

# Cosmology

## Lecture 3

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# Friedman equation

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

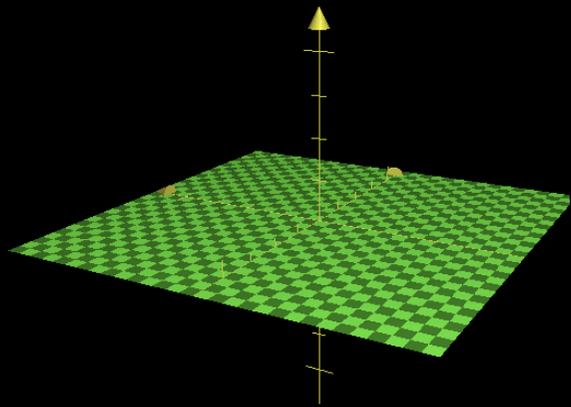
Rate of change of scale factor / scale factor - relative growth rate of universe

Depends on curvature

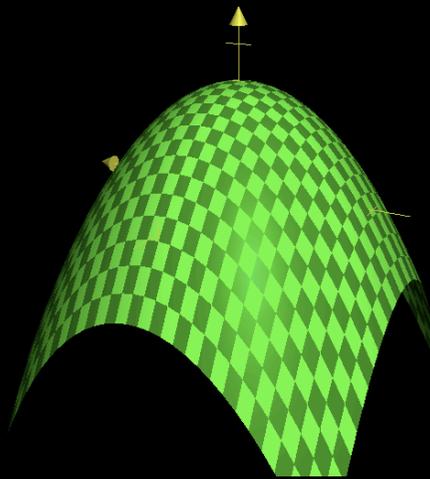
Depends on mass density

# Curvature

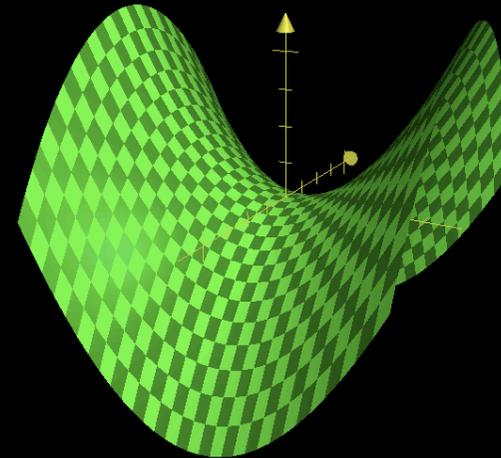
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Flat



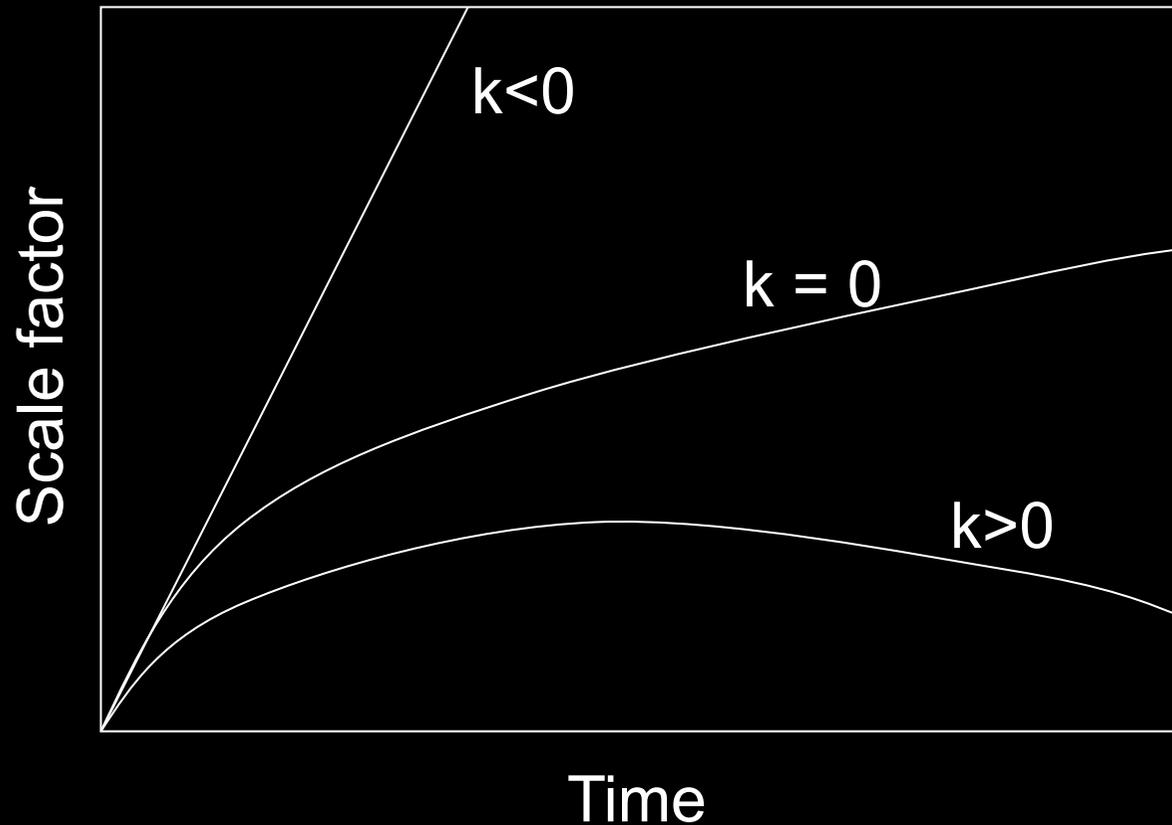
Positive



Negative

# Curvature and scale factors

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# Relativistic Friedman equation

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$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} \epsilon - \frac{\kappa c^2}{R_0^2 a^2} + \frac{\Lambda}{3} = H^2$$

- Consequence of mass energy
- $E^2 = m^2 c^4 + p^2 c^2$
- Photons contribute to the expansion of the universe

# Relativistic Friedman equation

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$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\epsilon - \frac{\kappa c^2}{R_0^2 a^2} + \frac{\Lambda}{3} = H^2$$

Rescaled curvature constant

Normalised against current radius  $R_0$  gives only 3 values

$\kappa = +1$	positive curvature
$\kappa = 0$	flat
$\kappa = -1$	negative curvature

# Relativistic Friedman equation

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$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\epsilon - \frac{\kappa c^2}{R_0^2 a^2} + \frac{\Lambda}{3} = H^2$$

Cosmological constant - “Einstein’s biggest blunder”

Proposed to balance steady state universe

# Measuring curvature- components of the universe

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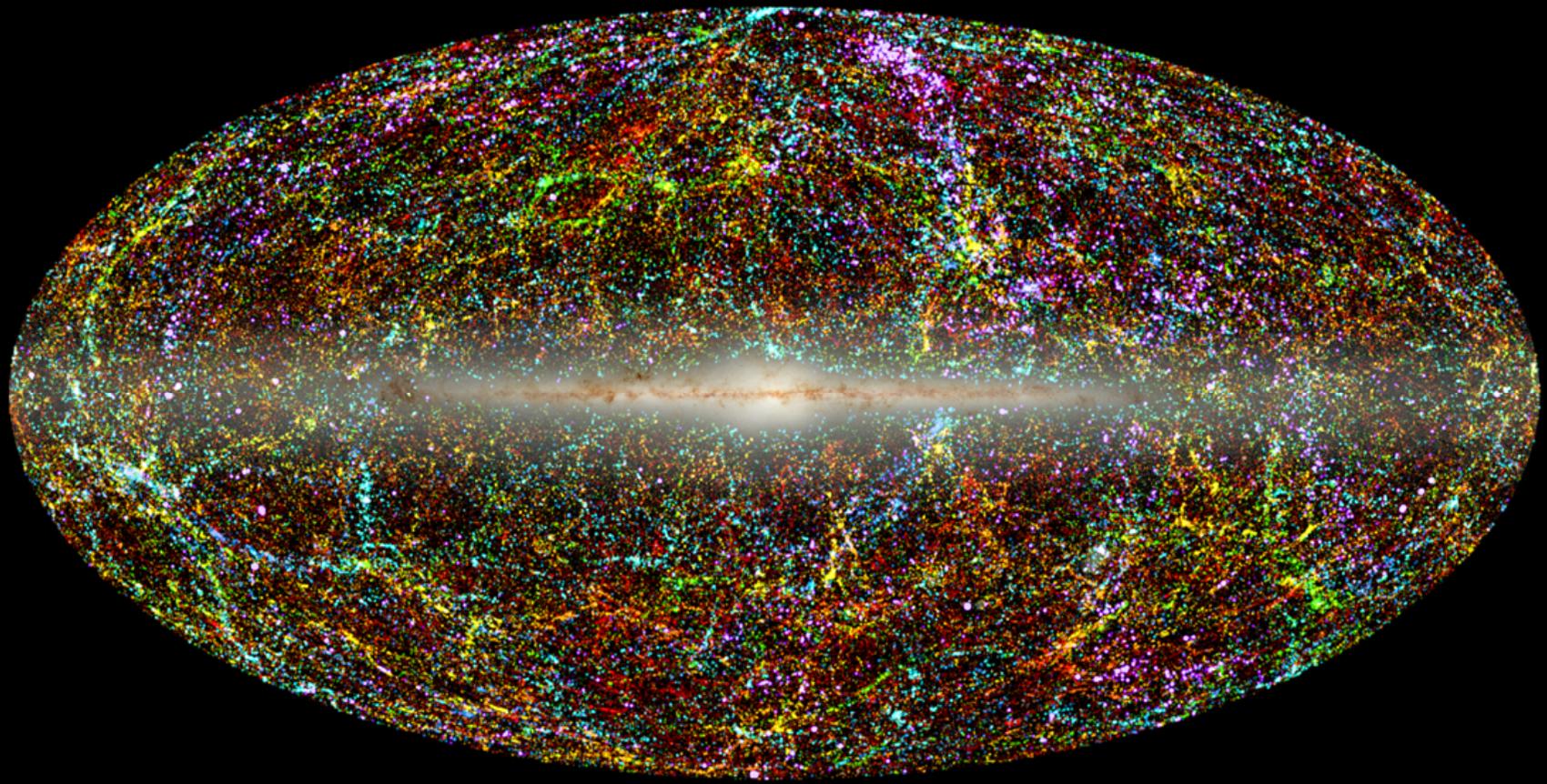
- If the universe has critical density, it will be flat

$$\rho_{crit} = \frac{3H^2}{8\pi G}$$

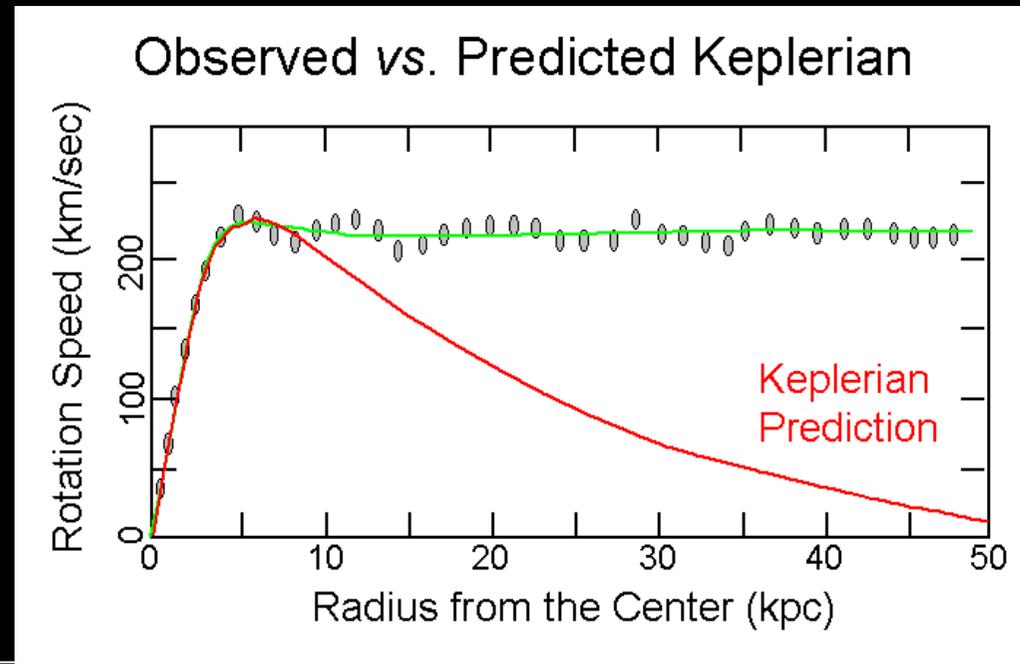
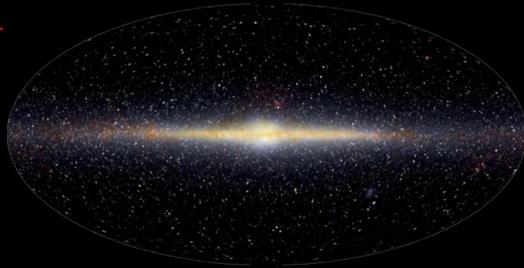
- “Add up” the components

# Stars and galaxies

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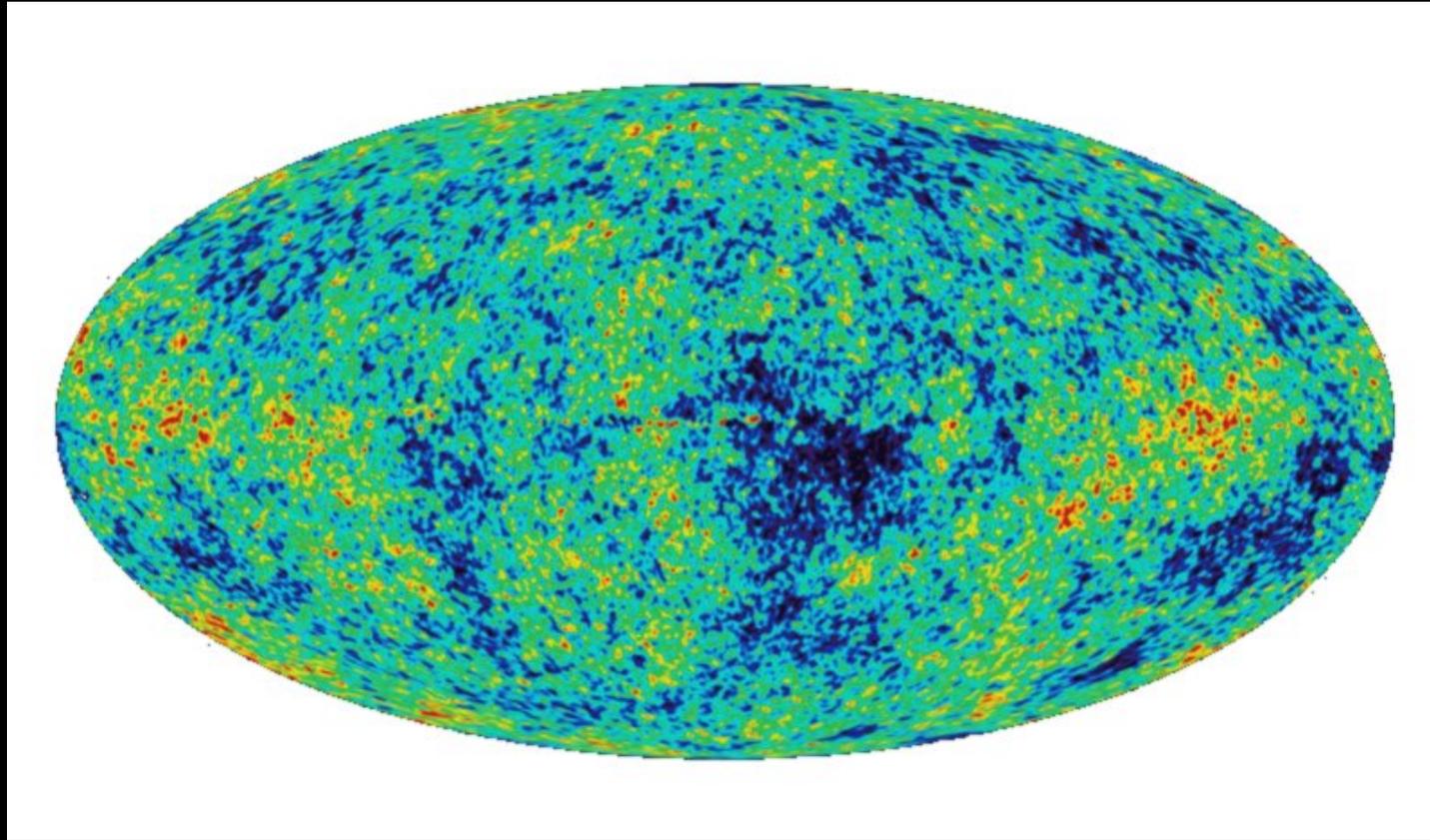
# Dark Matter



- More on dark matter later in the course

# Cosmic Microwave background

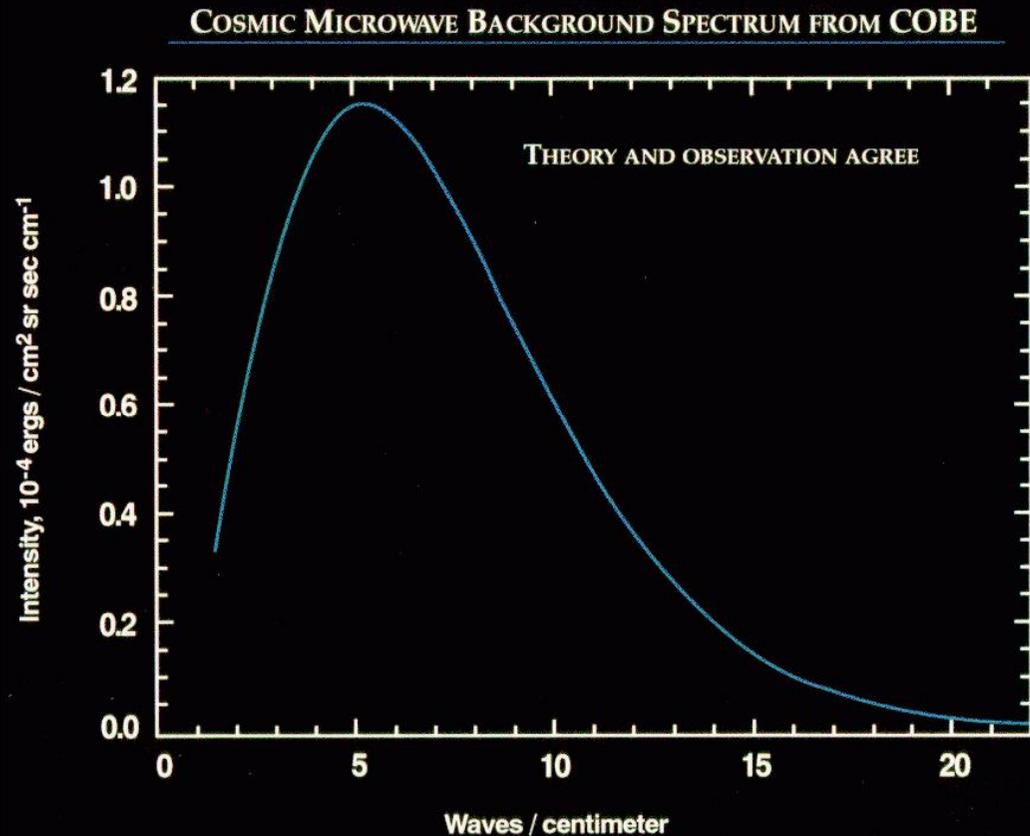
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# CMB temperature

- $T=2.8\text{K}$

- Theory and observation agree to incredible precision



# Where does the CMB come from?

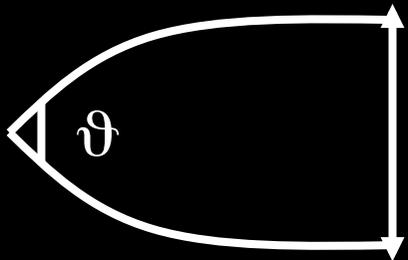
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Recombination of electrons + protons

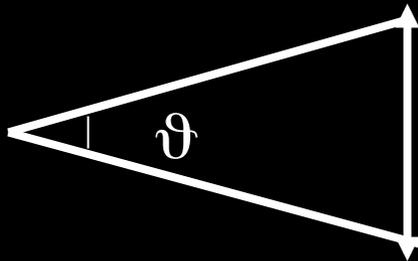
Last scattering roughly 300,000 years after the big bang

Some inhomogeneity due to movement of dark matter and plasma

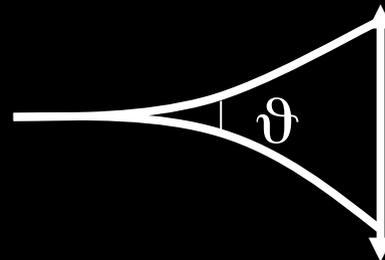
Can act as a standard ruler



Closed

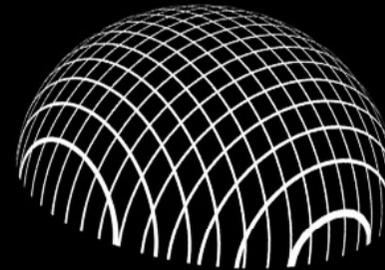
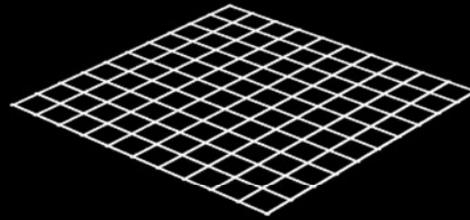
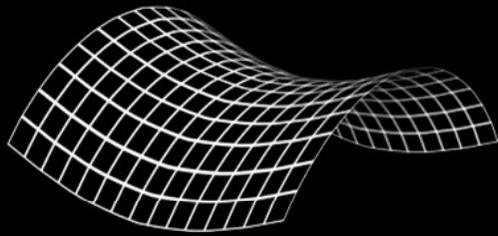
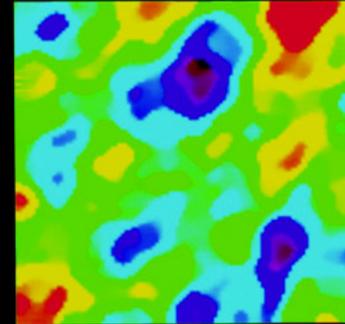
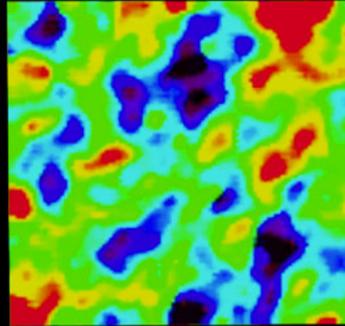
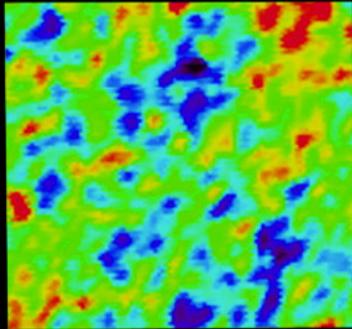


Flat



Open

# GEOMETRY OF THE UNIVERSE

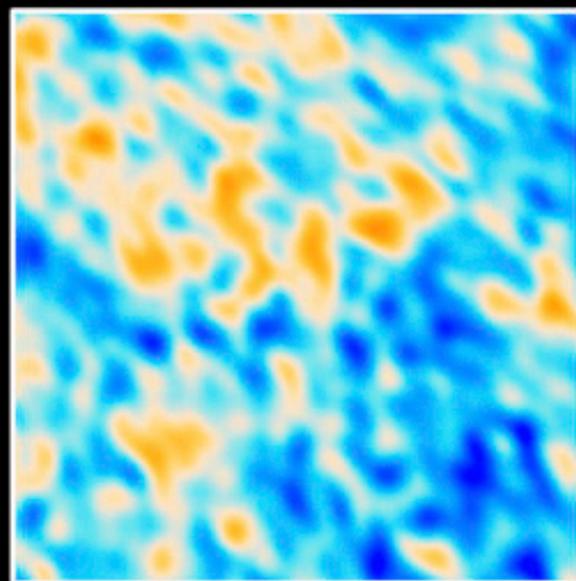
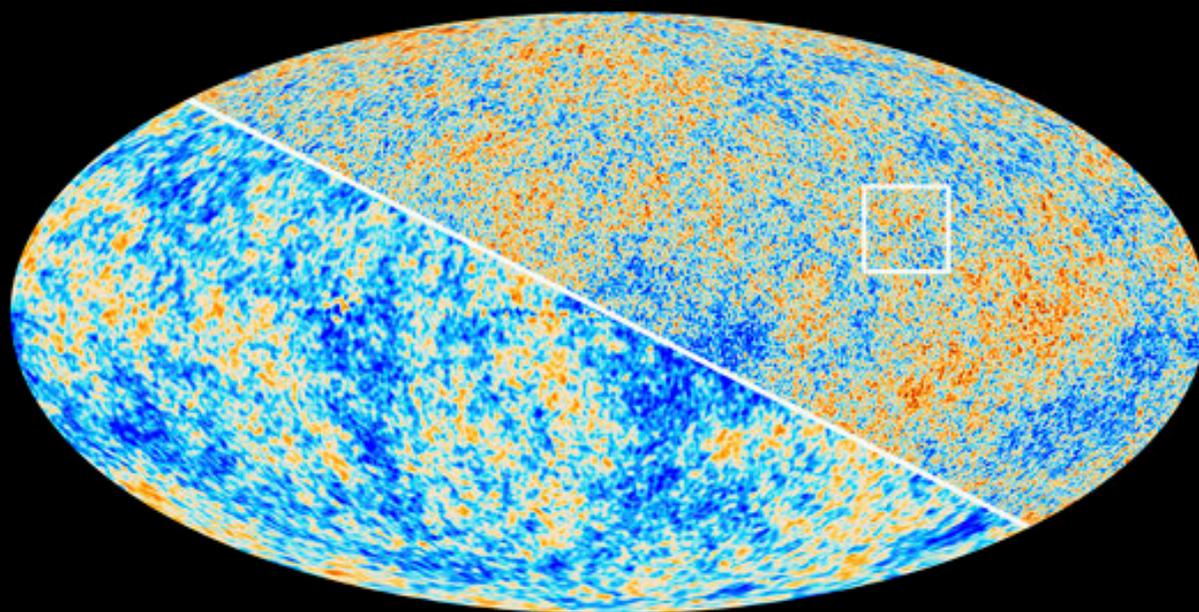


**OPEN**

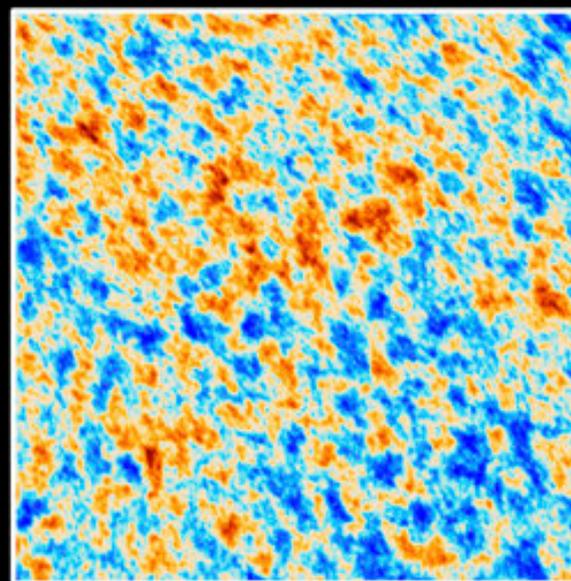
**FLAT**

**CLOSED**

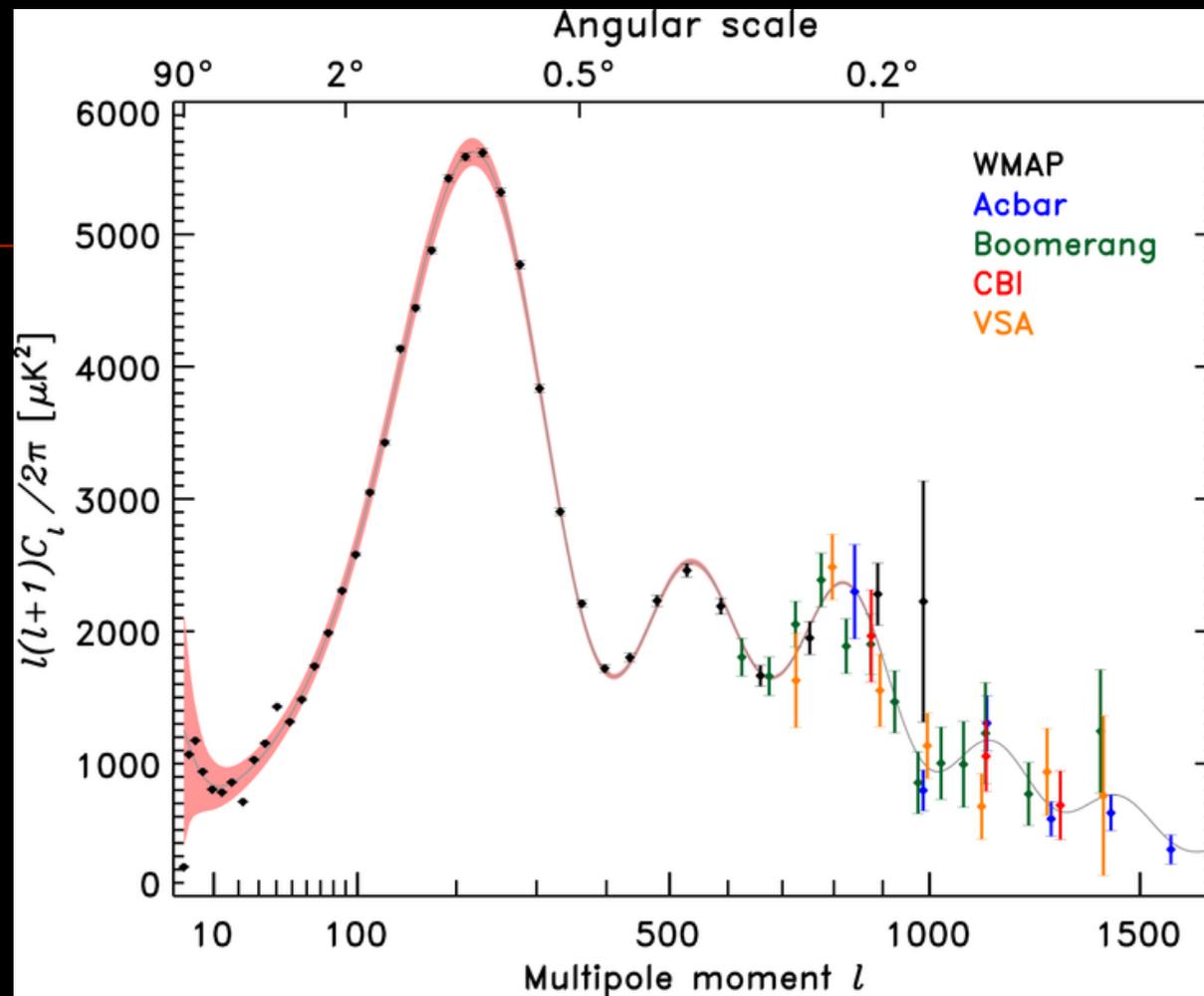
*The Cosmic Microwave Background as seen by Planck and WMAP*



*WMAP*



*Planck*



$\Omega = 1.0009 \pm 0.0005$  from most recent analysis  
(Planck 2013)

# The universe is flat

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- Where does the mass-energy come from?

- Stars? Not enough
- Dark Matter? Maybe, but need weird properties
- Dark Energy? Best bet

# Constituents

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	mass (Mev)	charge		$\Omega$
■ Protons	983.3	+1		
■ Neutrons	939.6	0		4%
■ Electrons	0.511	-1		
■ Photons	0	0		
■ Neutrinos	?	0		
■ Dark matter	?	0		23%
■ Dark Energy	?	0		73%

Overall, the universe is flat

# Dark Energy

- Cosmological Constant
- The universe is accelerating
- **This is a BIG surprise**

