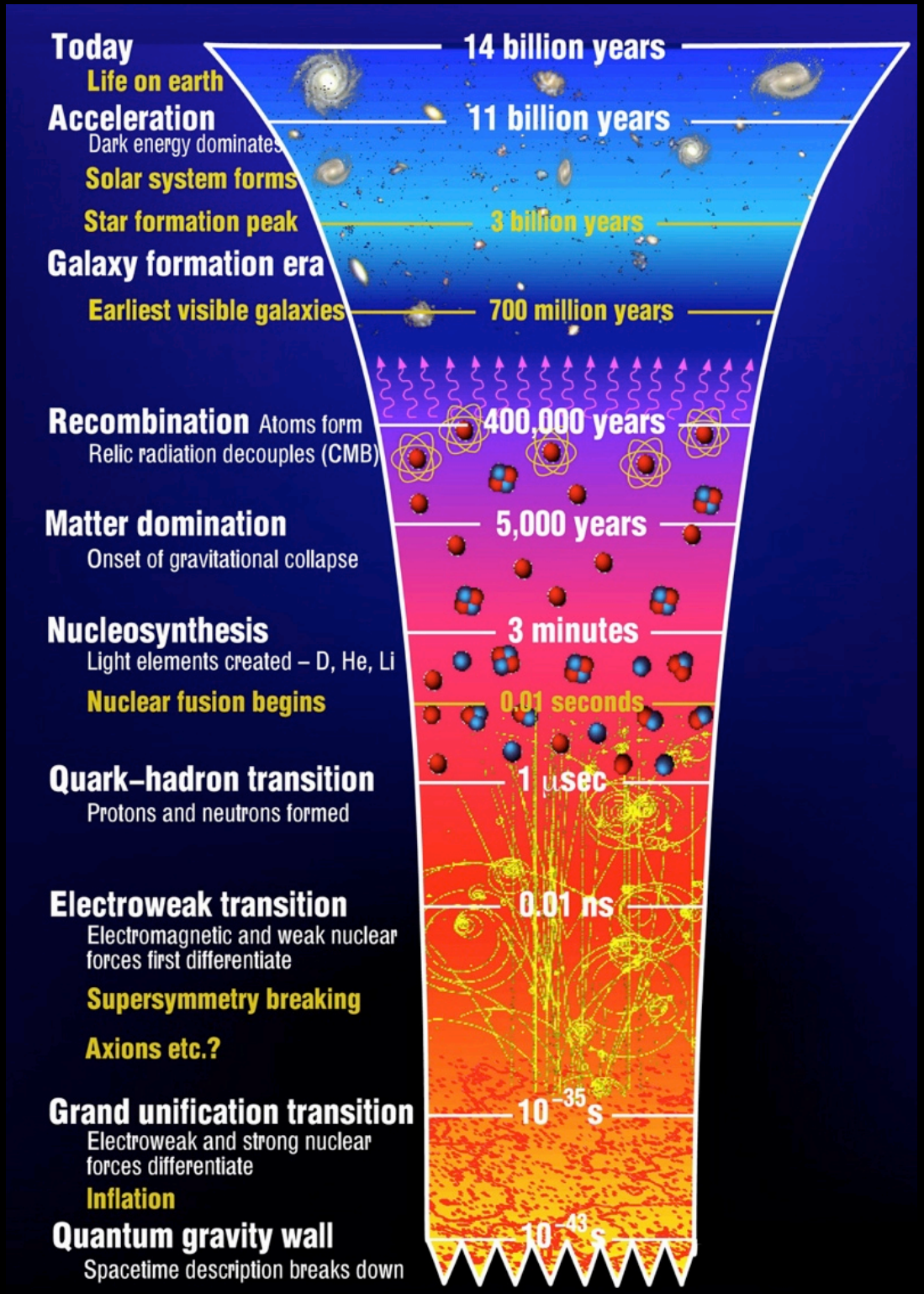
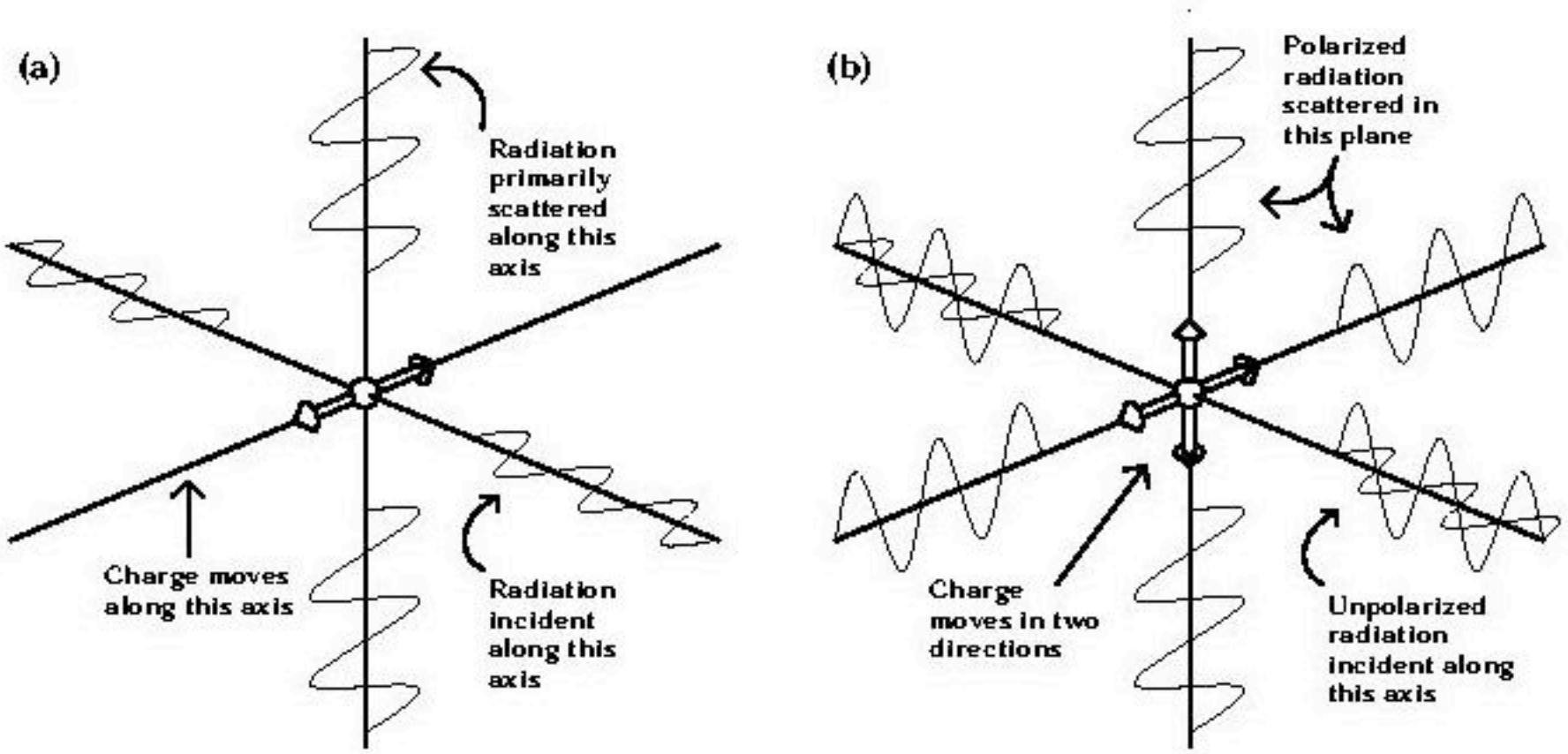
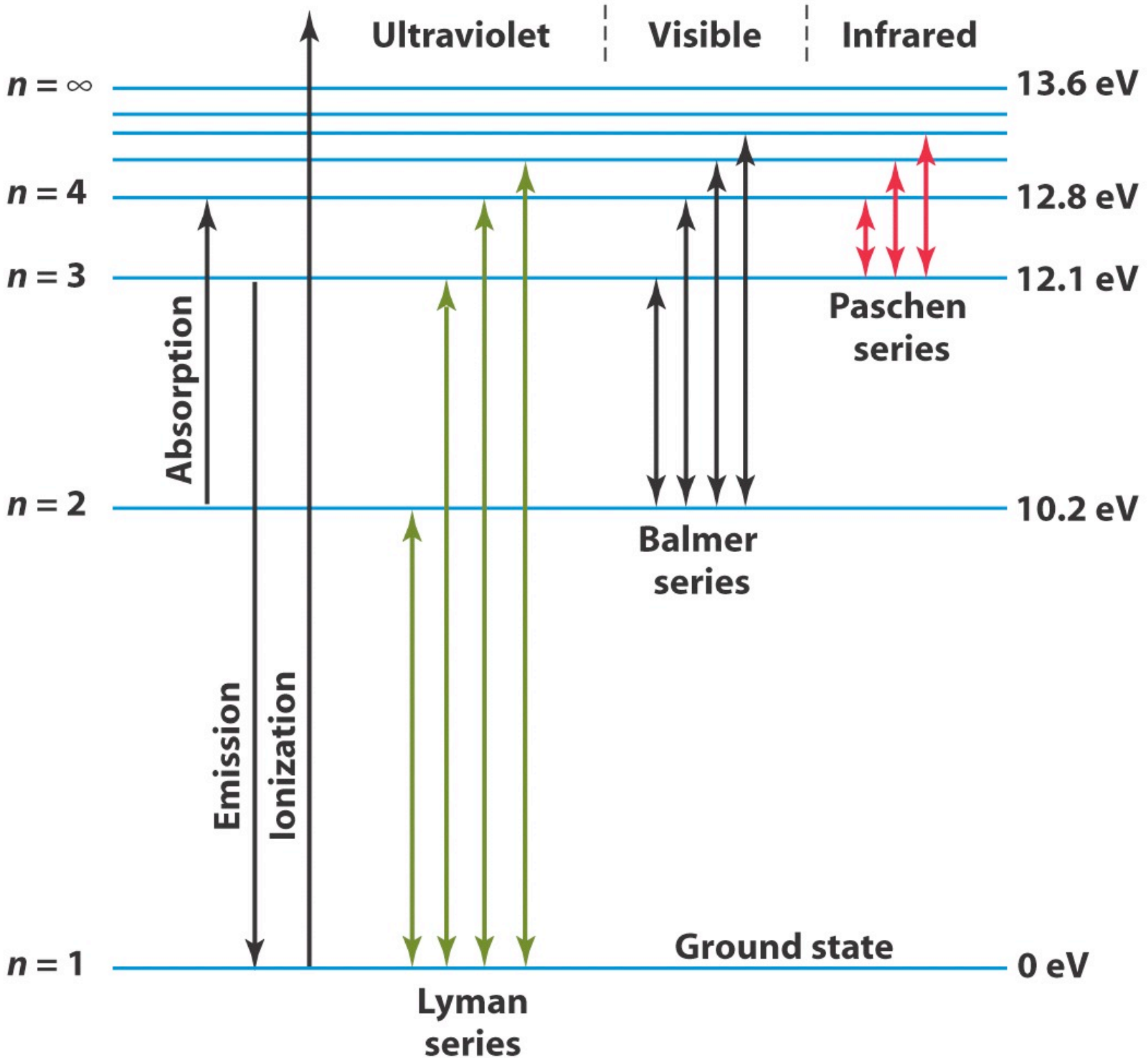
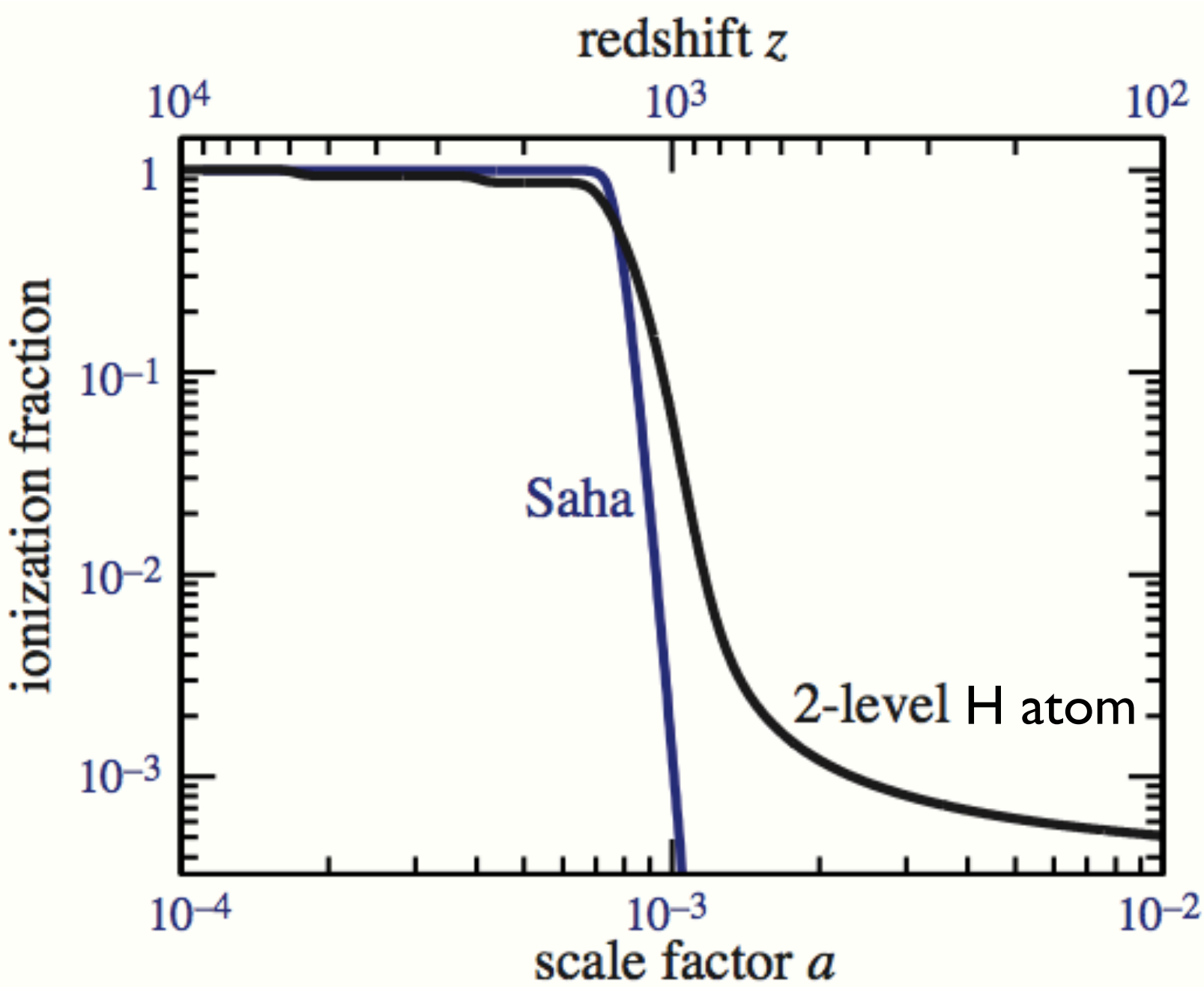
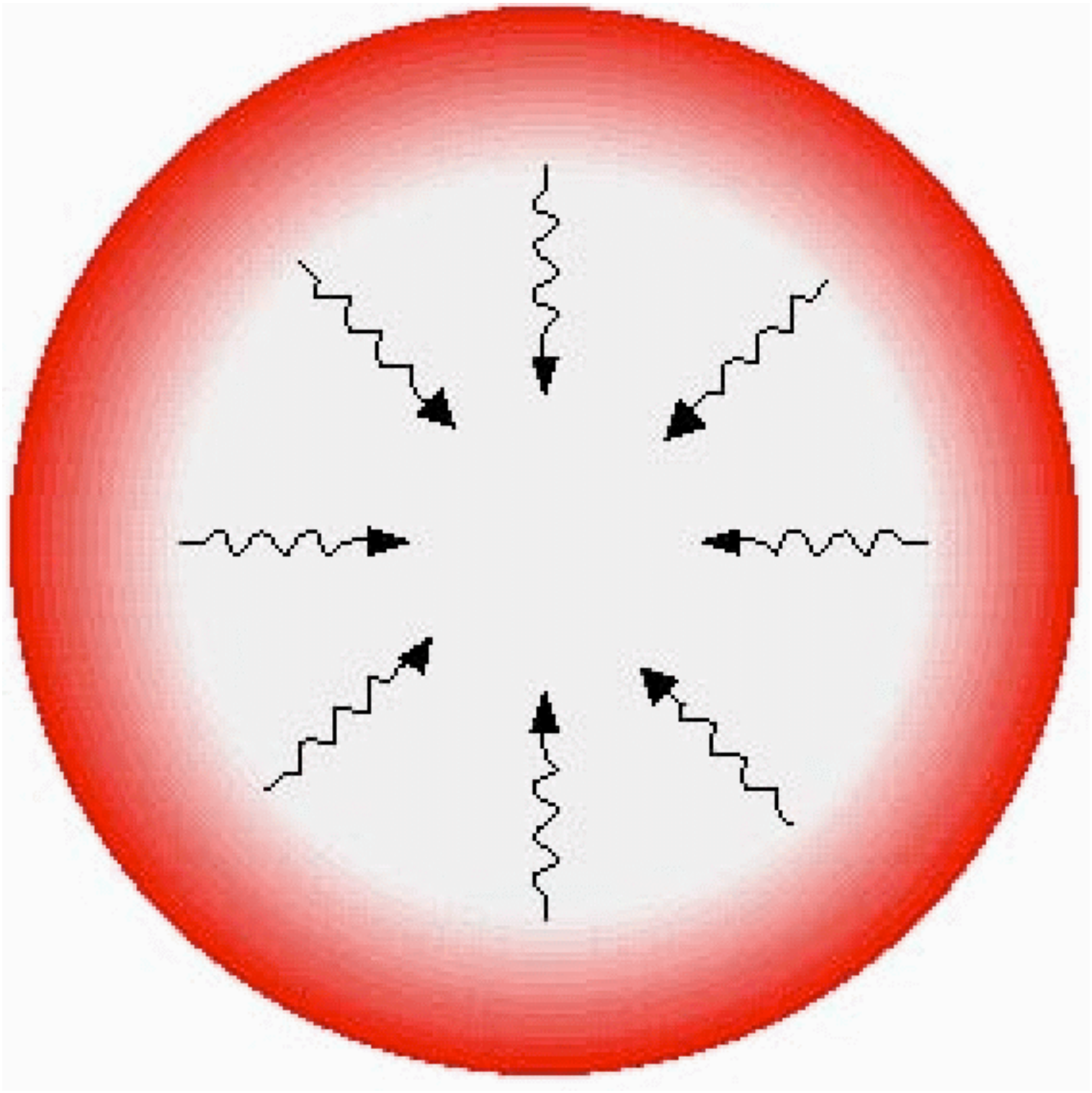
Introduction to Cosmology
Lecture 9


Today
14 billion years
Life on earth
Acceleration
11 billion years
Dark energy dominates
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
10 −35 s
Inflation
Quantum gravity wall
Spacetime description breaks down
10 −43 s

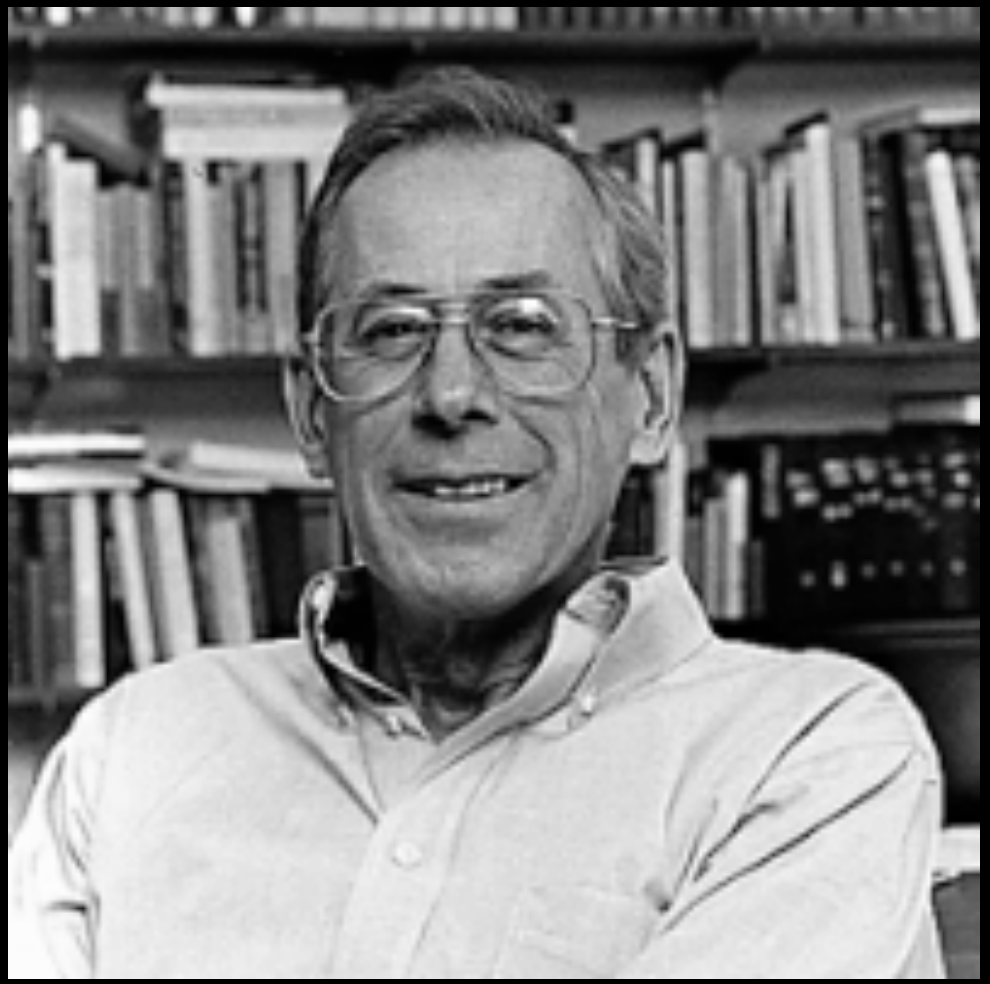

(a)
Radiation primarily scattered along this axis
Charge moves along this axis
Radiation incident along this axis
(b)
Polarized radiation scattered in this plane
Charge moves in two directions
Unpolarized radiation incident along this axis


Ultraviolet
Visible
Infrared
n = ∞
n = 4
n = 3
n = 2
n = 1
13.6 eV
12.8 eV
12.1 eV
10.2 eV
0 eV
Absorption
Emission
Ionization
Paschen series
Balmer series
Lyman series
Ground state


redshift z
10^4
10^3
10^2
1
10^{-1}
10^{-2}
10^{-3}
ionization fraction
Saha
2-level H atom
10^{-4}
10^{-3}
10^{-2}
scale factor a



Robert Dicke

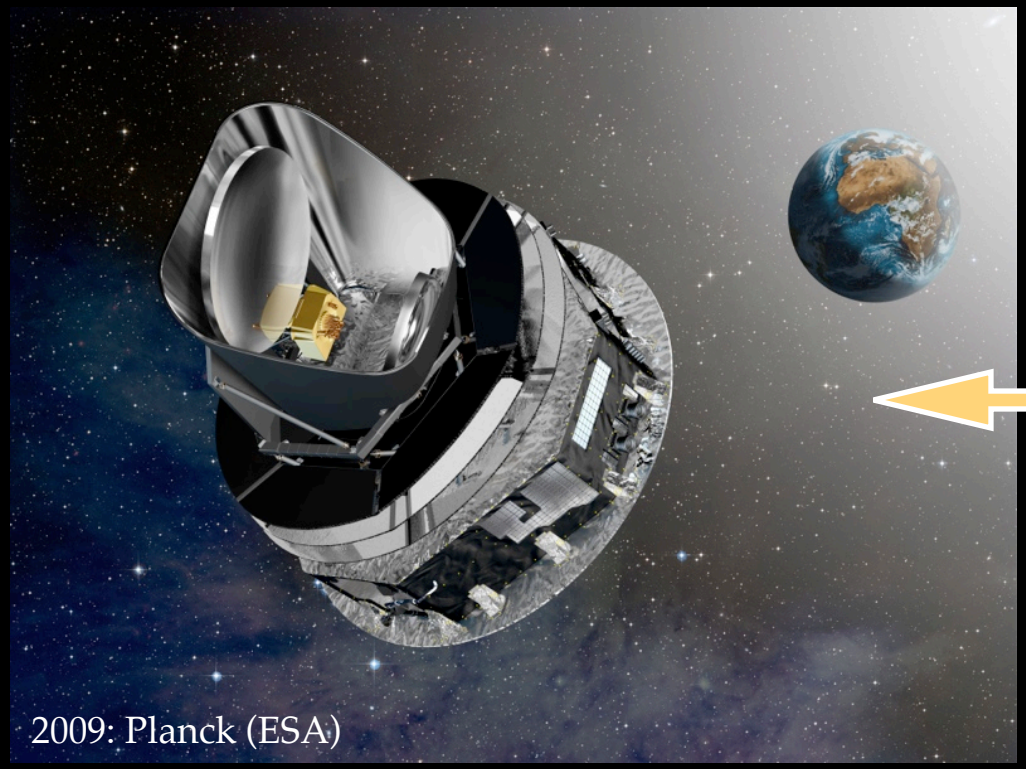


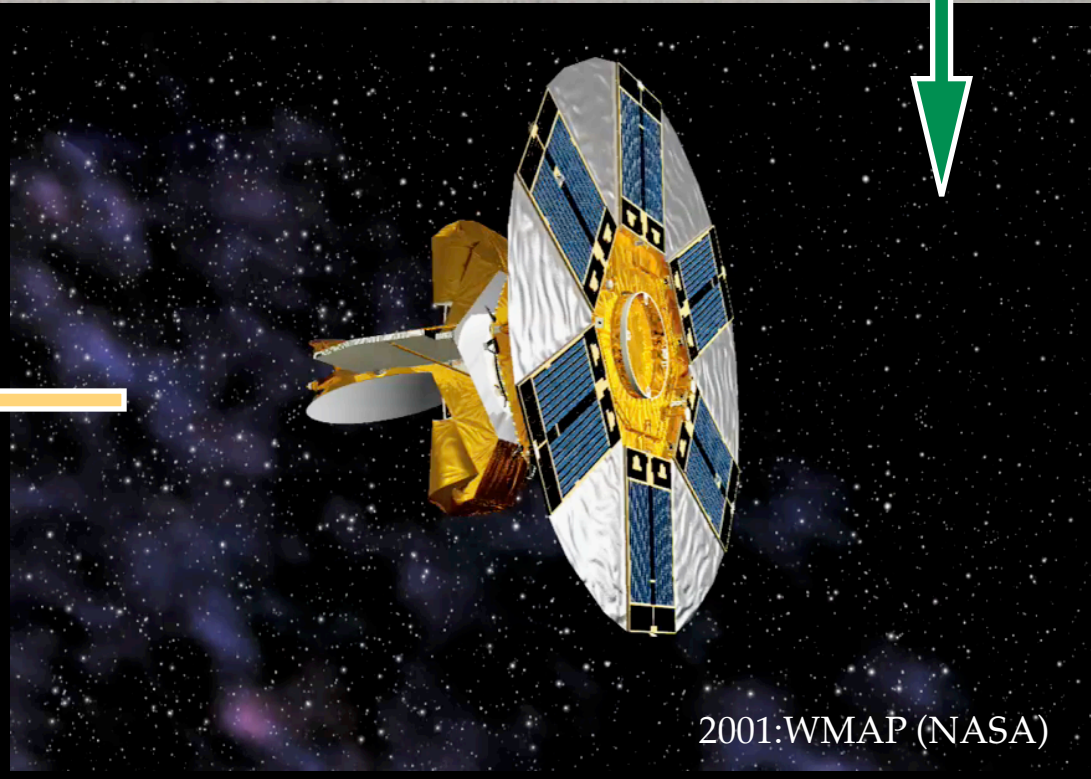
Jim Peebles

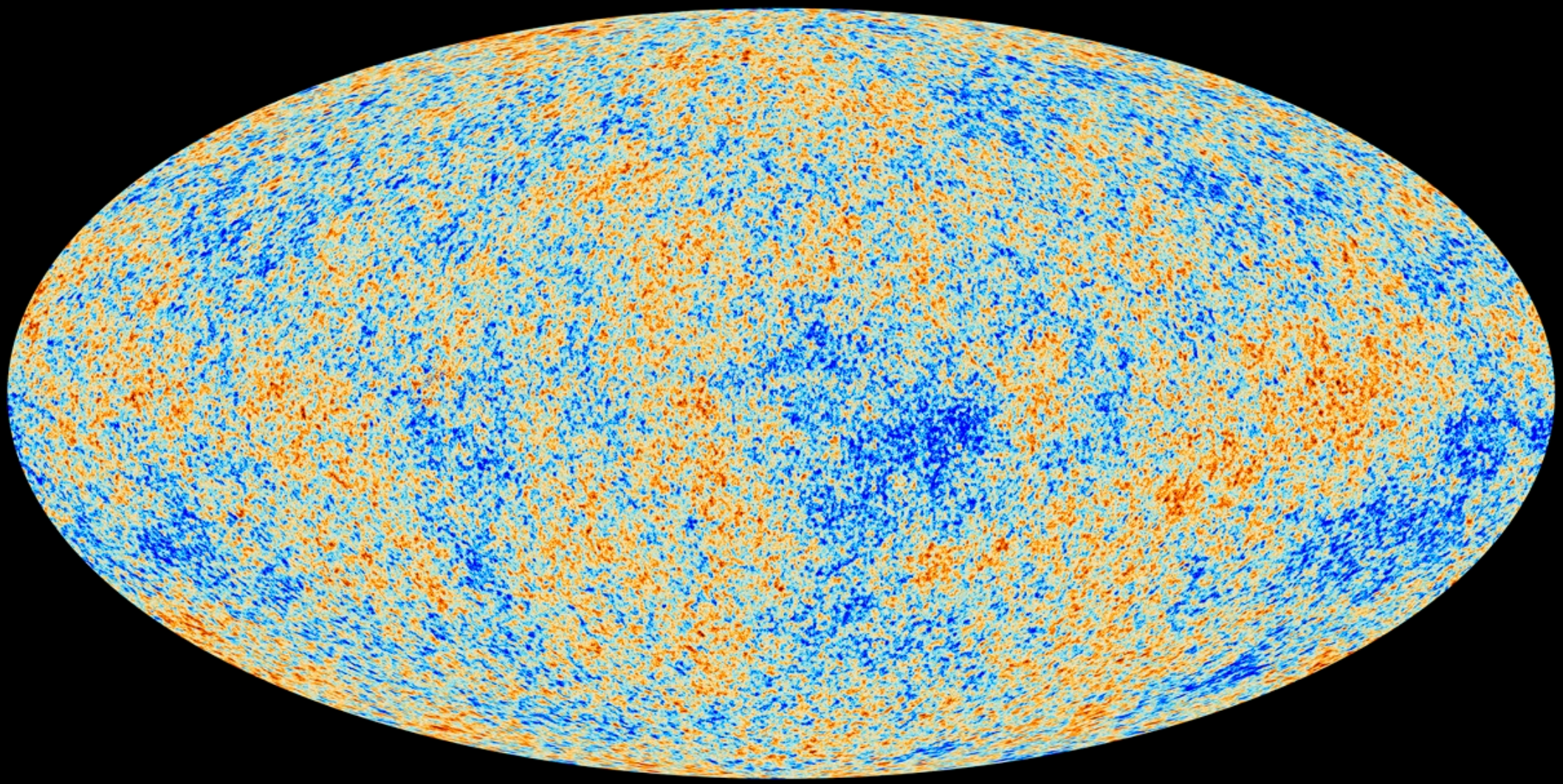
George
Gamow


1989: COBE (NASA)


1998: BOOMERanG (Caltech / Rome)

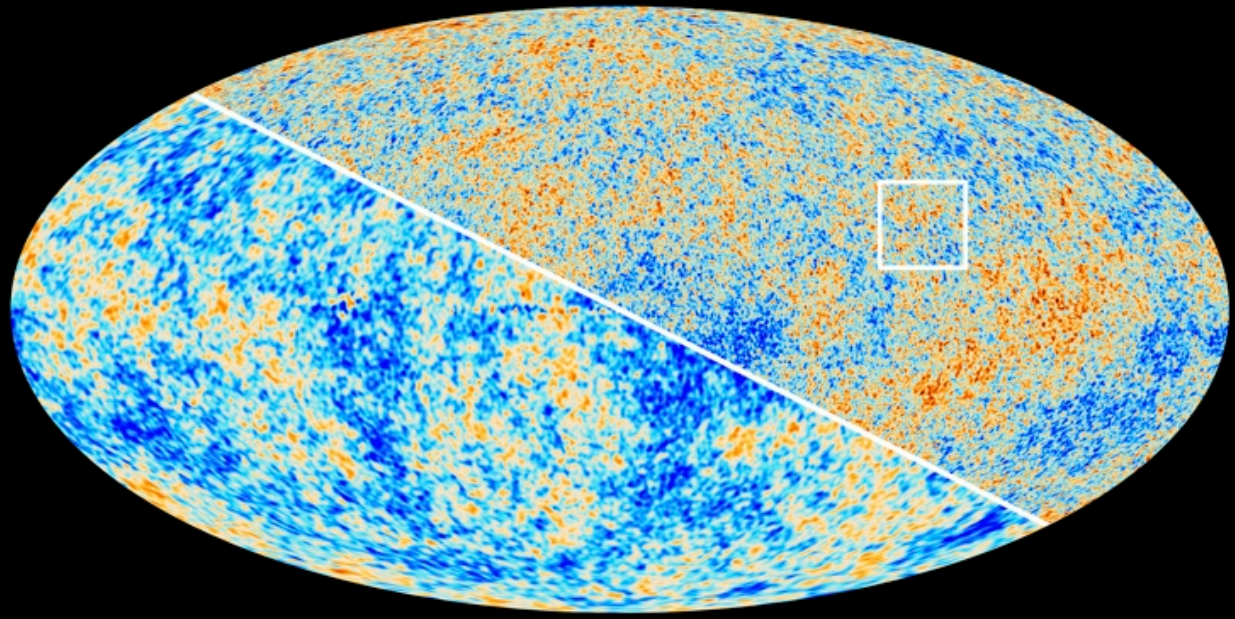

2009: Planck (ESA)

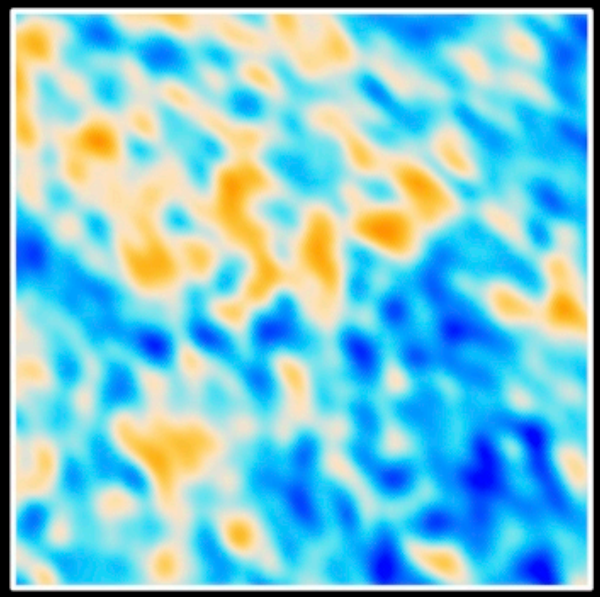

2001:WMAP (NASA)



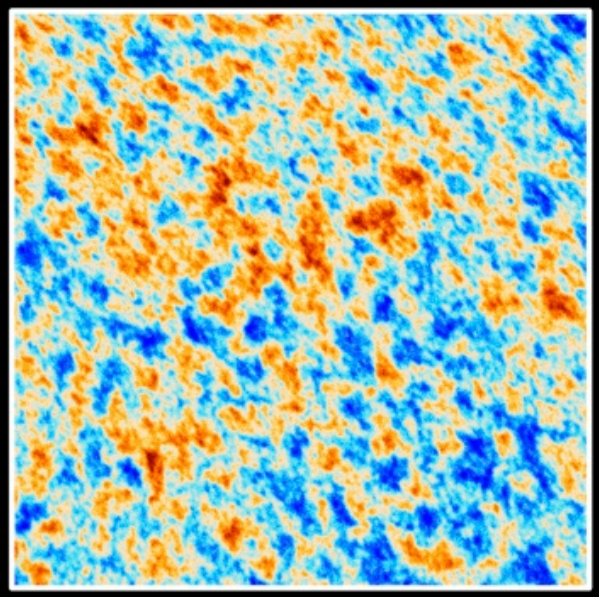
$$\frac{\delta T}{T}(\theta, \phi) = \frac{T(\theta, \phi) - \langle T \rangle}{\langle T \rangle}$$

The Cosmic Microwave Background as seen by Planck and WMAP

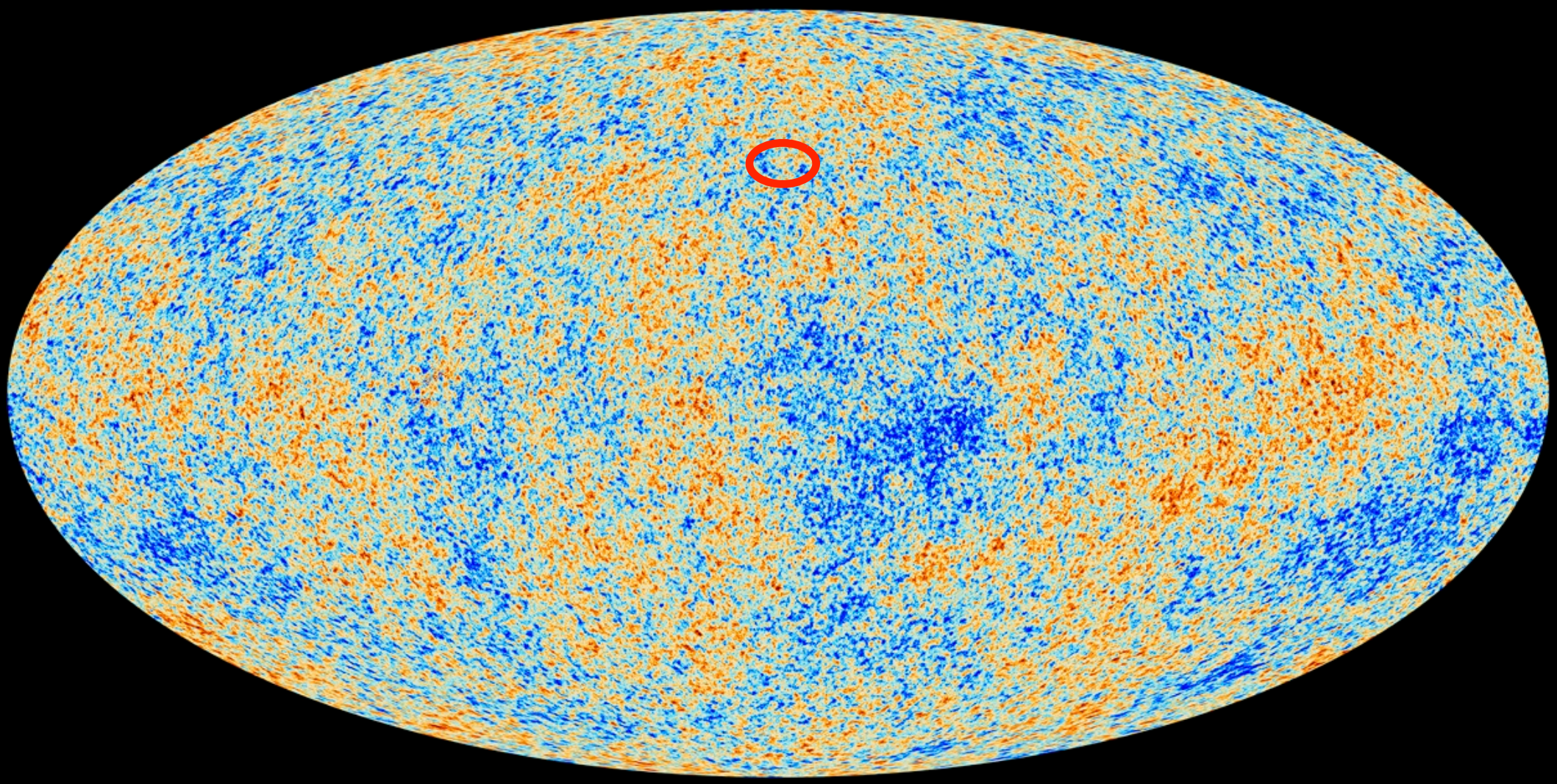




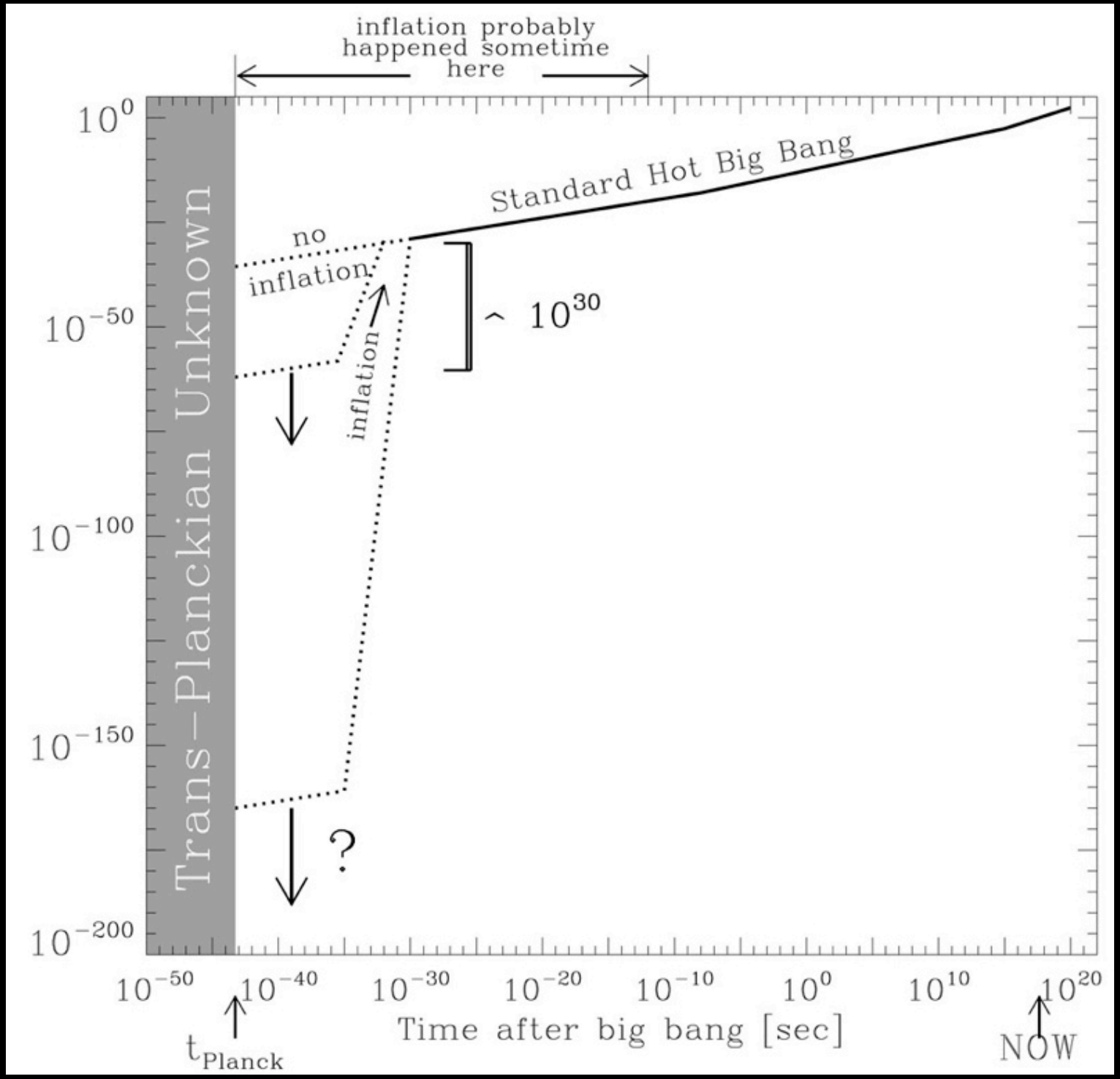
WMAP

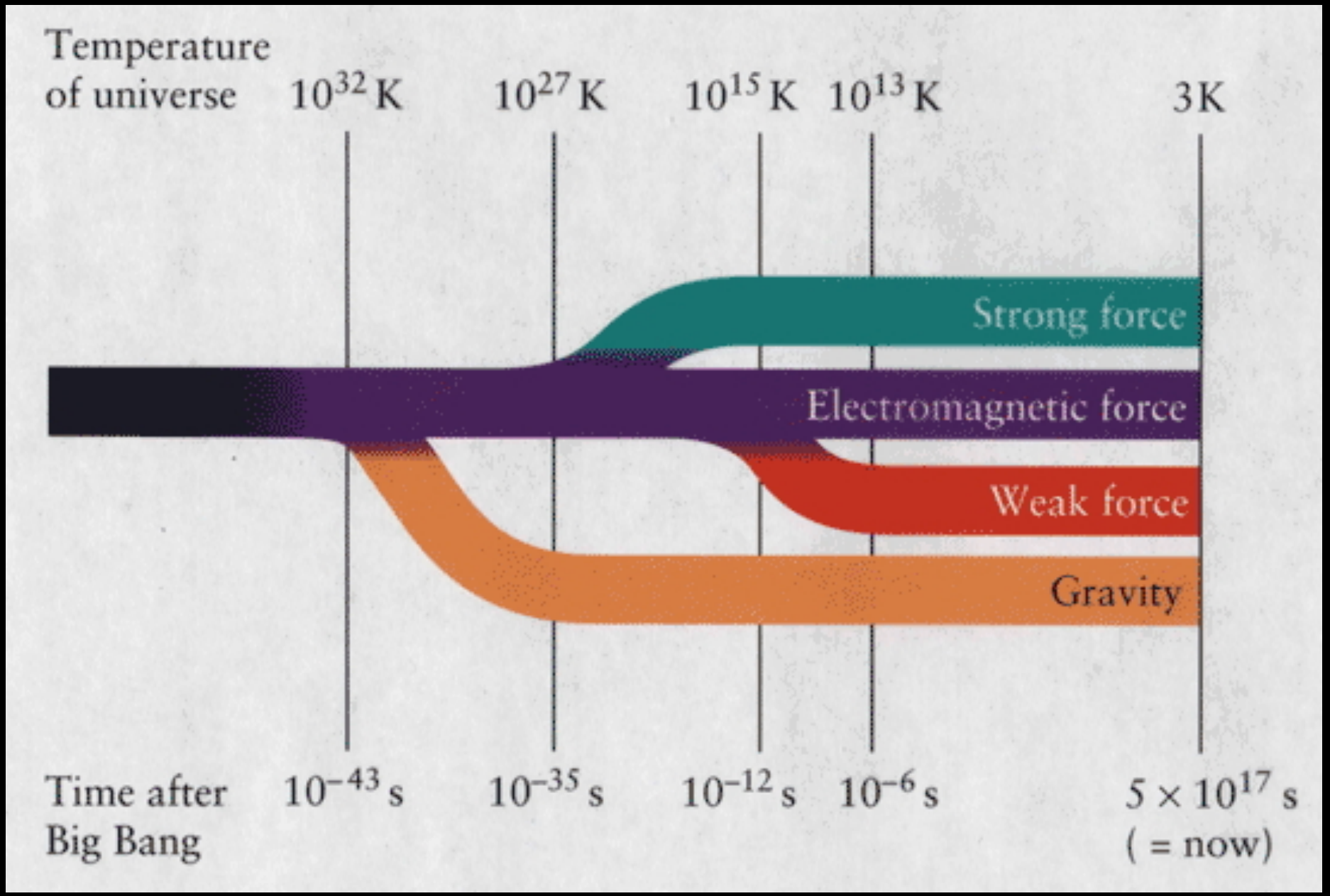


Planck



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


inflation probably
happened sometime
here
Standard Hot Big Bang
no
inflation
inflation
~ 10^30
Trans−Planckian Unknown
?
10^0
10^−50
10^−100
10^−150
10^−200
10^−50
10^−40
10^−30
10^−20
10^−10
10^0
10^10
10^20
t_Planck
Time after big bang [sec]
NOW


Temperature of universe
10^{32} K
10^{27} K
10^{15} K
10^{13} K
3K
Strong force
Electromagnetic force
Weak force
Gravity
Time after Big Bang
10^{-43} s
10^{-35} s
10^{-12} s
10^{-6} s
5×10^{17} s
(= now)