Mass Scales and the CMBR

Observation and analysis of the glow of the Big Bang mark the beginning of ‘precision cosmology’ (and the end of classical astronomical methods)

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Equations of Motion

- **Einstein Equation**
- **Friedmann Equation**
- **Required:**
  - Global Cosmic Parameters
  - Equation of State
  - Particle Processes

Einstein Equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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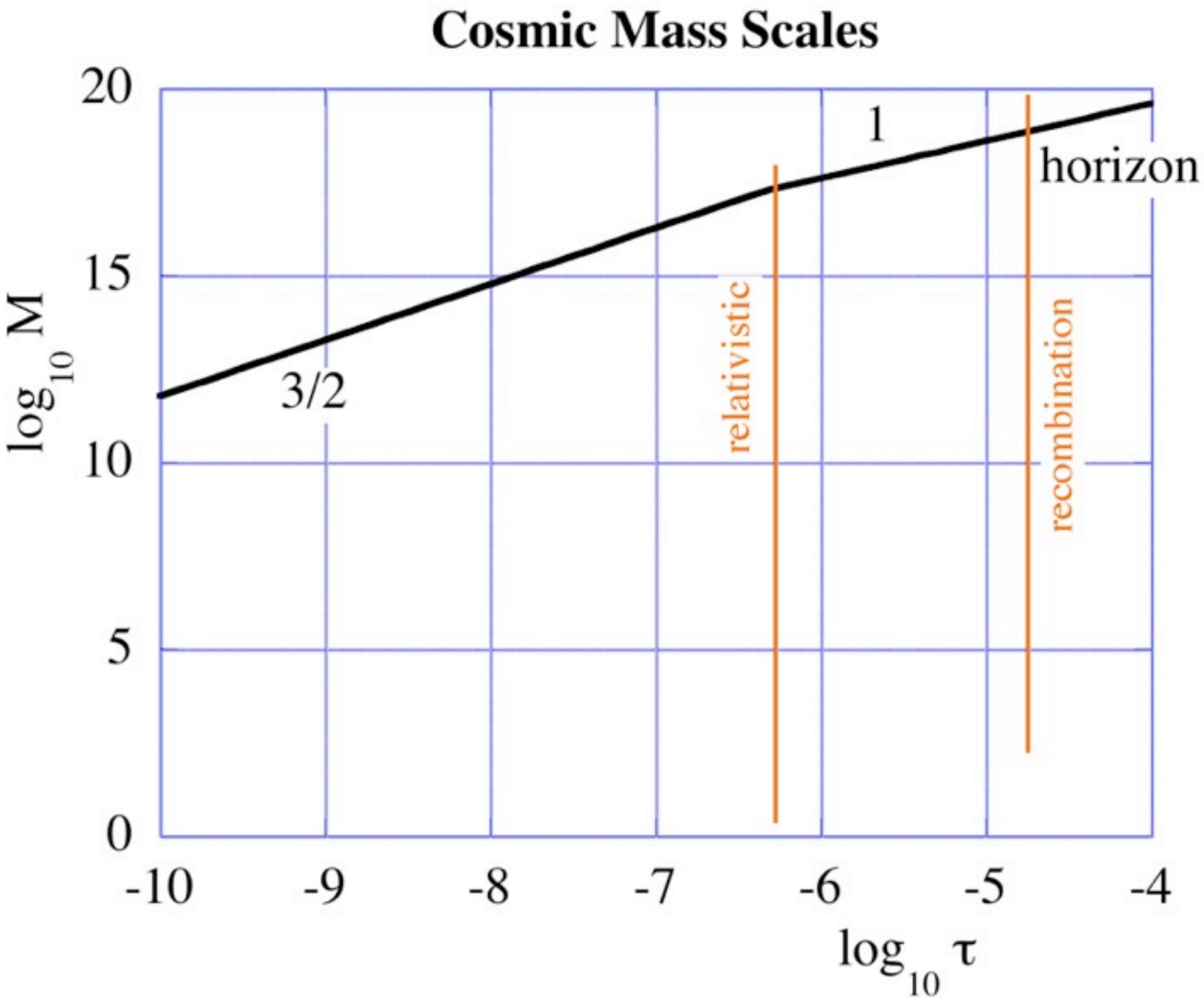
Friedmann Equations

$$\left(\frac{da}{dt}\right)^2 = \frac{8\pi}{3}G\rho a^2 - kc^2 + \frac{\Lambda}{3}a^2$$

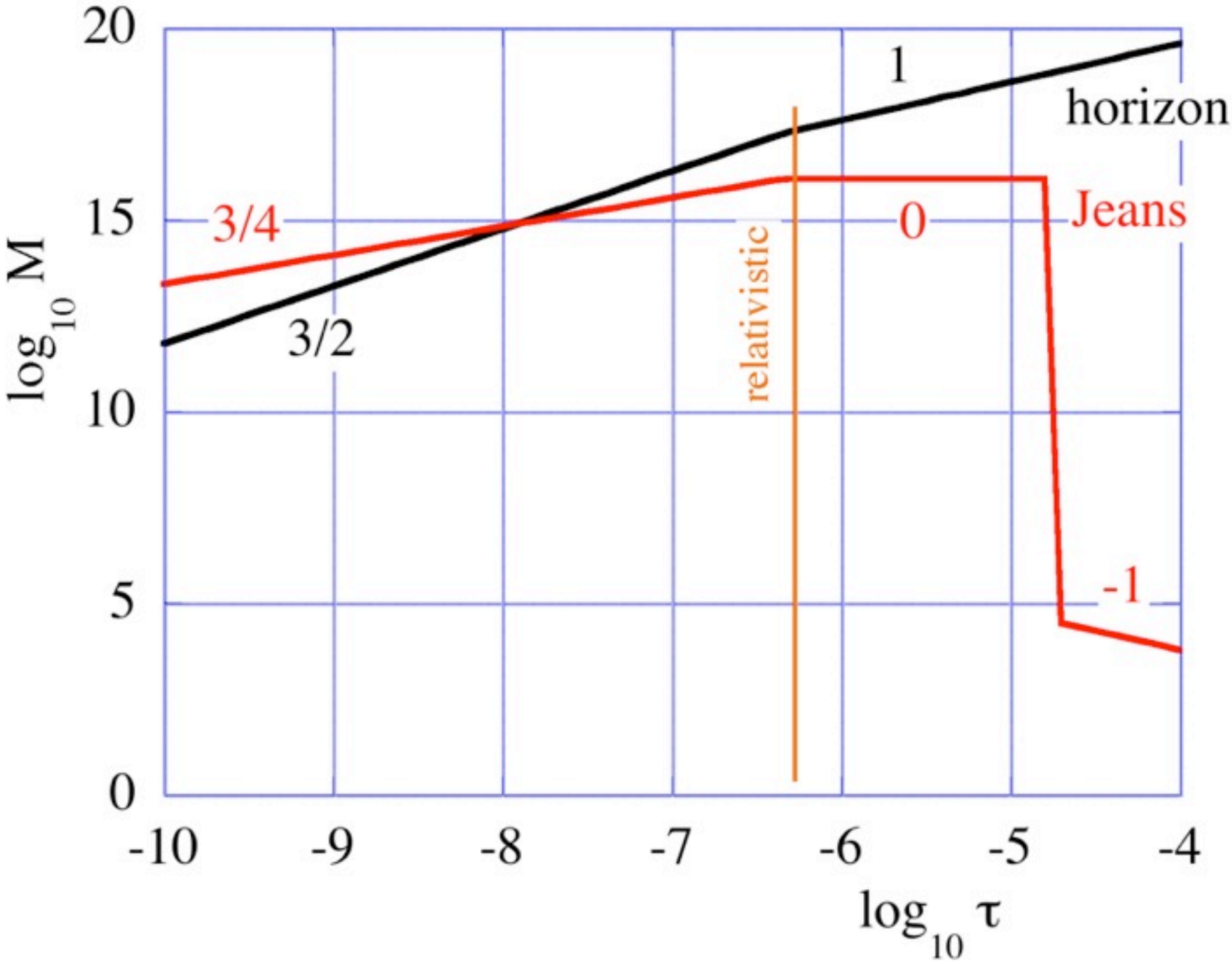
$$\frac{d}{dt}\left(\rho a^3\right) + \frac{P\,da^3}{c^2\,dt} = 0$$

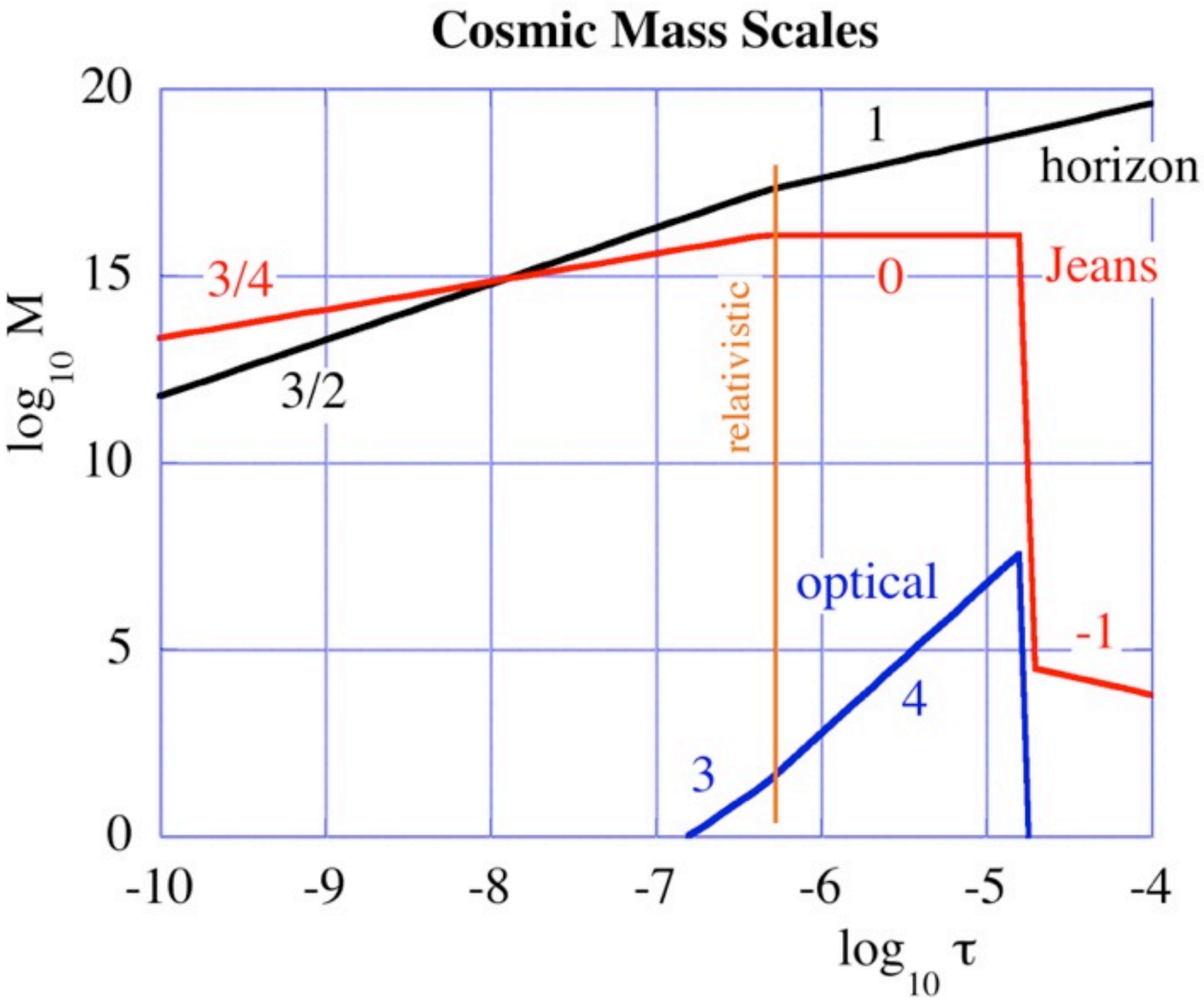
Mass Scales

- Analytic Examples
- Einstein-De Sitter Models
- (Non)relativistic
- Thermal Processes


Cosmic Mass Scales
20
15
10
5
0
log10 M
-10
-9
-8
-7
-6
-5
-4
log10 τ
3/2
1
horizon
relativistic
recombination

Cosmic Mass Scales




Cosmic Mass Scales
20
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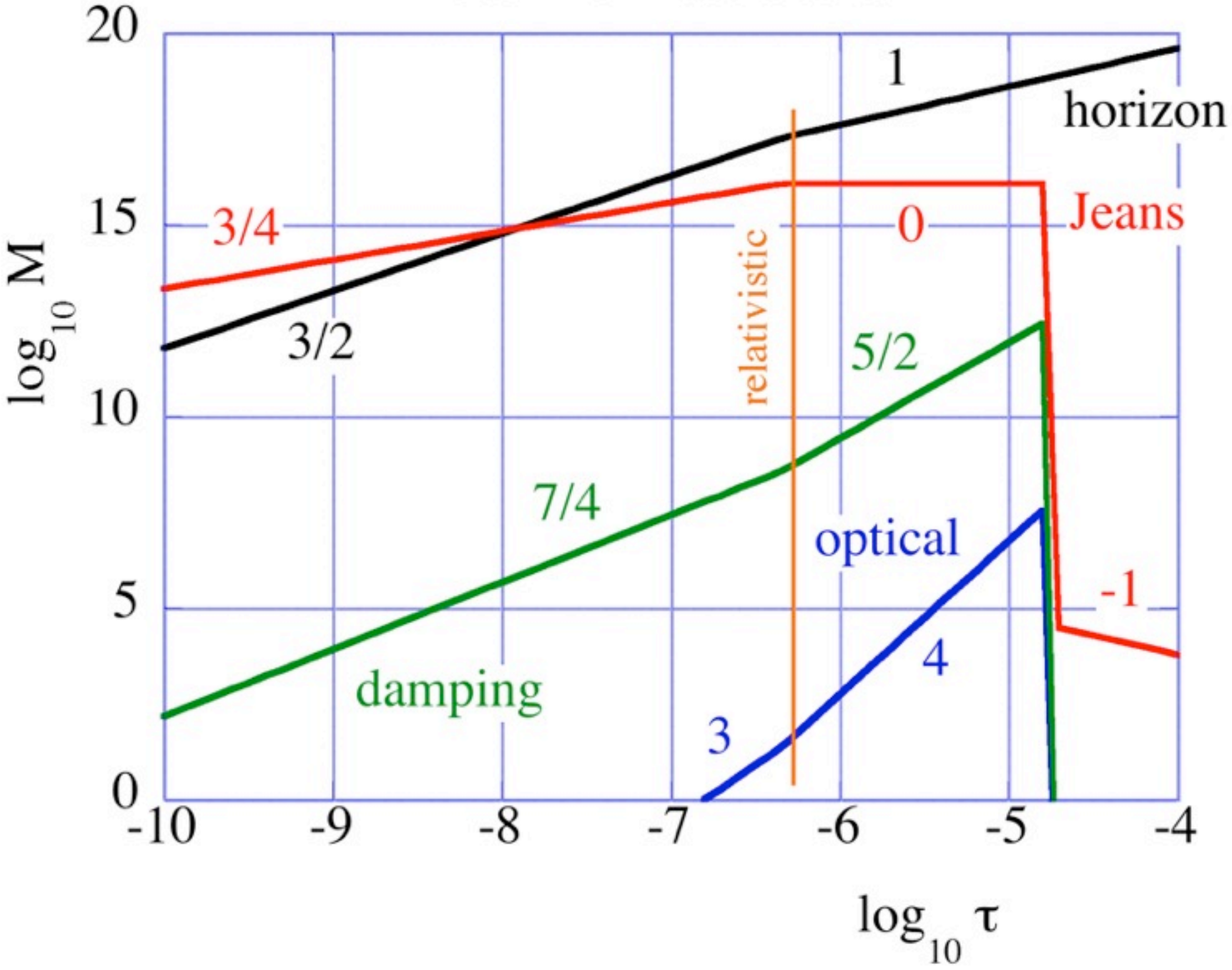
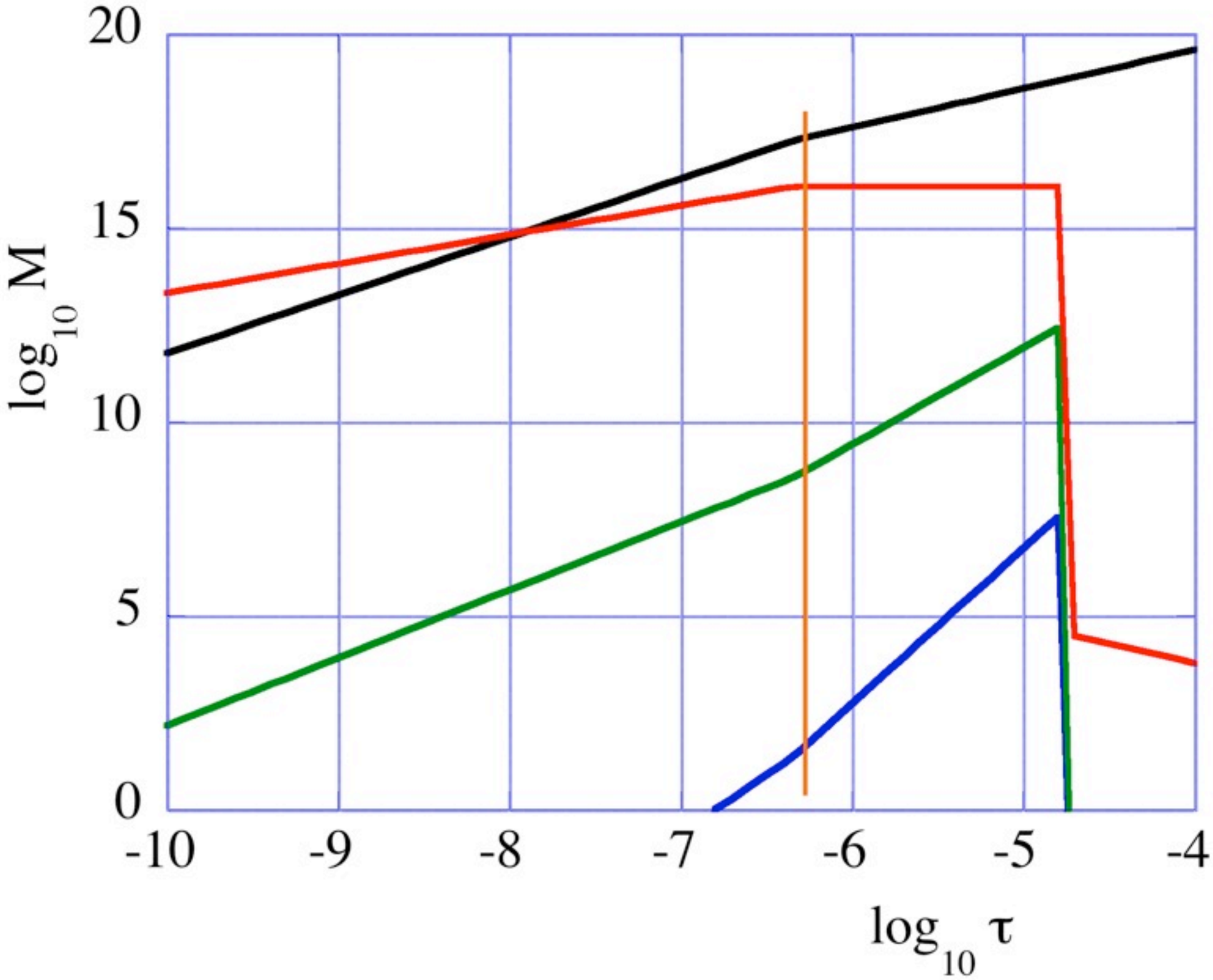
-8
-7
-6
-5
-4
log10 τ
1
horizon
3/4
0
Jeans
3/2
relativistic
optical
-1
4
3

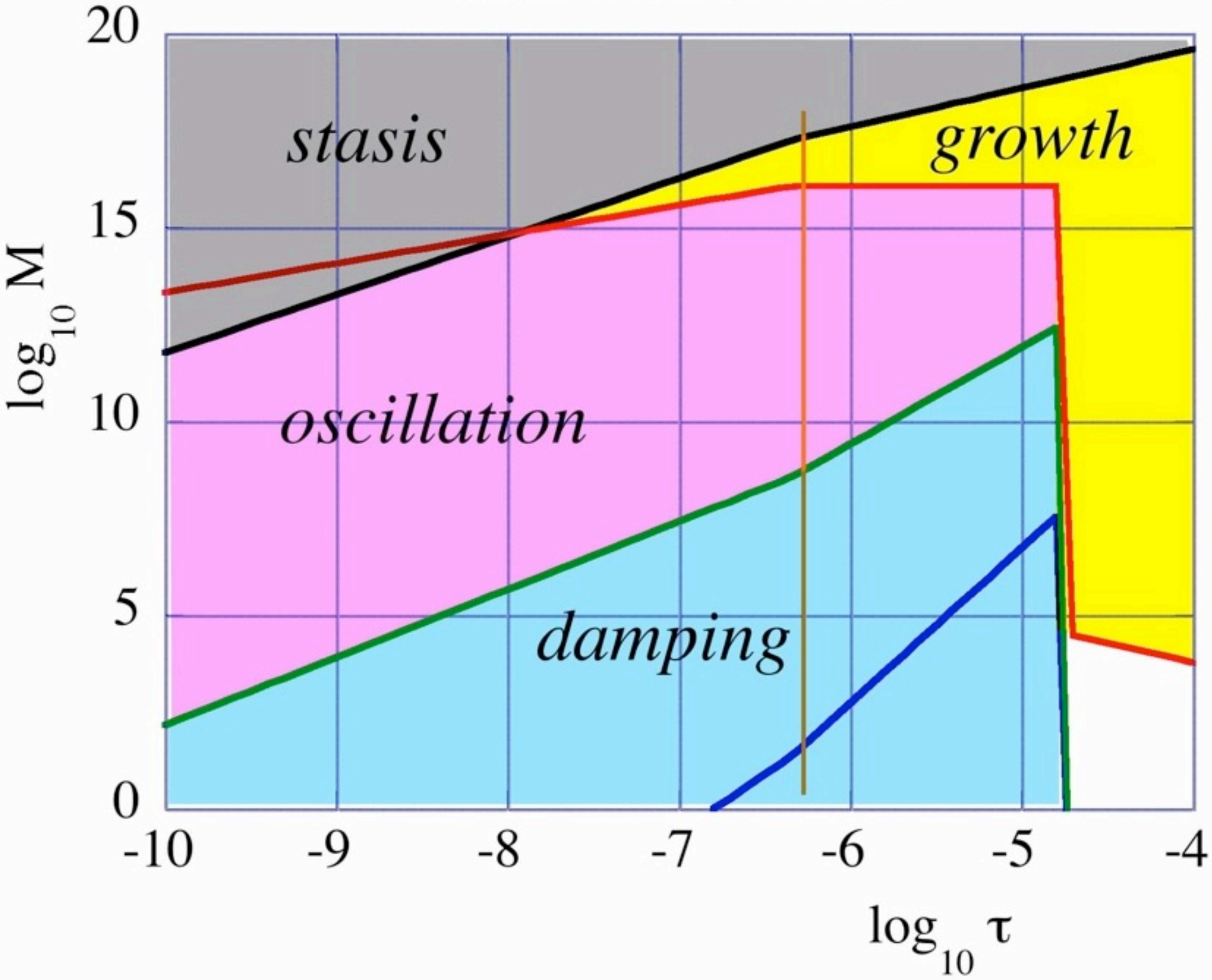
Cosmic Mass Scales



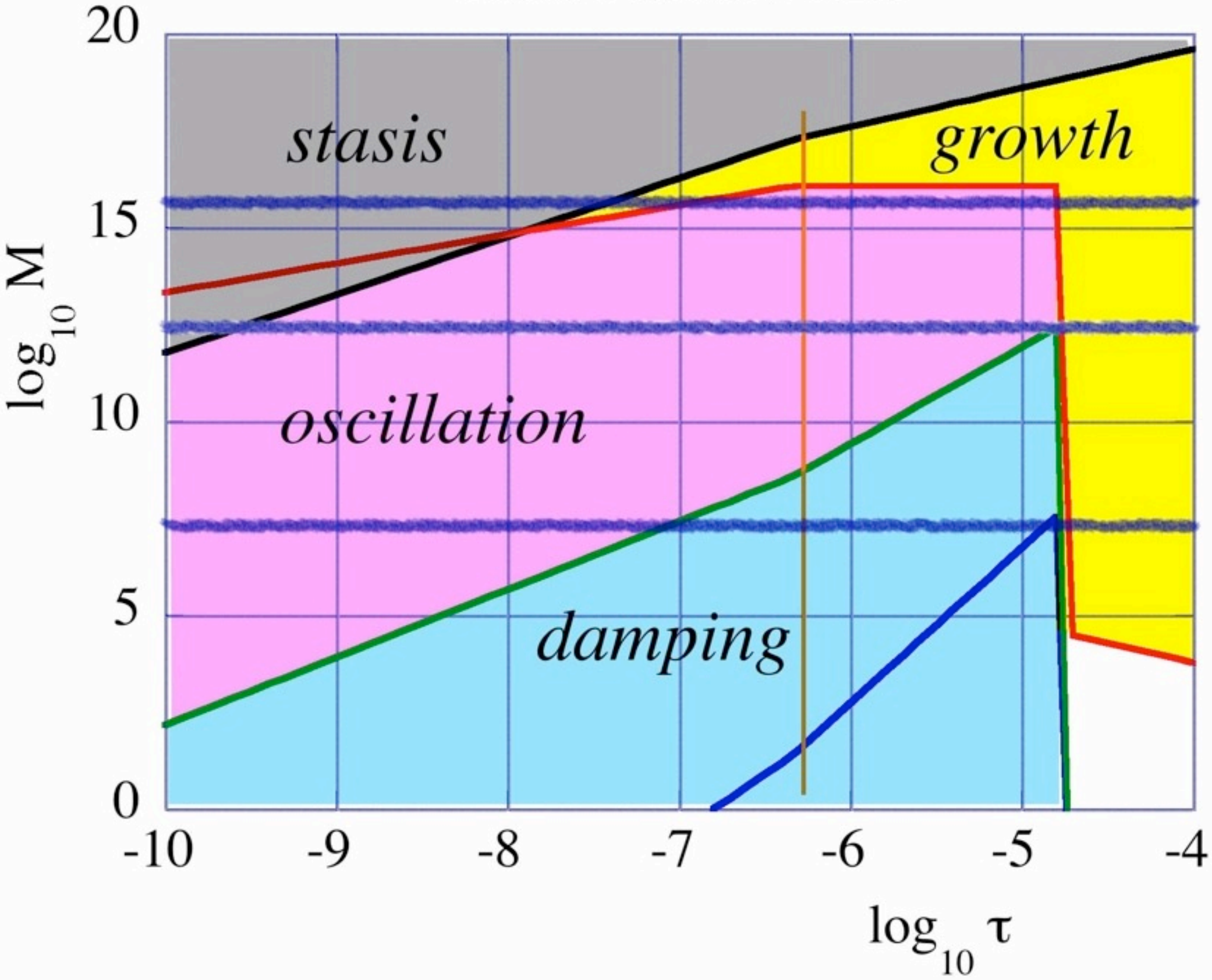
Cosmic Mass Scales



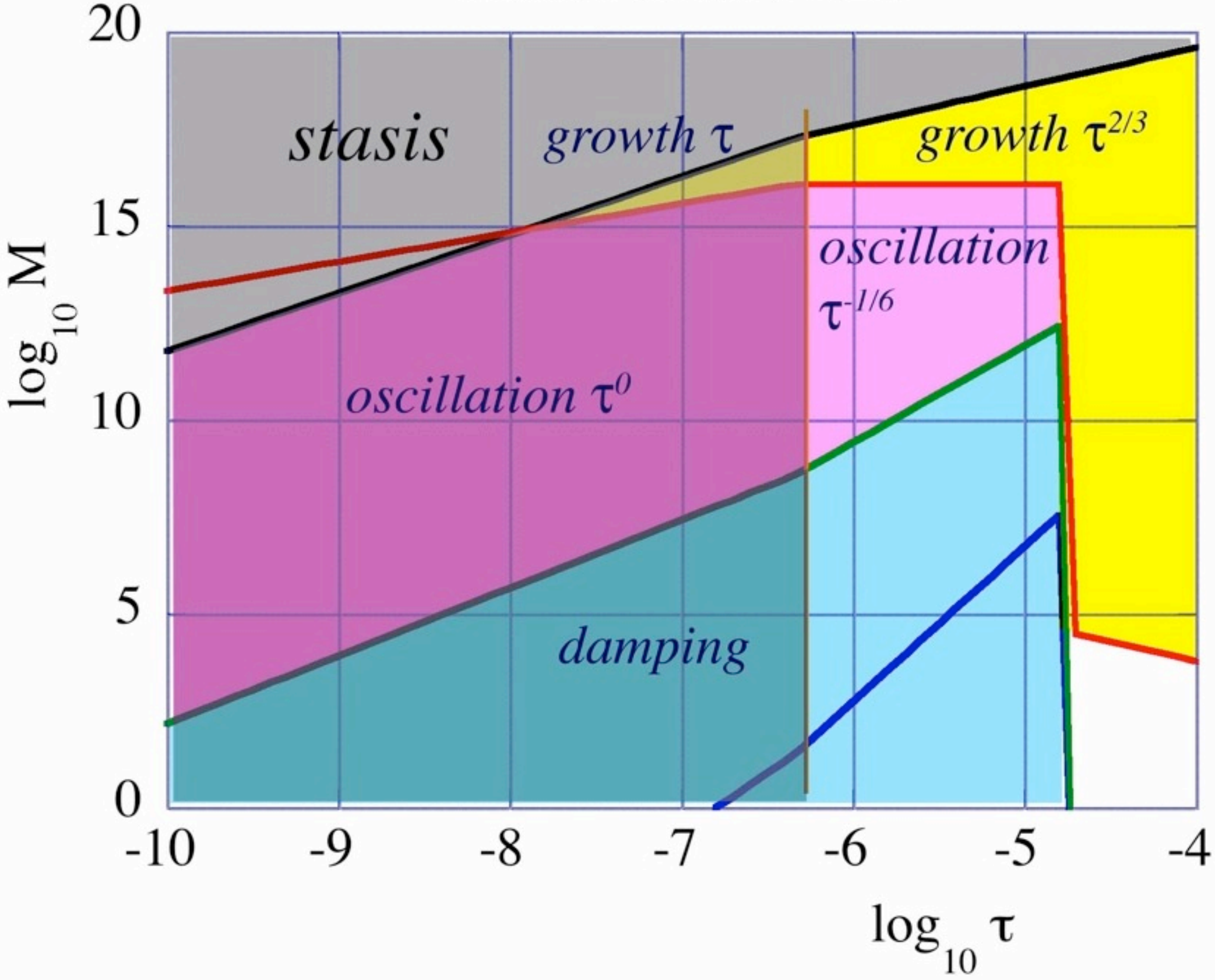
Cosmic Mass Scales



Cosmic Mass Scales

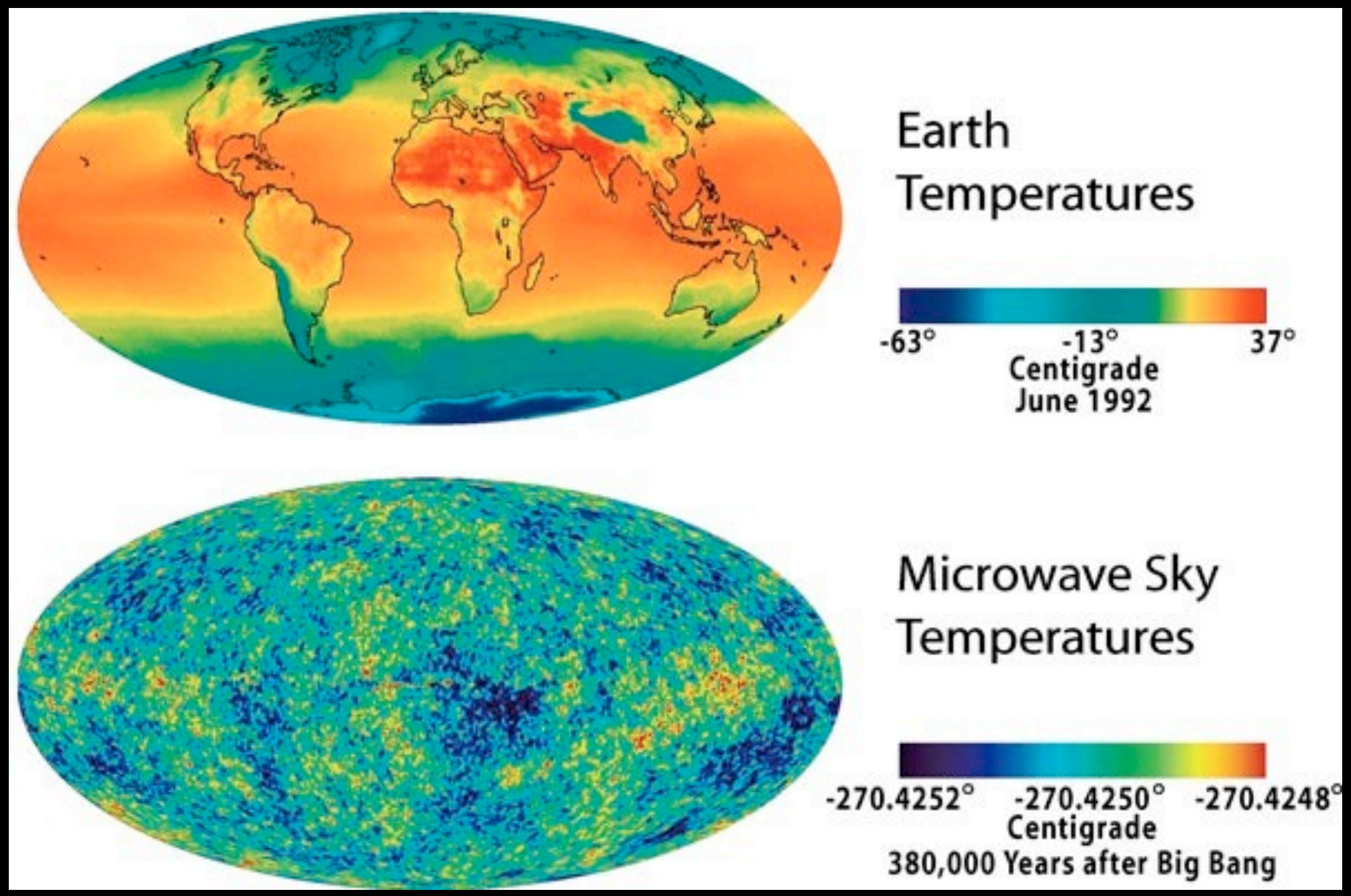


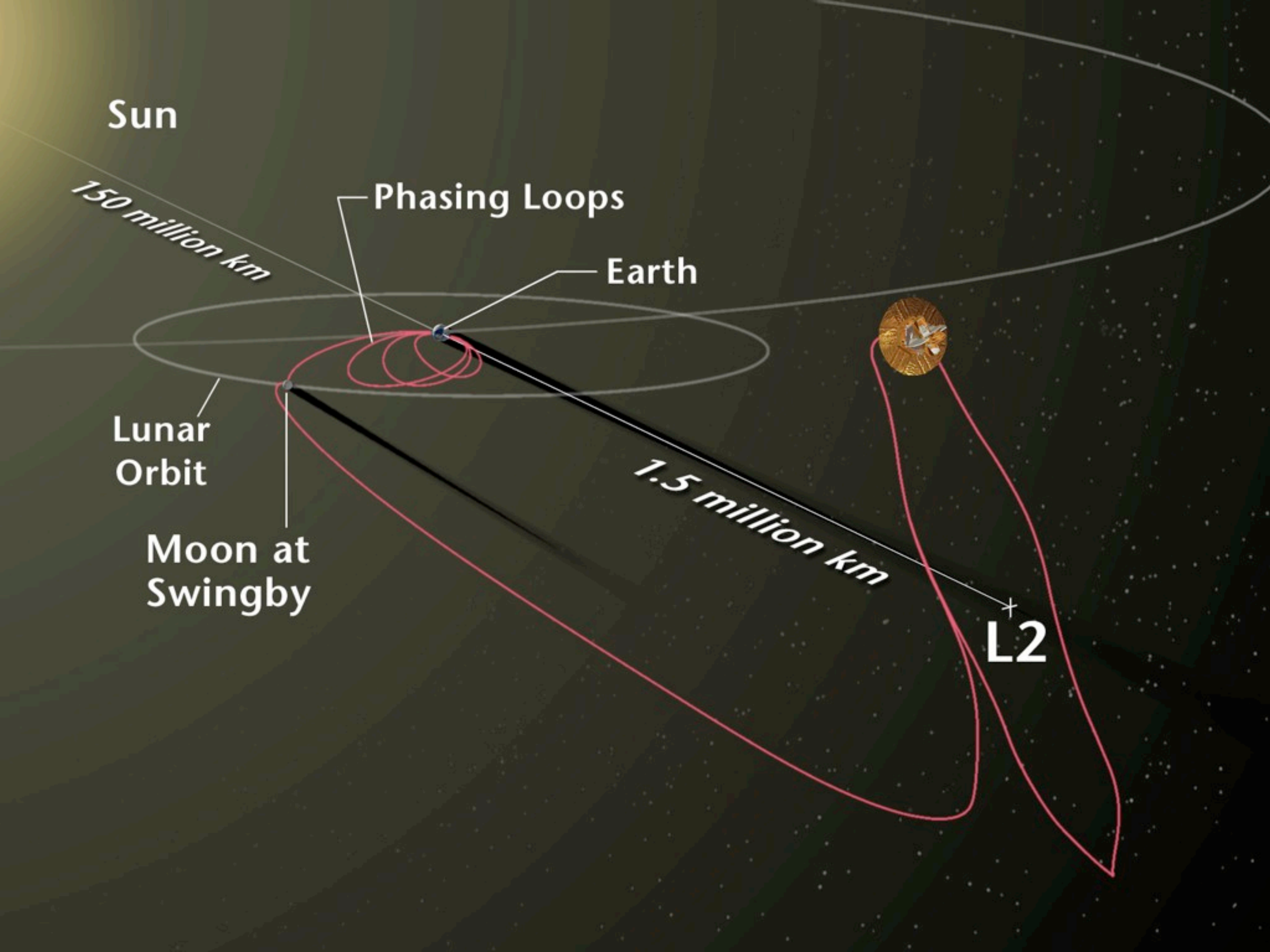
Cosmic Mass Scales

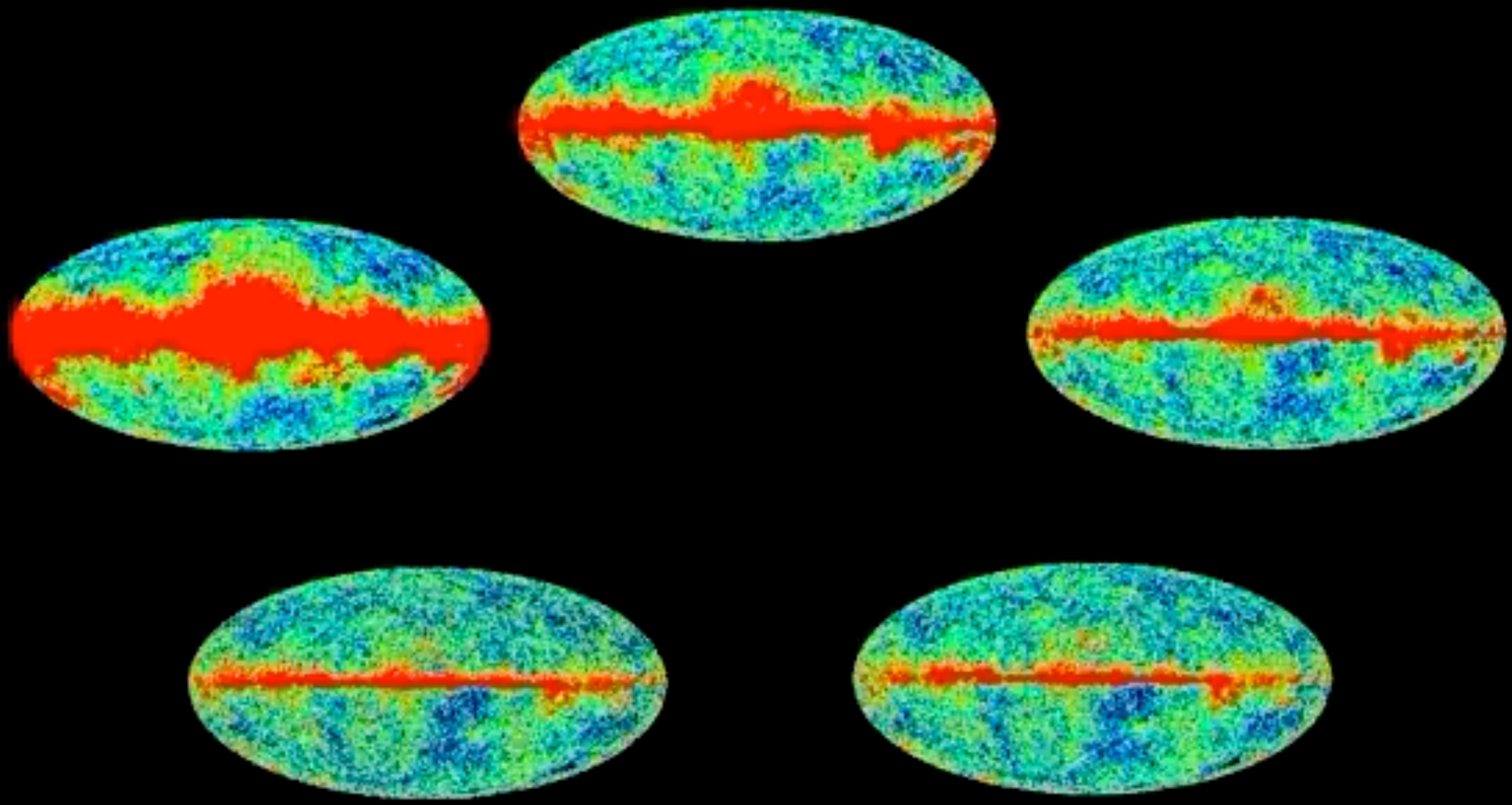


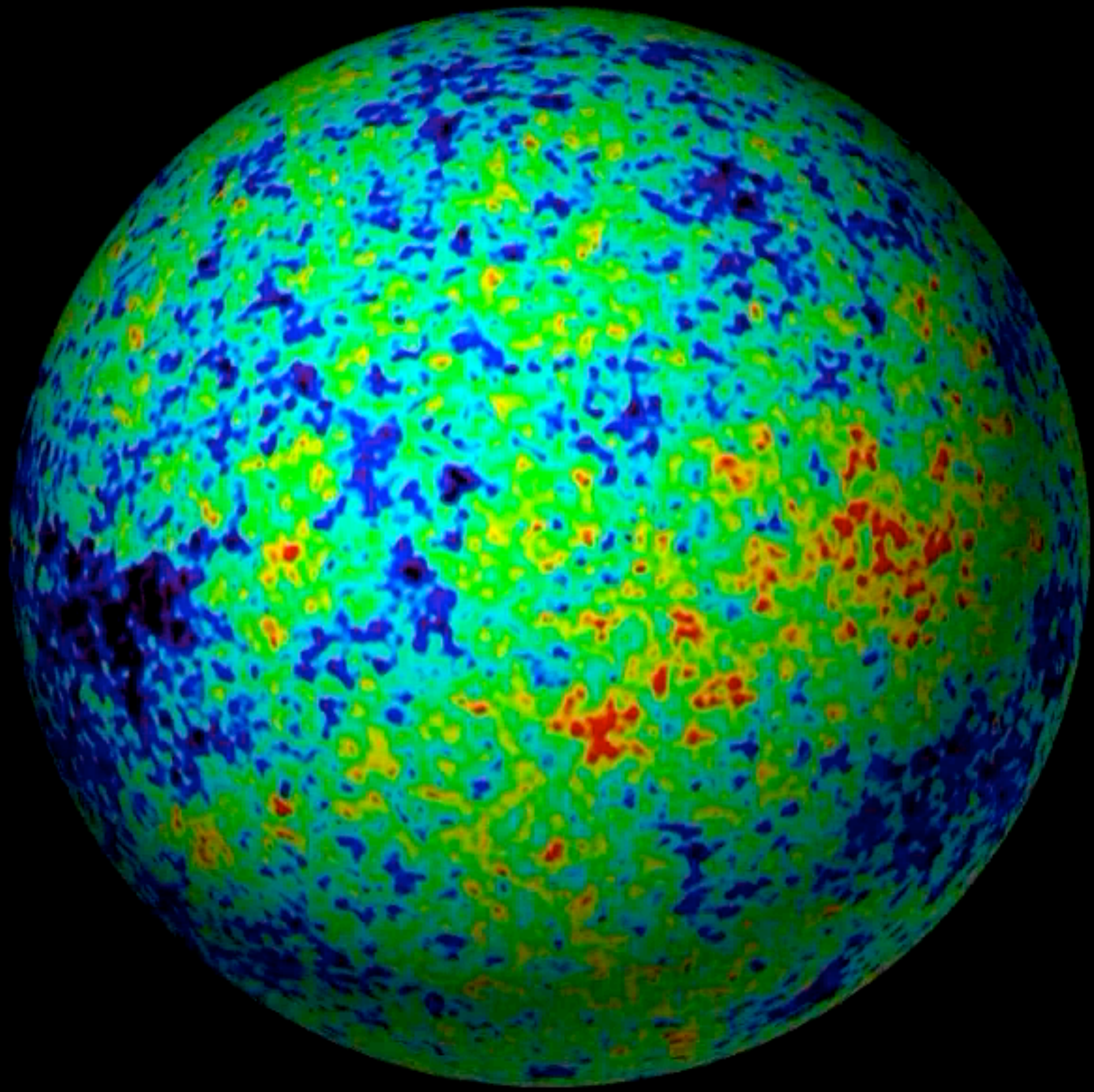
WMAP Introduction

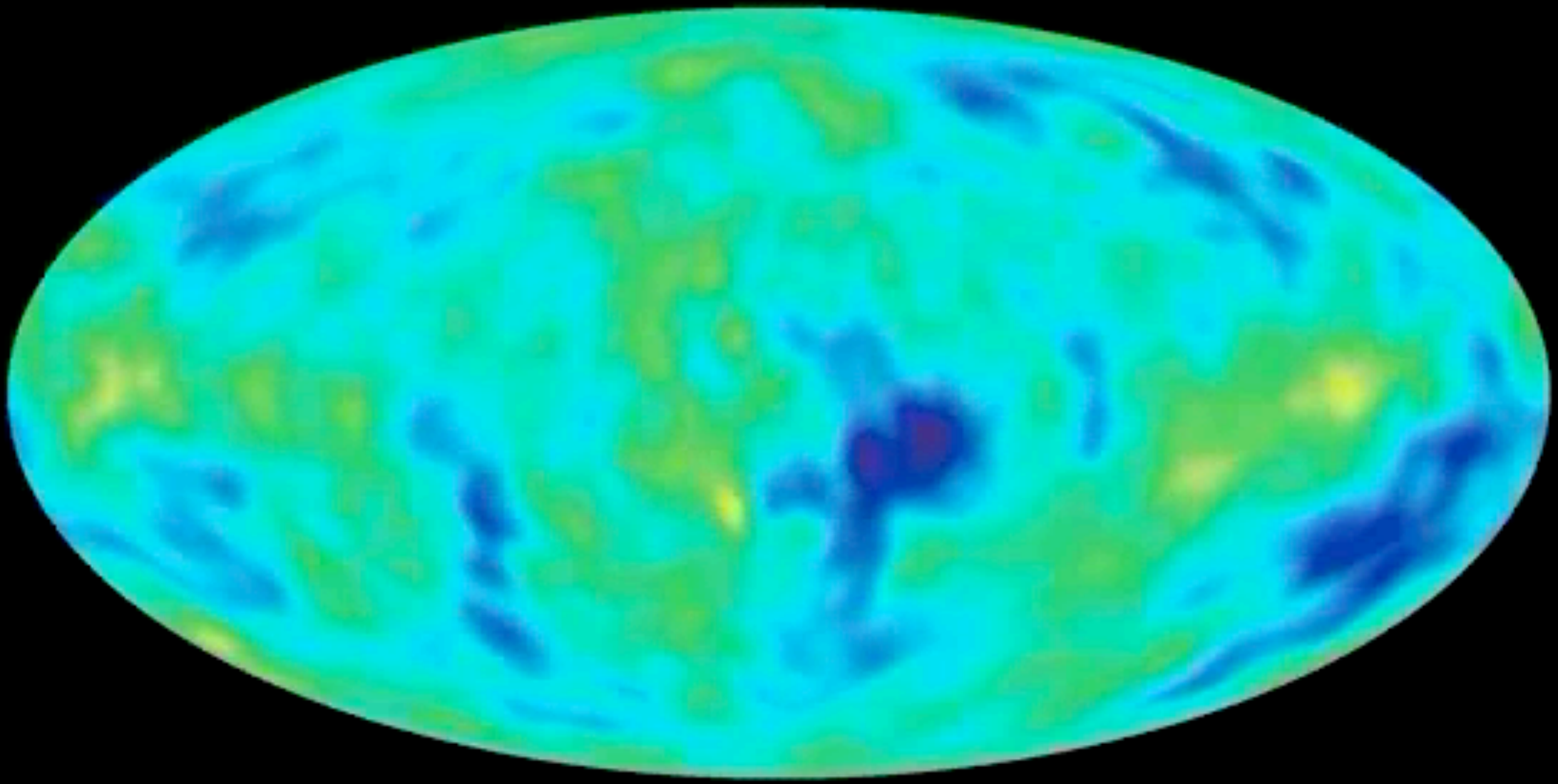
- Wilkinson Microwave Anisotropy Probe
- Long-term all-sky mapping
- Remove foreground signal
- Multipole analysis of signal on sphere

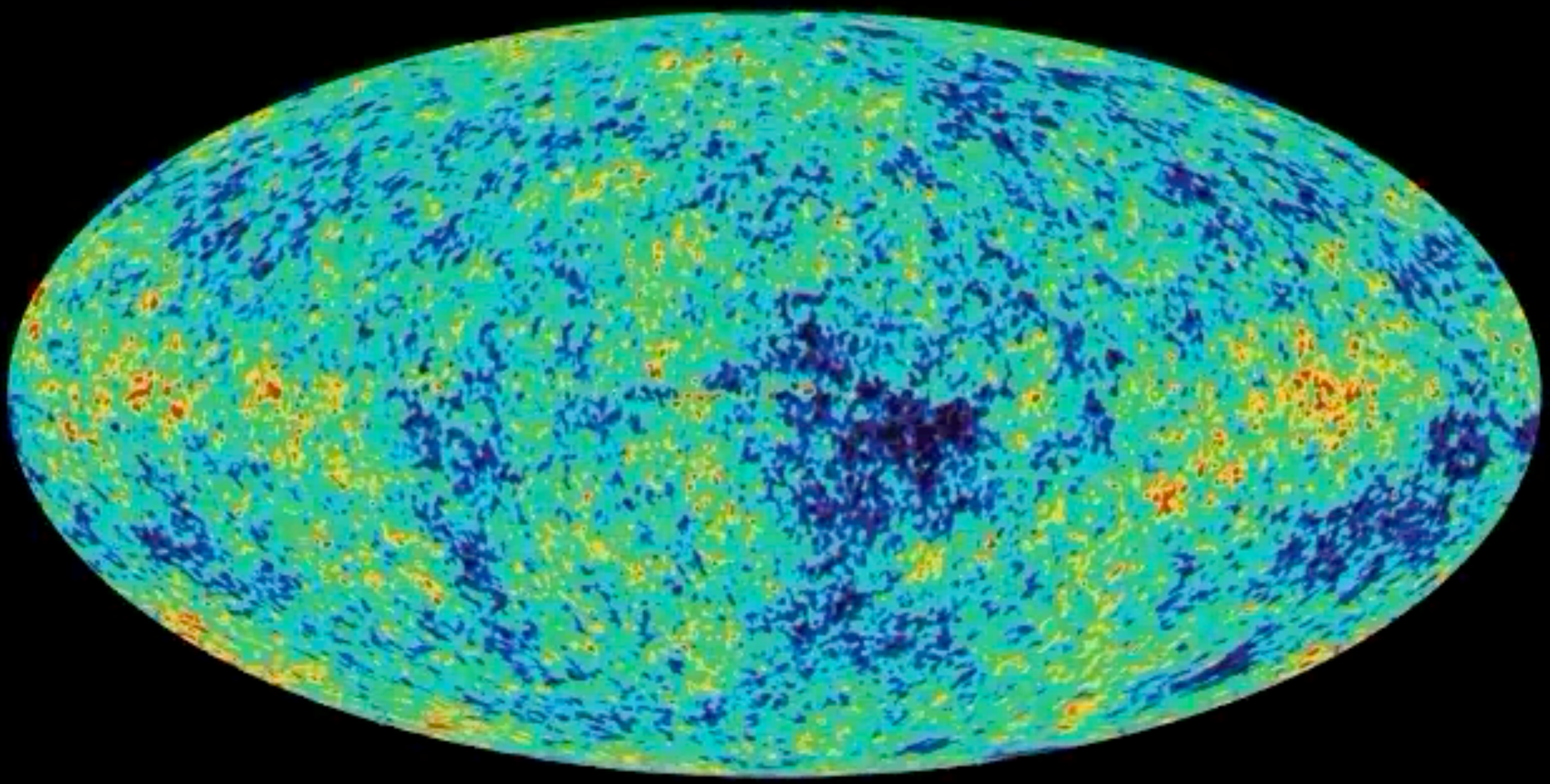

Earth
Temperatures
-63°
-13°
37°
Centigrade
June 1992
Microwave Sky
Temperatures
-270.4252°
-270.4250°
-270.4248°
Centigrade
380,000 Years after Big Bang

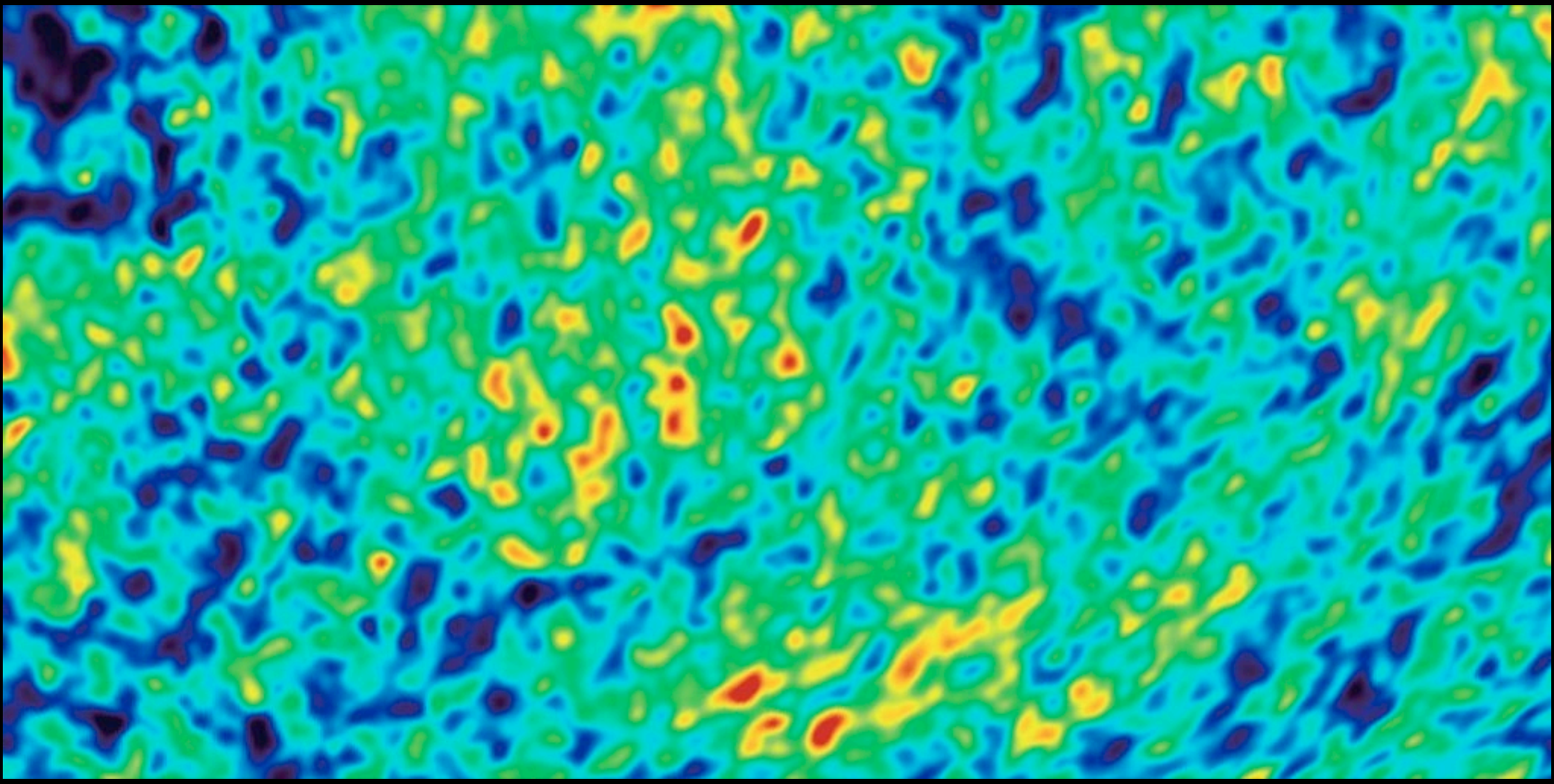

Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

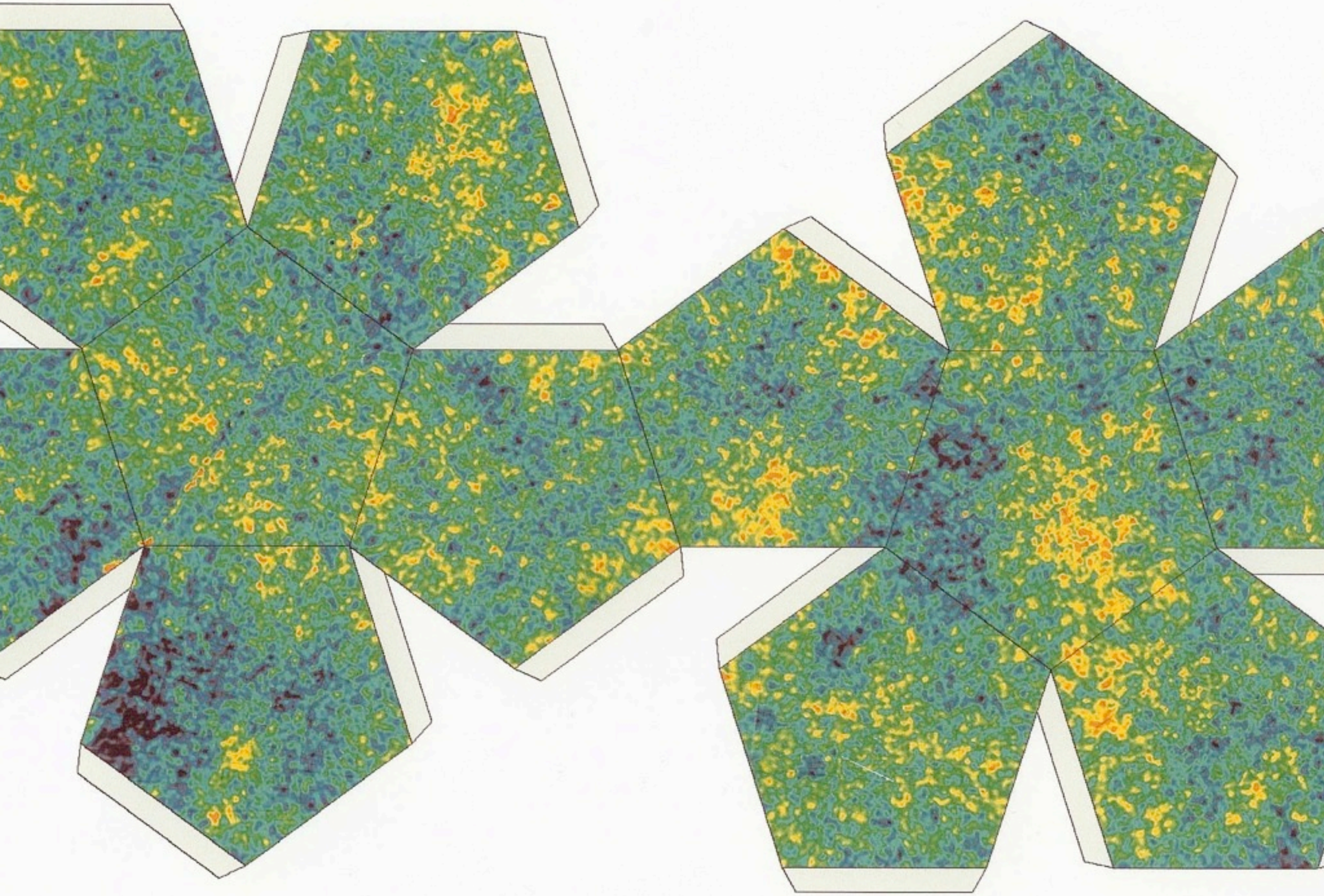








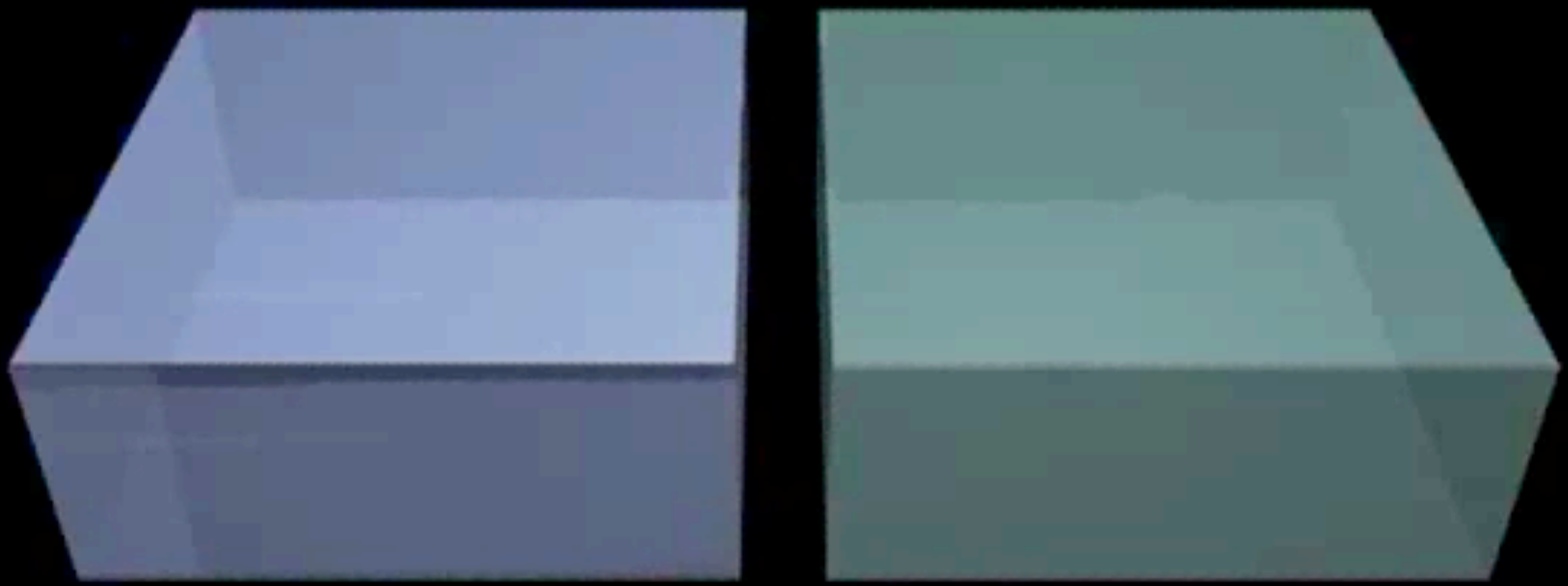




f the Cosmic Microwave Background as observed by the WMAP Satellite

WMAP Oscillations

- Anisotropic cosmology
- Requires full Einstein Equations...
- ...but linearized due to smallness of anisotropy
- Probes the Equation of State
- Probes the isotropic background metric



Plasma Era: Horizon Crossing Silk Oscillations Sachs-Wolfe Ripples

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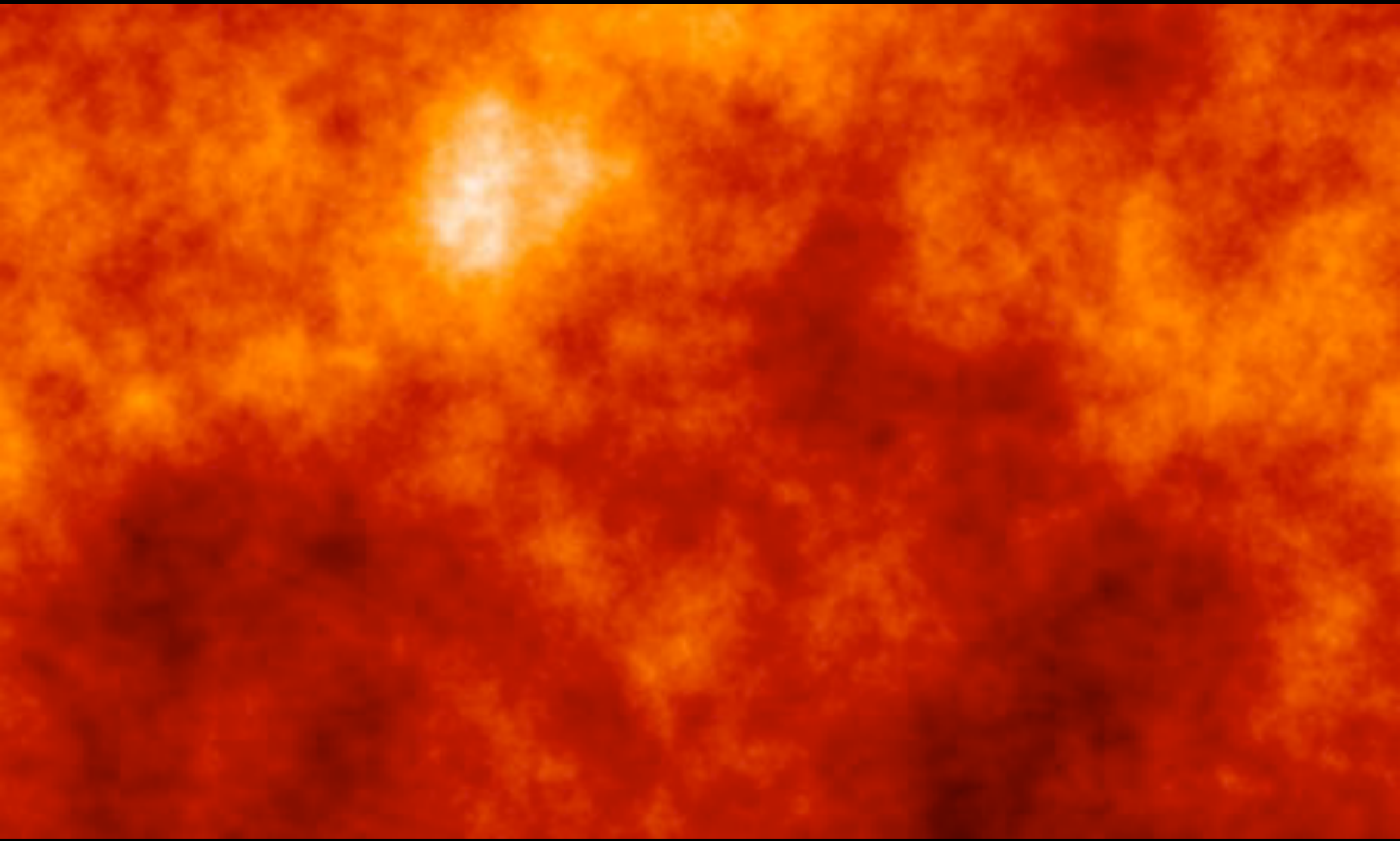
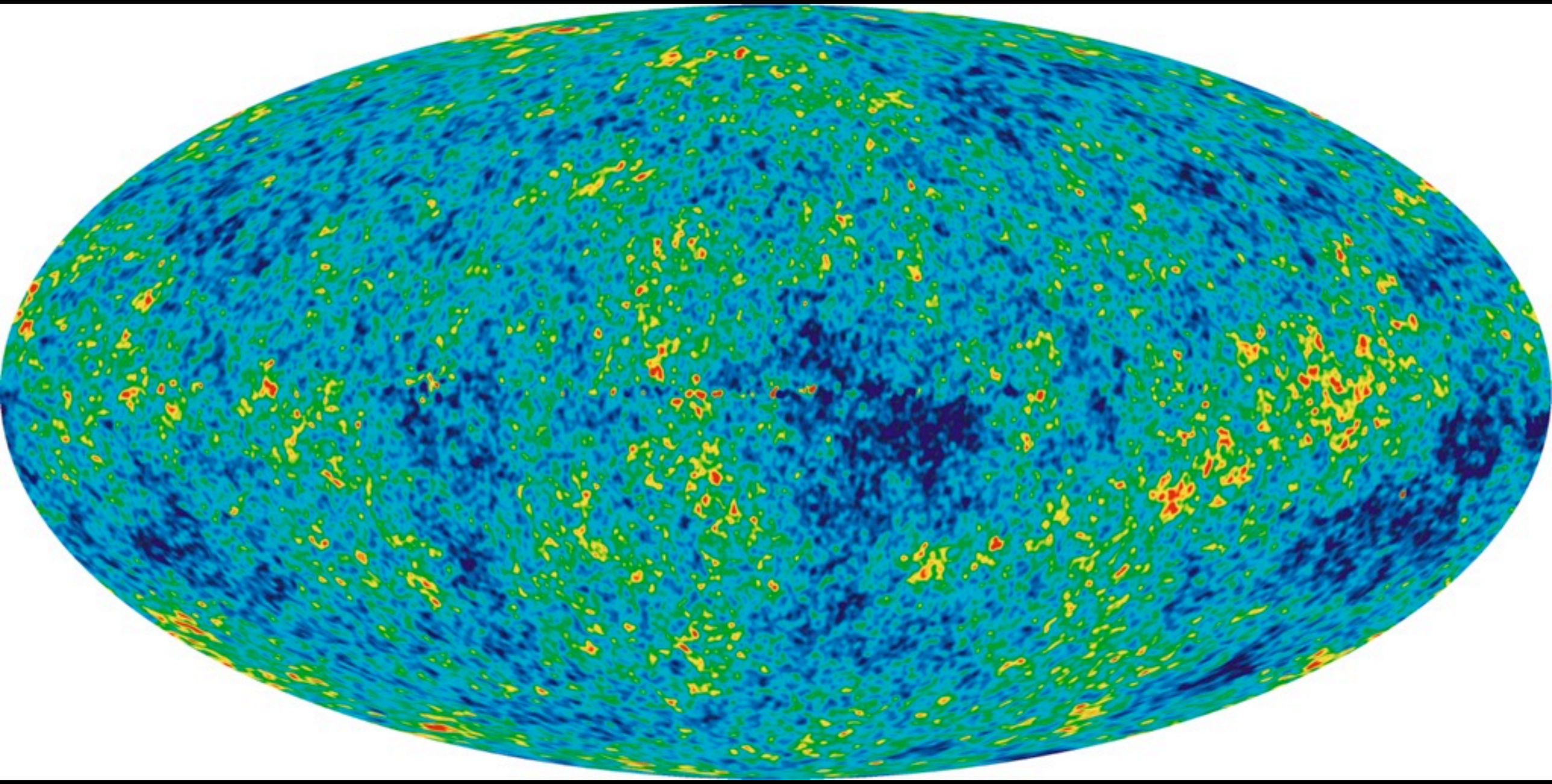




Acoustic Peaks

- Inhomogeneities start to oscillate as soon as the horizon becomes larger than their size
- Amplitude at decoupling is determined by the acoustic frequency and the time until recombination
- “First acoustic peak” is a measure of the acoustic horizon at recombination
- Thus, it is a primary observable for fixing cosmic parameters

Angular Scale

90° 2° 0.5° 0.2°

6000
5000
4000
3000
2000
1000
0

Anisotropy Power (μK^2)

10 100 500 1000

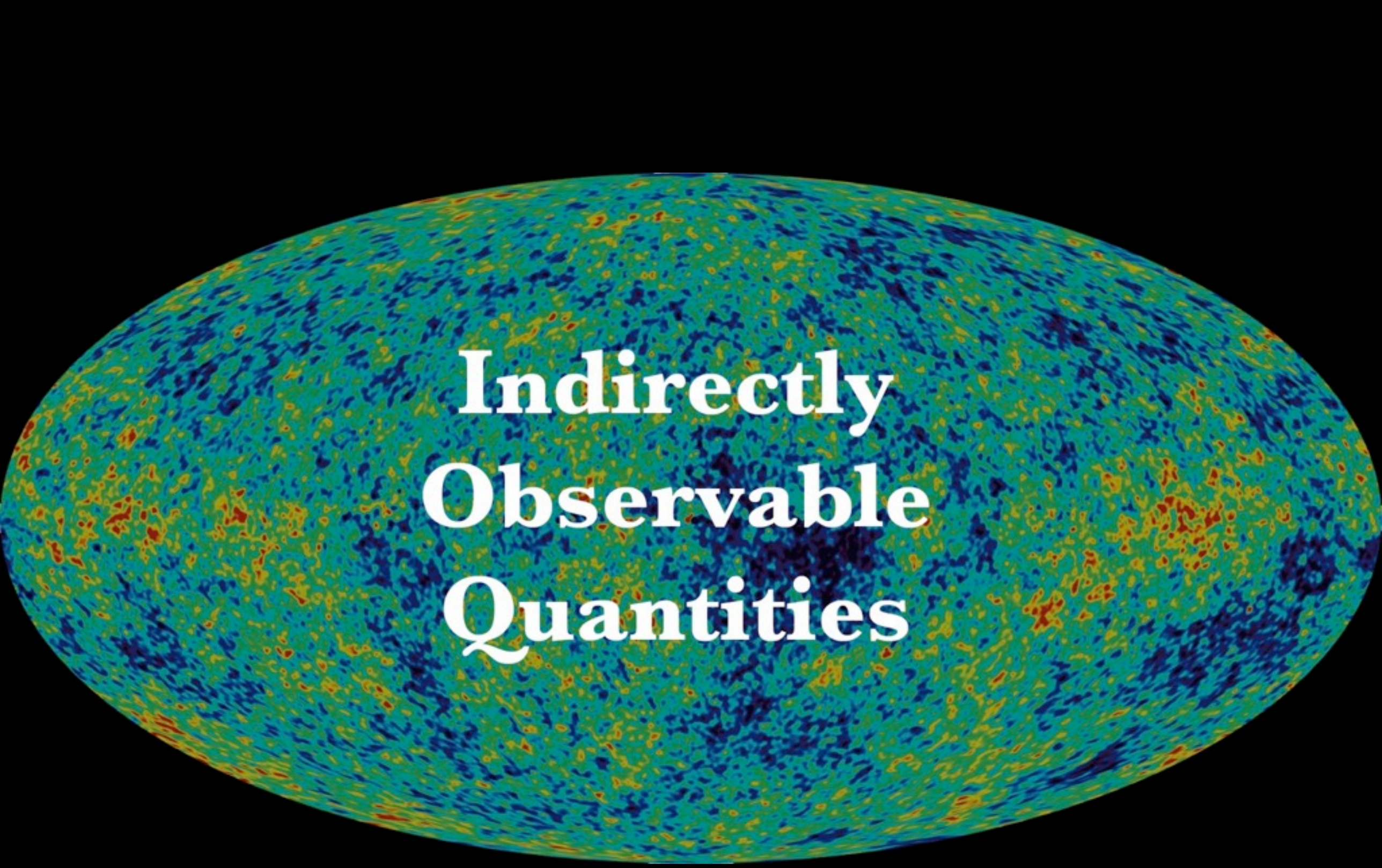
Multipole moment (l)

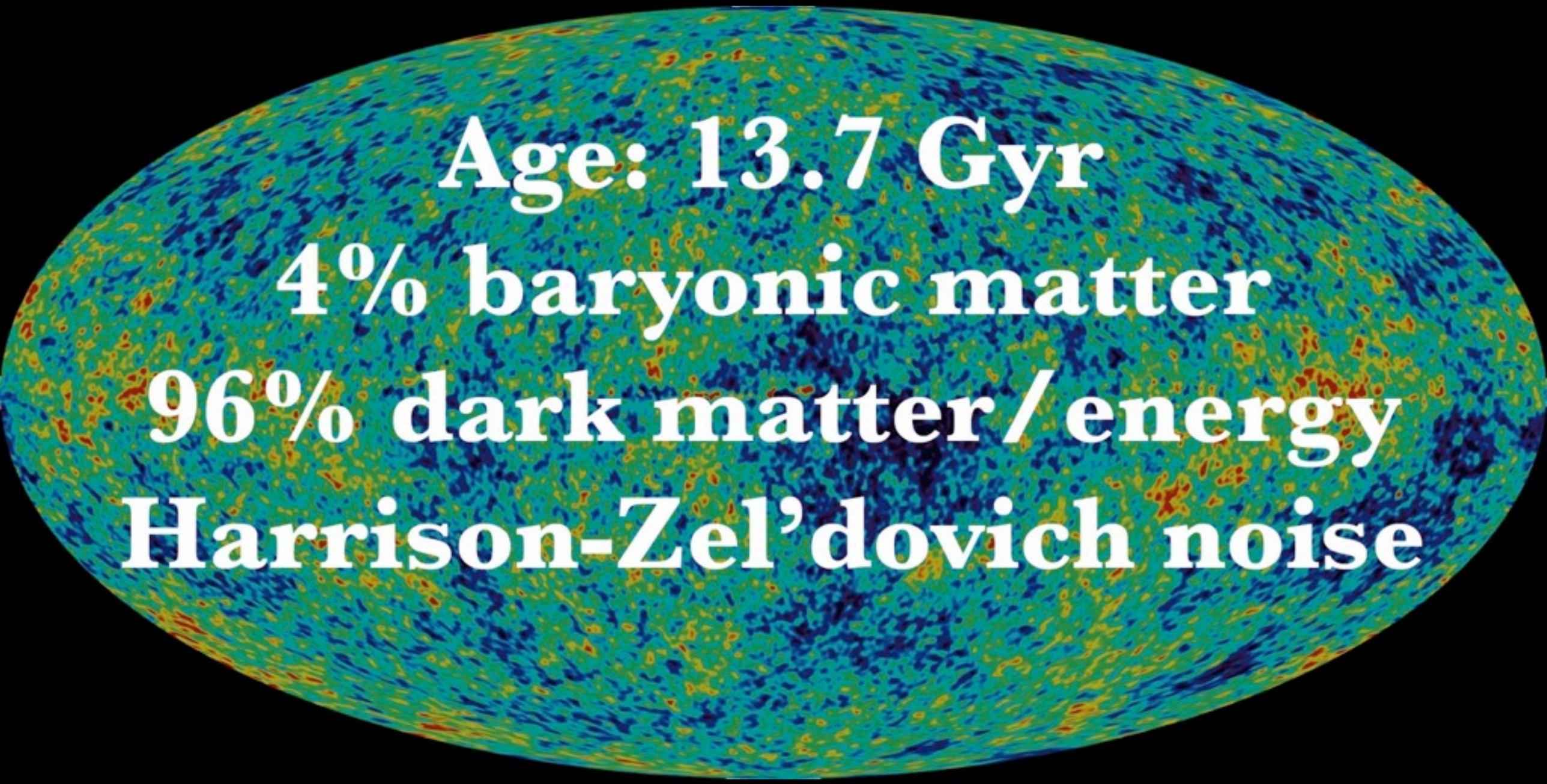
Initial conditions

- Origin of homogeneity and isotropy
- Disjunct parts of Universe have same properties
- Inflation...?
- But why are physical laws, constants etc. the same?
- Answers in interactions between particles and space-time?

WMAP Results

- Superb thermal blackbody spectrum
- Anisotropy amplitude 10^{-5}
- Harrison-Zel'dovich isocurvature noise
- Silk peaks
- Ideal baryonic gas
- Dark stuff 95%


Indirectly
Observable
Quantities


Age: 13.7 Gyr
4% baryonic matter
96% dark matter/energy
Harrison-Zel'dovich noise

Solutions

$$\left(\frac{da}{dt}\right)^2 = \frac{8\pi}{3}G\rho a^2 - kc^2 + \frac{\Lambda}{3}a^2$$

Observations