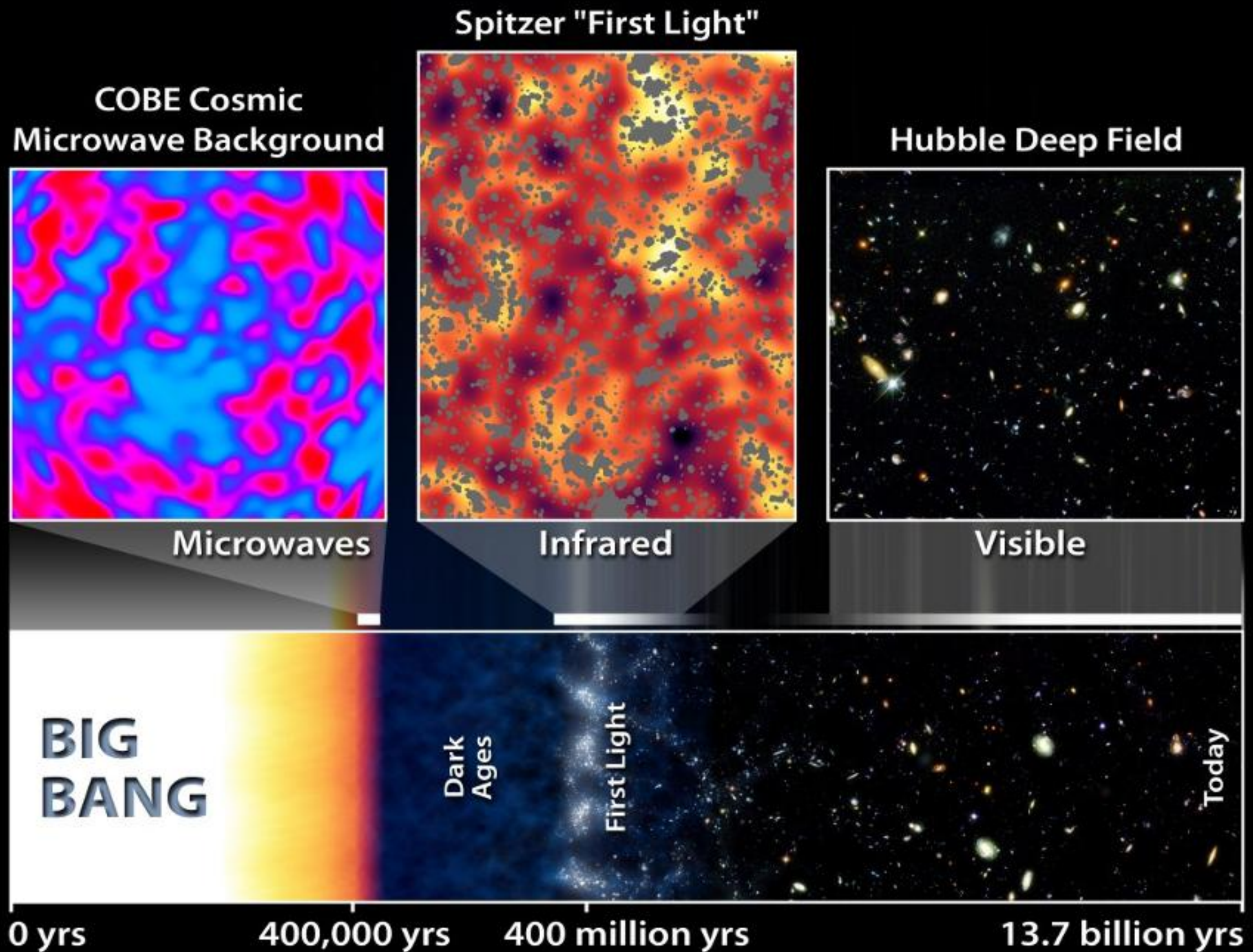
FRW Equation

$$H^2 = \frac{8\pi G\rho}{3c^2} - \frac{k}{R^2} + \frac{\Lambda c^2}{3} \quad \text{where } \Lambda = \text{cosmological constant}$$

The Case for Λ CDM







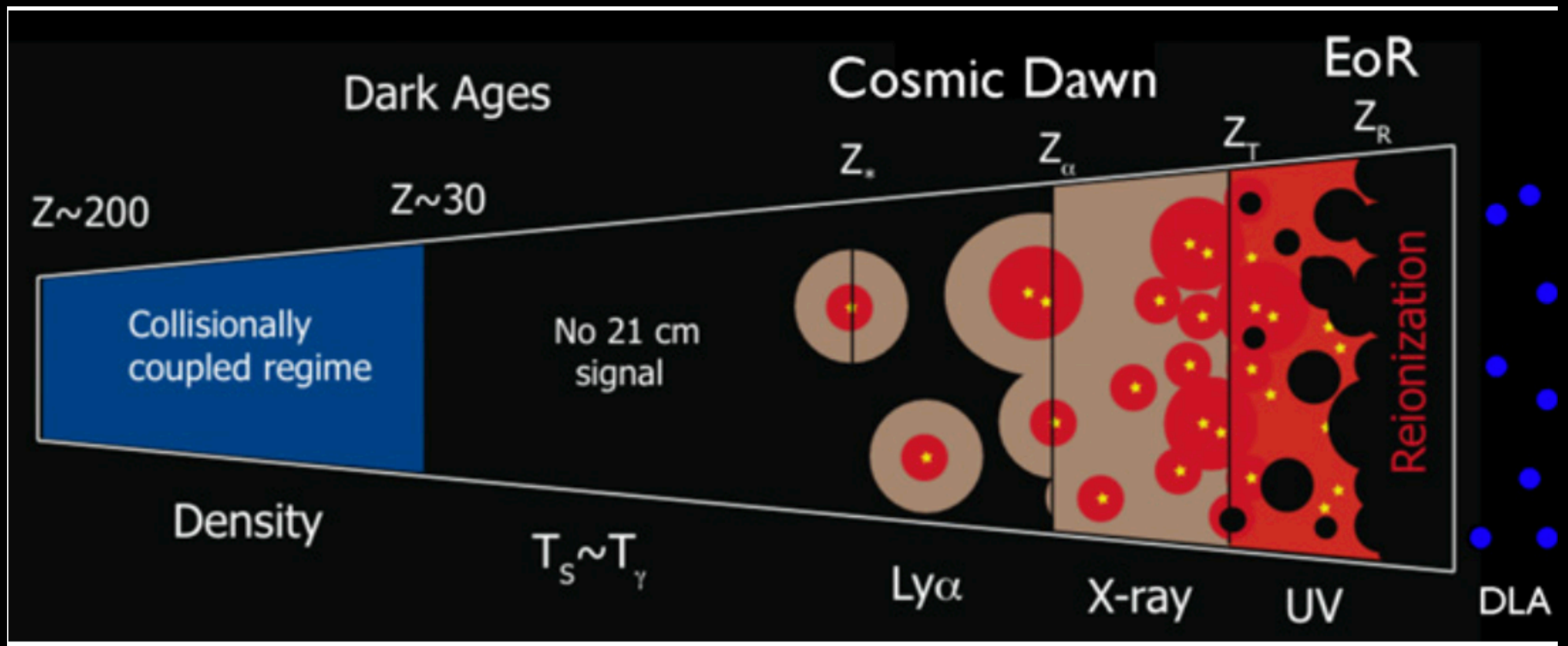
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Square Kilometer Array: 21 cm



Square Kilometer Array: 21 cm

