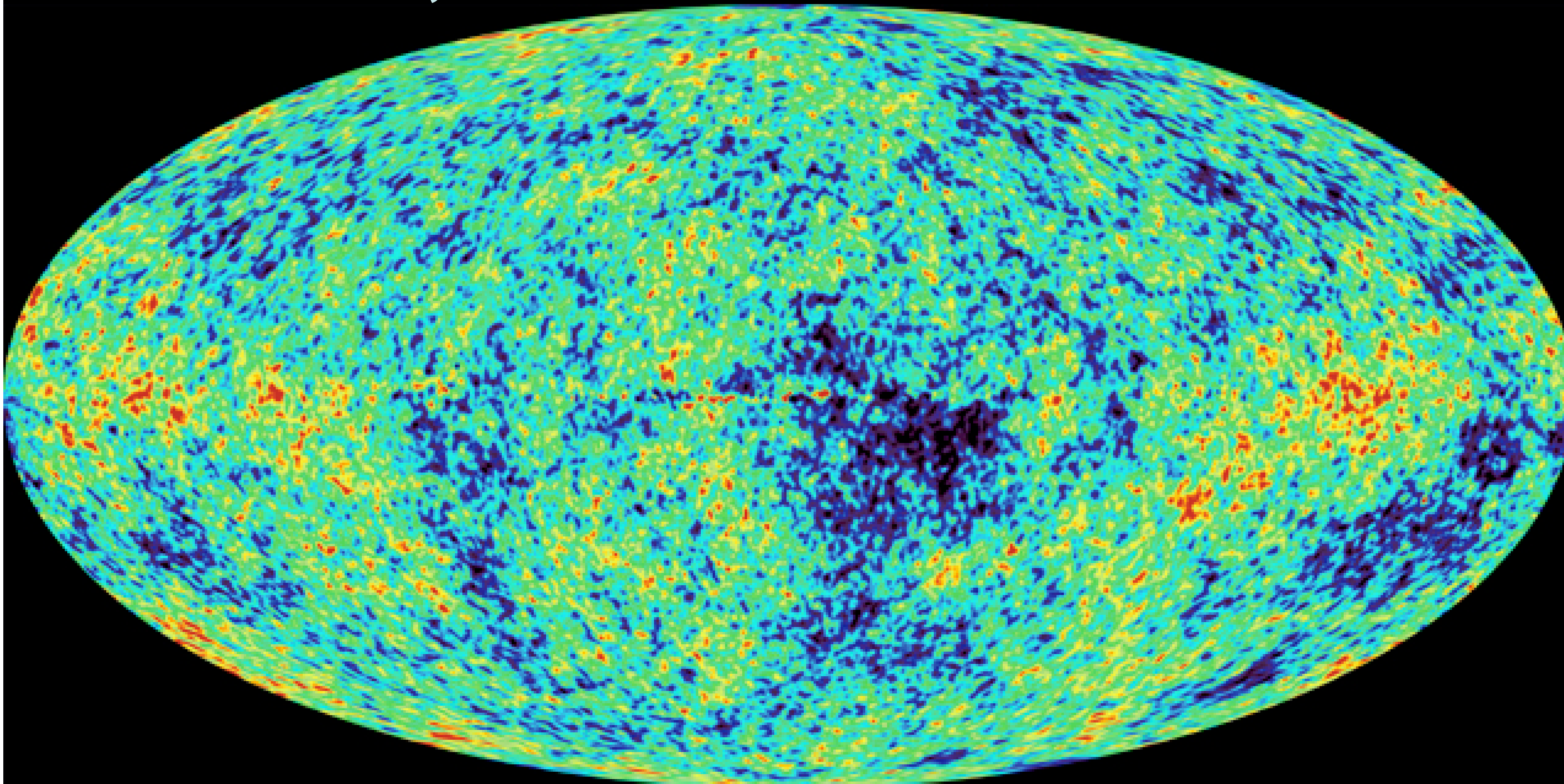
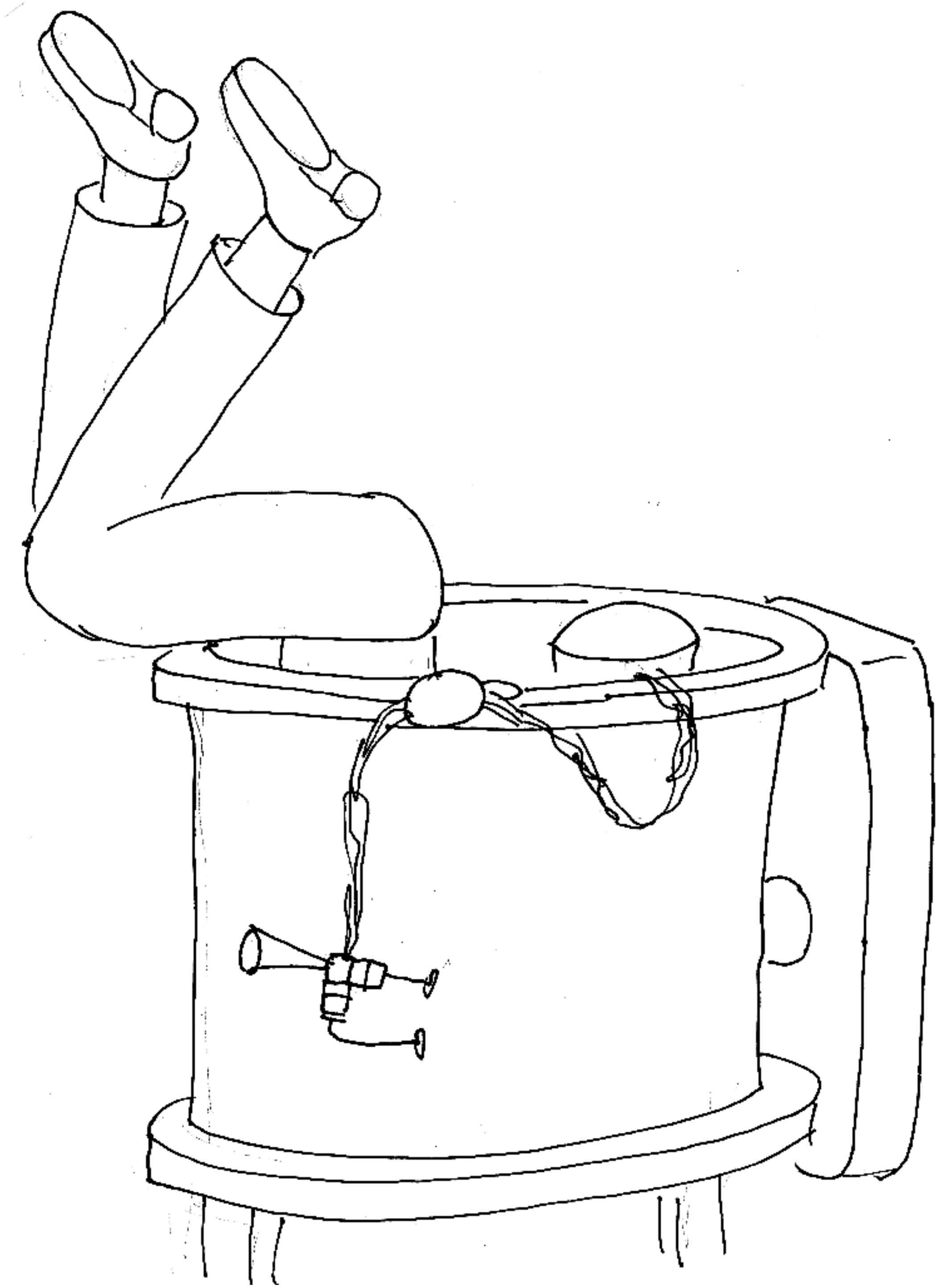
The Age of Things:

Sticks, Stones and the Universe



Parameterizing the Age of the Universe

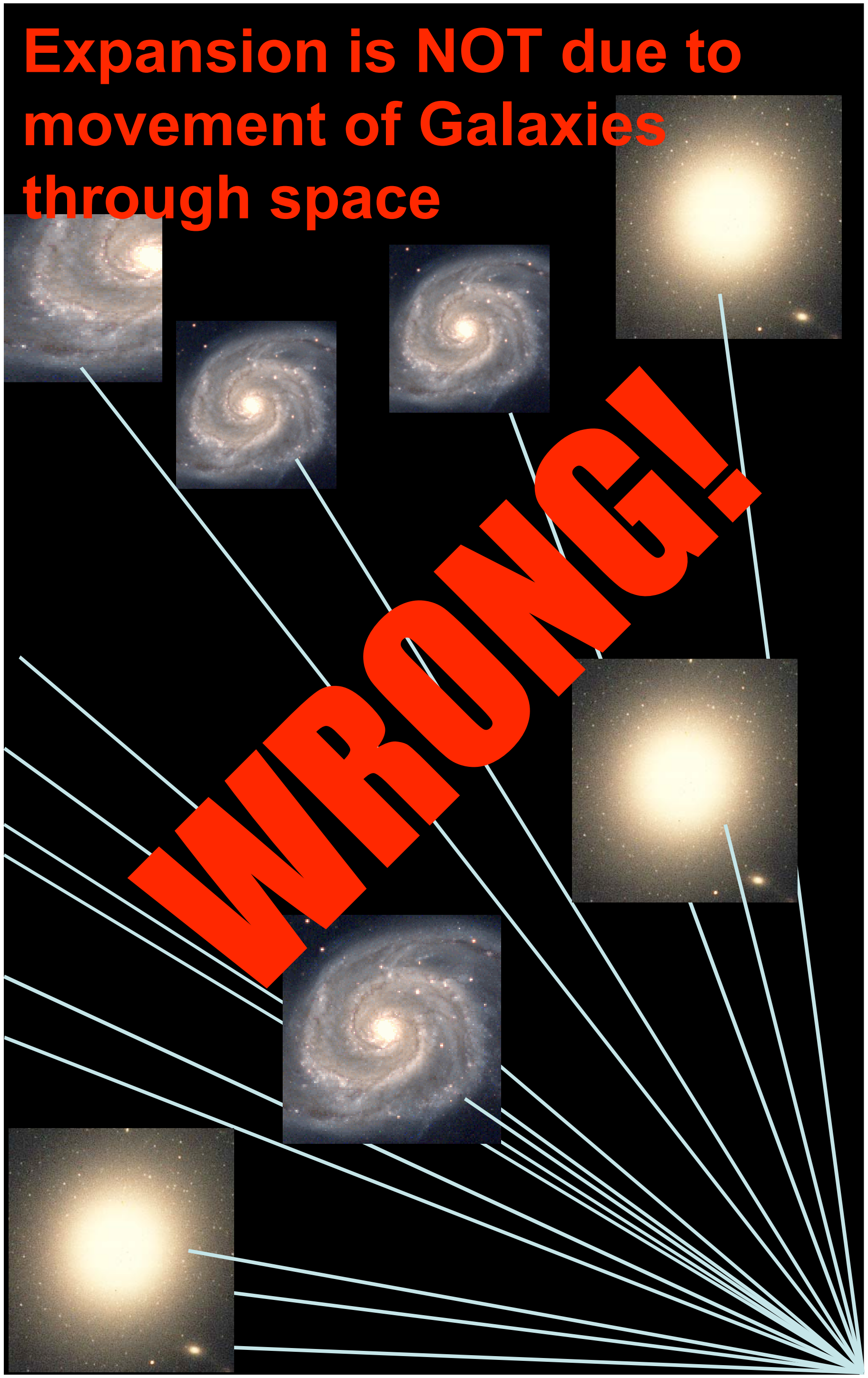
http://cfcp.uchicago.edu/~mmhedman/compton1.html



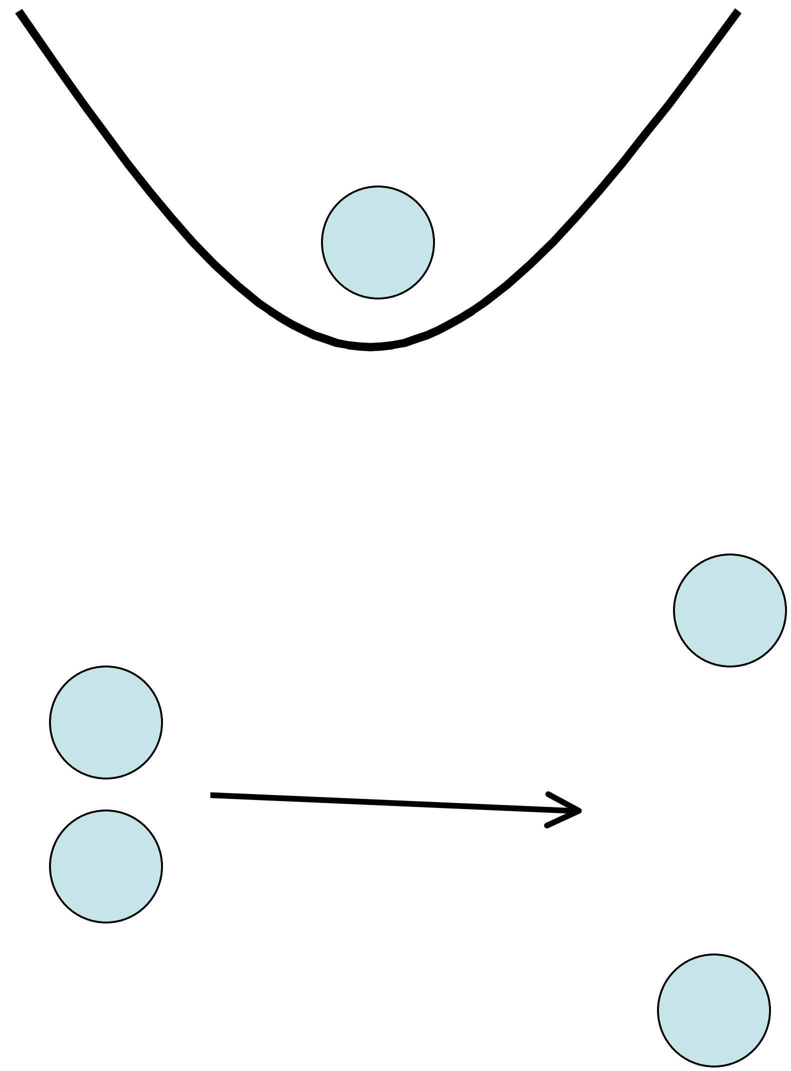
WARNING!

Cosmologist talking about Cosmology!

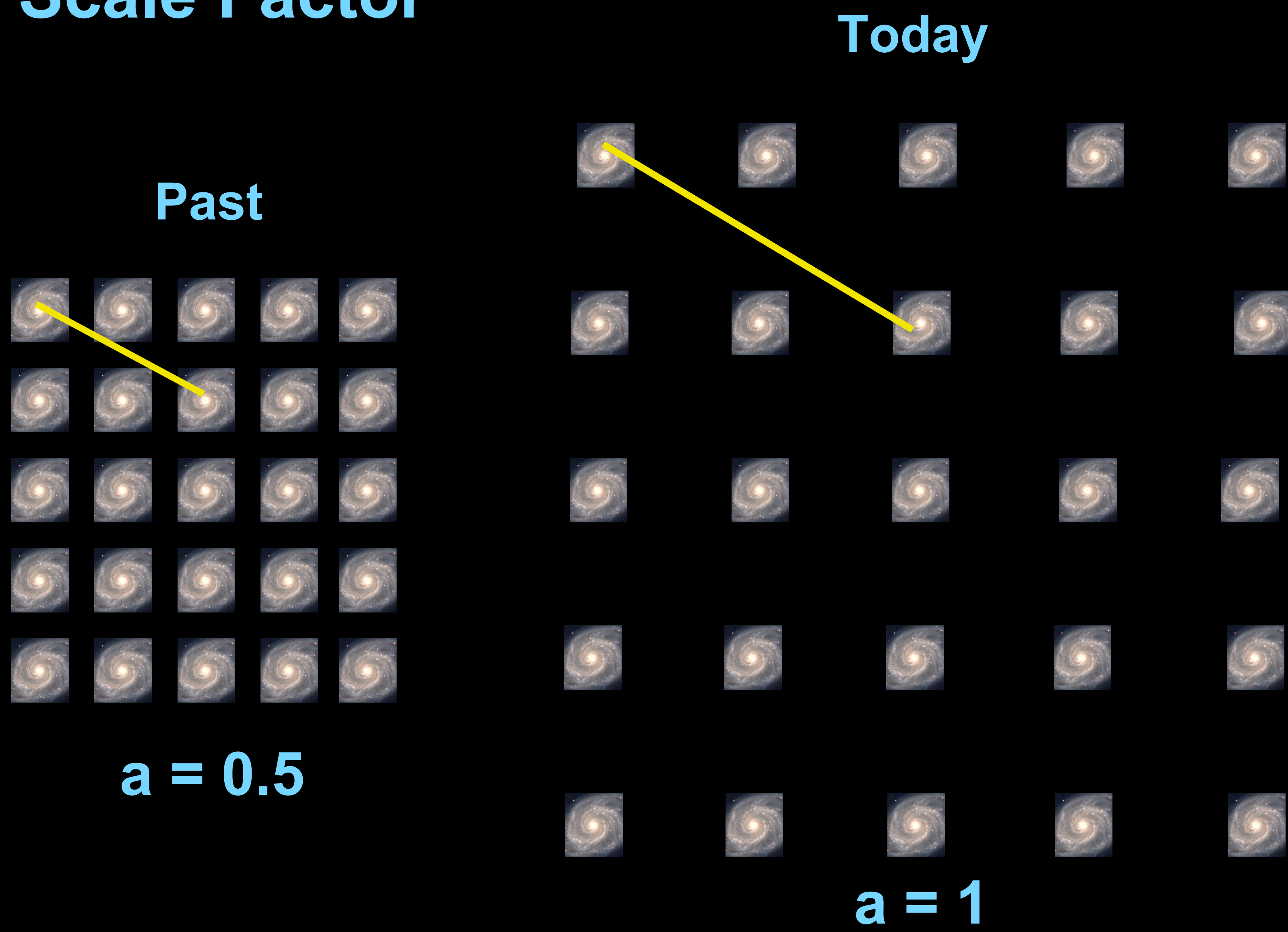
Last Time: The Expanding Universe



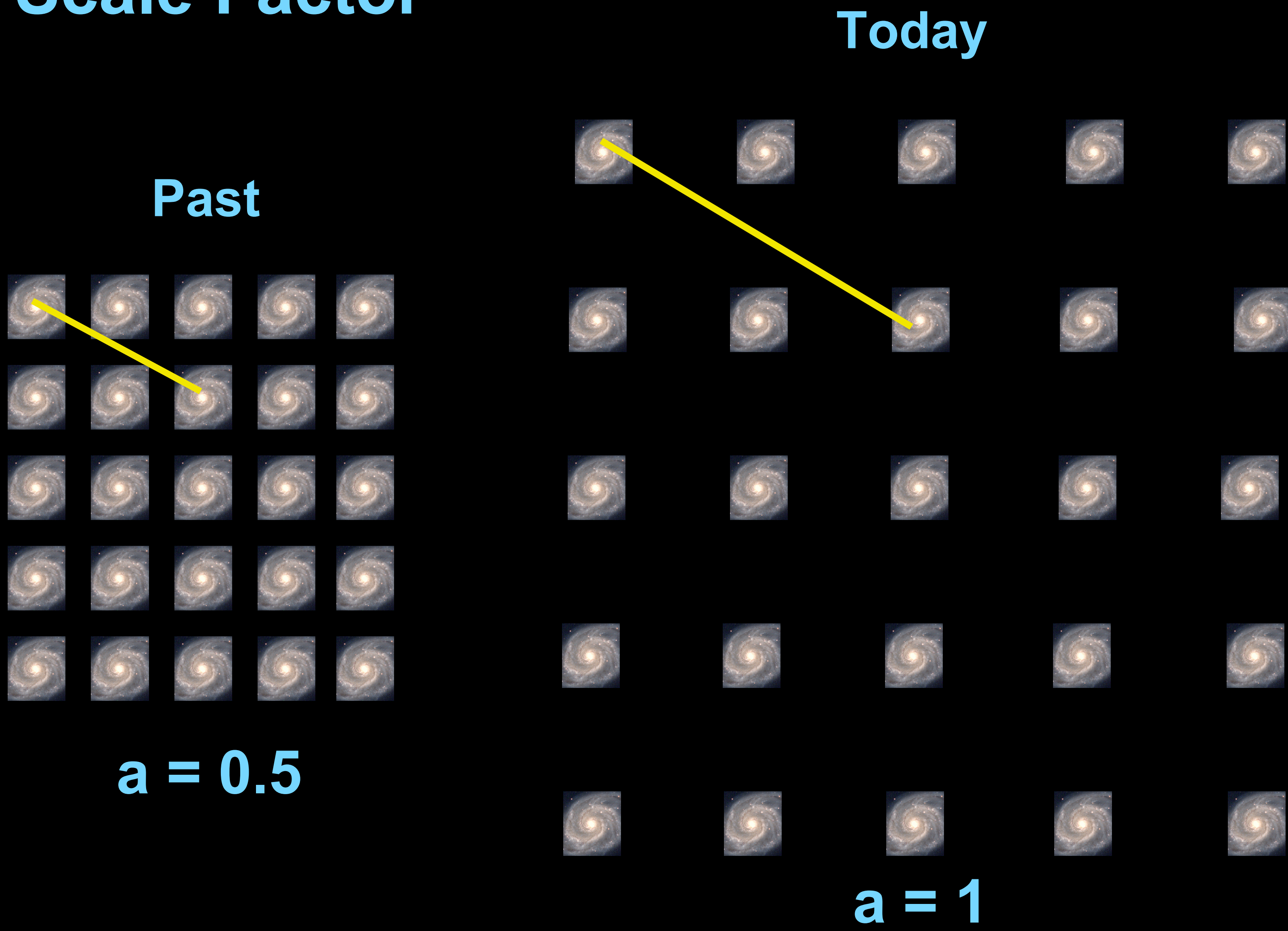
Expansion is due to changes in geometry caused by the presence of matter



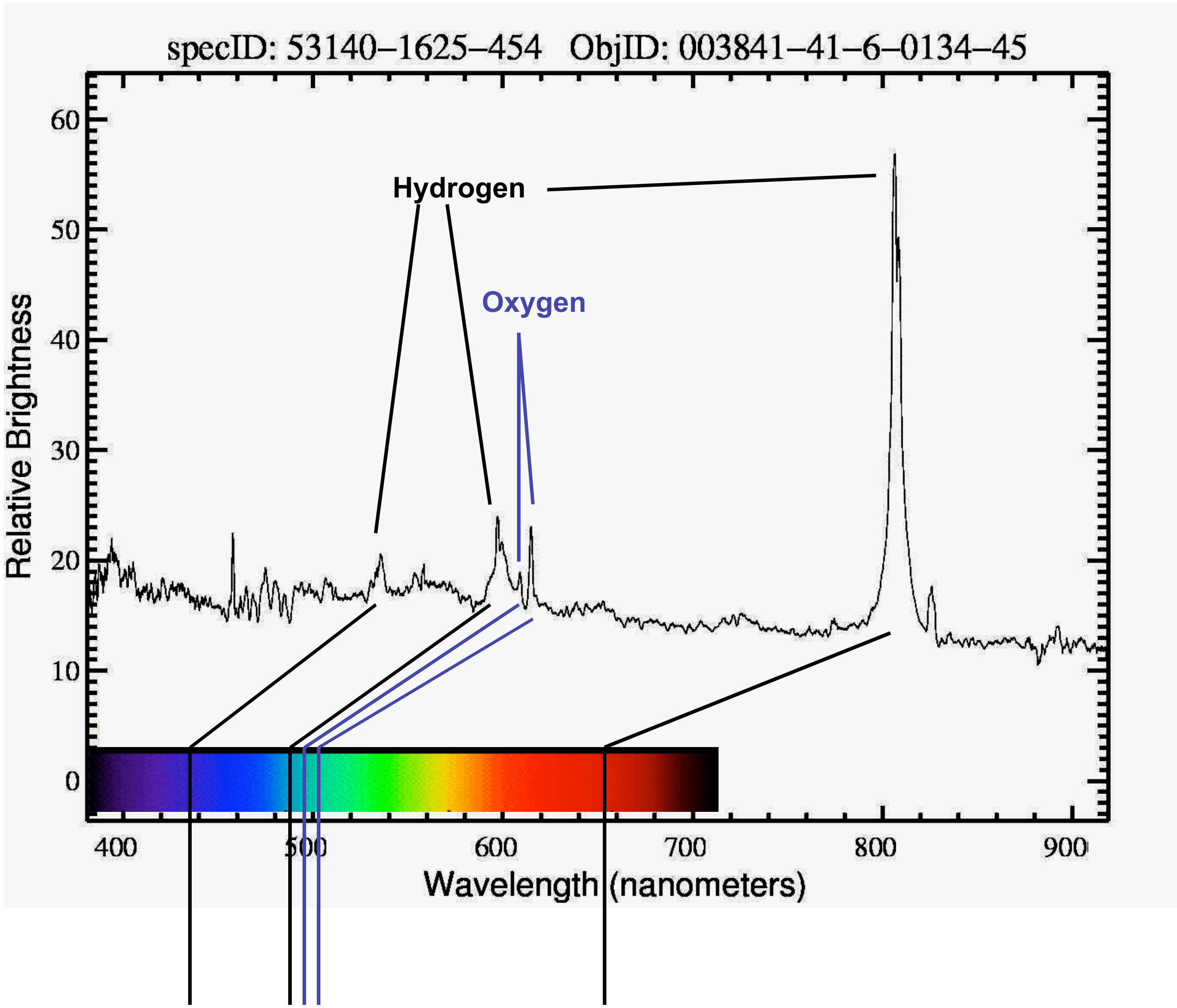
The Scale Factor



The Scale Factor



The Big Bang happens when a = 0

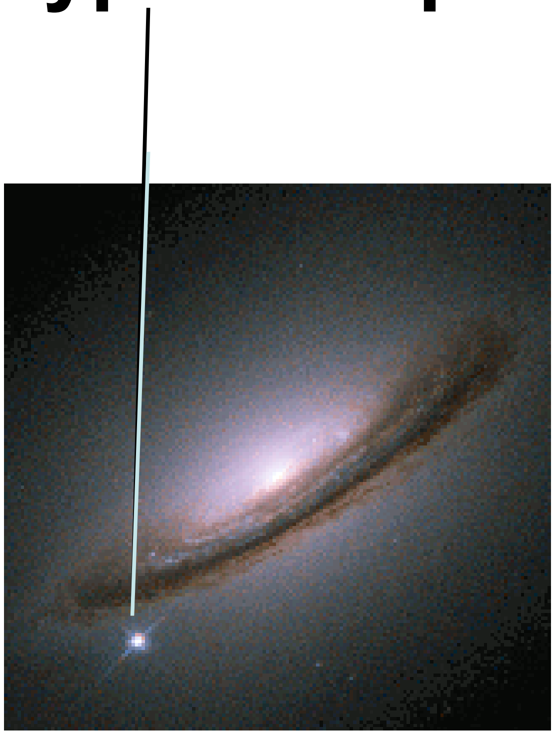


Wavelengths measured in Laboratory

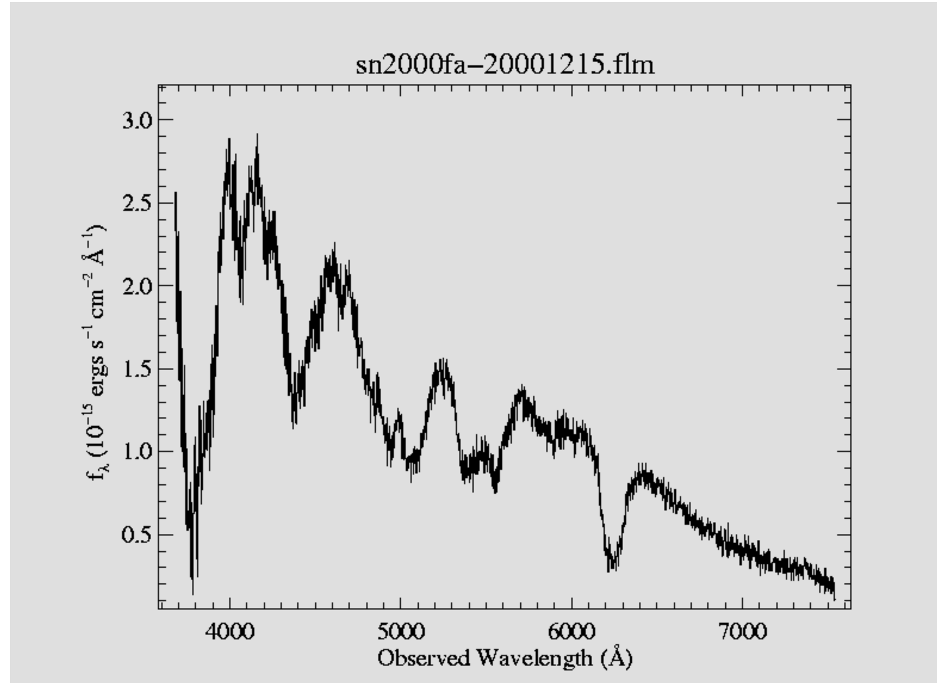
(Coutesy of E. Sheldon)

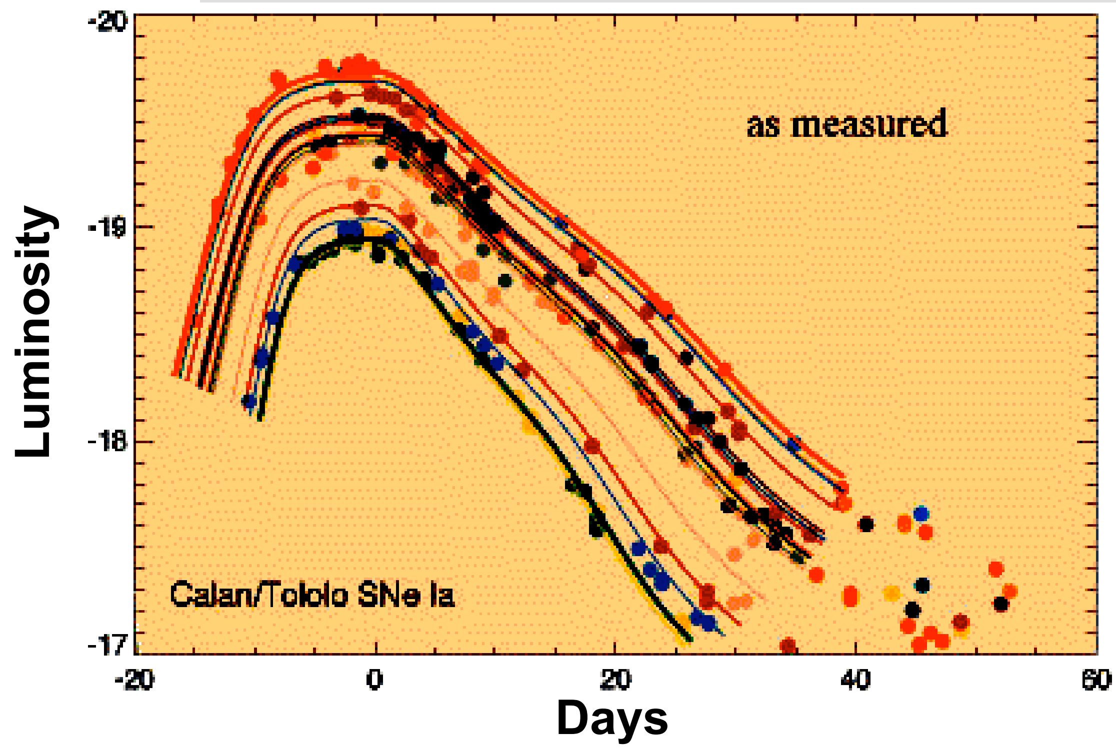
Scale Factor from Redshifts

Galaxy Distances: Type Ia Supernova

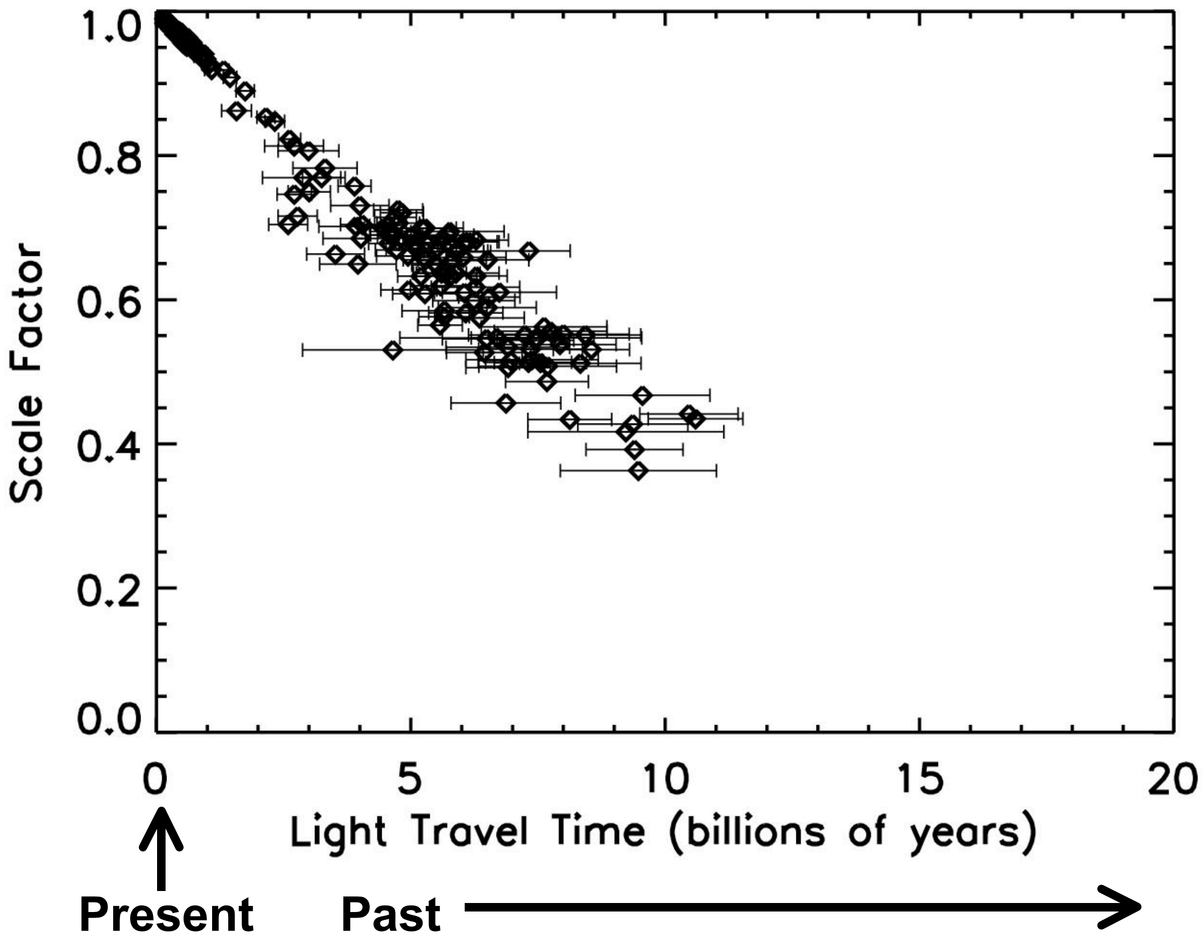


Supernova 1994D





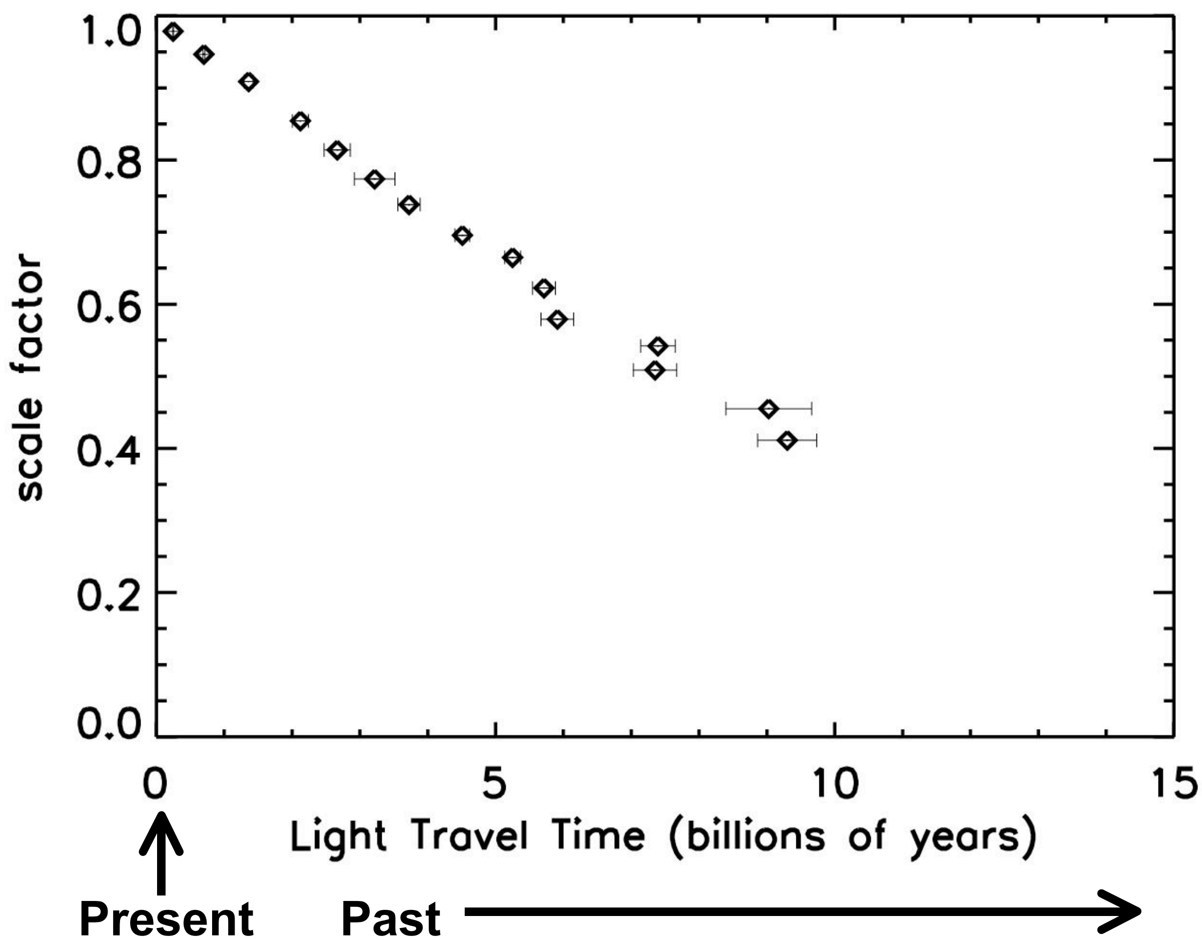
The Scale Factor Over Time



Supernova 1994D

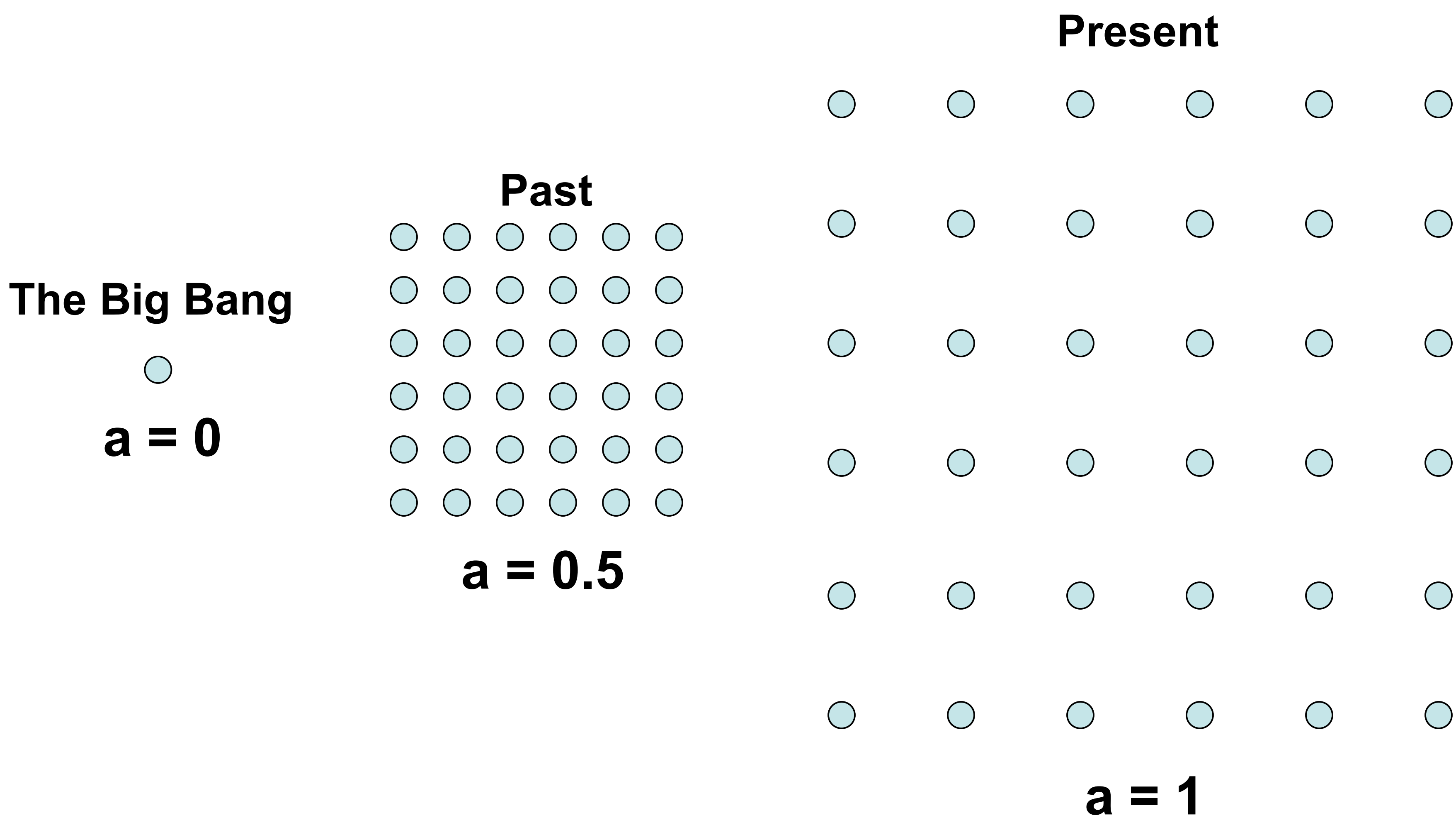
Based on Data from Riess et. al. astro-ph/0402512

The Scale Factor Over Time

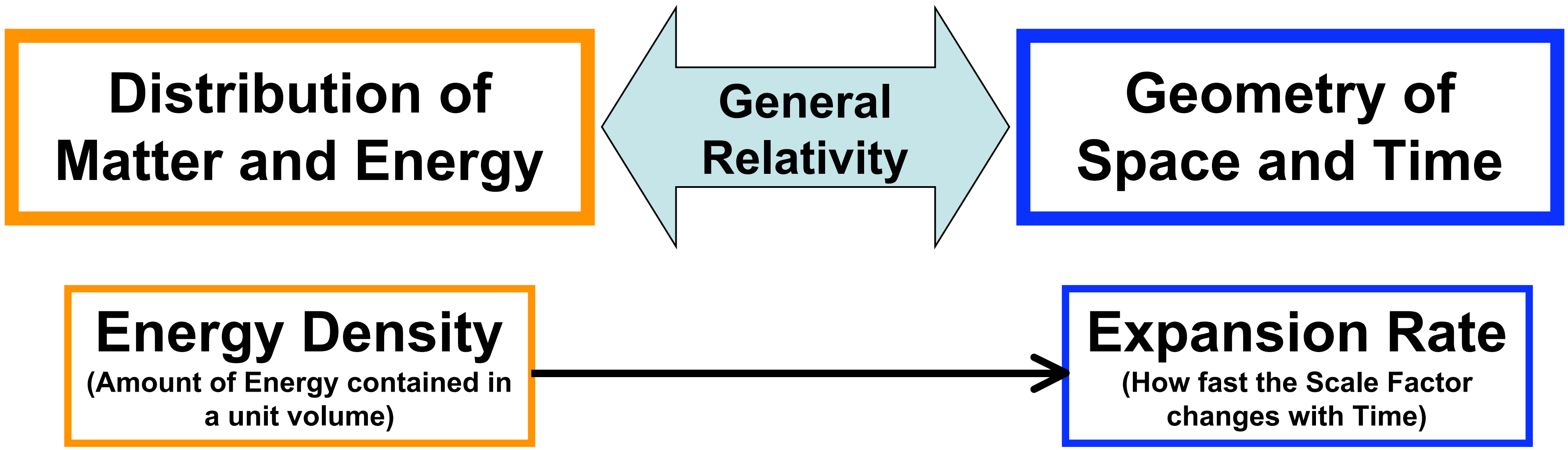


Supernova 1994D

The Scale Factor



The Expansion History and Material Content of the Universe



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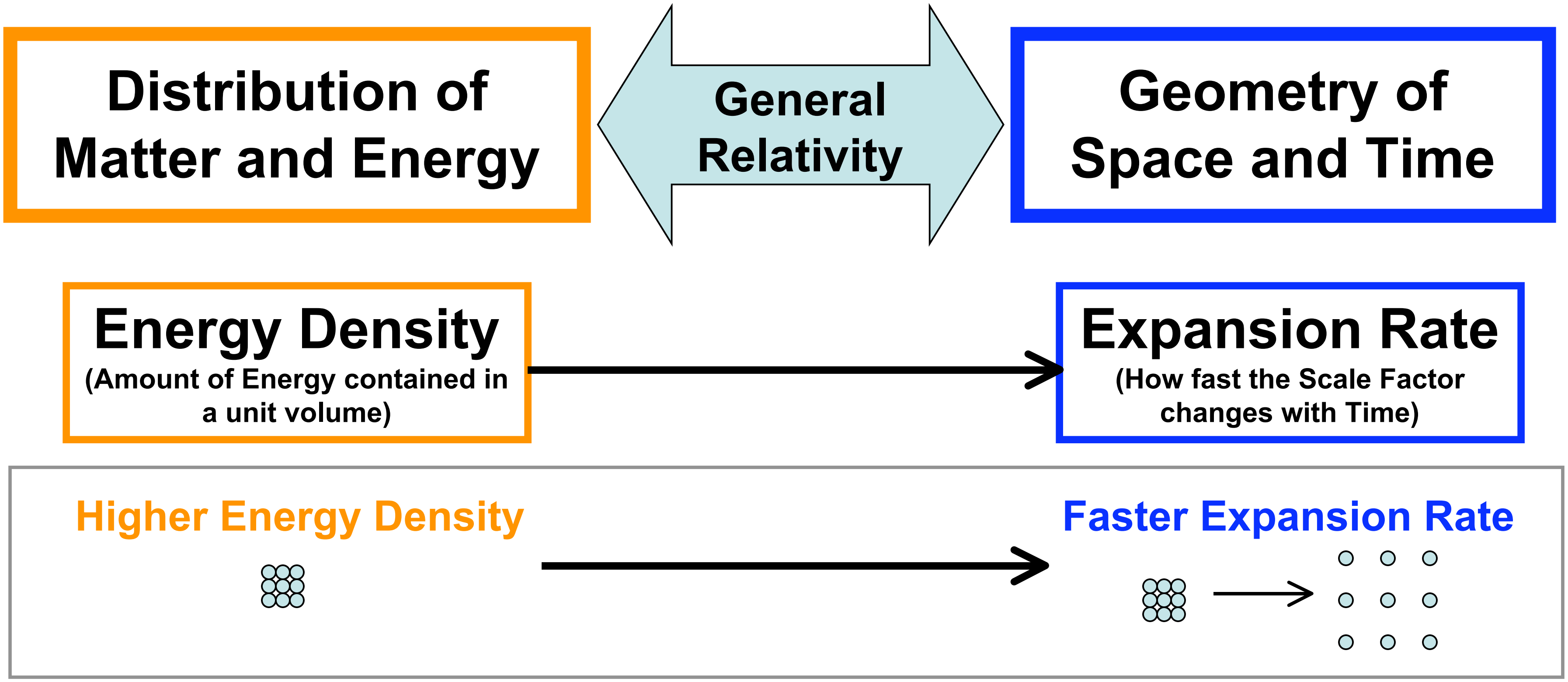

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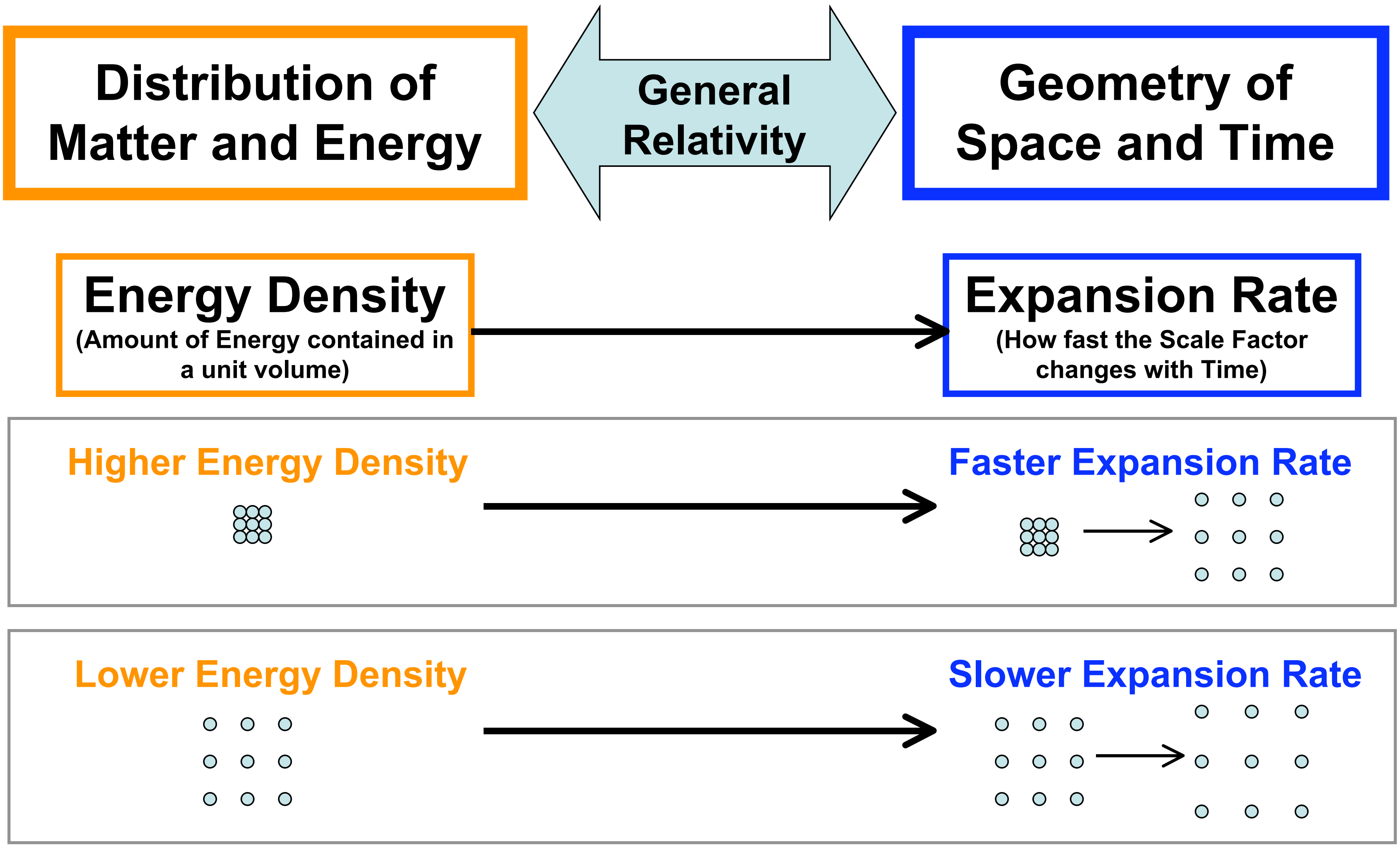

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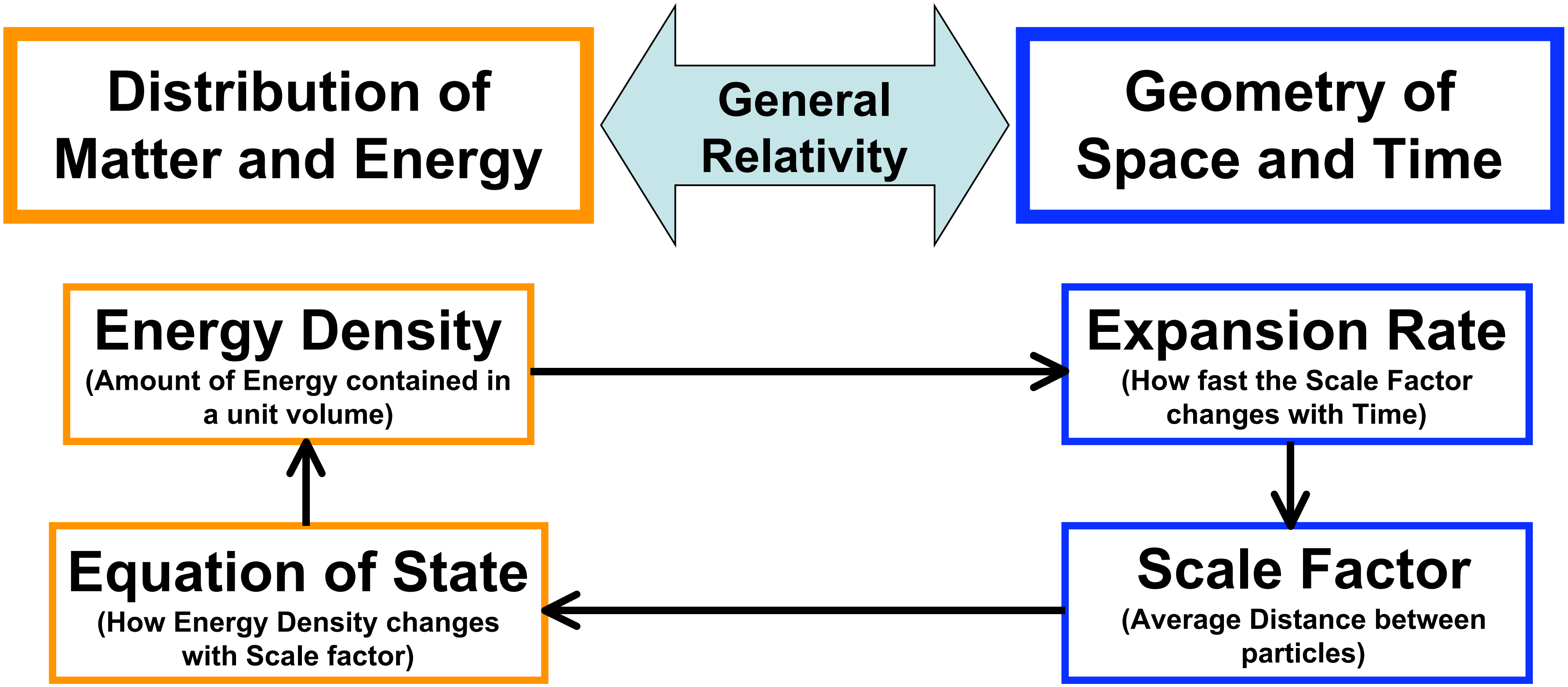
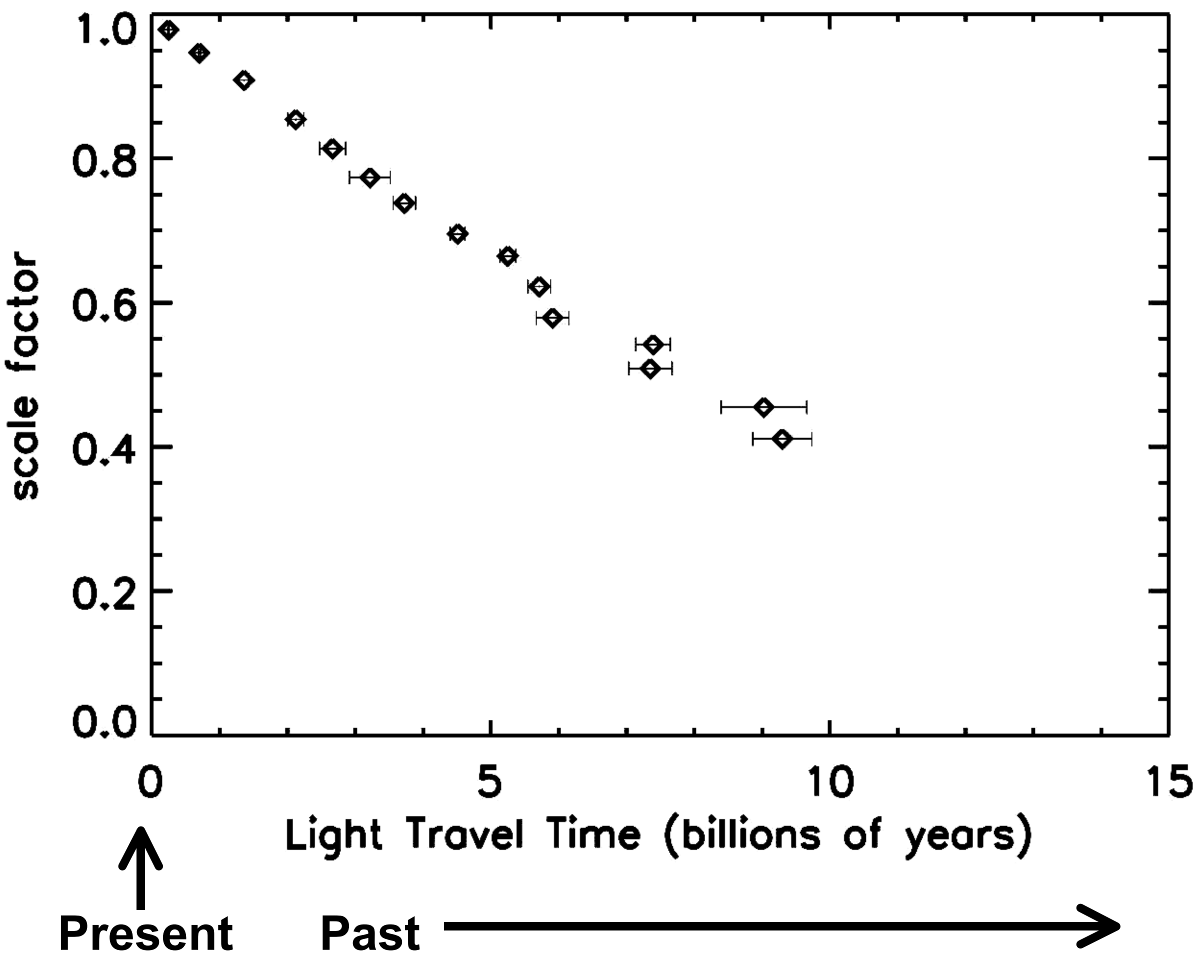
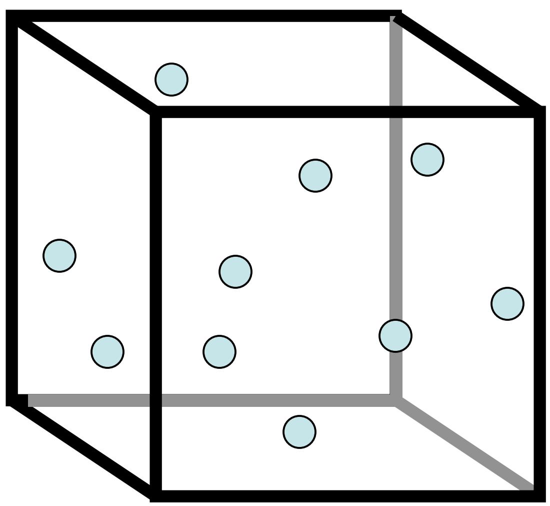


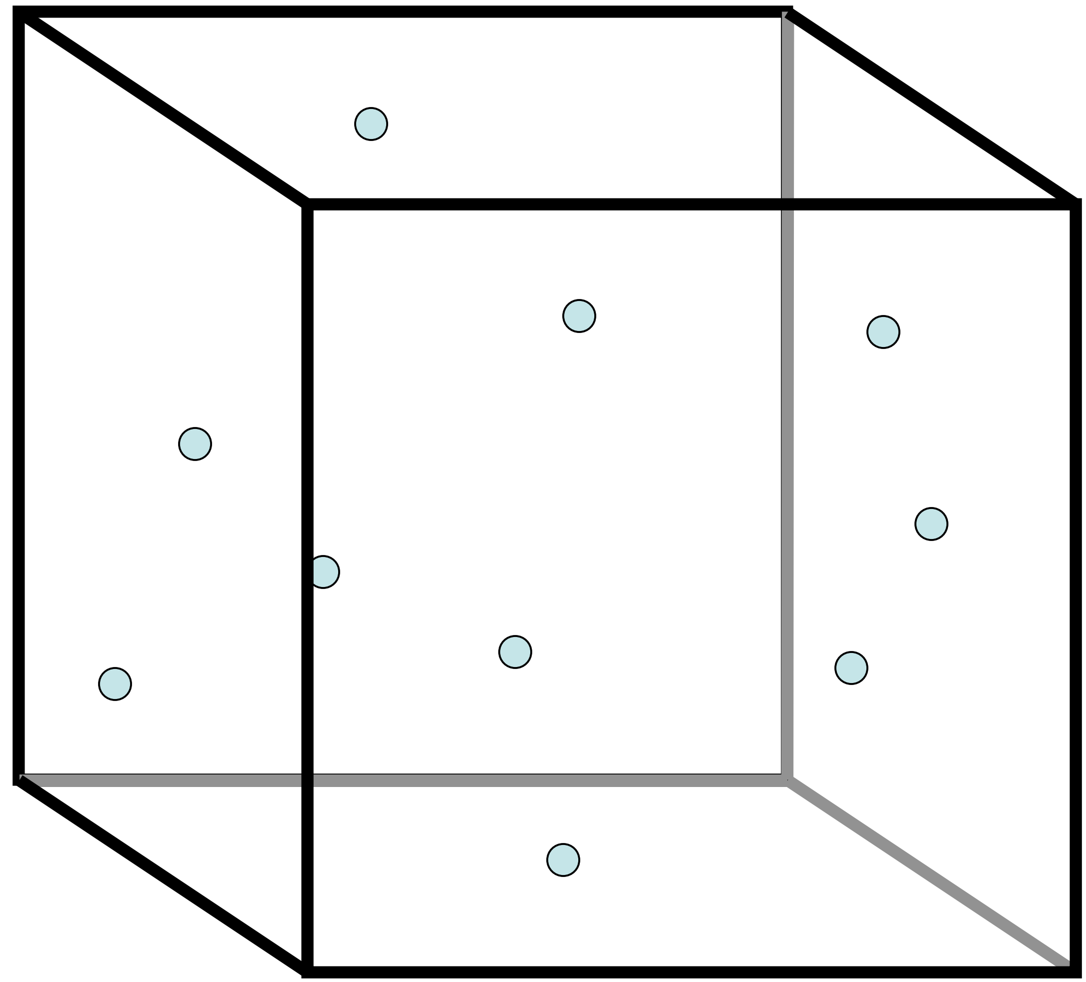
A closer look at the expanding universe



Types of Energy: Matter

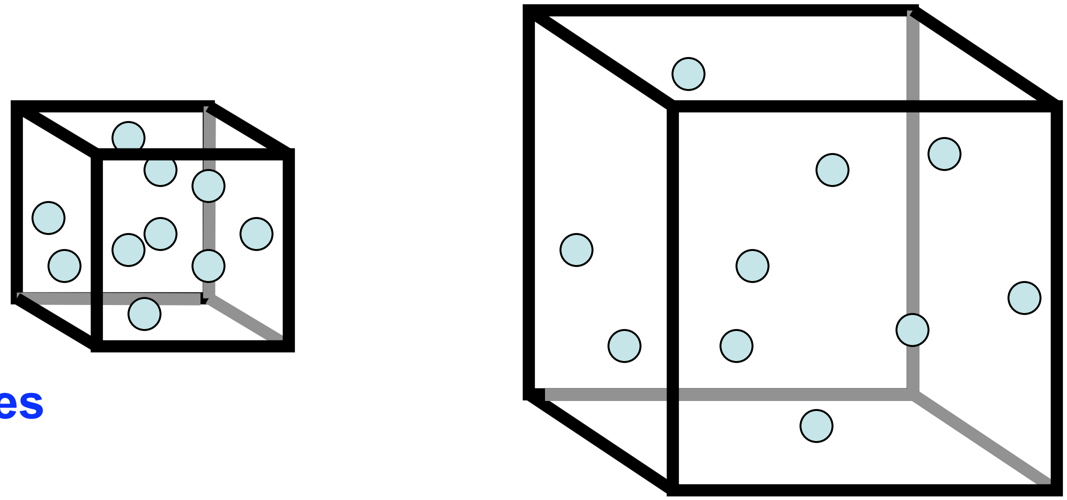


Scale Factor Increases
Energy Density Falls
Expansion Rate Slows



Types of Energy

Matter



Scale Factor Increases
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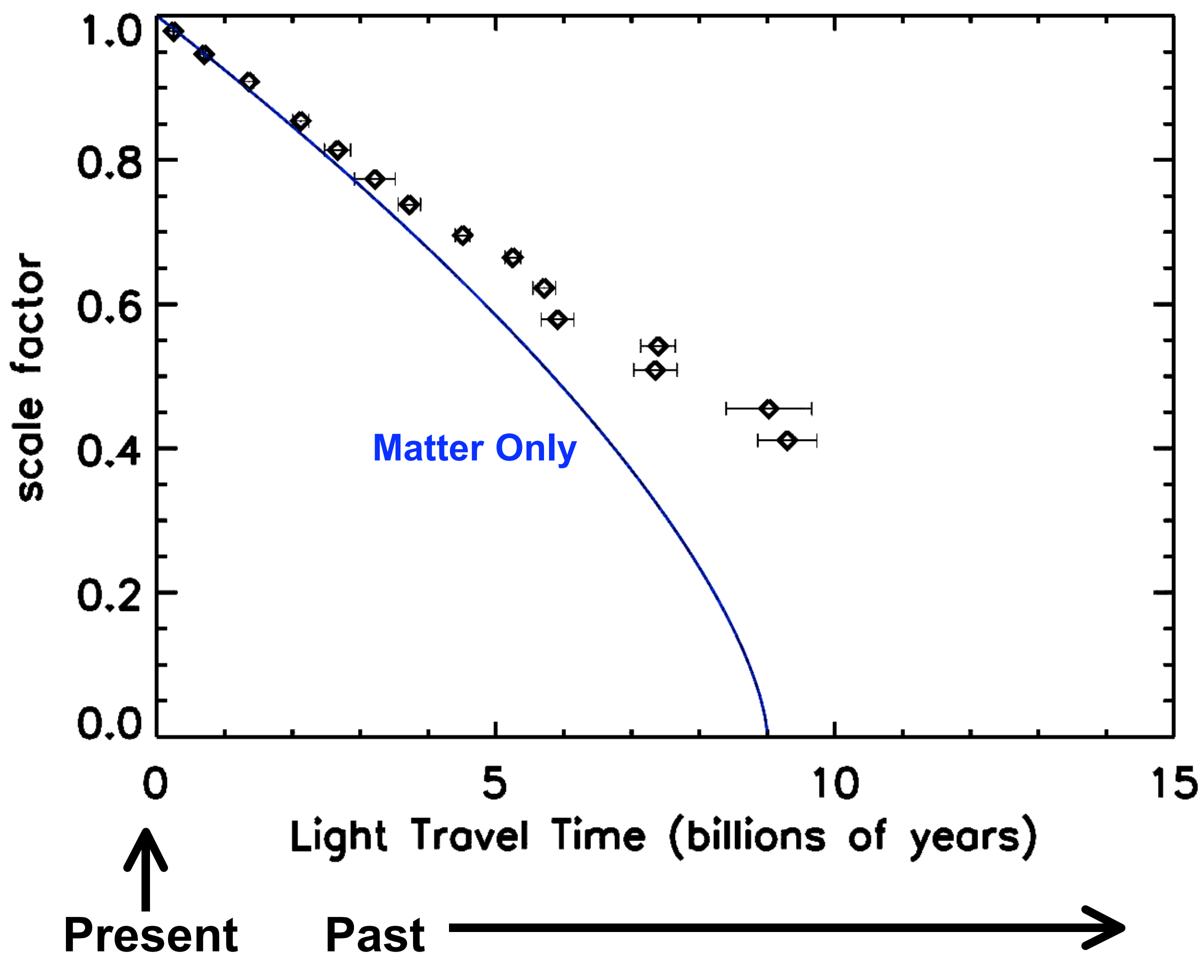
Predictions for a Universe with only Matter



Matter

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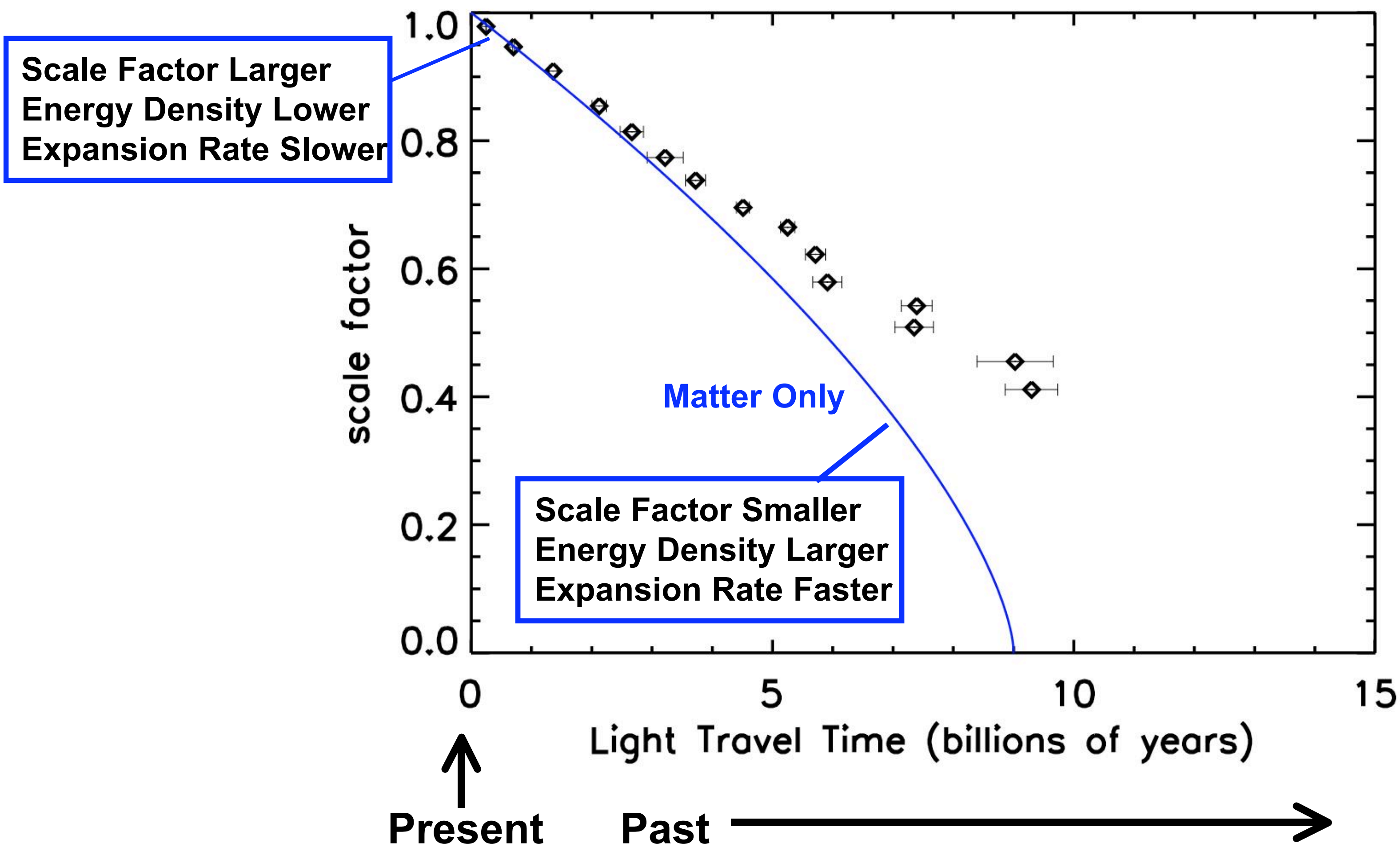

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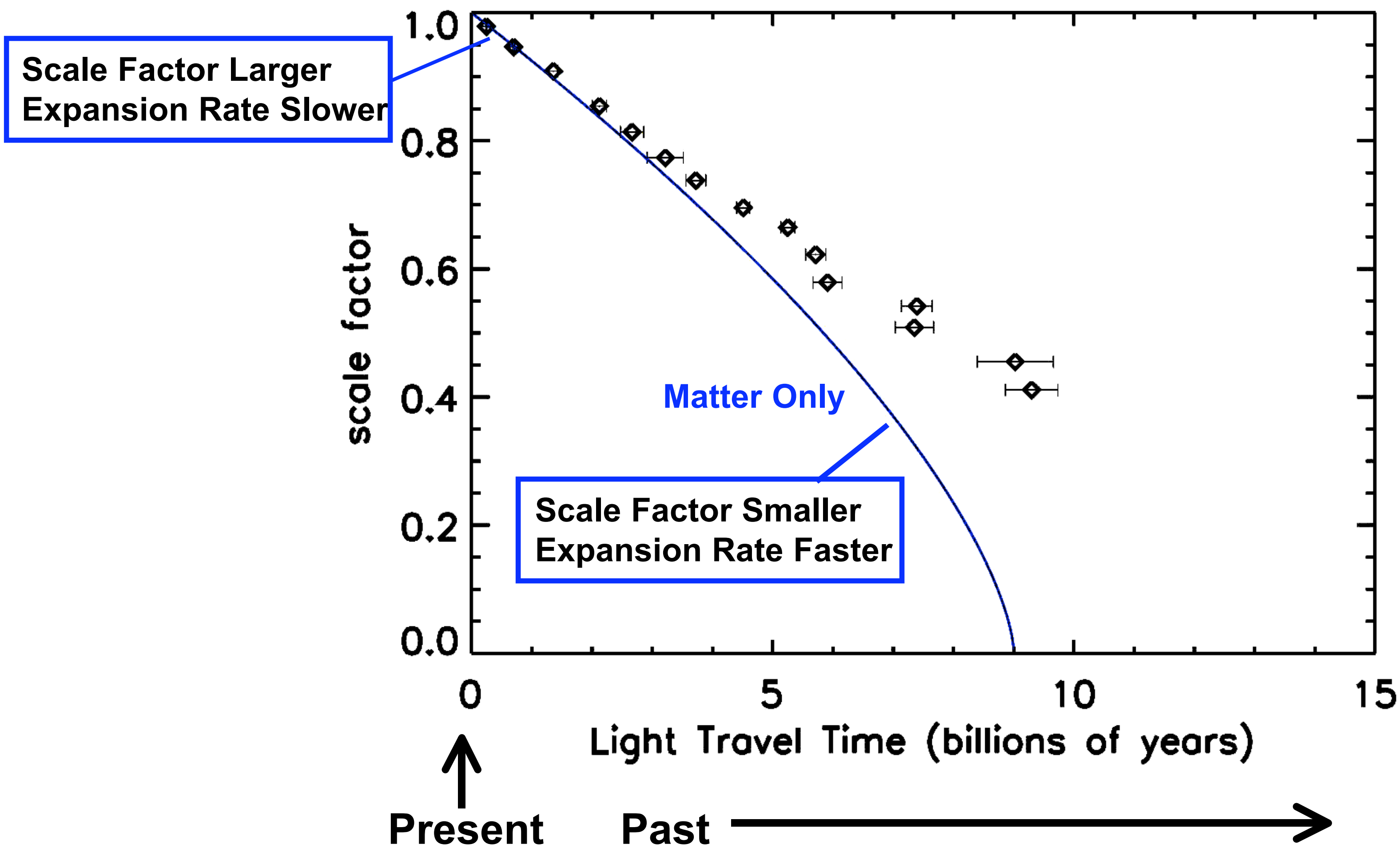
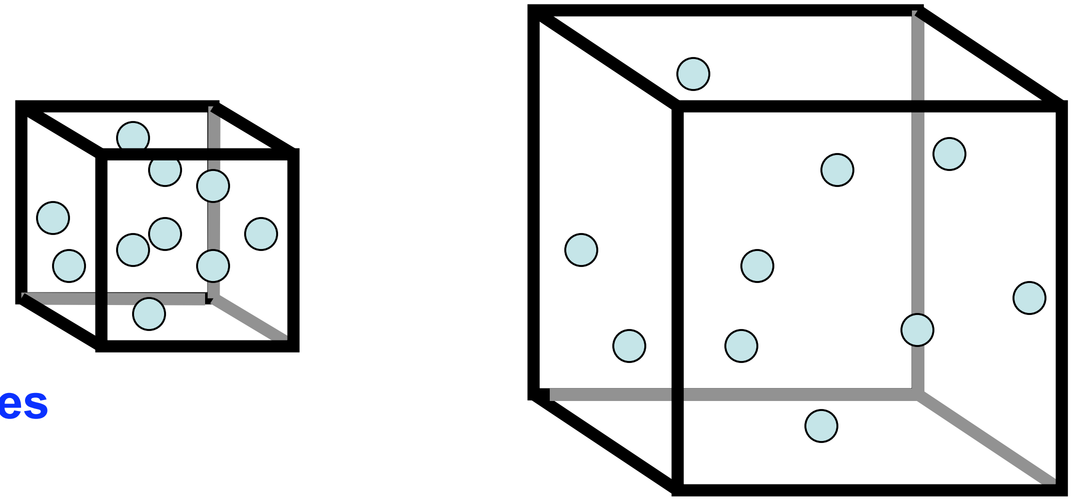


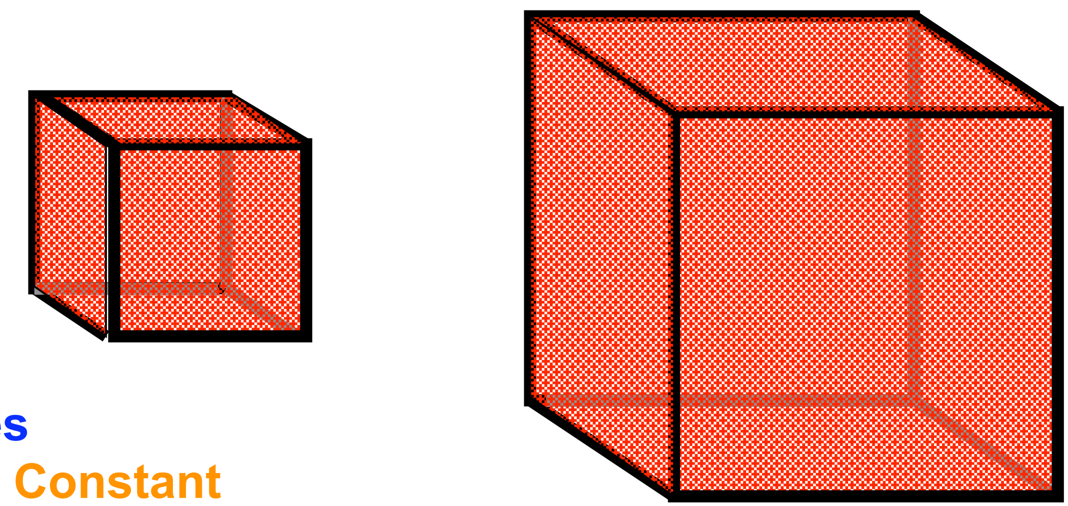
Types of Energy

Matter



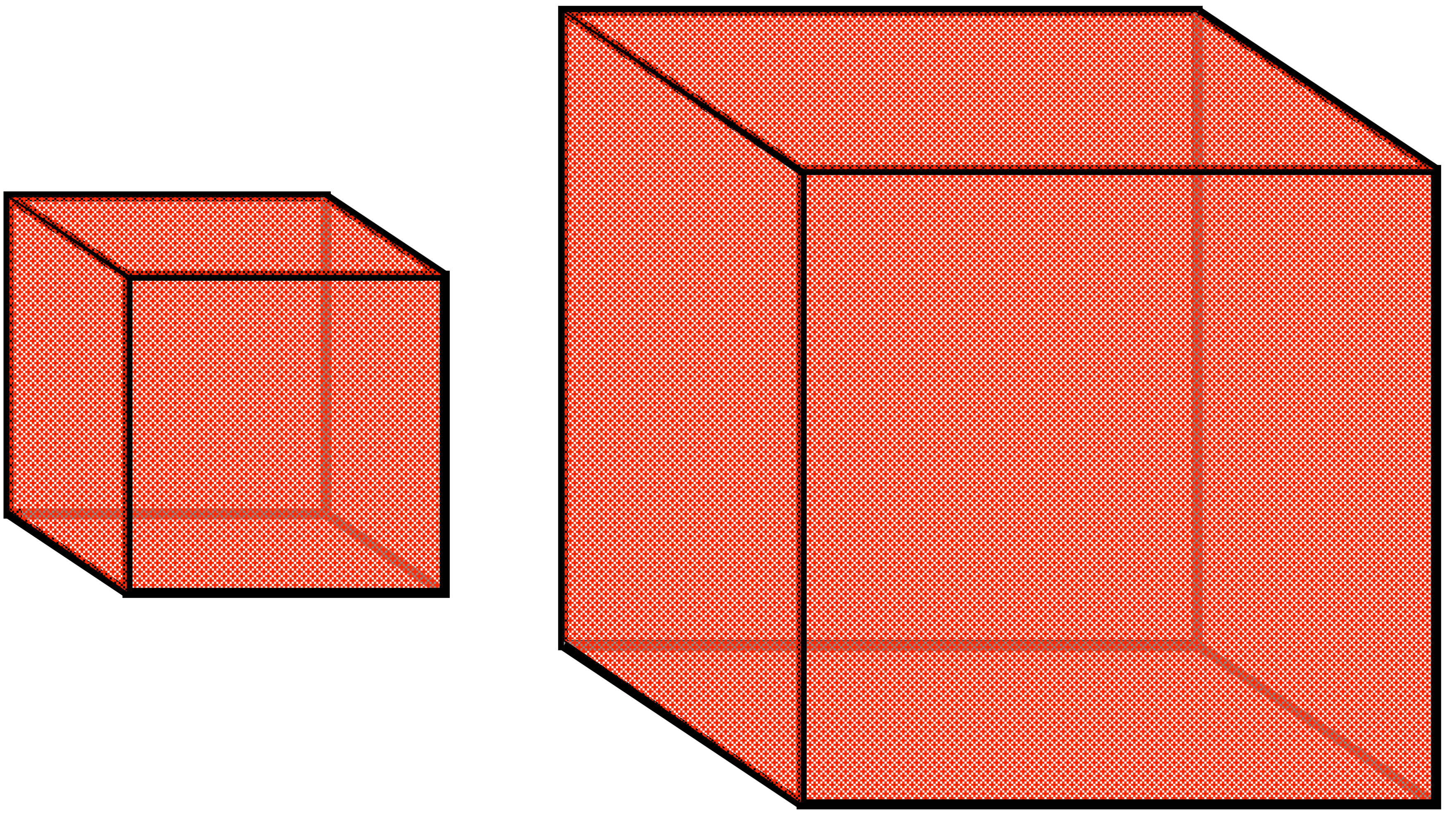
Scale Factor Increases
Energy Density Falls
Expansion Rate Slows

Dark Energy

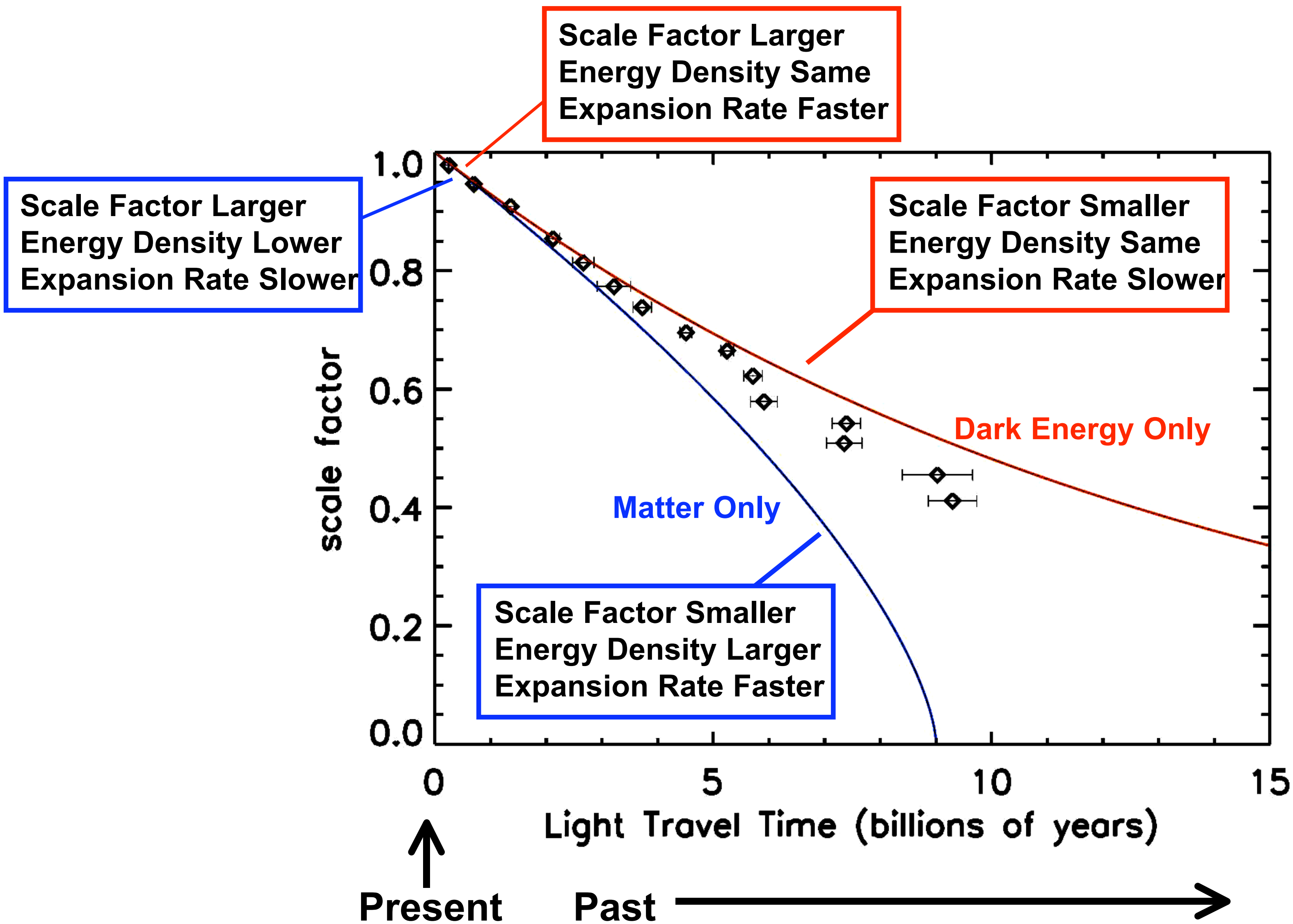


Scale Factor Increases
Energy Density Stays Constant
Expansion Rate Grows

Types of Energy: Dark Energy



Predictions for a Universe with only Dark Energy



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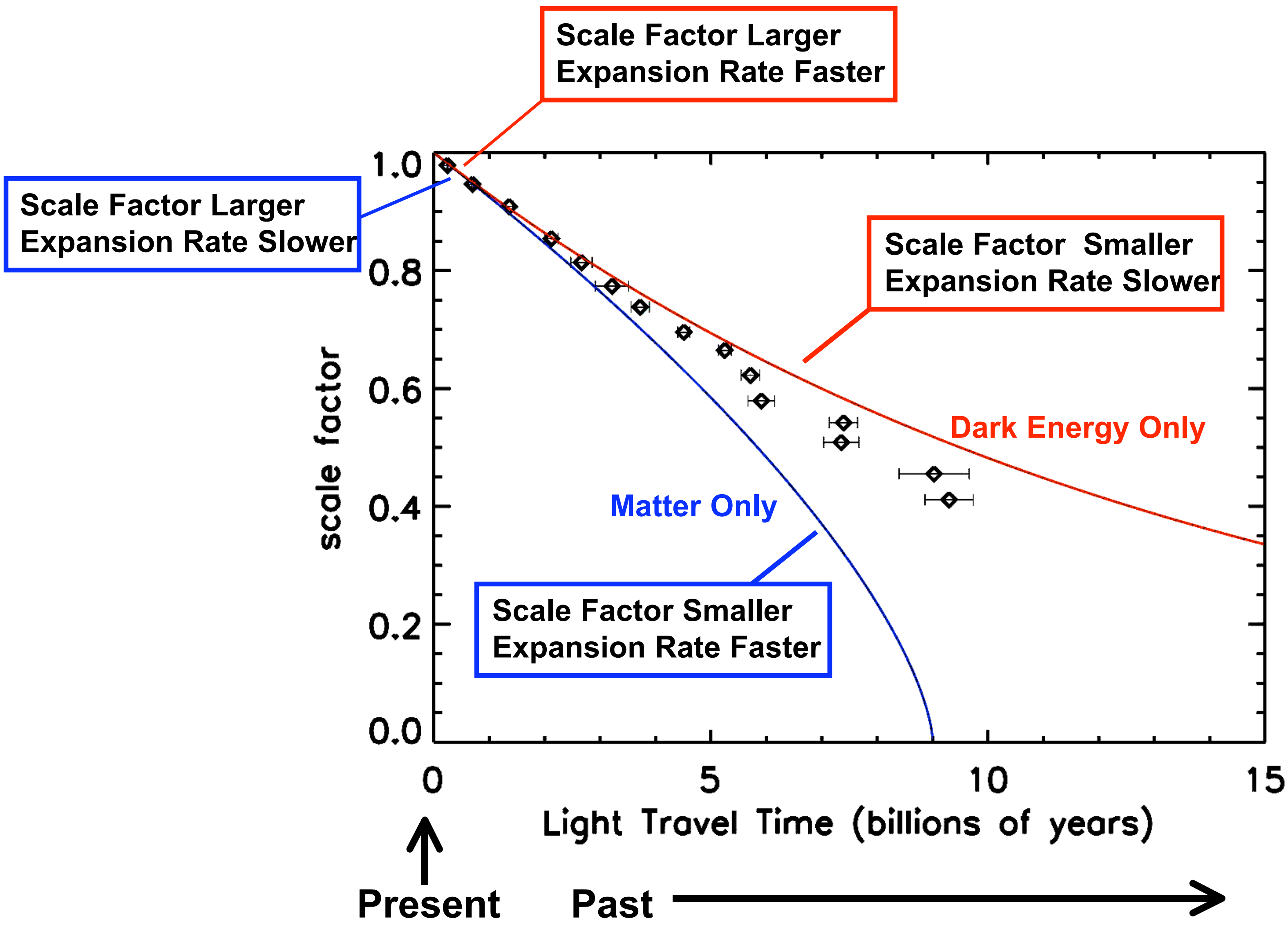
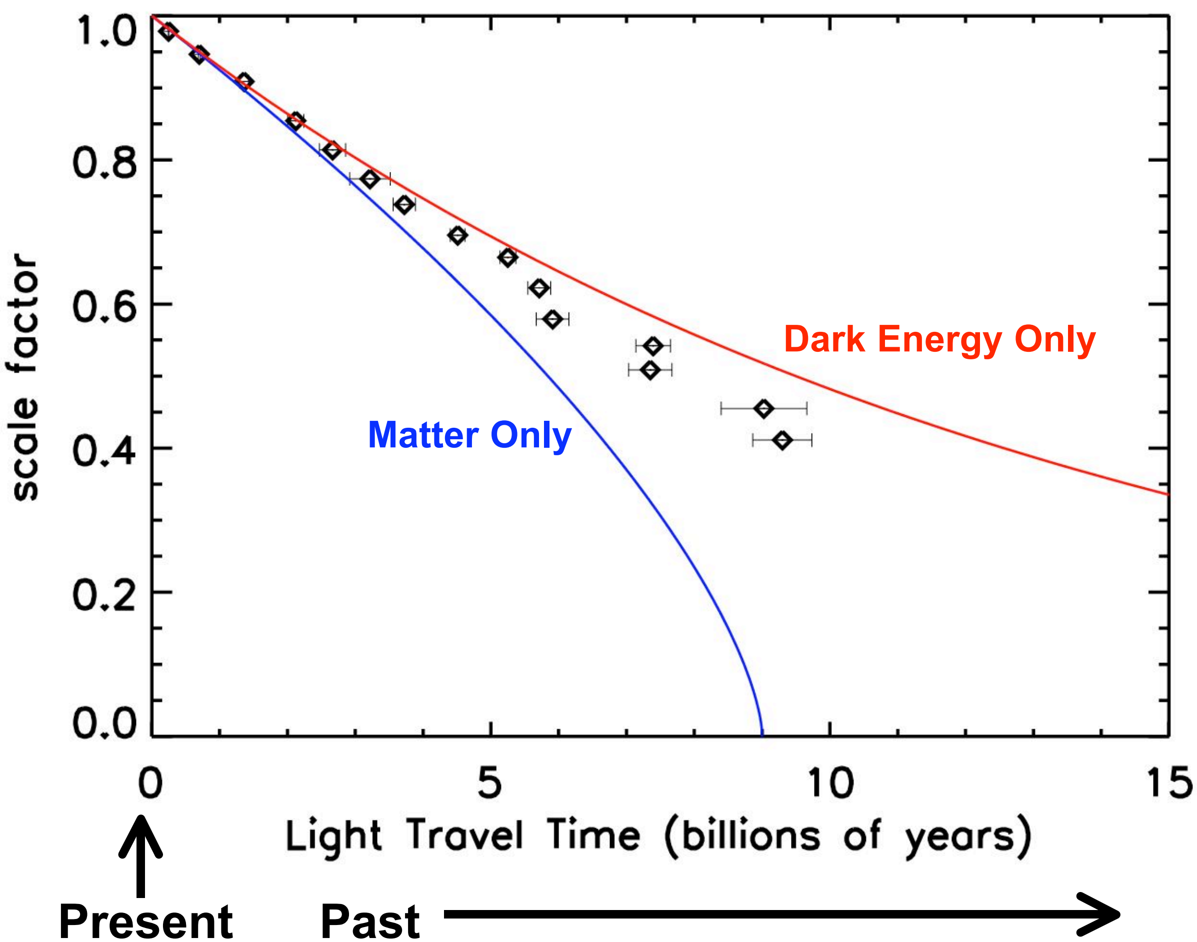


Predictions for a Universe with only Dark Energy



Matter

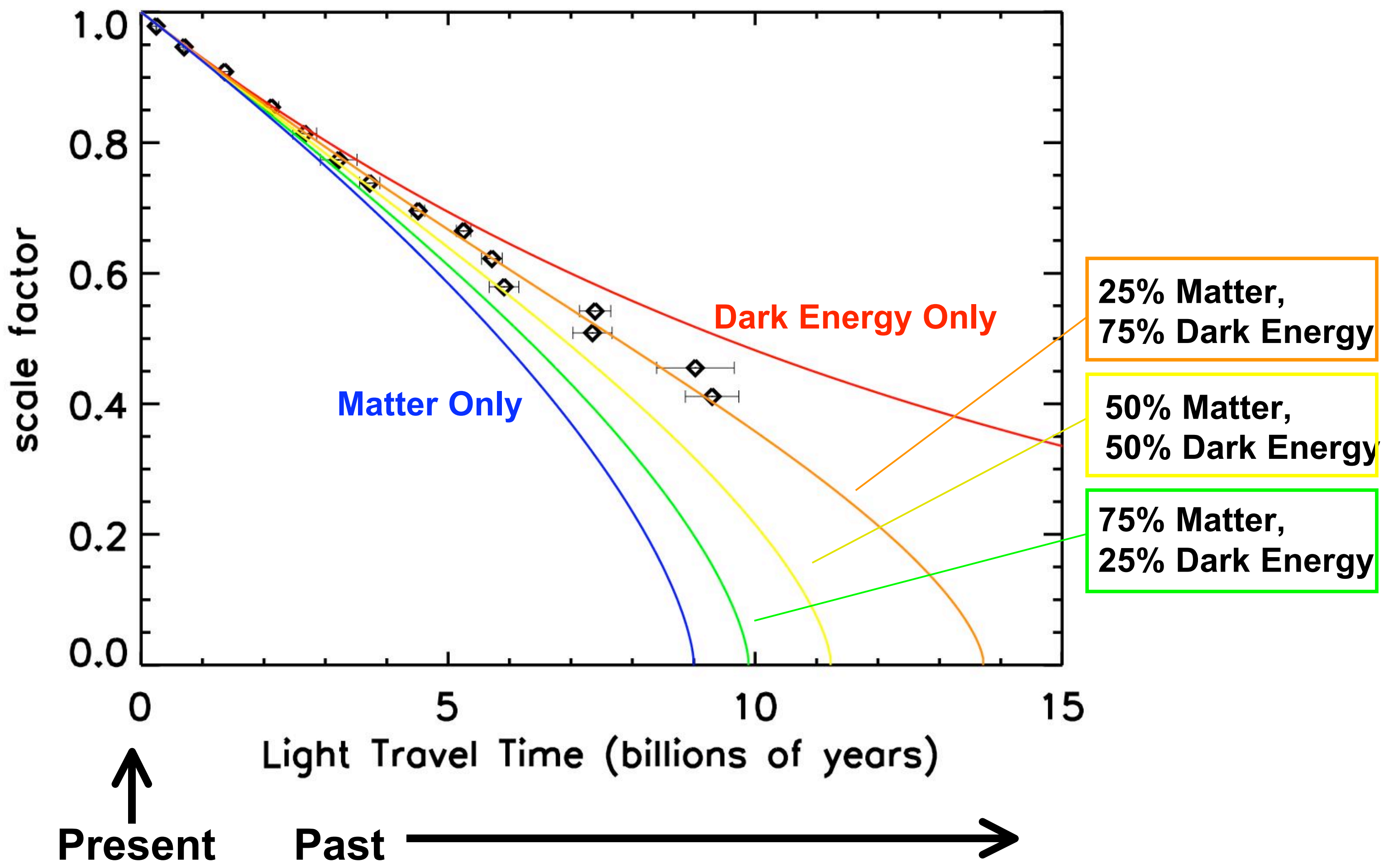
Scale Factor Increases
Energy Density Falls
Expansion Rate Slows

Dark Energy

Scale Factor Increases
Energy Density Stays Constant
Expansion Rate Grows

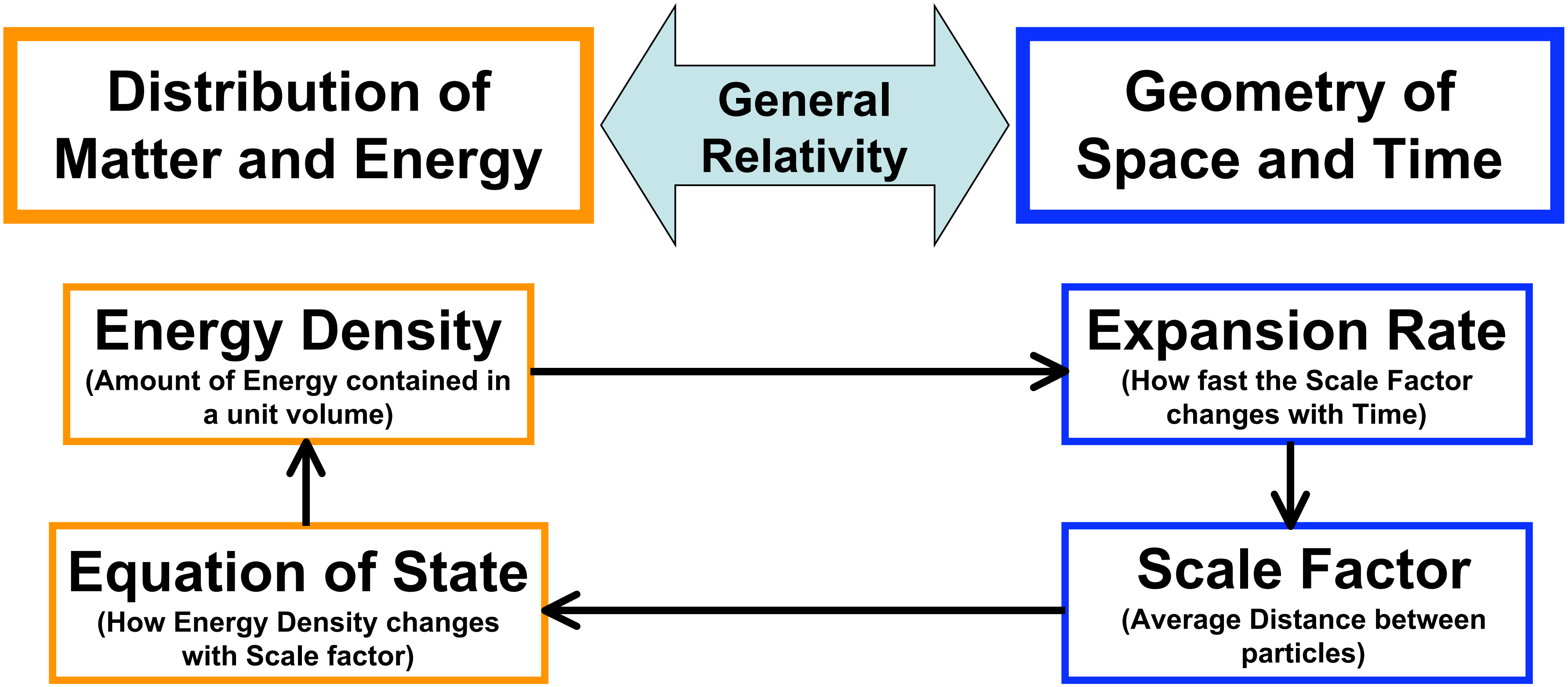
Predictions for a Universe with mixtures of matter and D.E.

Best Fit is about 3 Parts Dark Energy for every 1 part Matter



Note Fractions only valid today

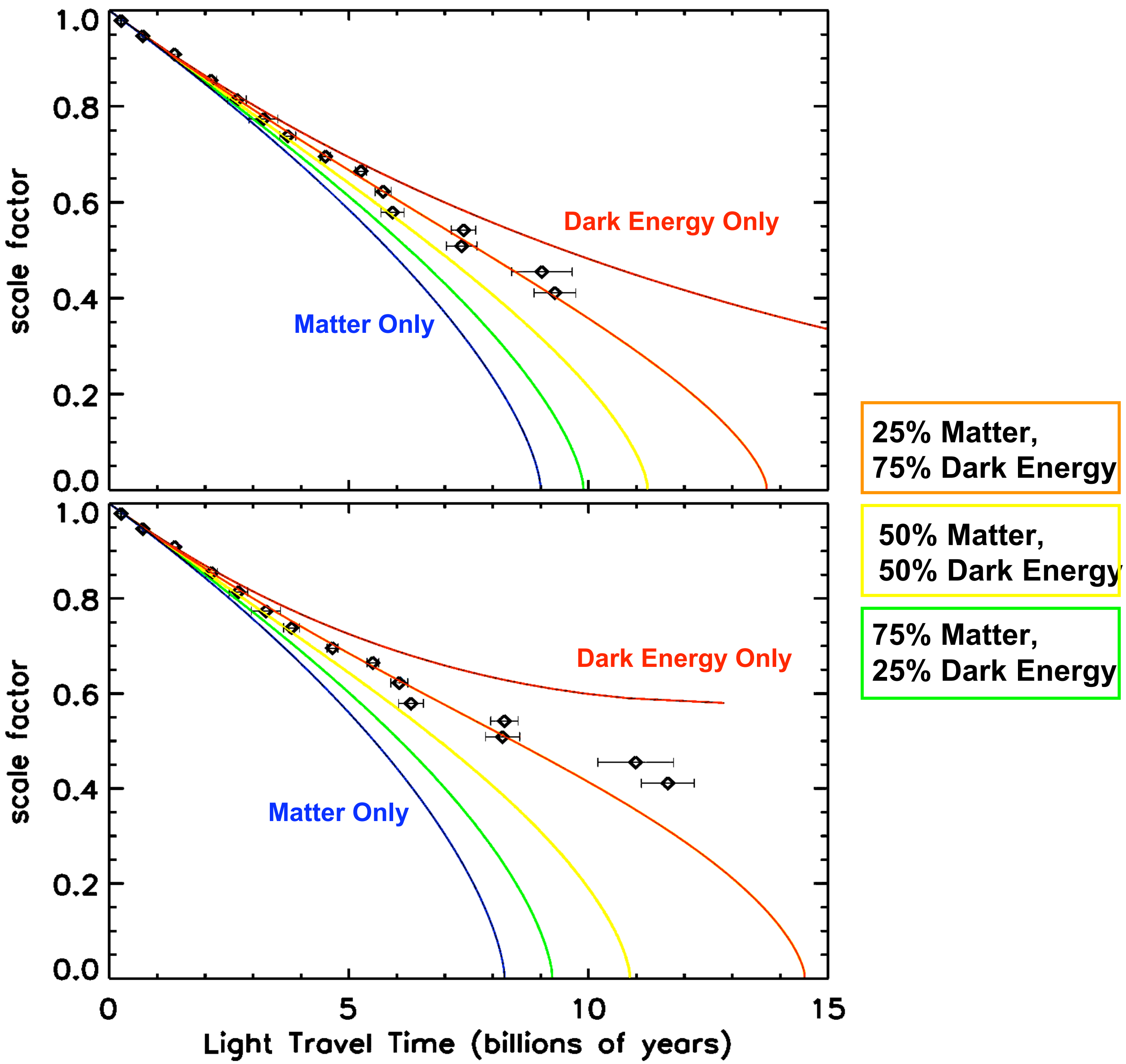
The Expansion History and Material Content of the Universe



Predictions for Universes with different total Energy Densities

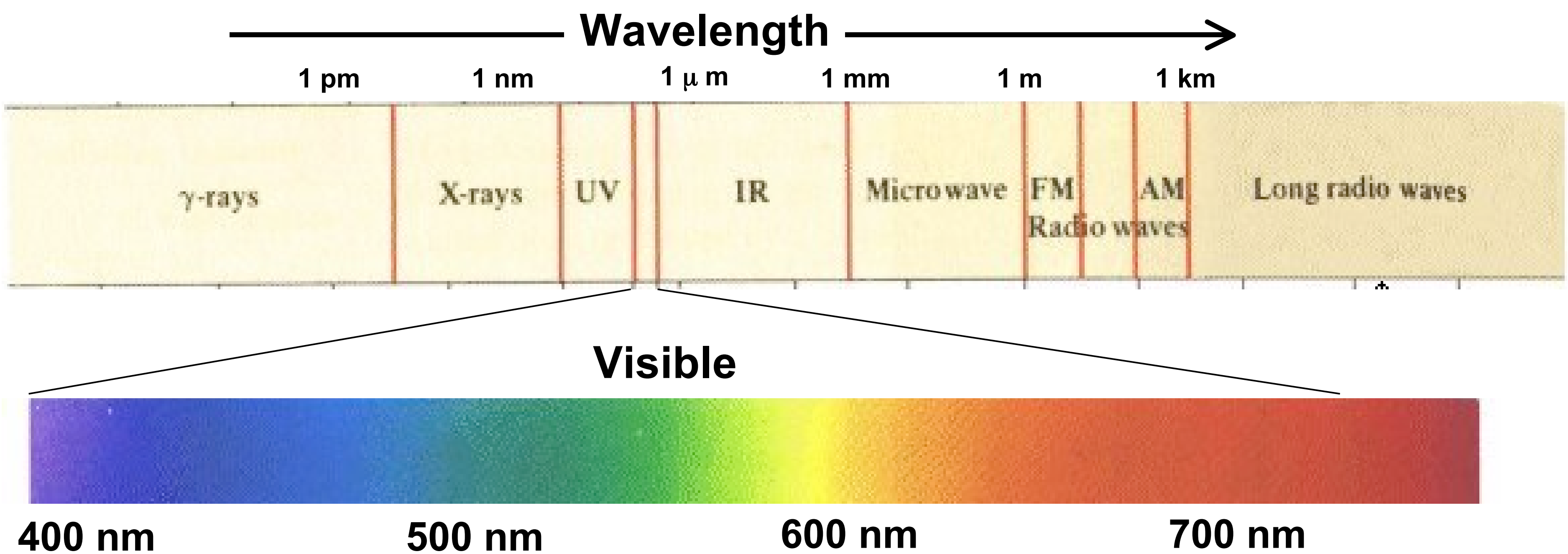
Energy Density Today
=
Critical Density

Energy Density Today
=
1.5 x Critical Density

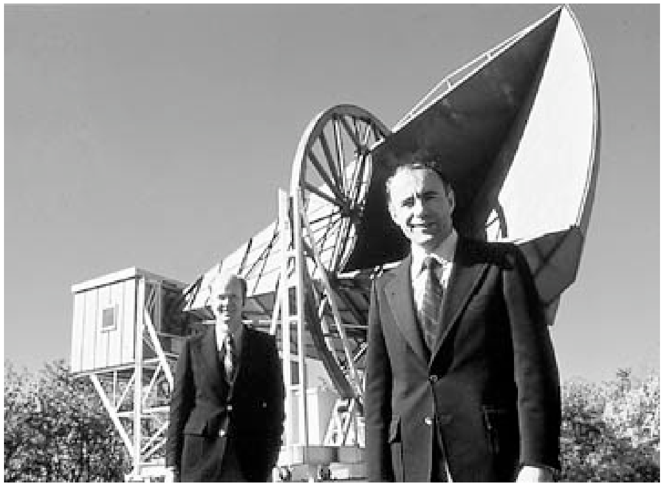


What is the Cosmic **Microwave** Background?

Microwaves are Electromagnetic Radiation with Wavelengths between 1 mm and 10 cm



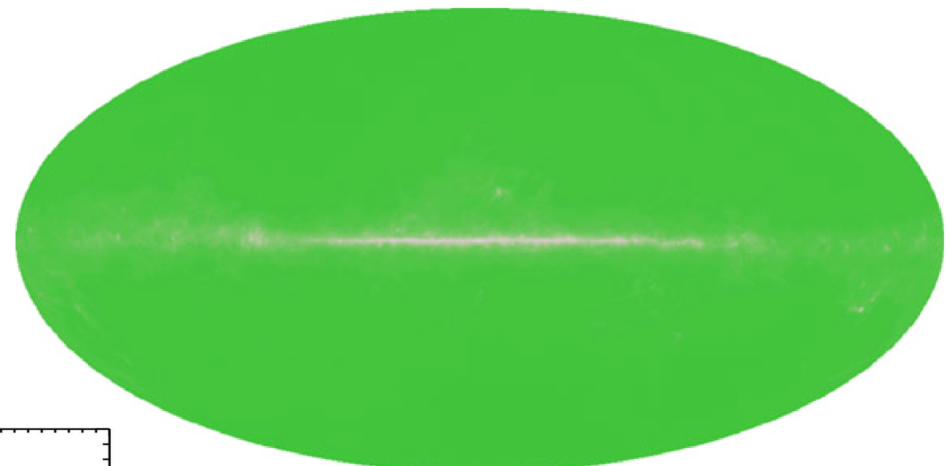
What is the Cosmic Microwave **Background** ?

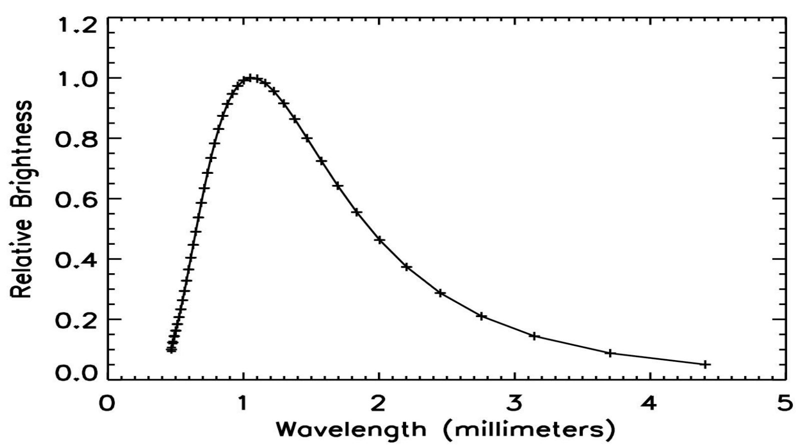


Penzias and Wilson, discoverers of the CMB

Telescopes sensitive to microwaves detect a signal from space

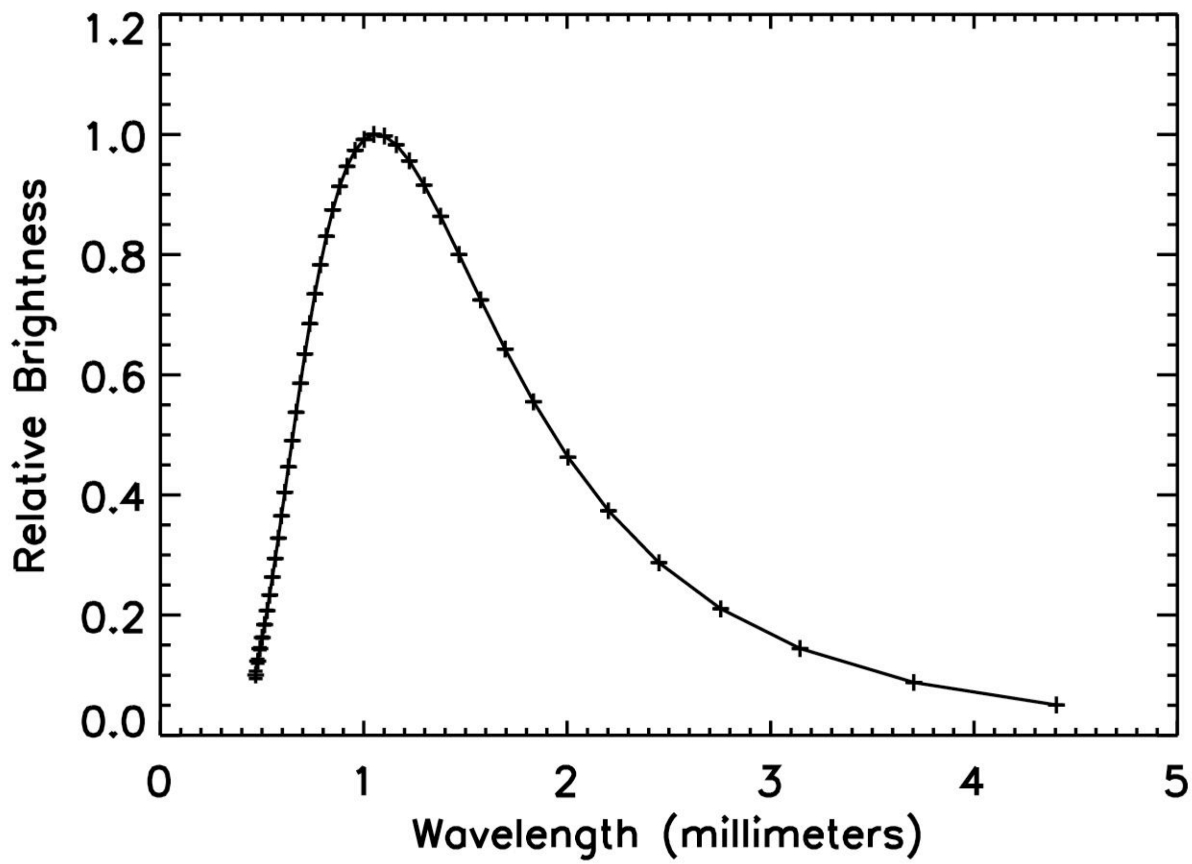
This signal is nearly the same from every point on the sky (it is nearly isotropic)





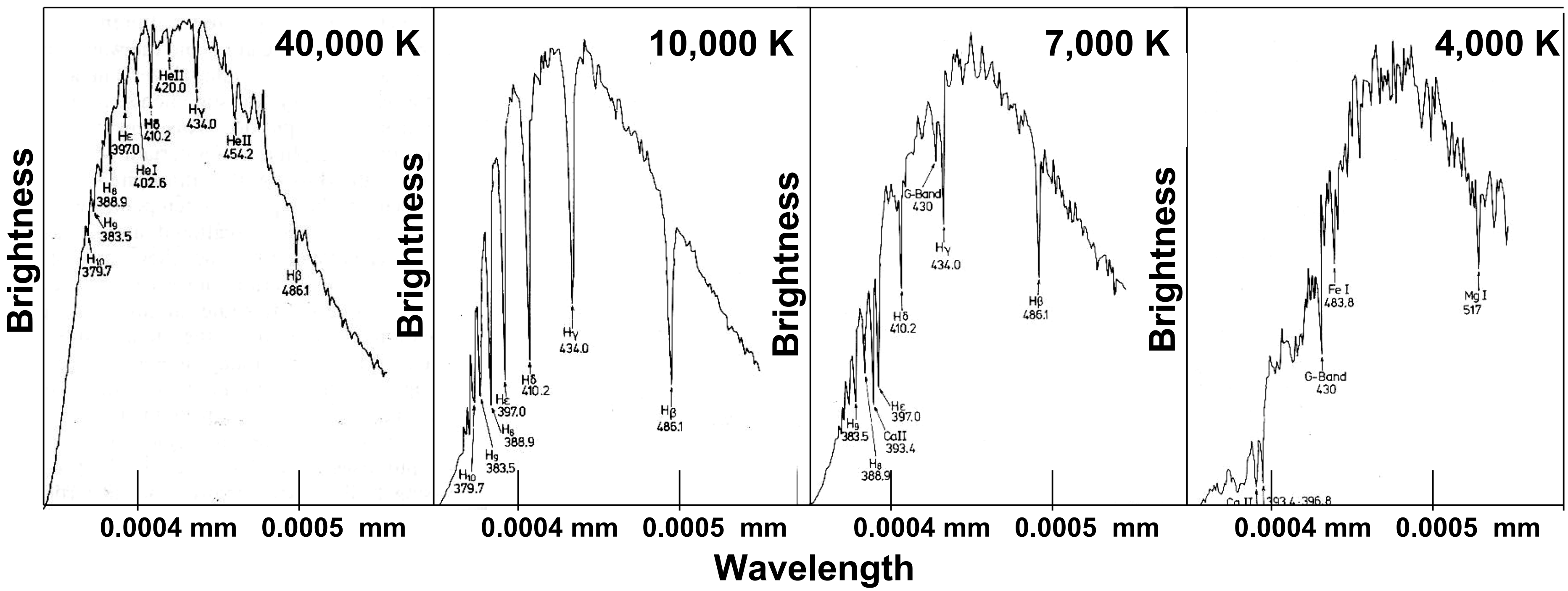
This radiation has a spectrum characteristic of heavily redshifted thermal radiation

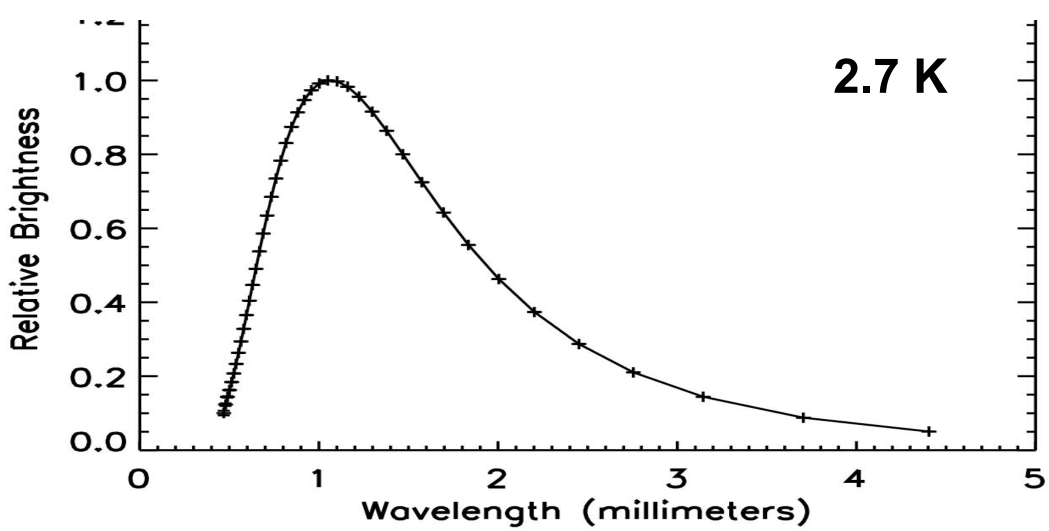
The Spectrum of the Cosmic Microwave Background



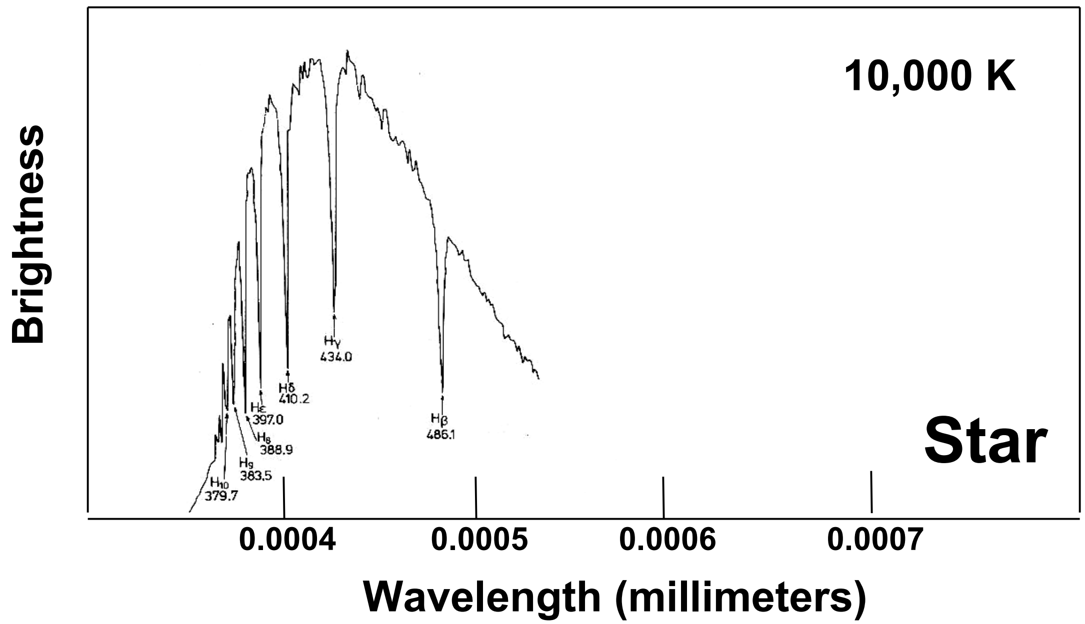
Points = Data
Line = 2.7 K Blackbody Thermal Radiation

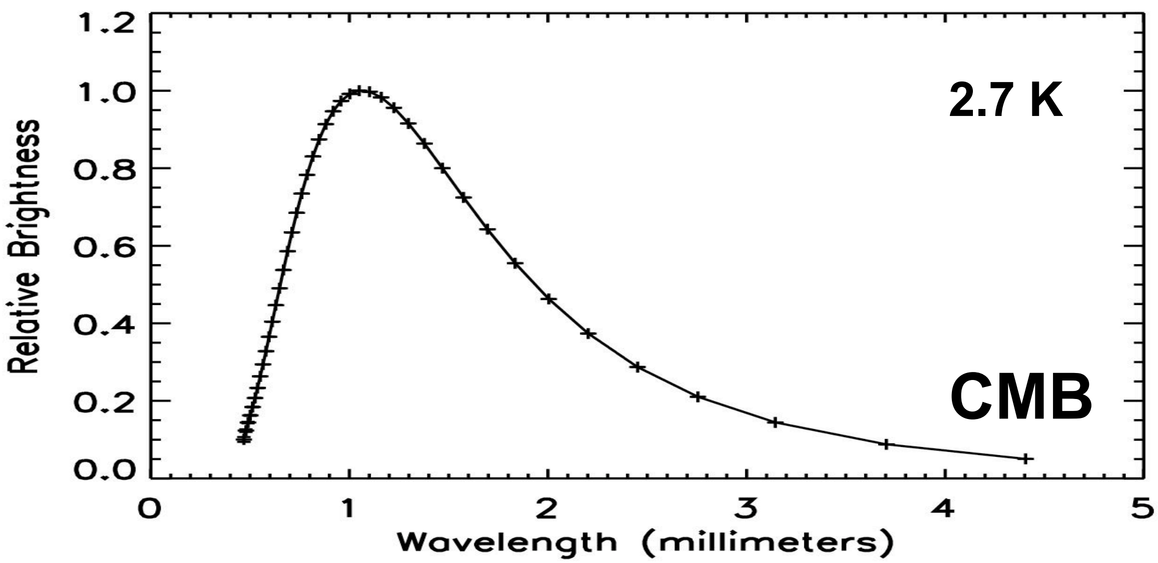
The Thermal Spectra of Stars and the CMB





The Thermal Spectra of Stars and the CMB





Interactions between light and matter

Proton Electron

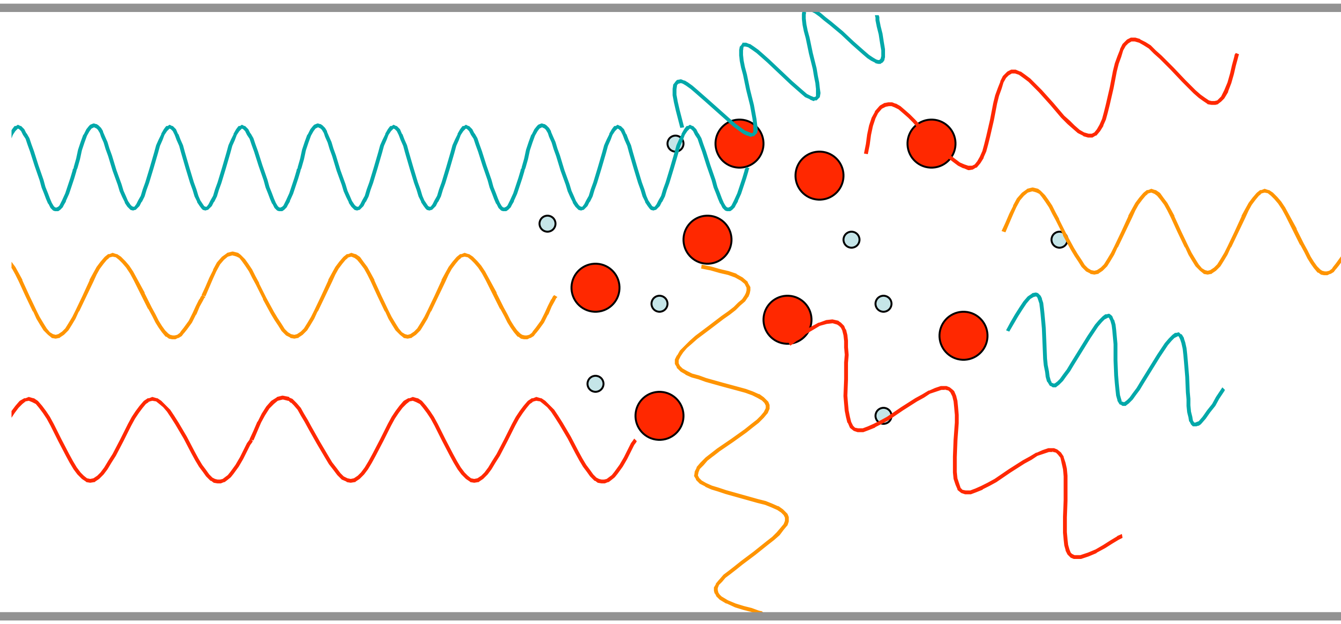
Plasma:

Free Charged Particles

Strong coupling to Electromagnetic Waves

Produces Blackbody Radiation

Typically exists at High Temperatures



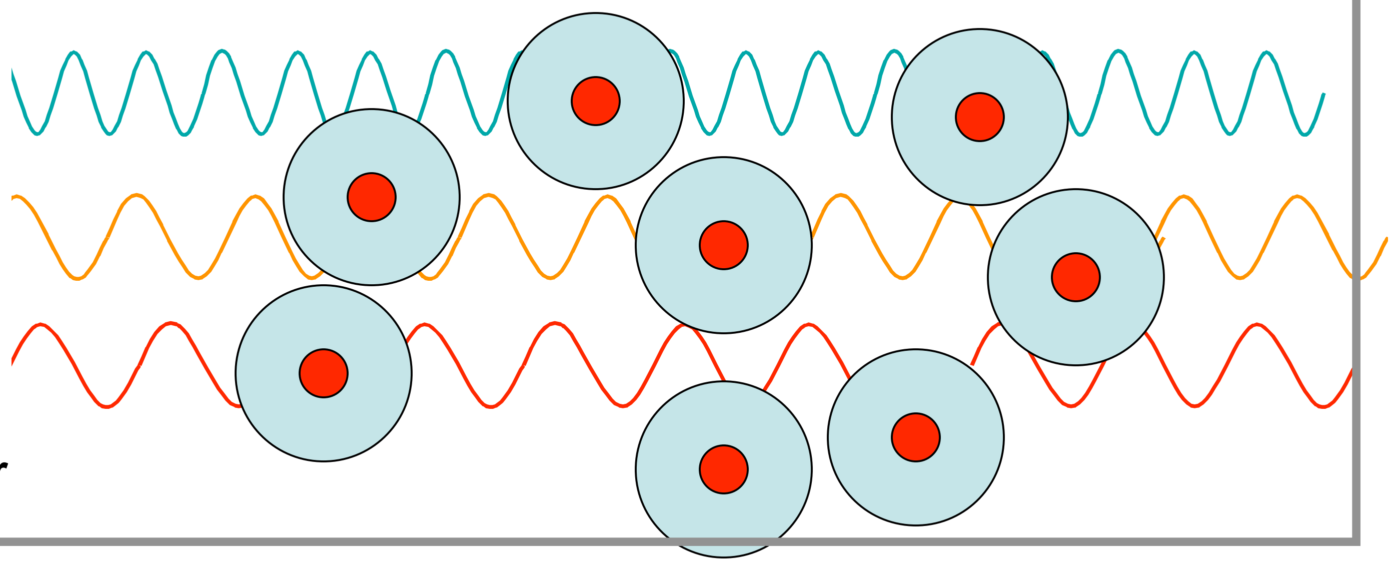
Gas:

Neutral Atoms

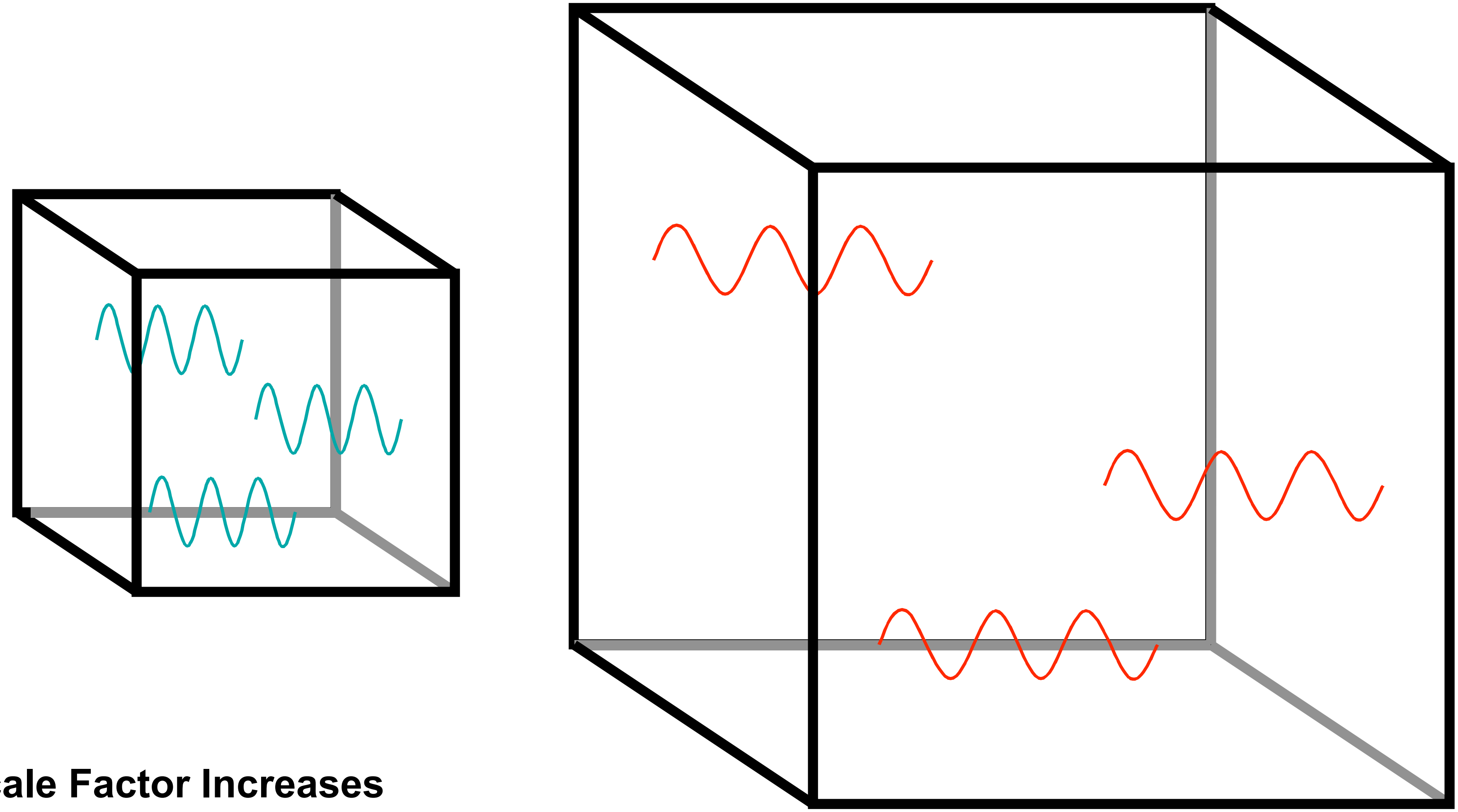
Generally does not couple strongly with Electromagnetic Waves

Does not produce Blackbody Radiation

Typically exists at lower Temperatures



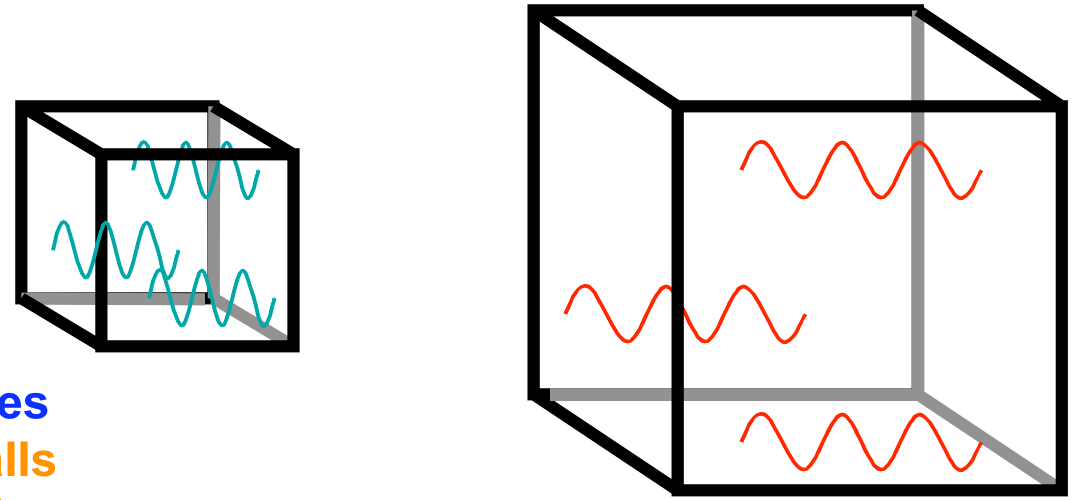
Radiation in an expanding Universe



Scale Factor Increases
Radiation Density Decreases
Photon Wavelength Increases
Effective Temperature Decreases

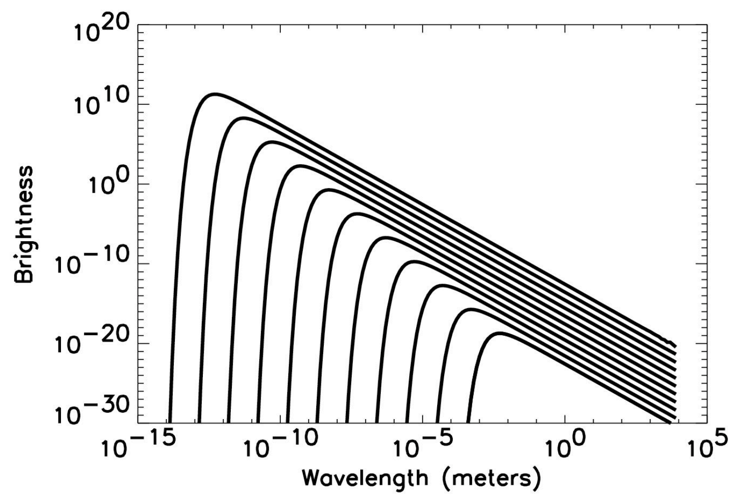
Radiation in an Expanding Universe

Radiation



Scale Factor Increases
Radiation Density Falls
Photon Wavelength Increases
Effective Temperature Drops

The CMB had a higher effective temperature in the past when the scale factor was smaller



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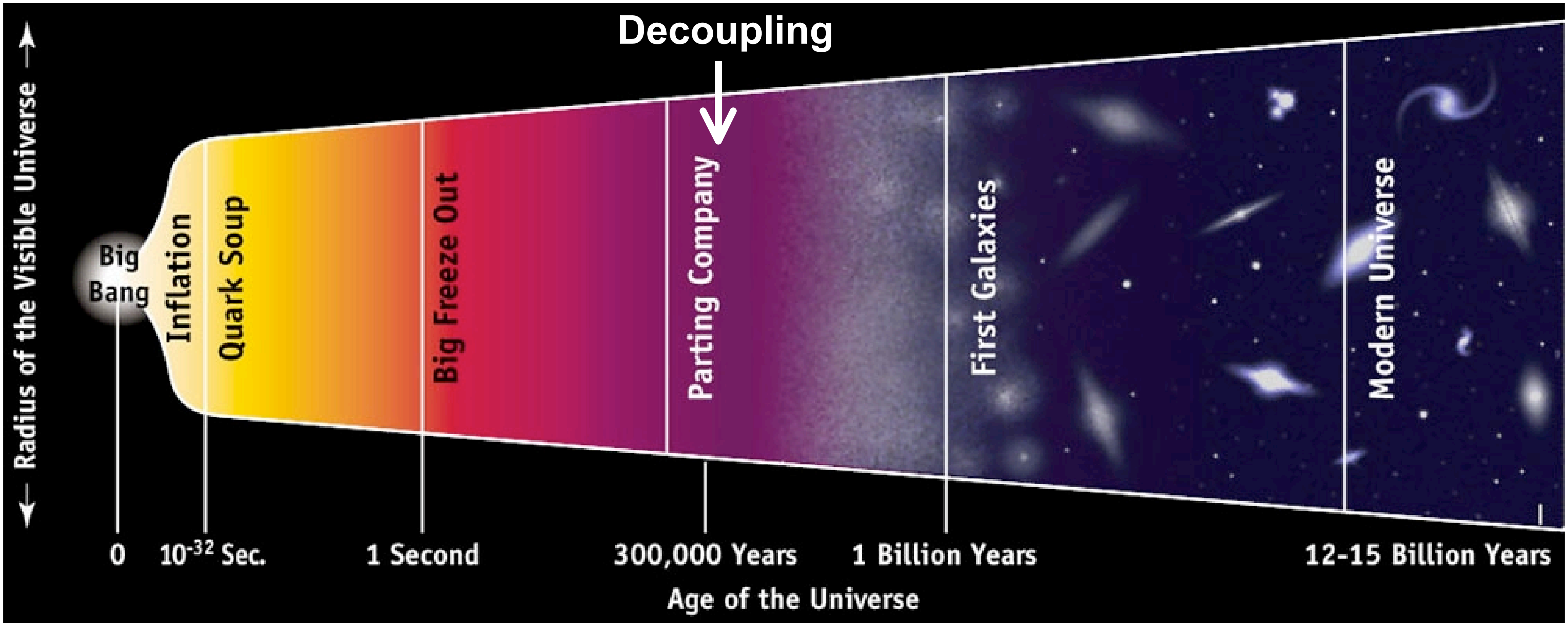
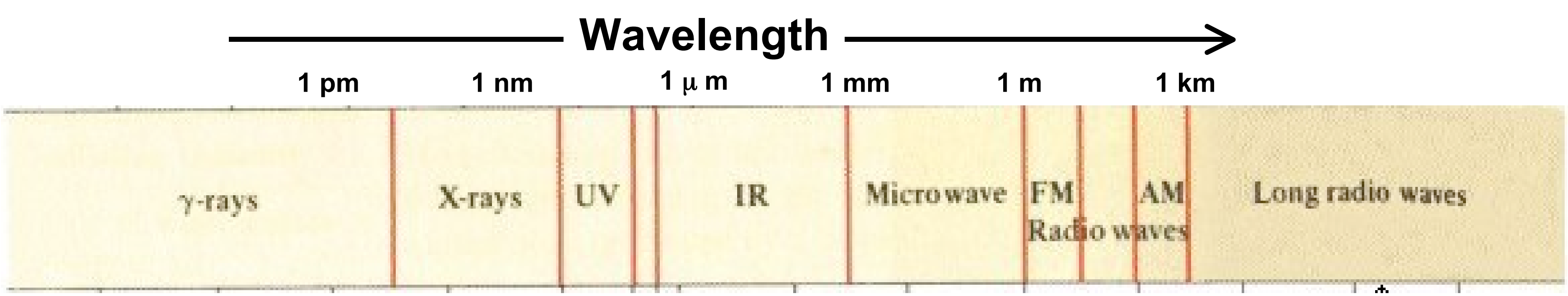
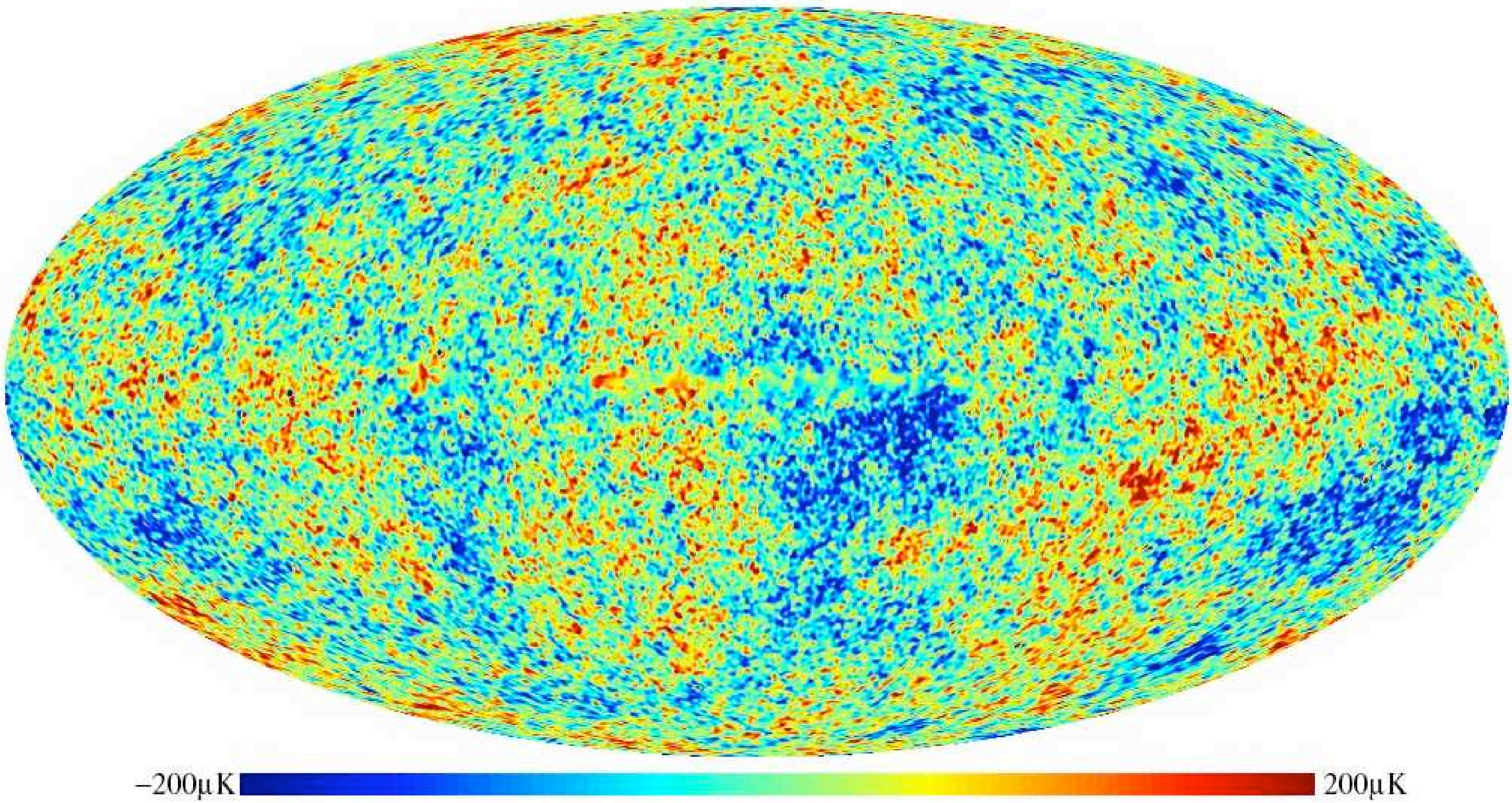


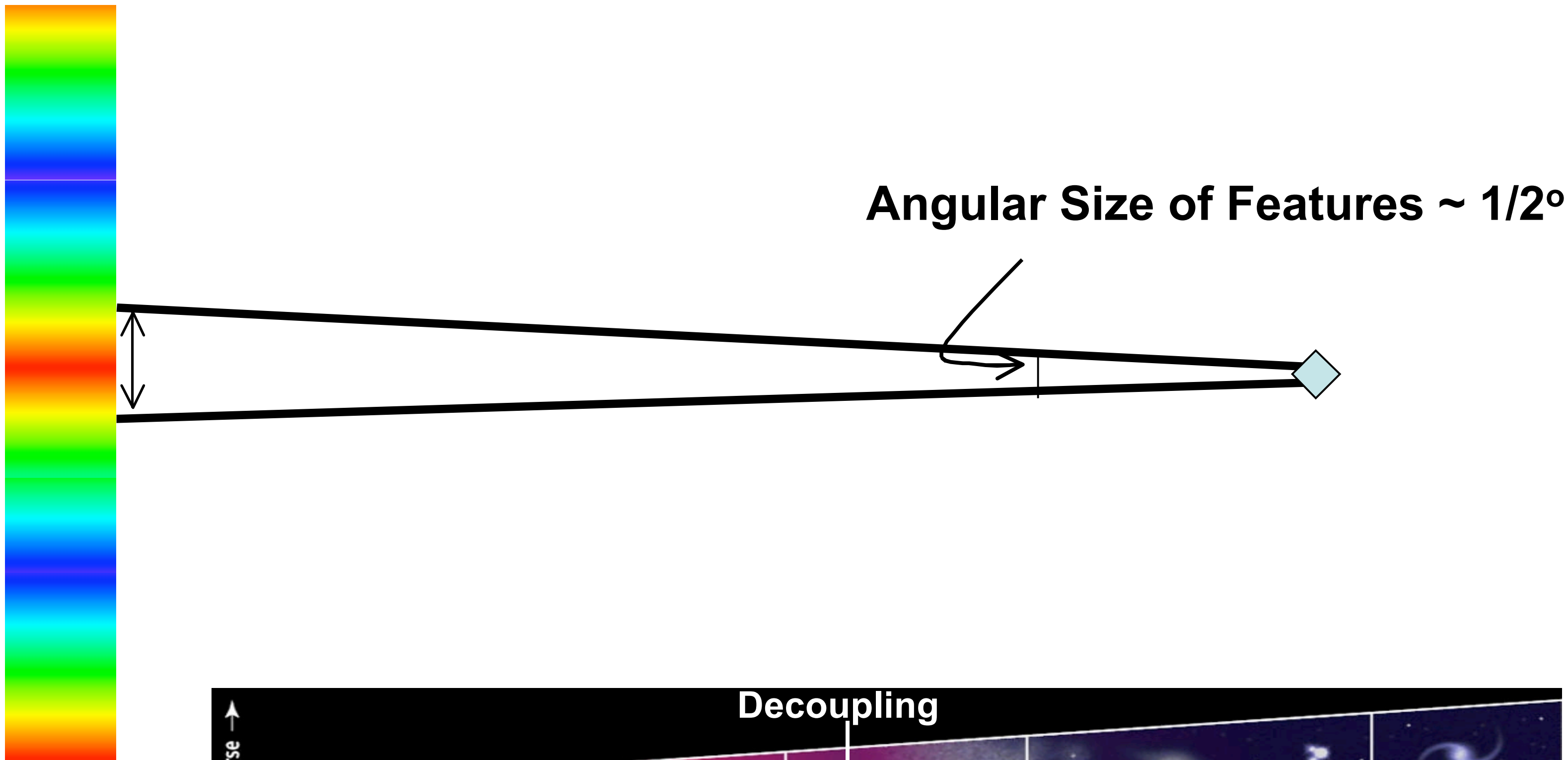


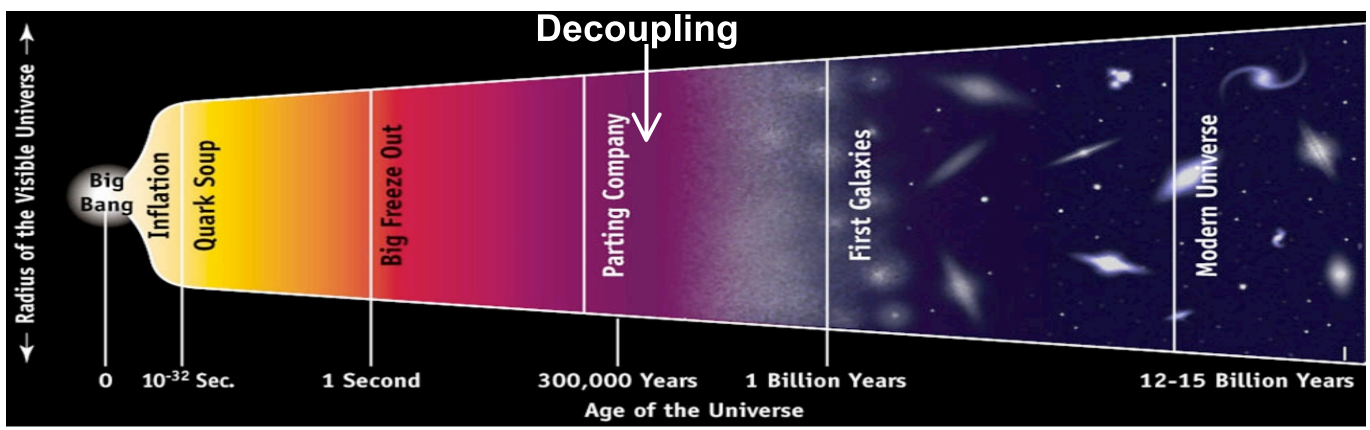
Brightness Variations in the Cosmic Microwave Background



Data from the WMAP Satellite, processed by Tegmark et. al.

The Size of features in the CMB





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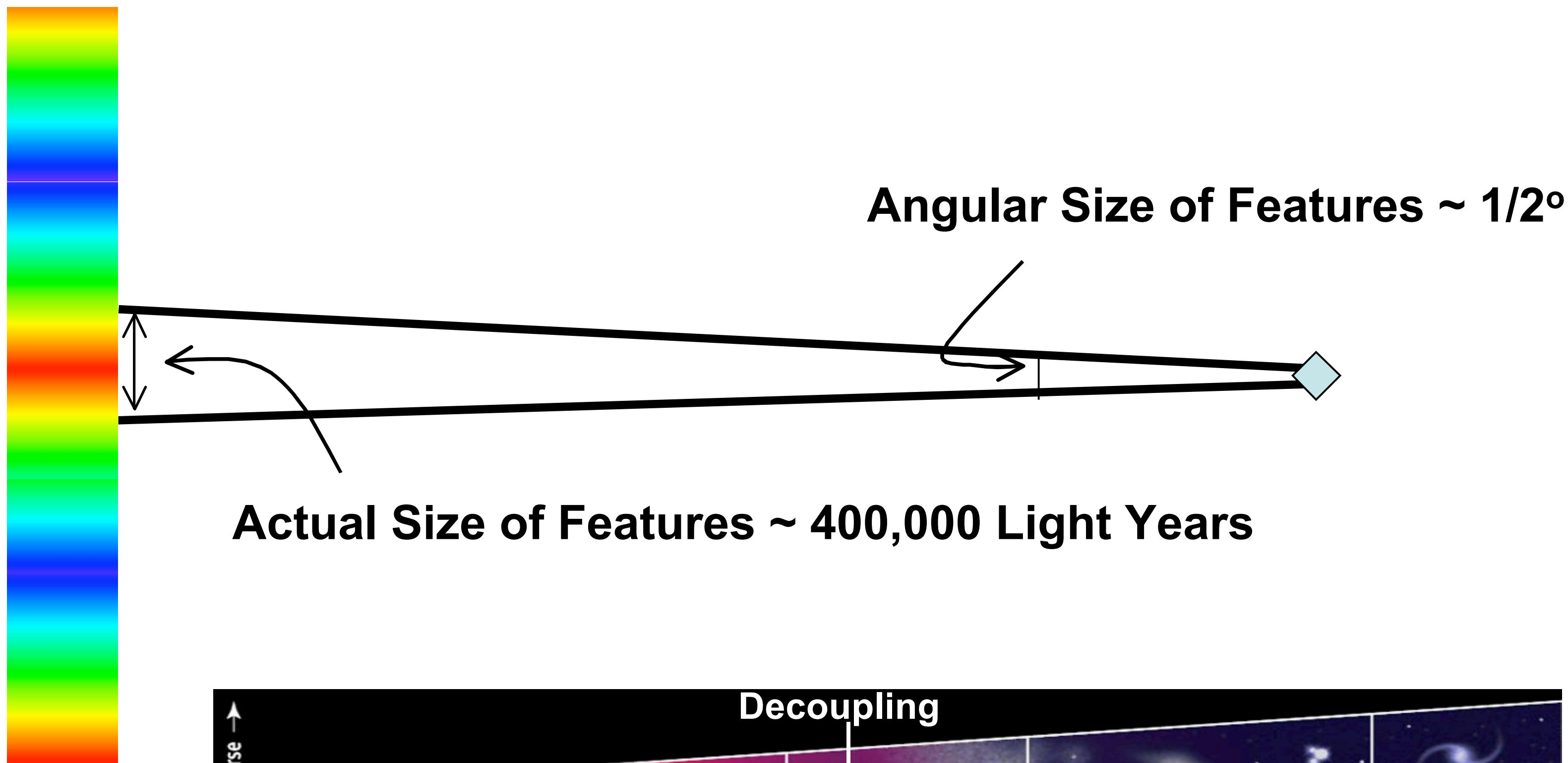
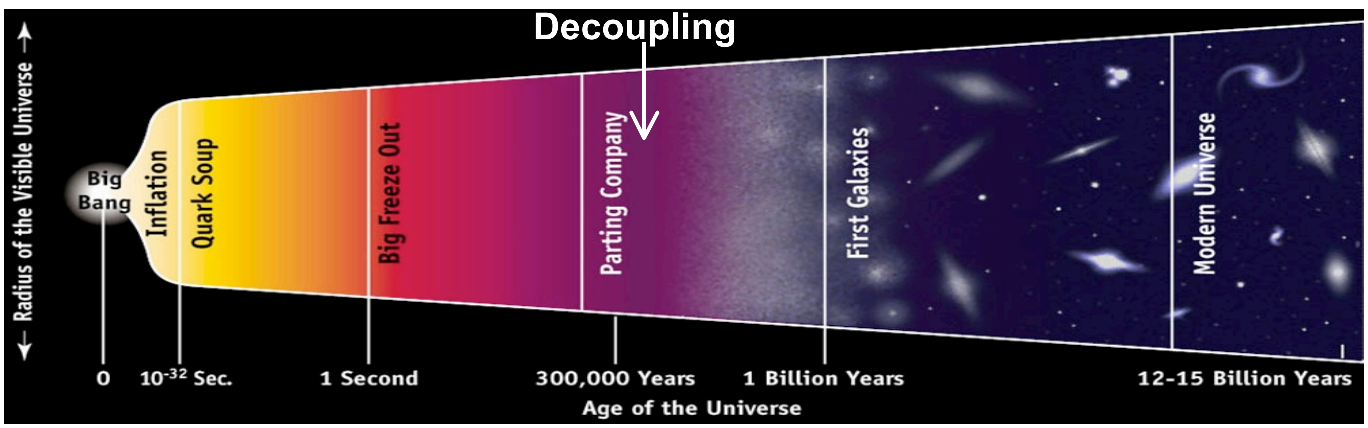
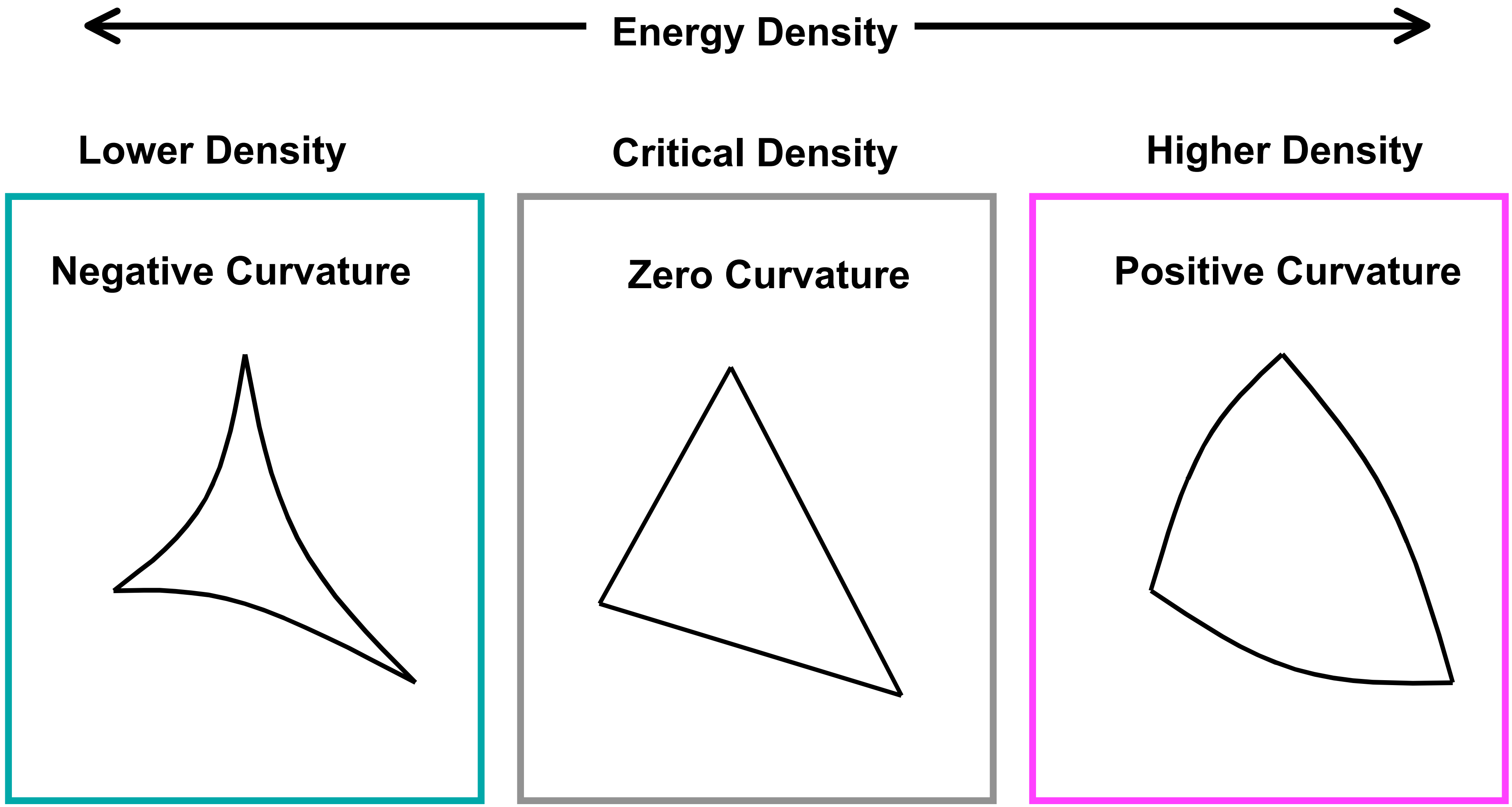


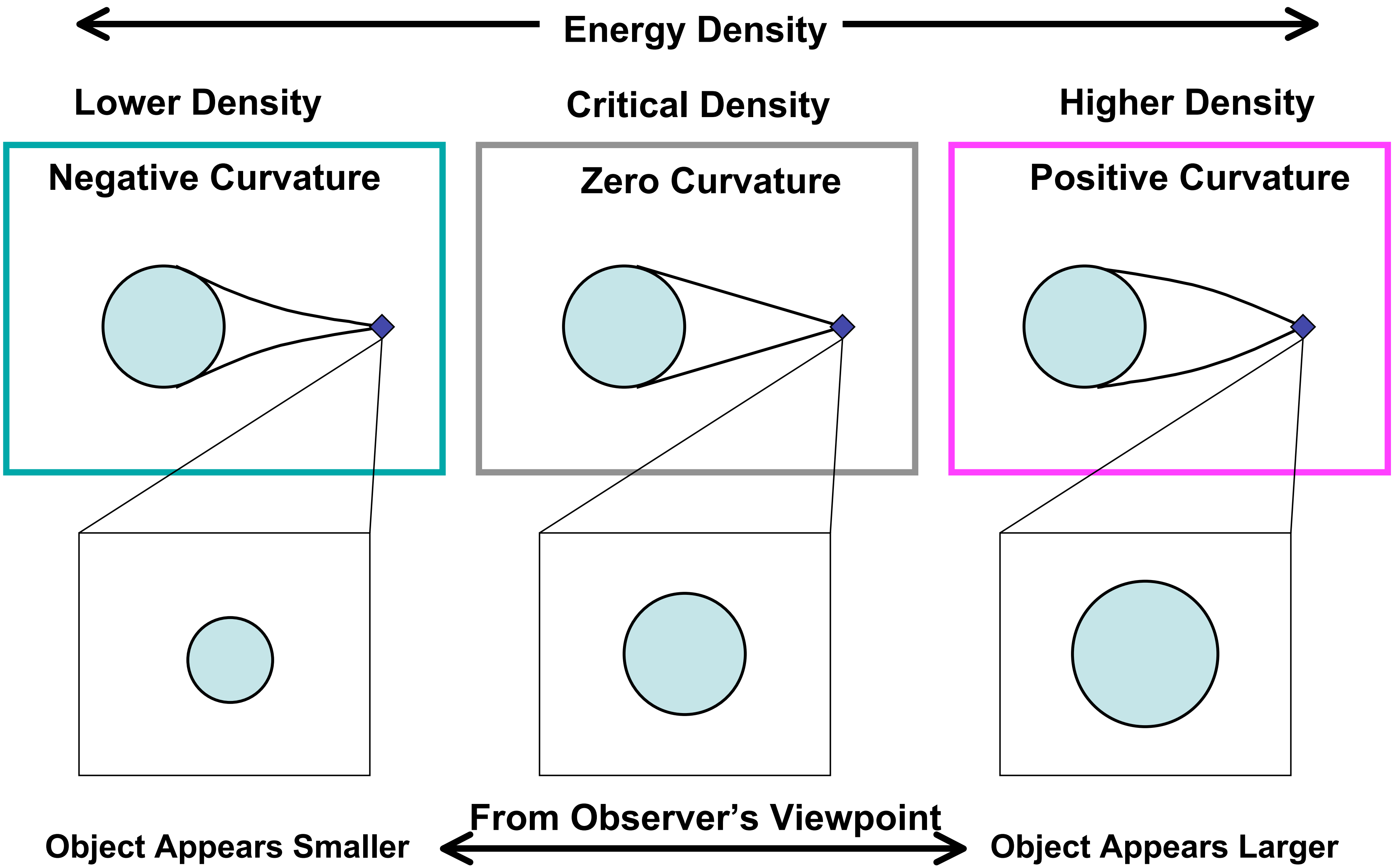


Curvature

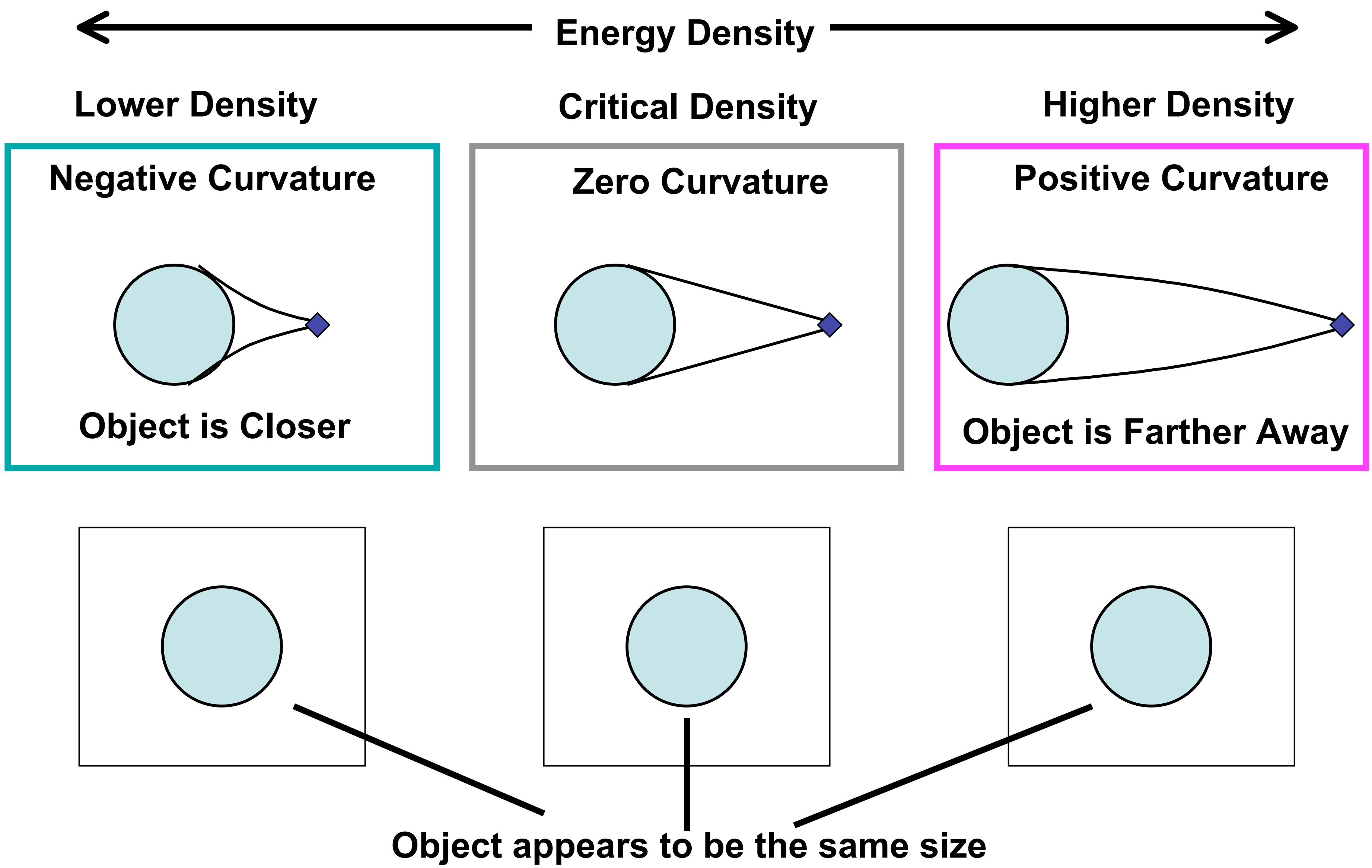


Energy Density
Lower Density
Critical Density
Higher Density
Negative Curvature
Zero Curvature
Positive Curvature

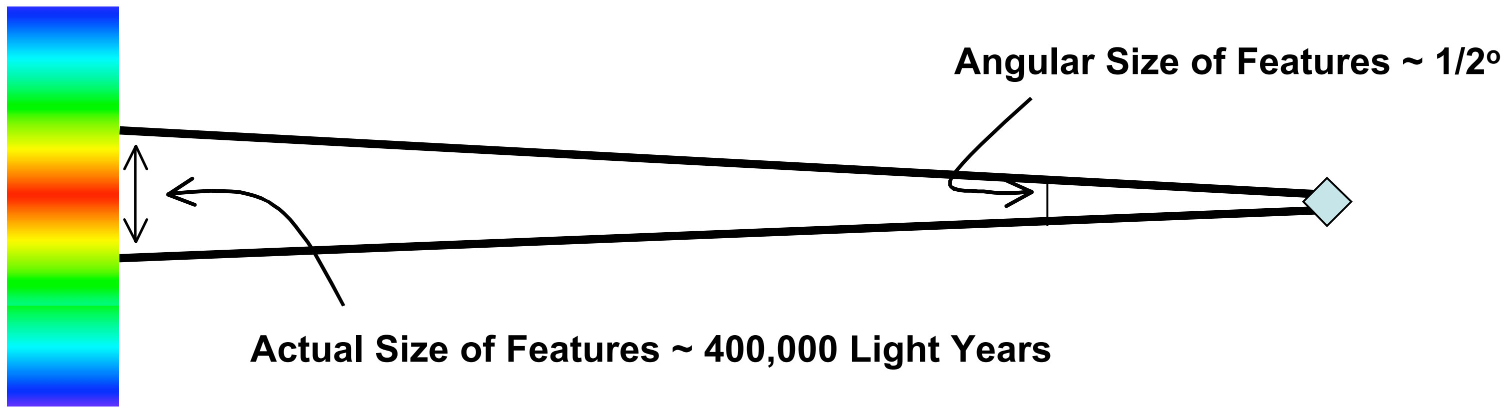
Curvature and the Apparent Size of Objects



Curvature and the Apparent Distance to Objects

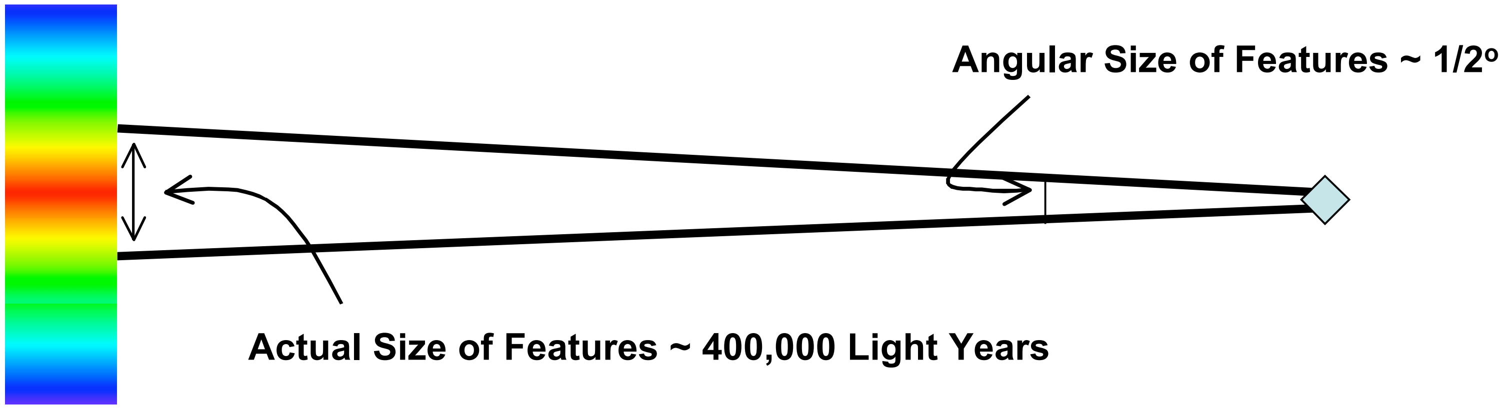


The CMB and the total energy density of the Universe



The distance the light has to travel depends on the curvature

The CMB and the total energy density of the Universe



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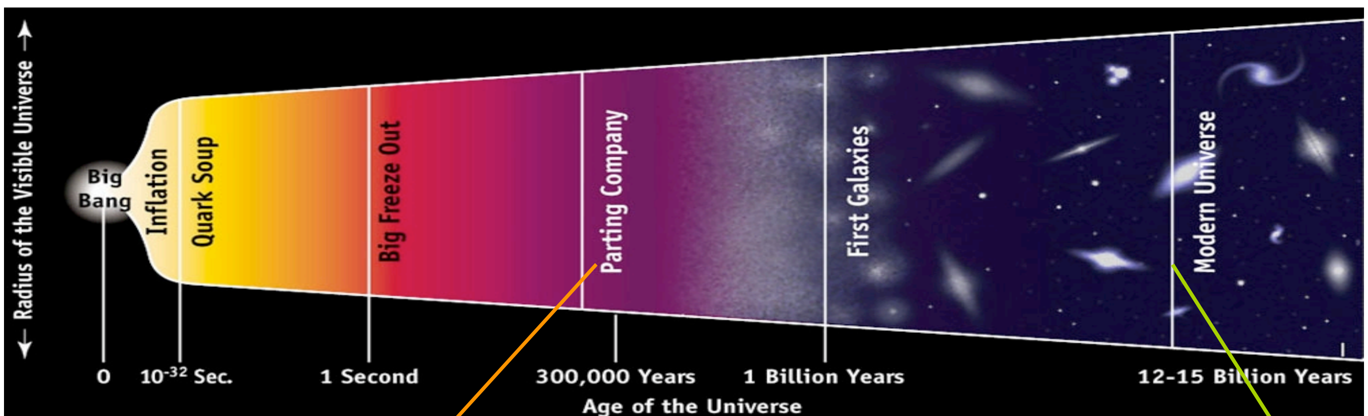


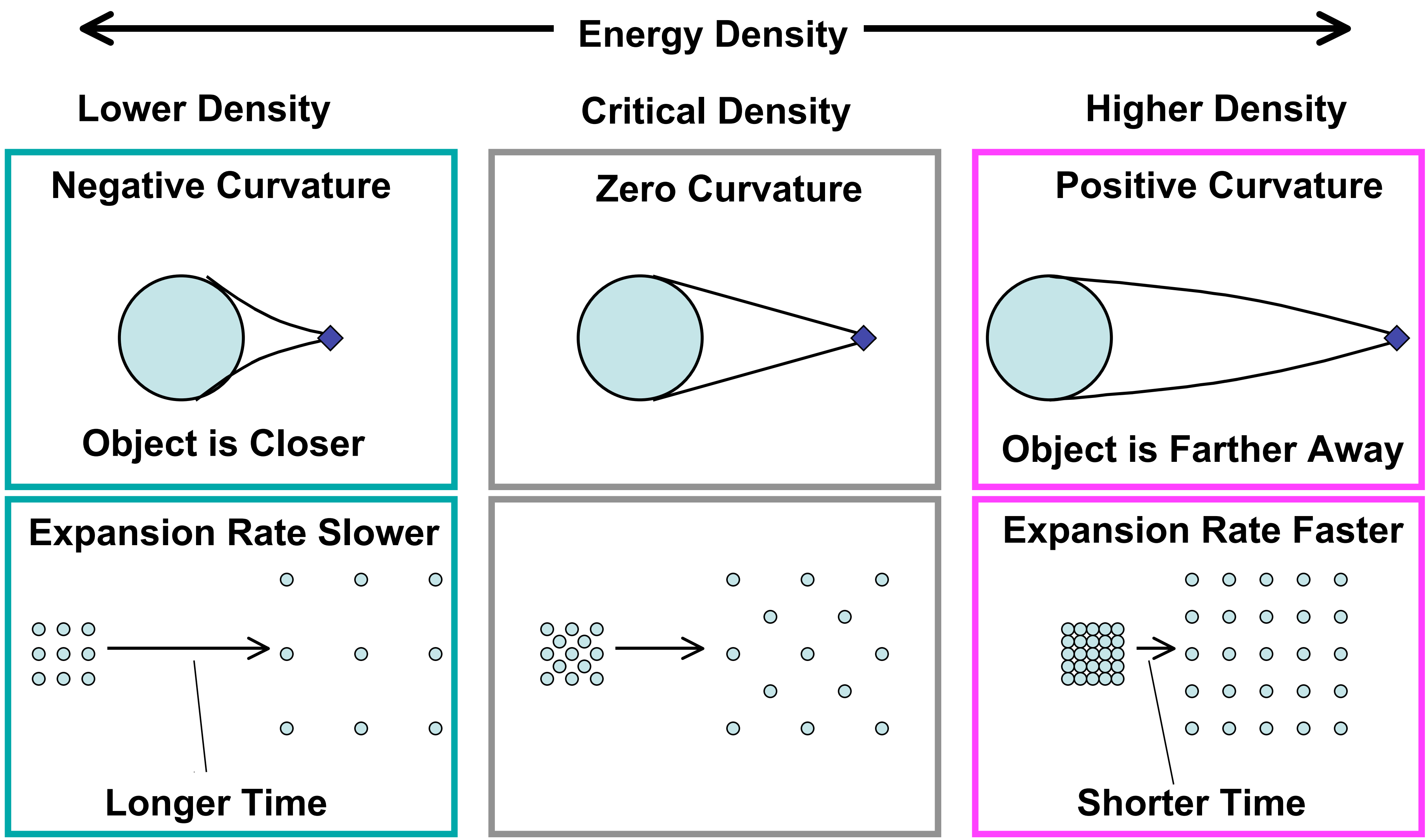
Decoupling, radiation mostly in visible:
wavelength ~ 500 nm

Today, radiation mostly in microwaves
wavelength ~ 1 mm

The Scale Factor increases by a factor
of 1000 between decoupling and Today

The amount of time this takes depends on the total energy density

Distance and Time



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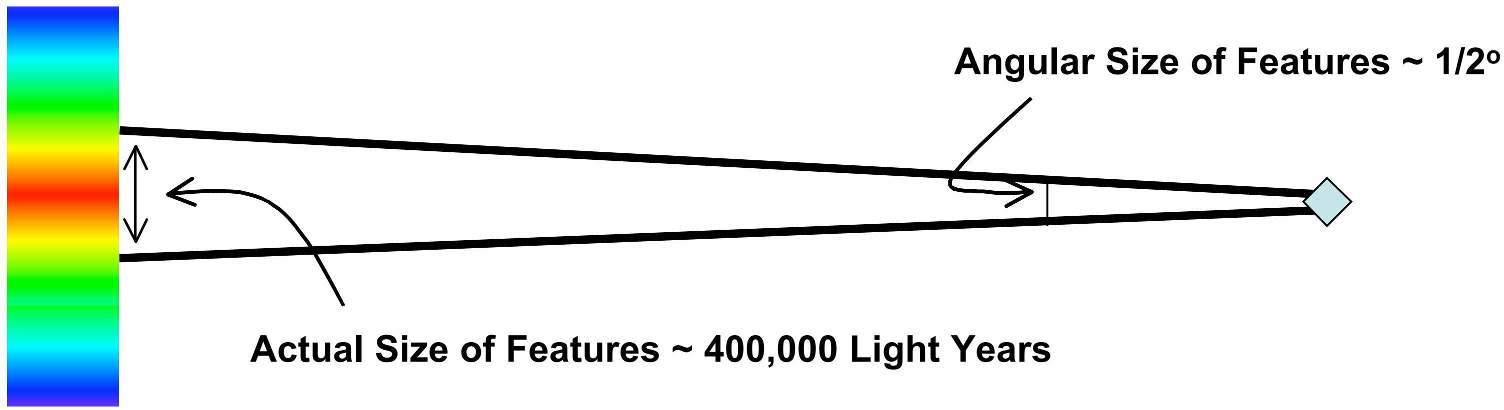

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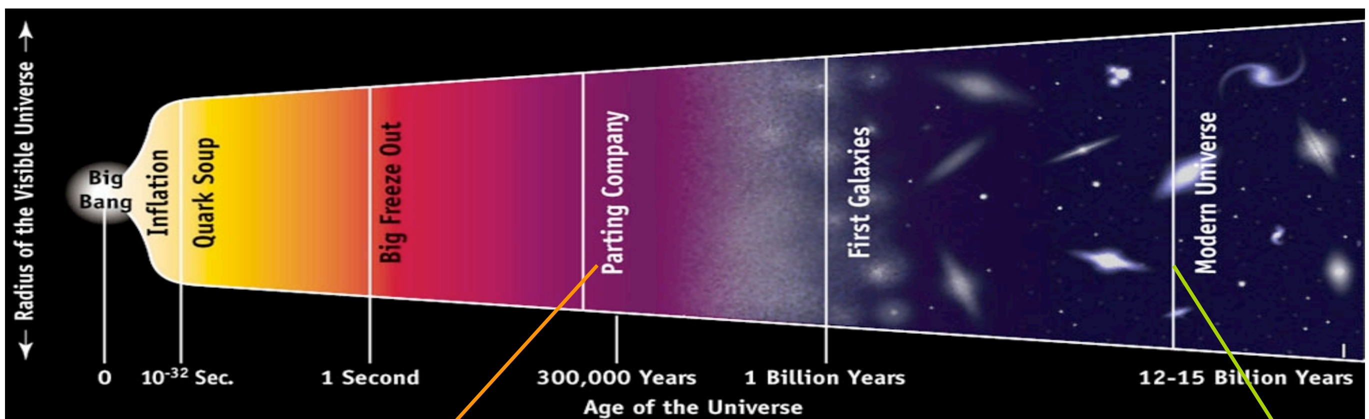

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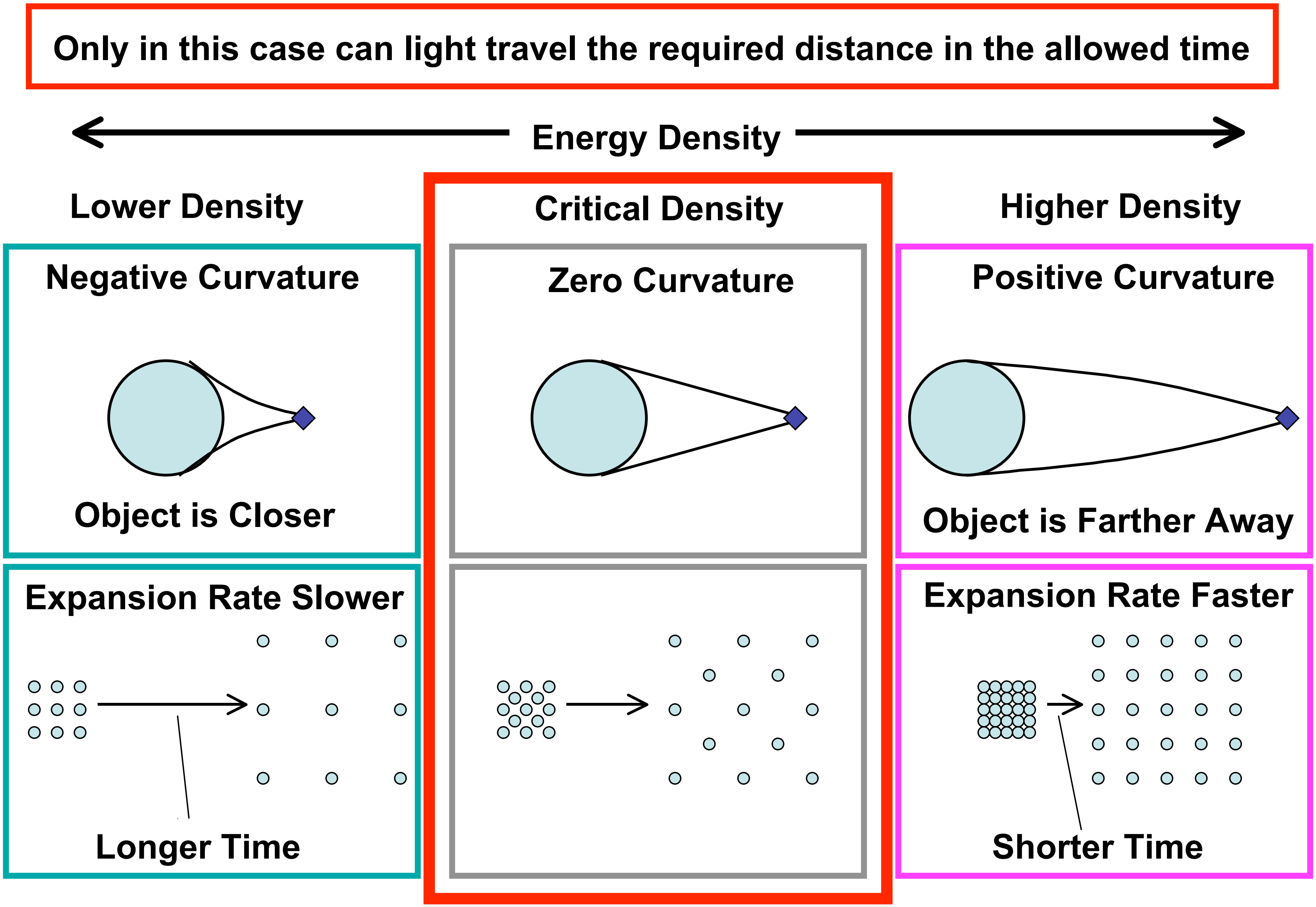
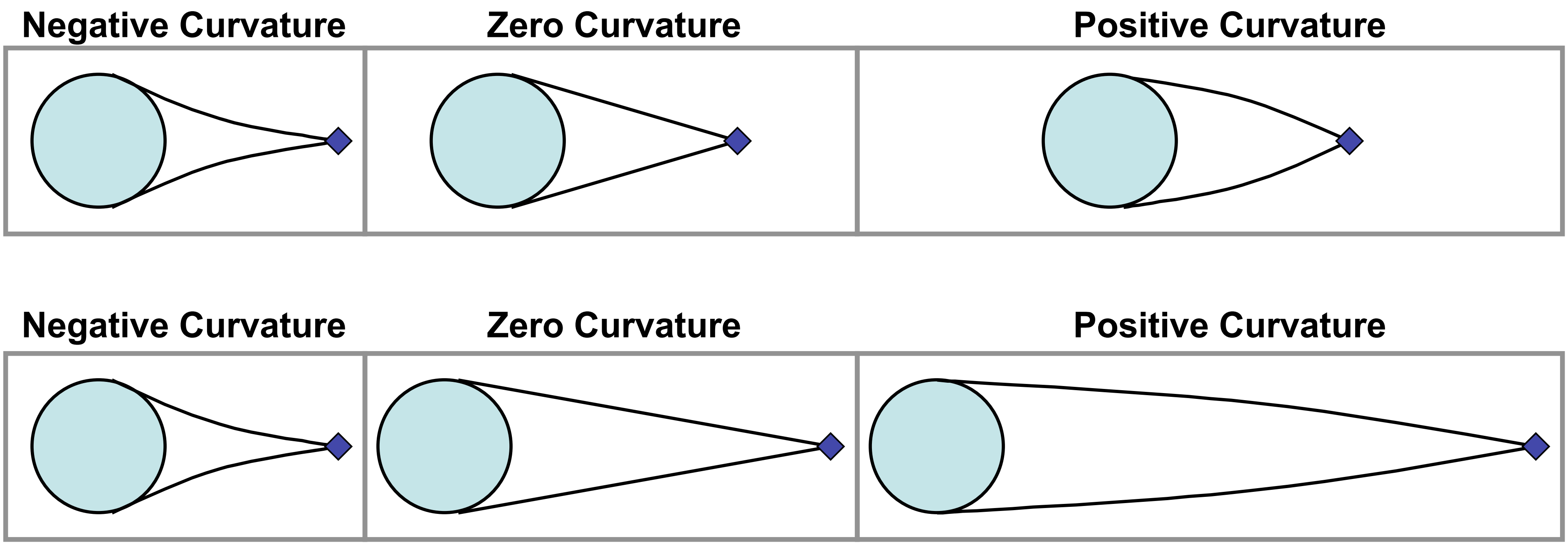
Apparent Size of CMB Features is only consistent with Zero Curvature



Curvature and the Apparent Distance to Objects



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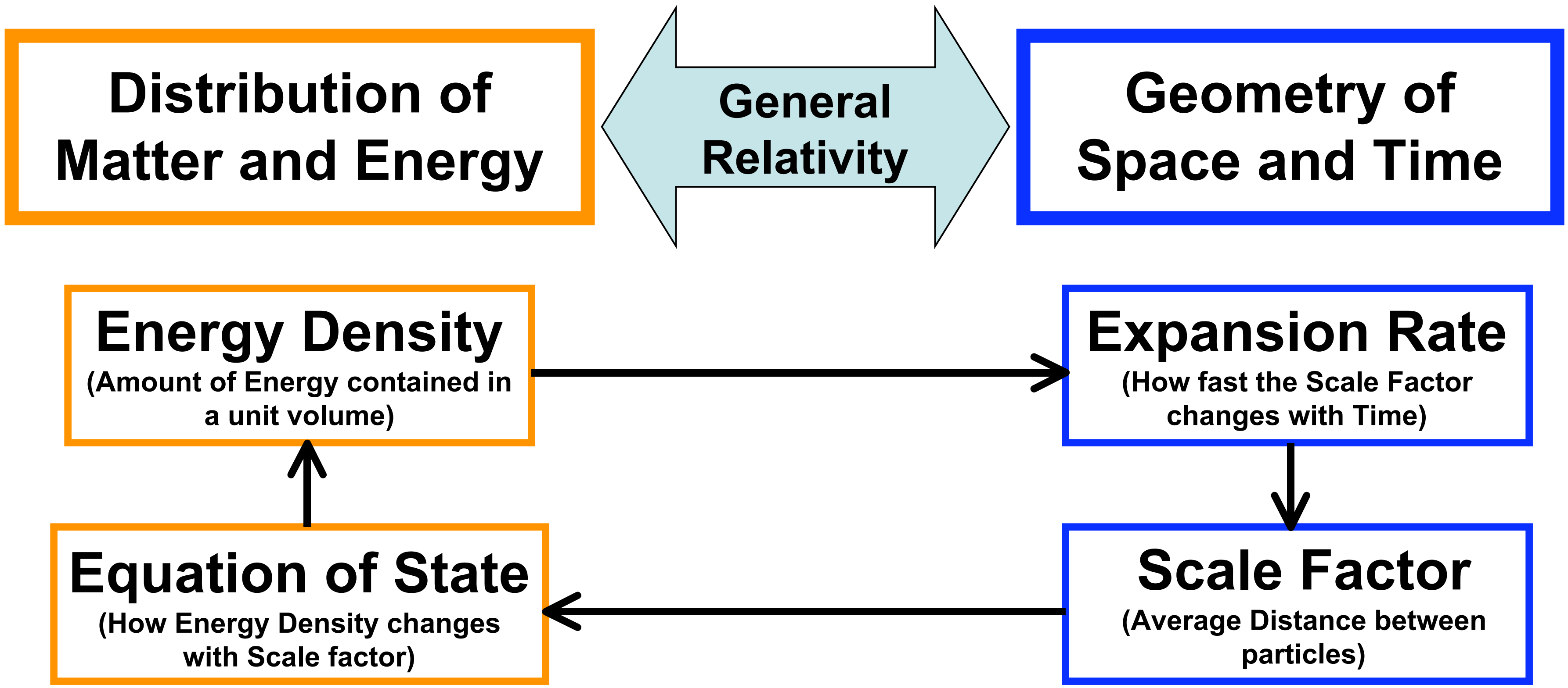
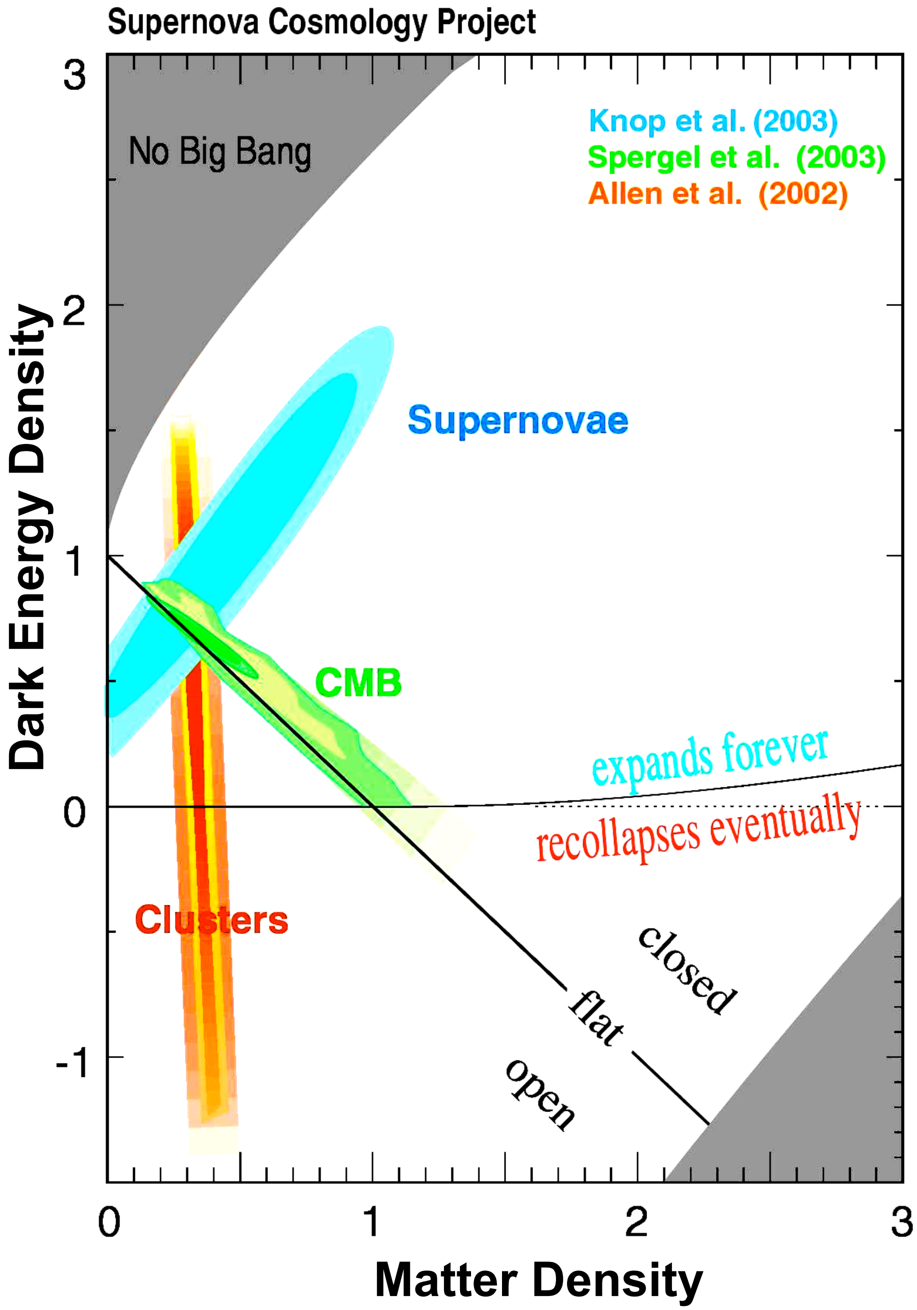
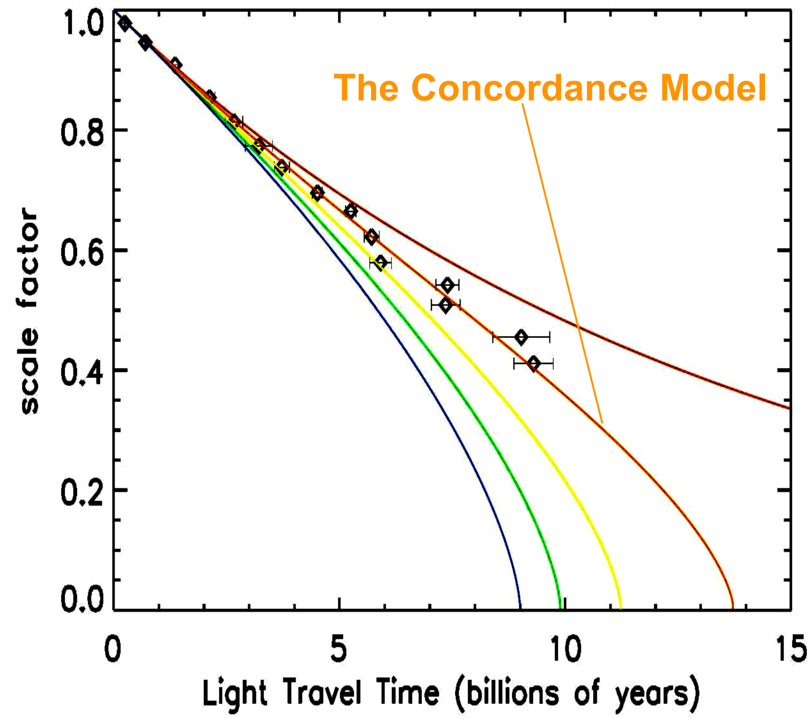


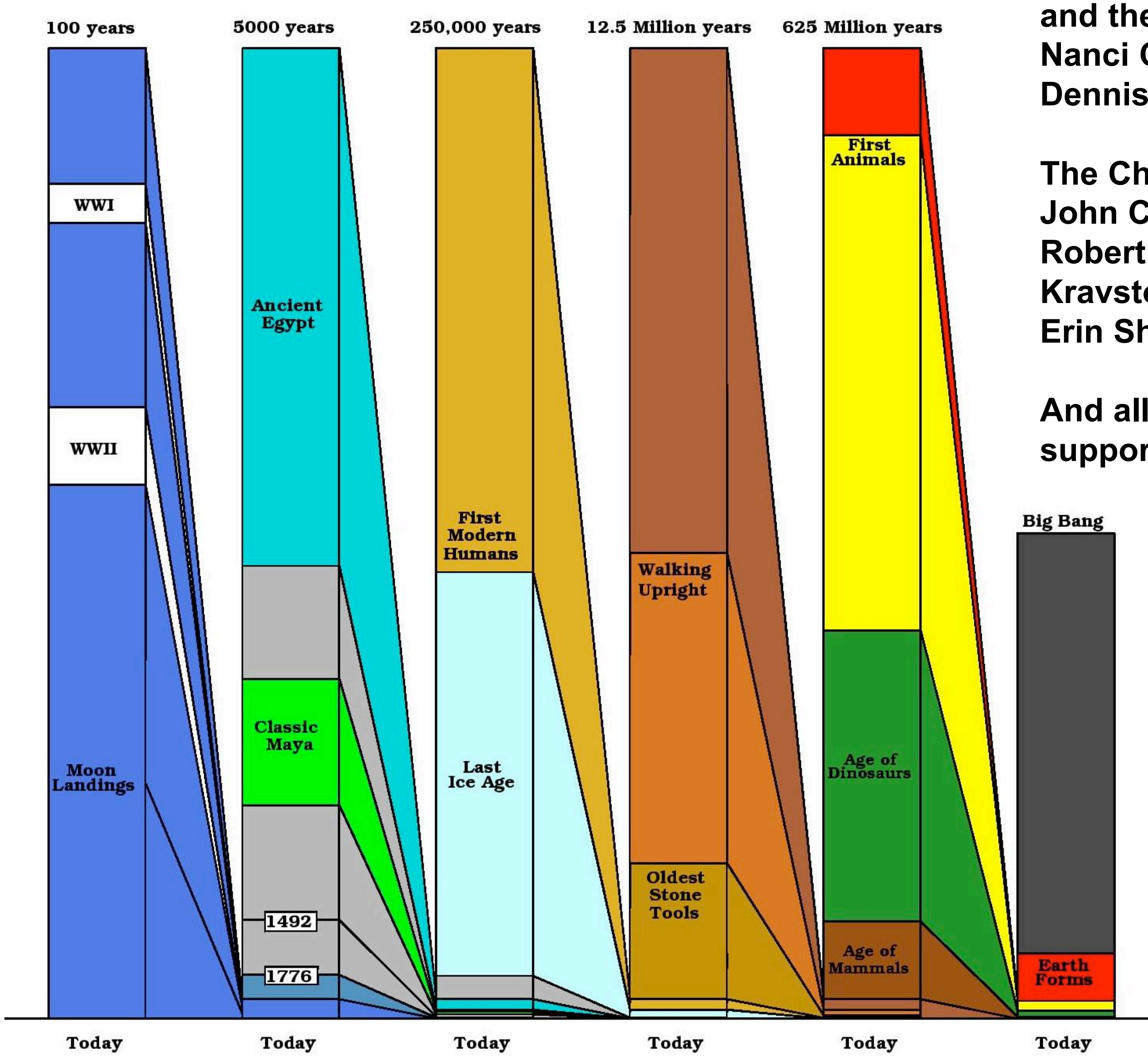
Cosmological Consistency





The Age of the Universe is
13.6 billion years,

Give or take a few hundred million years



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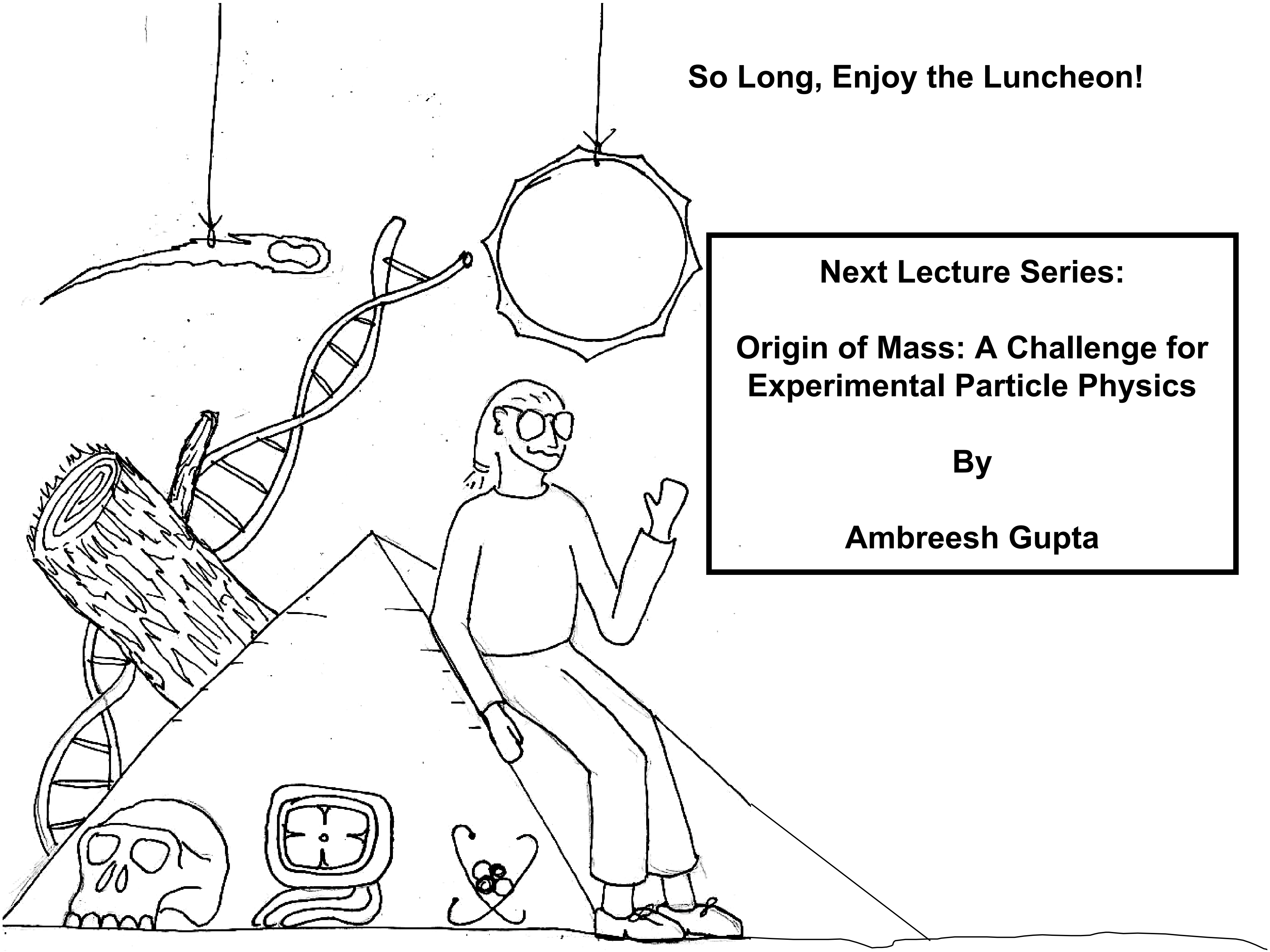
And all the people who attend and support these lectures!

So Long, Enjoy the Luncheon!



Next Lecture Series:

Origin of Mass: A Challenge for Experimental Particle Physics

By

Ambreesh Gupta