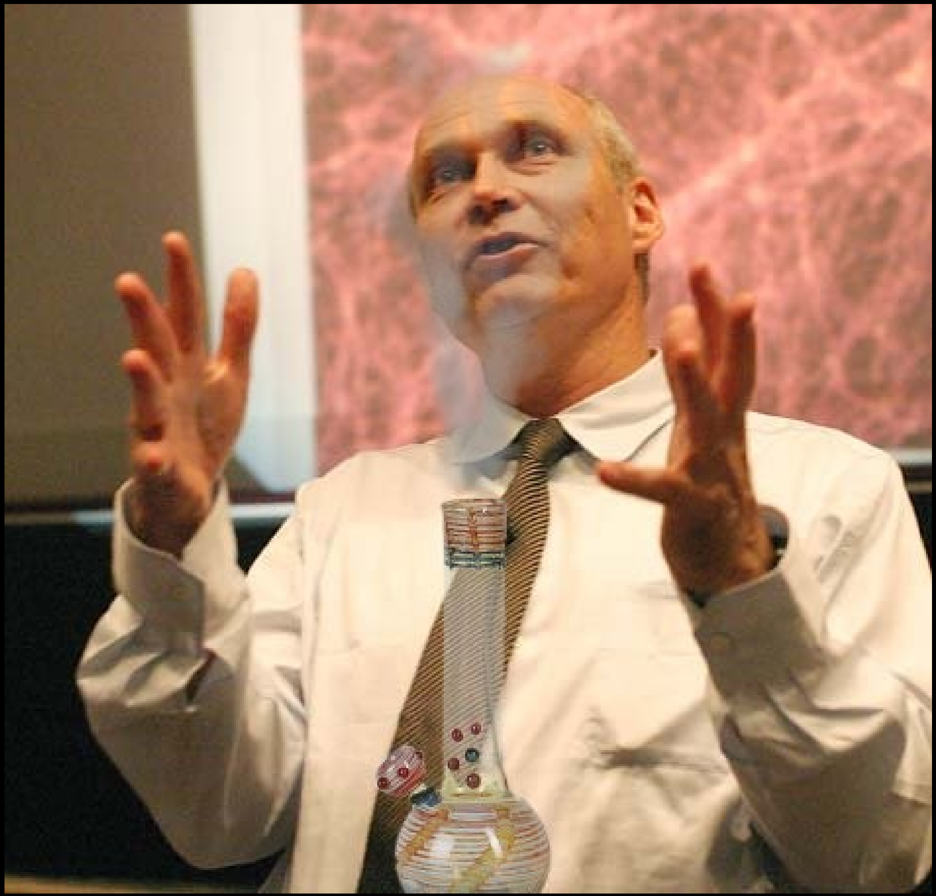
Smoke This!

The CMB, the Big Bang, Inflation, and WMAP's latest results



Spergel *et al*, 2006, *Wilkinson Microwave Anisotropy Probe (WMAP) Three Year results: Implications for Cosmology*, astro-ph/0603449, submitted to Ap. J.

I. Four Basic Concepts in Cosmology
   A. Robertson-Walker Metric
   B. Comoving Coordinates
   C. Cosmological Redshift
   D. Distance = Time

II. A History of the Universe

III. The Cosmic Microwave Background
   A. What it is
   B. What the power spectrum is
   C. Why the power spectrum has structure

IV. What's new?
   A. Damn, that's good agreement
   B. Polarization
   C. Reionization
   D. Inflation's Smoking Gun

Cosmology Concept #1

The Robertson-Walker Metric

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

r, θ, ϕ = "comoving coordinates"

R = scale factor

k = curvature (-1 = open, +1 = closed, 0 = flat)

Compare to special relativistic metric:

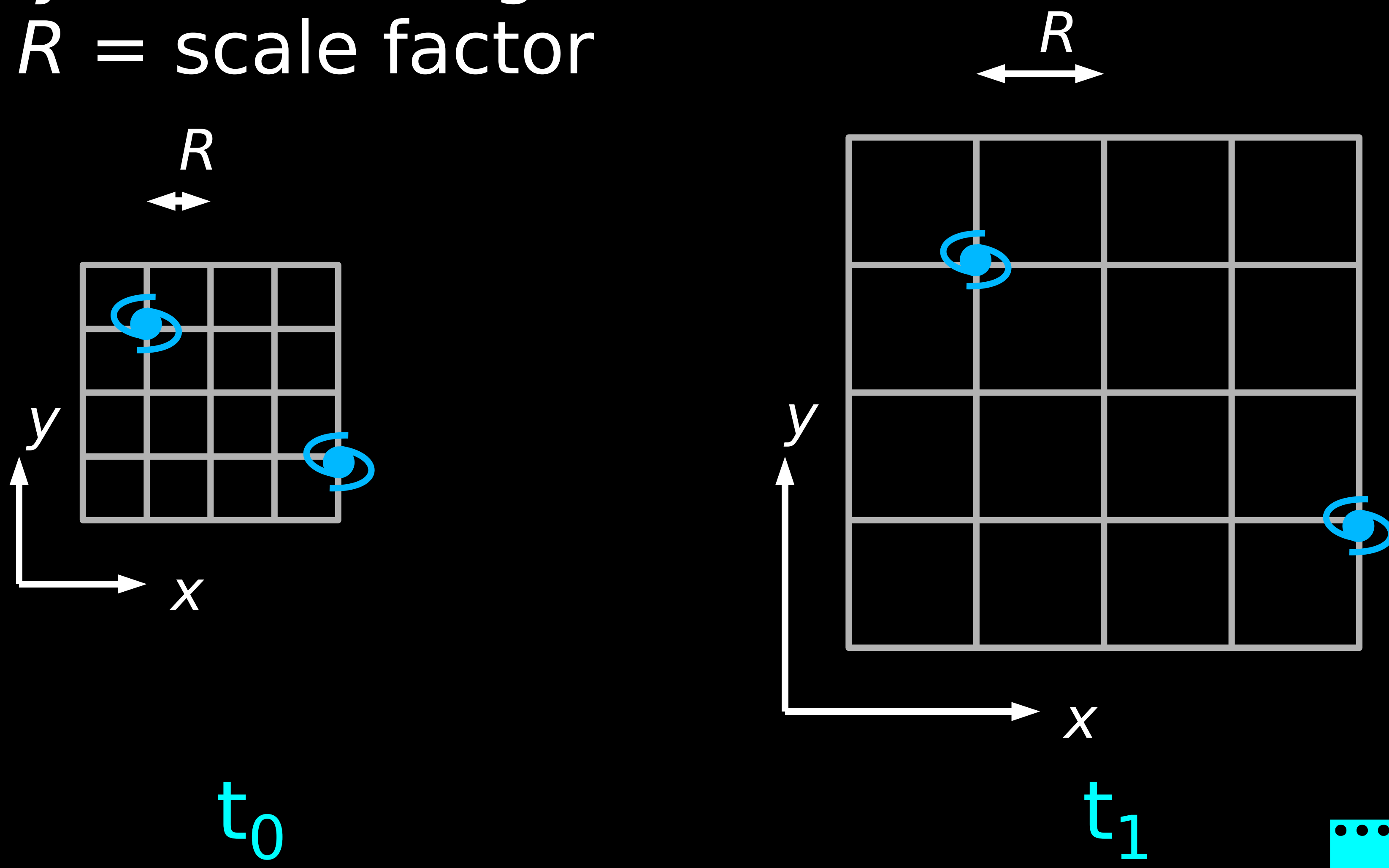
$$ds^2 = dt^2 - dx^2 - dy^2 - dz^2$$

$$ds^2 = dt^2 - \left(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

Cosmology Concept #2

Comoving Coordinates

x, *y* = comoving coordinates
R = scale factor



Cosmology Concept #3

Redshift = Amount of Expansion

$$z \equiv \frac{\lambda_{\rm obs} - \lambda_{\rm em}}{\lambda_{\rm em}}$$

λ_{em} = Emitted wavelength

λ_{obs} = Observed wavelength

$$1 + z = \frac{R_0}{R(t_{\rm em})}$$

Cosmology Concept #4

Distance = Time

Standard candle magnitude=
 "luminosity distance" = lookback time

Age of Universe = size of horizon
 (how far a photon can have gone)

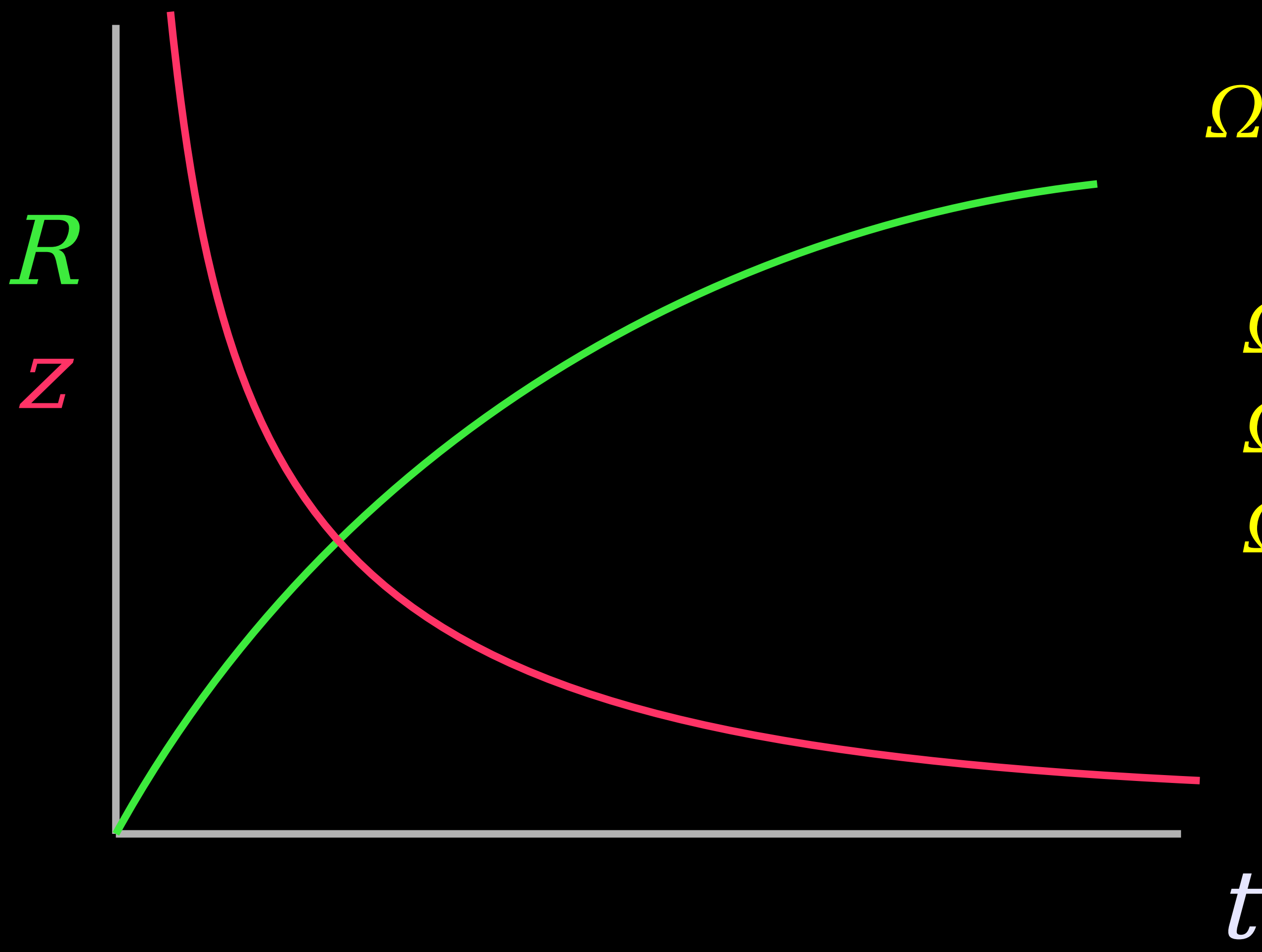
(Please do not look under the rug.)

R(t) governed by H_0, Ω_R, Ω_M, Ω_Λ

H_0 = present expansion rate (Hubble Constant)

Ω_M = Mass Density Ω_R = Radiation Density

Ω_Λ = Cosmological Constant (Dark Energy Density)

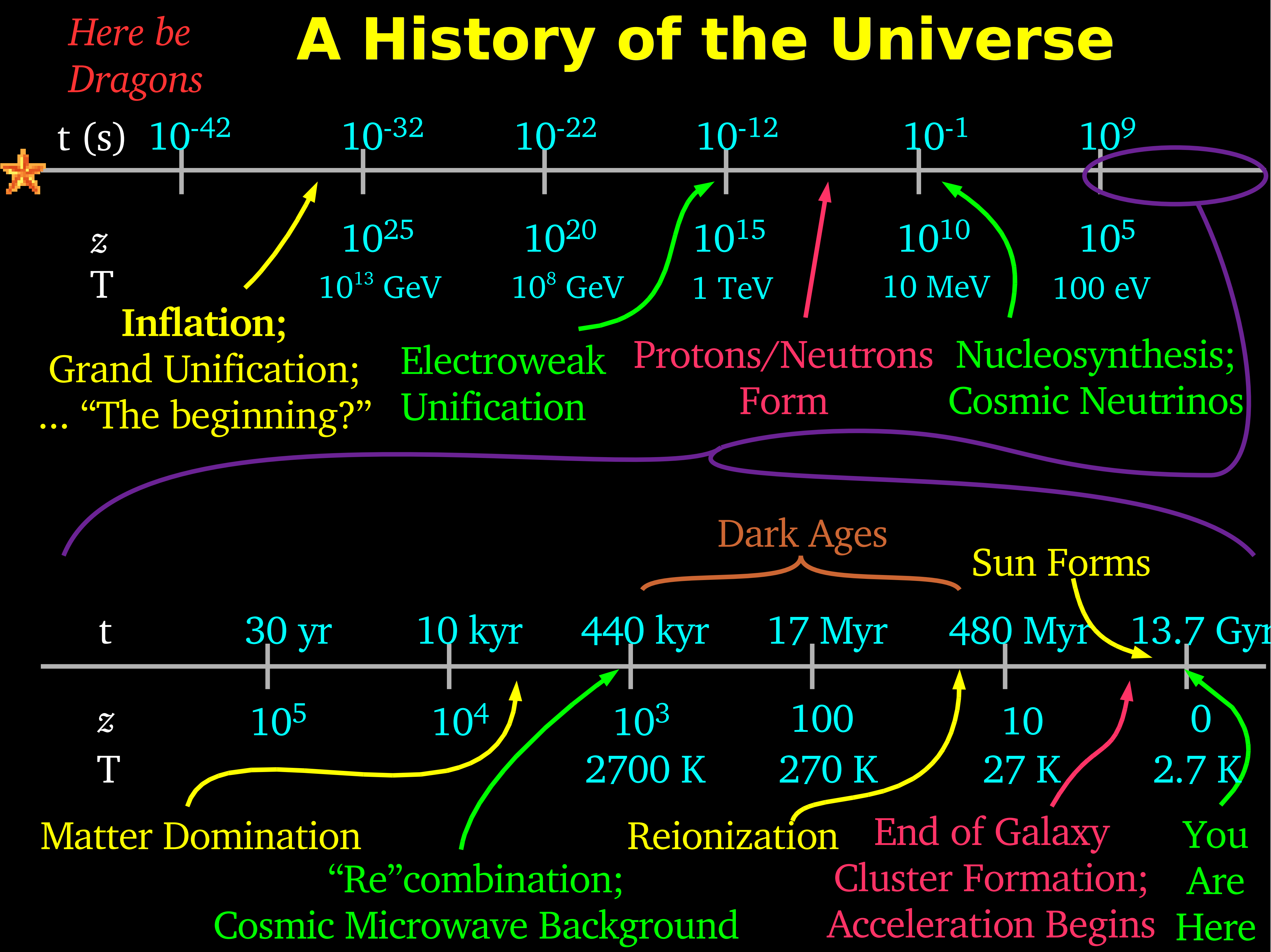


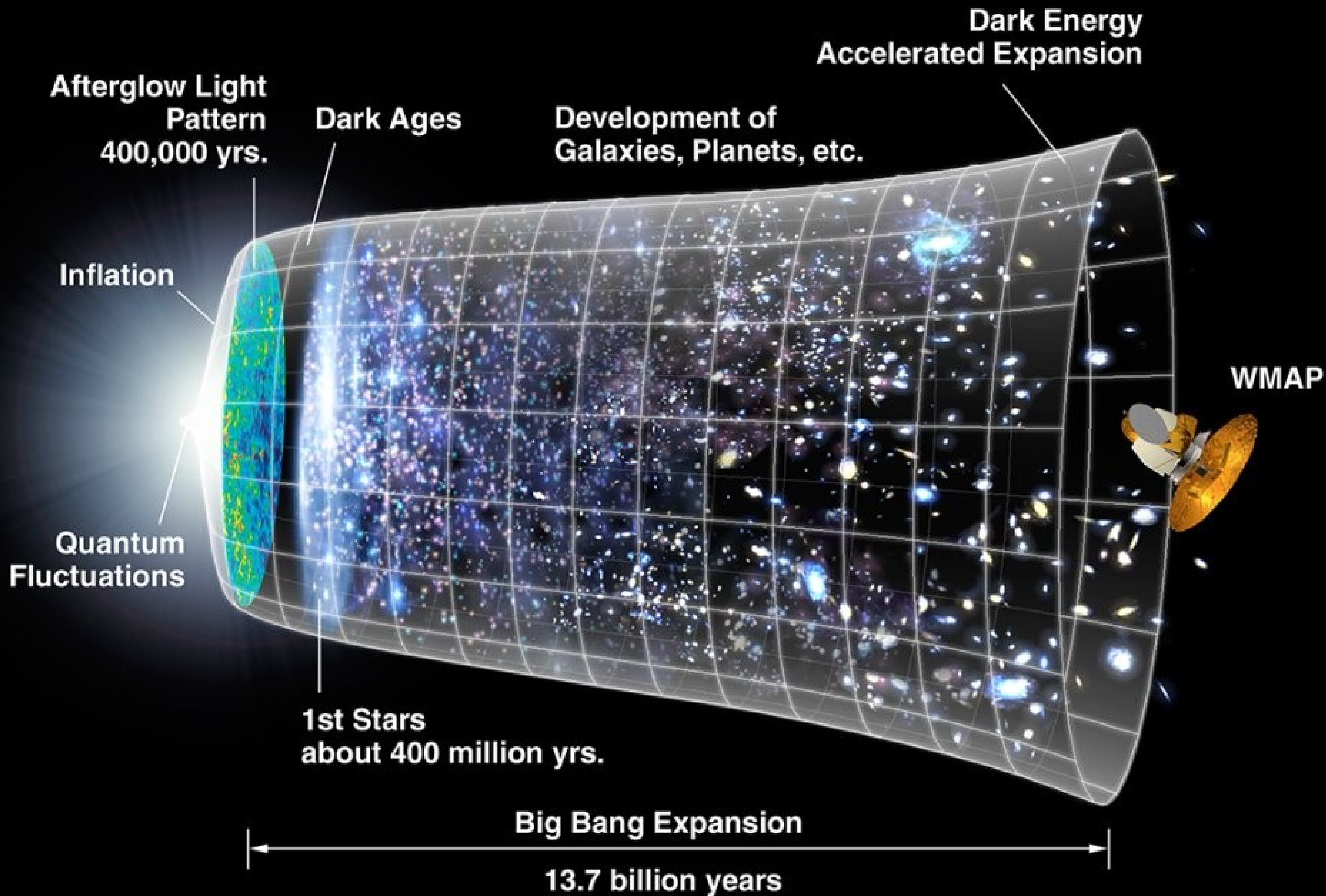
$\Omega_{tot} = \Omega_M + \Omega_R + \Omega_\Lambda$

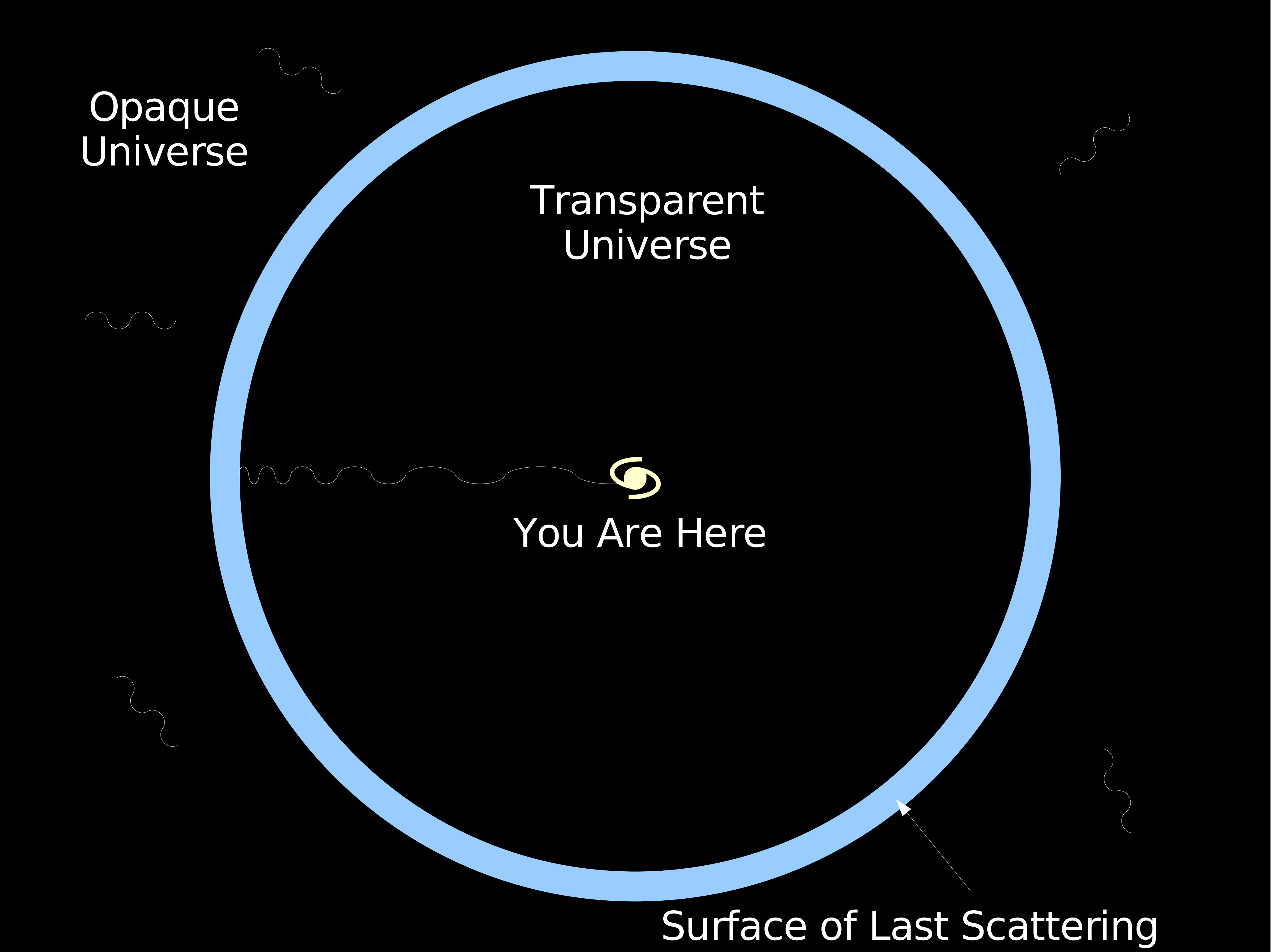
$\Omega_{tot} < 1$: Open

$\Omega_{tot} = 1$: Flat

$\Omega_{tot} > 1$: Closed


A History of the Universe
Here be Dragons
t (s)
10^-42
10^-32
10^-22
10^-12
10^-1
10^9
z
T
10^25
10^13 GeV
10^20
10^8 GeV
10^15
1 TeV
10^10
10 MeV
10^5
100 eV
Inflation;
Grand Unification;
… "The beginning?"
Electroweak Unification
Protons/Neutrons Form
Nucleosynthesis;
Cosmic Neutrinos
Dark Ages
Sun Forms
t
30 yr
10 kyr
440 kyr
17 Myr
480 Myr
13.7 Gyr
z
T
10^5
10^4
10^3
2700 K
100
270 K
10
27 K
0
2.7 K
Matter Domination
"Re"combination;
Cosmic Microwave Background
Reionization
End of Galaxy Cluster Formation;
Acceleration Begins
You Are Here


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


Opaque Universe
Transparent Universe
You Are Here
Surface of Last Scattering

The Cosmic Microwave Background

Photons emitted from the “surface of last scattering” at recombination when the universe became transparent.

$z \approx 1100$

Size of universe = 10^{-3} today's size

Spectrum = Blackbody

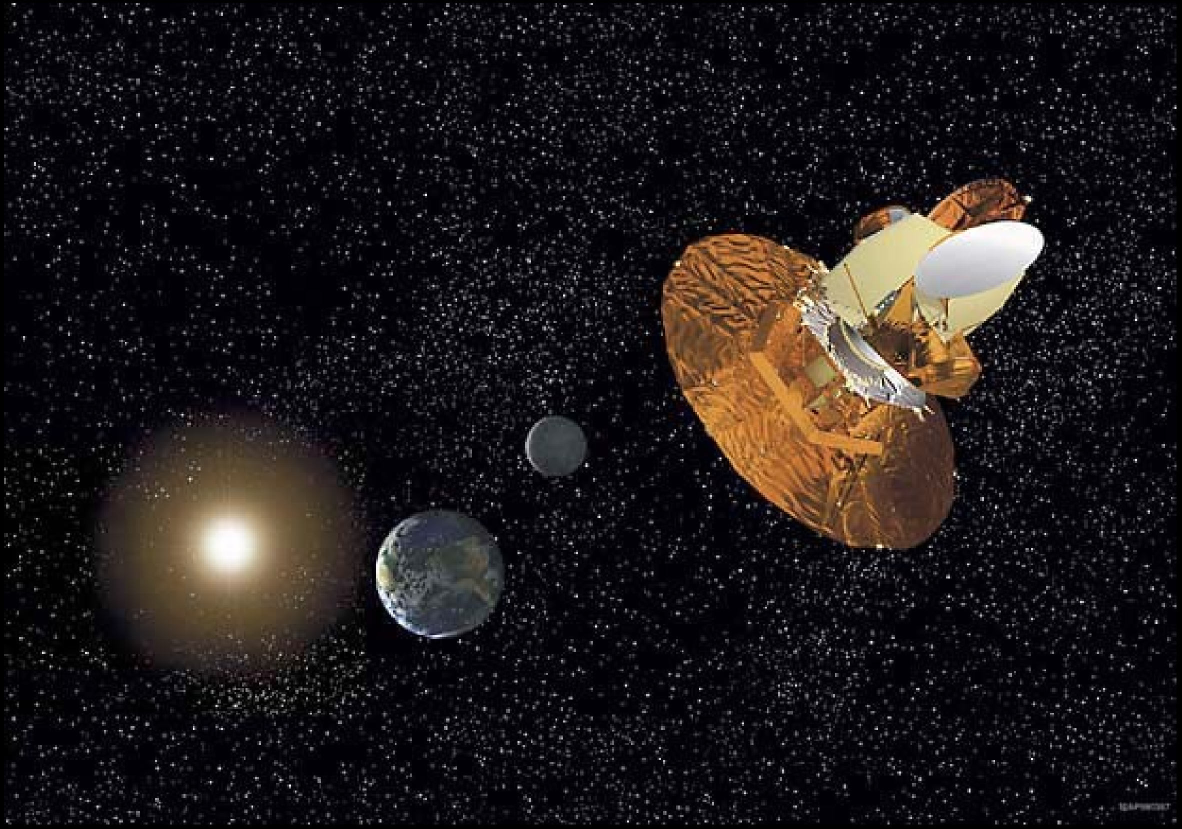
Temperature today: 2.7 K

Temperature at emission: 3000 K

Spatially very smooth (isotropic)

WMAP

Wilkinson Microwave Anisotropy Probe



Launch June 30, 2001

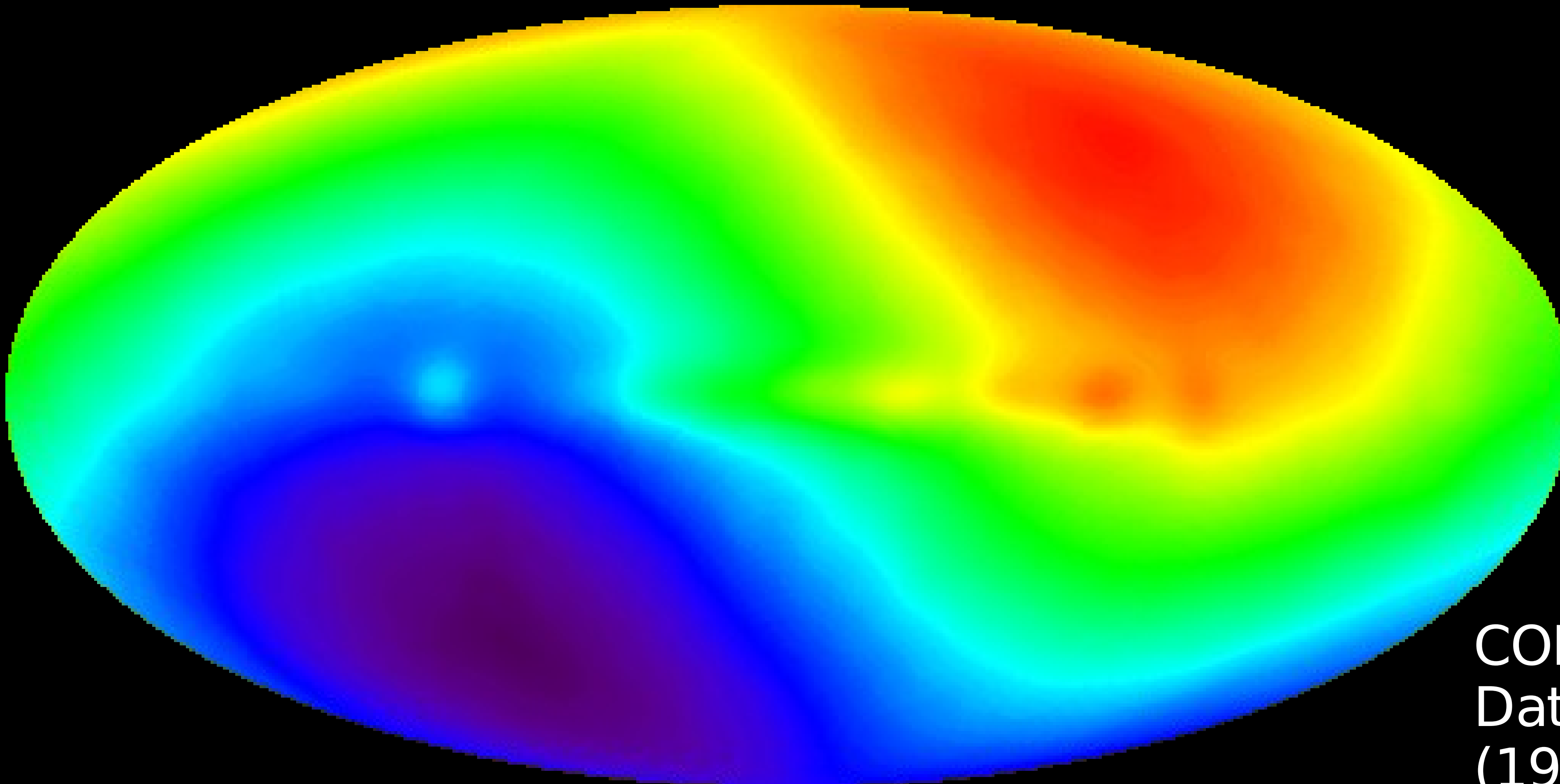
Orbits at L_2

Mission ~3 years

Two 1.4m × 1.6m reflectors

Detectors at 94, 61, 41, 33, and 23 GHz

CMB Anisotropy 1 : Dipole

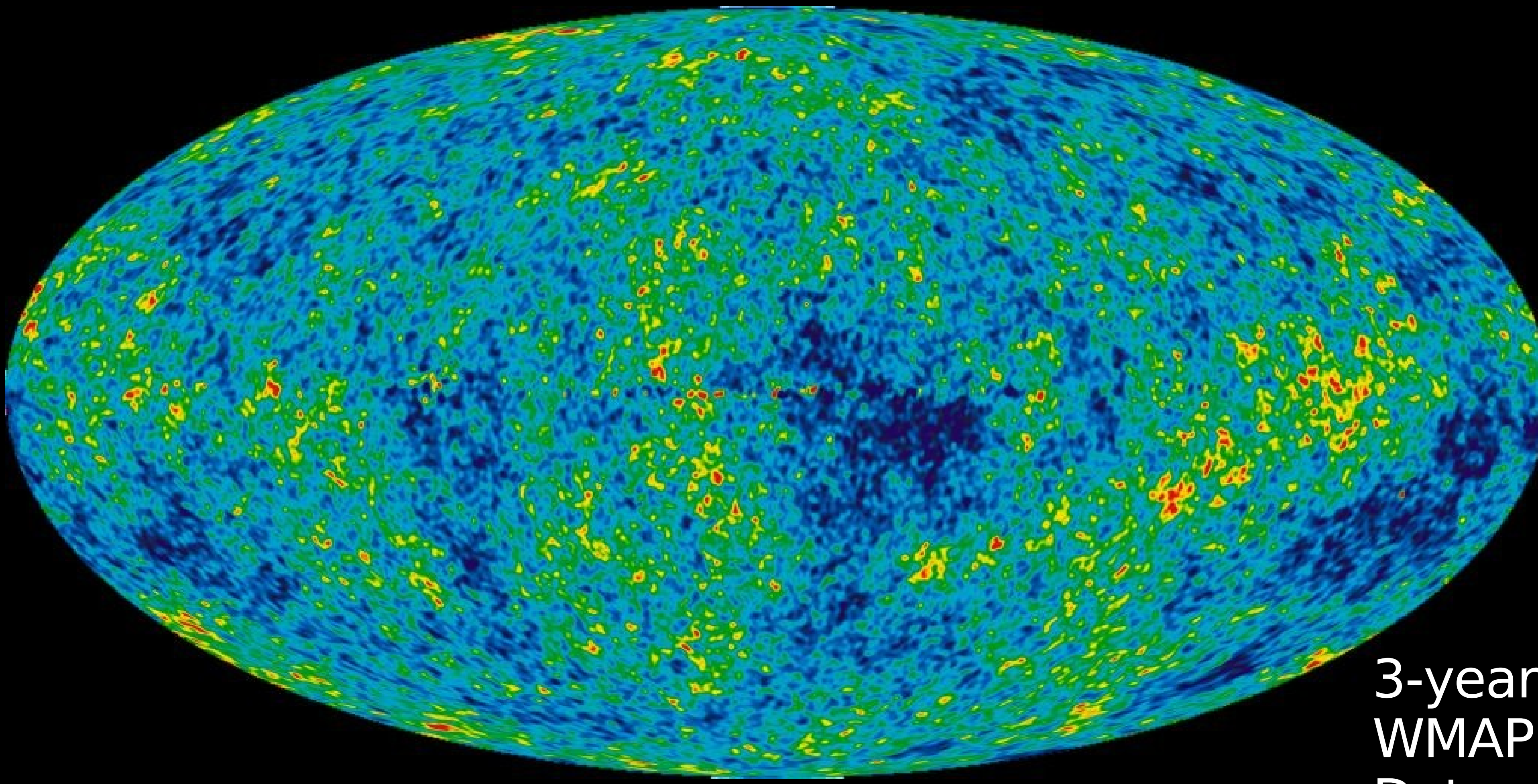


COBE Data (1992)

Motion of Sun (Galaxy, Local Group) Relative to CMB

3.346 ± 0.017 mK towards (l,b) = (263.85°, 48.25°)

CMB Anisotropy 2 : Fluctuations



3-year
WMAP
Data

Maximum fluctuation amplitude : 75 μK

Quantifying Temperature Fluctuations

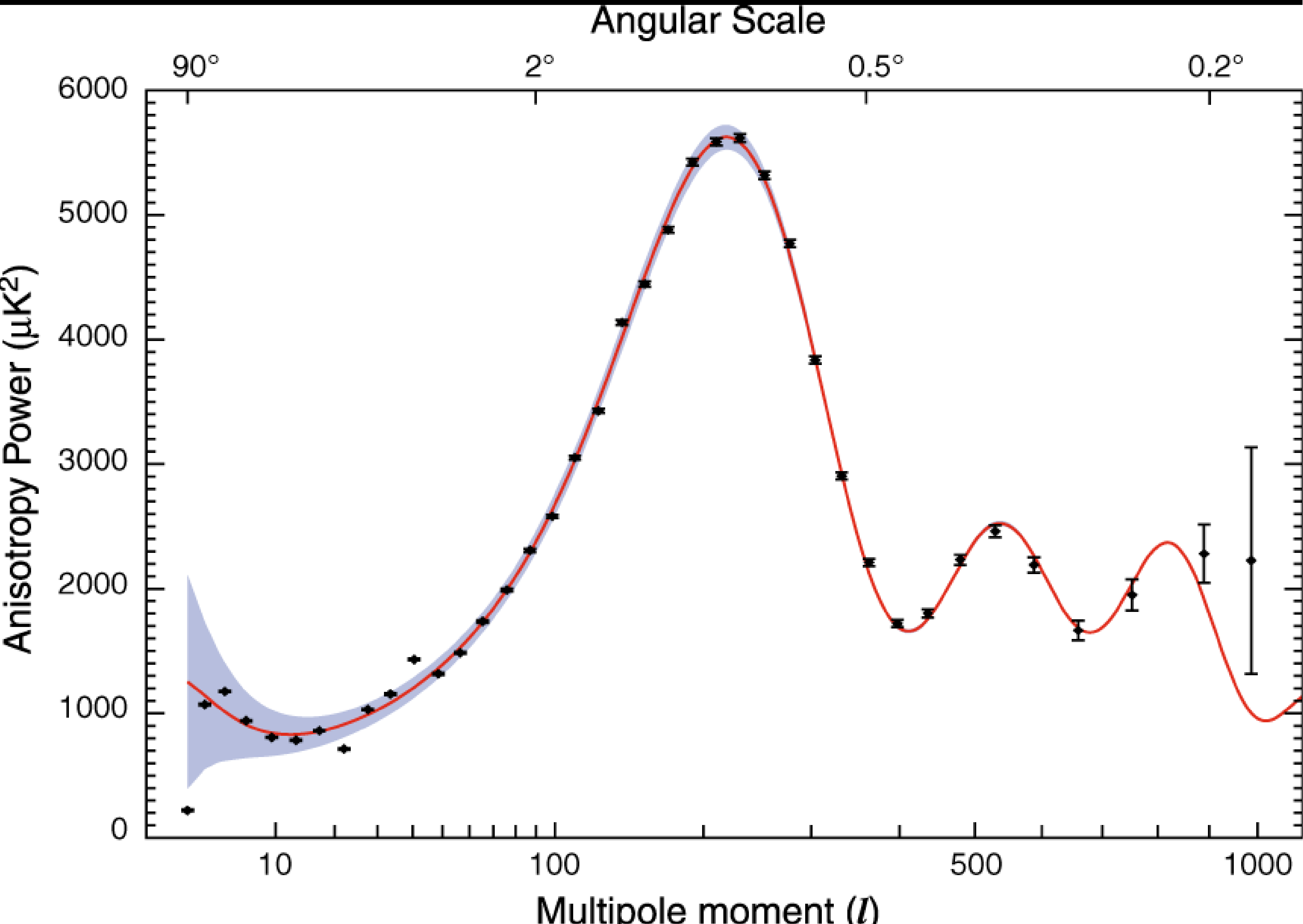
$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

Power Spectrum: $C_l = < |a_{lm}|^2 >$

Average over many Universes and over m

Observed Power Spectrum: $C_l^{sky} = \frac{1}{2l+1} \sum_m |a_{lm}|^2$

Average over m



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK2)
10
100
500
1000
Multipole moment (l)

Source of Fluctuations

"Primordial" fluctuations in density left over from inflation.

Radiation: $\rho_\gamma \propto T^4$

Density Fluctuation = Temperature Fluctuation

(= Presure Fluctuation)

(= Gravitational Potential Fluctuation)

Primordial fluctuations are *almost* scale invariant.

Fourier expand the temperature field
(k = “comoving wave number”):

$$T(\mathbf{x}) = \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} T(\mathbf{k})$$

Small perturbations → linear evolution →
Fourier modes evolve independently

Euler equations for pressure-driven oscillations yeild:

$$\ddot{T} + c_s^2 k^2 T = 0$$

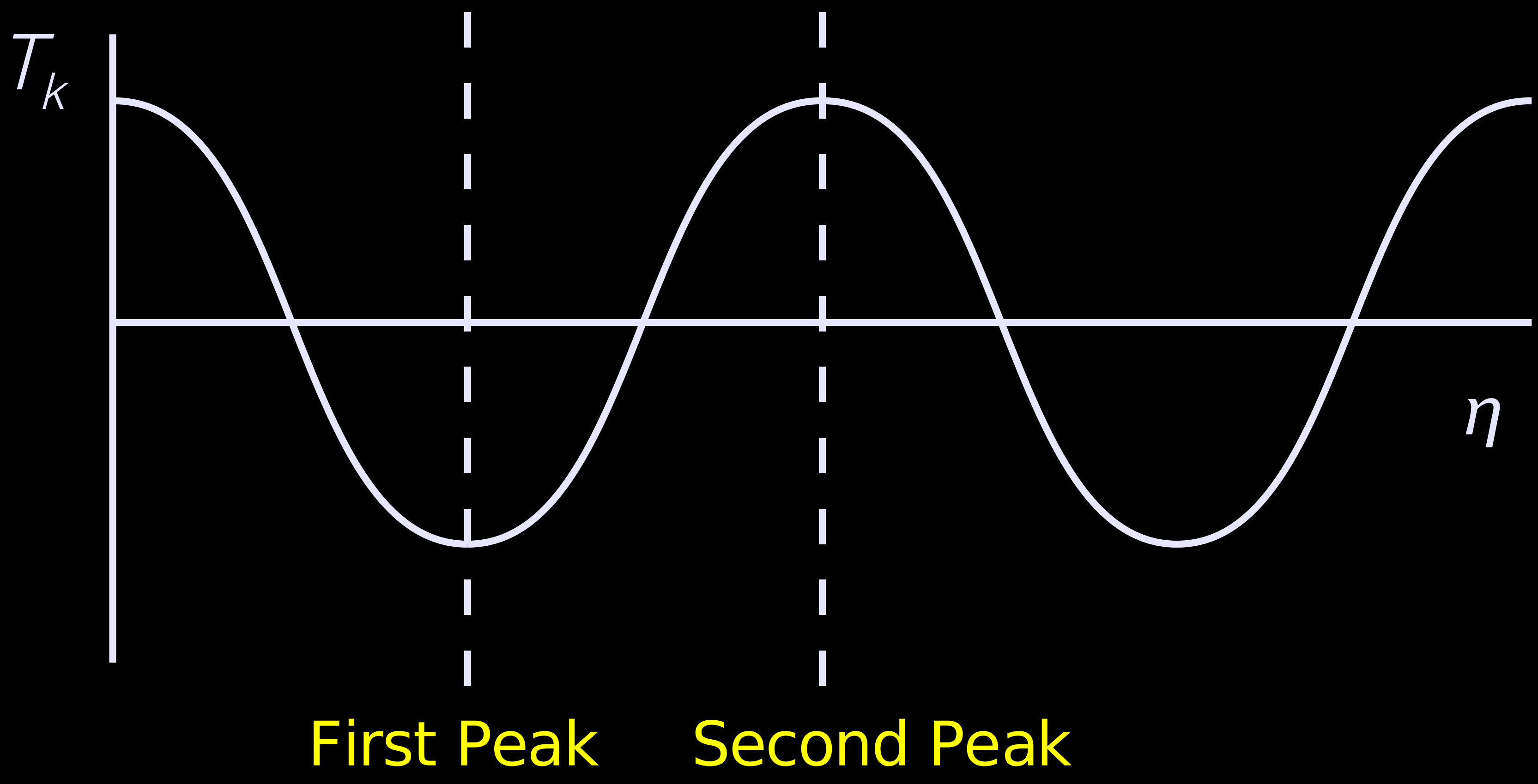
Time variable η =“conformal time”=comoving horizon

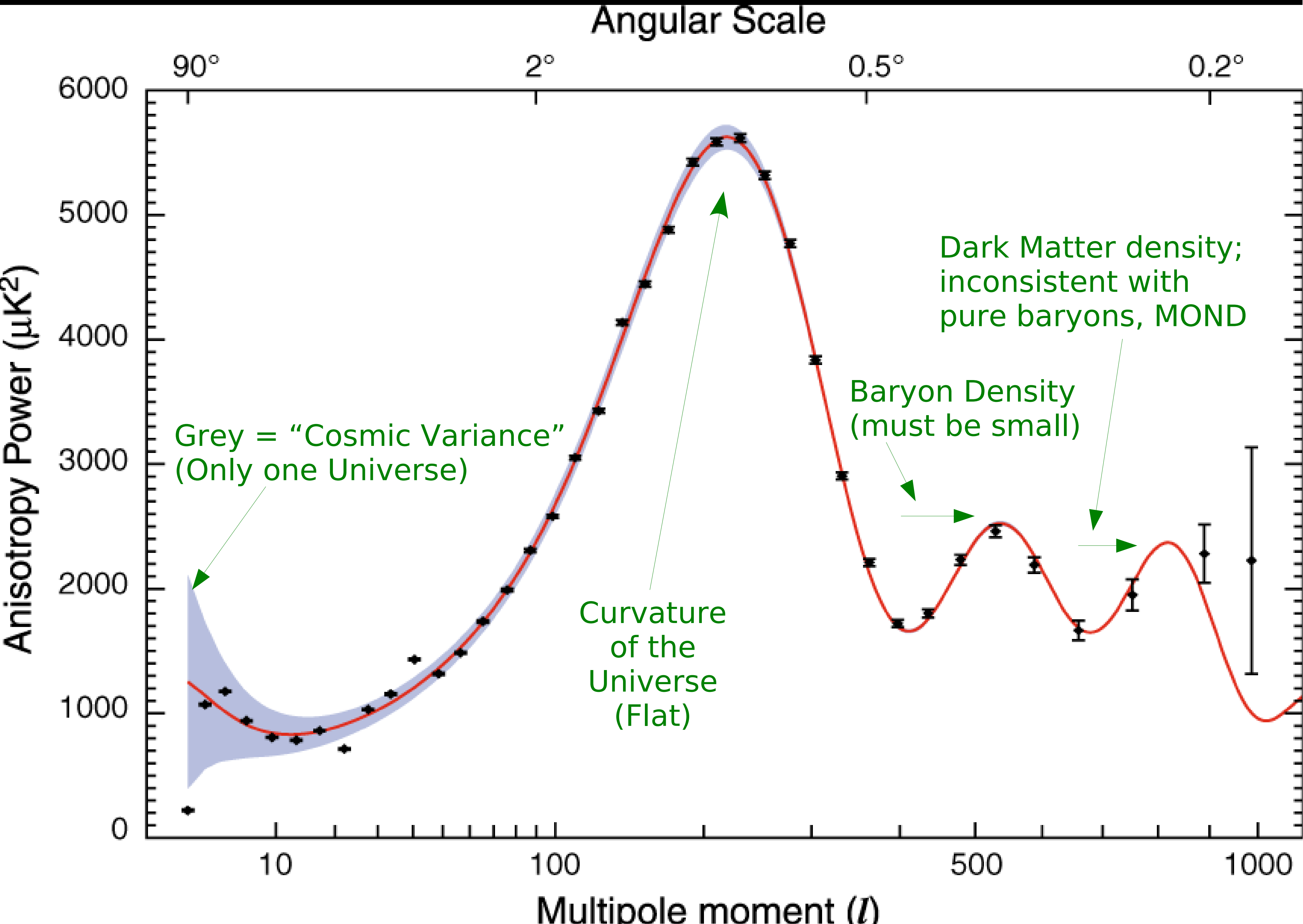
c_s = sound speed = $c/\sqrt{3}$

Fluctuation growth is small for modes larger than the horizon

$$T(\eta) = T(0)\cos(ks)$$

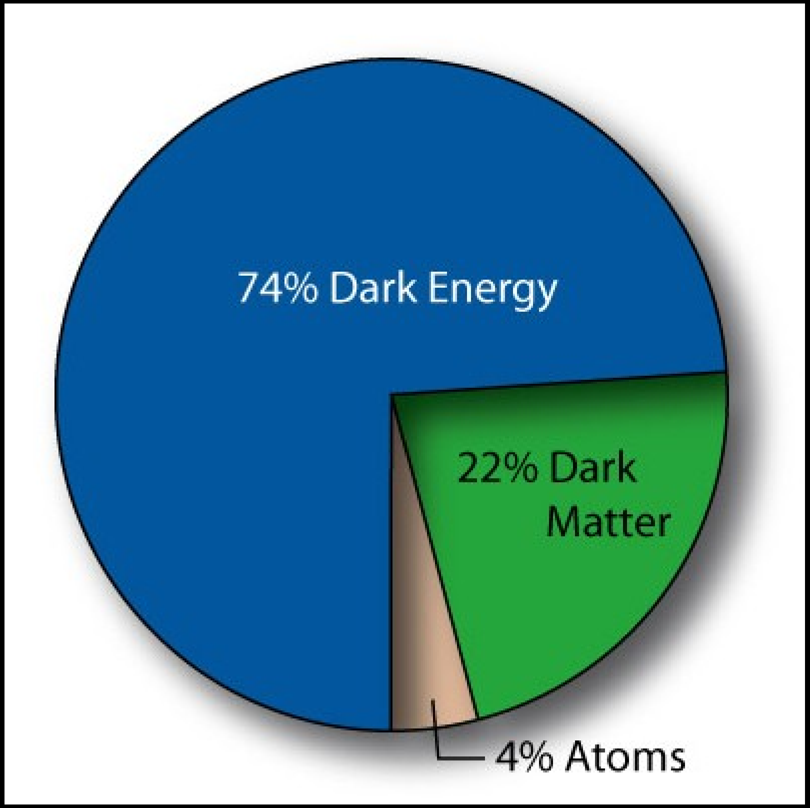
s = comoving "sound horizon" = $\eta / \sqrt{3}$




Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (l)
Grey = "Cosmic Variance"
(Only one Universe)
Curvature
of the
Universe
(Flat)
Baryon Density
(must be small)
Dark Matter density;
inconsistent with
pure baryons, MOND

What's New #1 :
Damn, that's good agreement!

"The ΛCDM model is still an excellent fit to the WMAP data."



$H_0 = 73 \pm 3$ km/s/Mpc

$\Omega_b h^2 = 0.0223 \pm 0.0008$

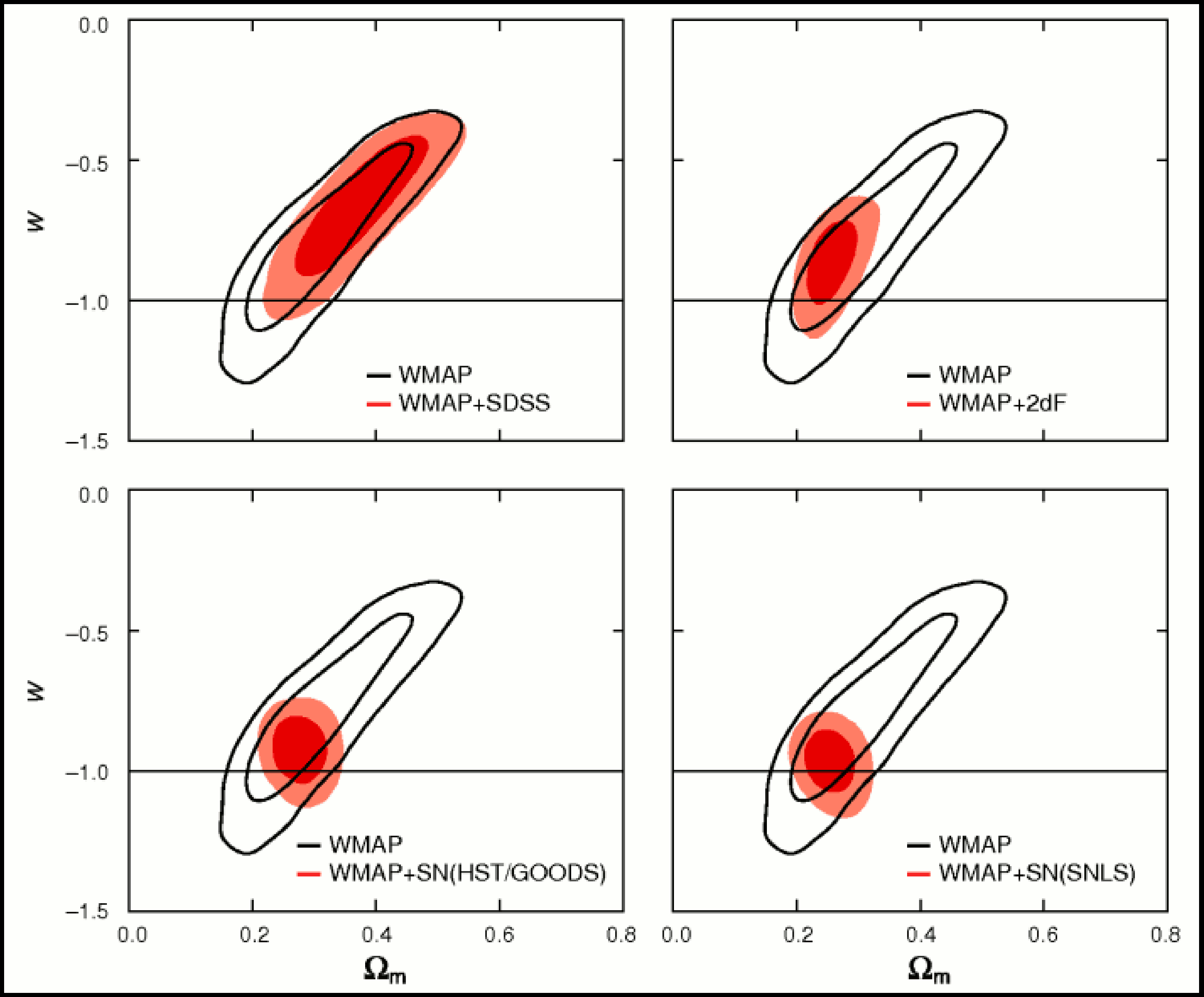
$\Omega_m h^2 = 0.126 \pm 0.009$

$\Omega_m \quad = 0.24 \pm 0.04$

What's New #1a :

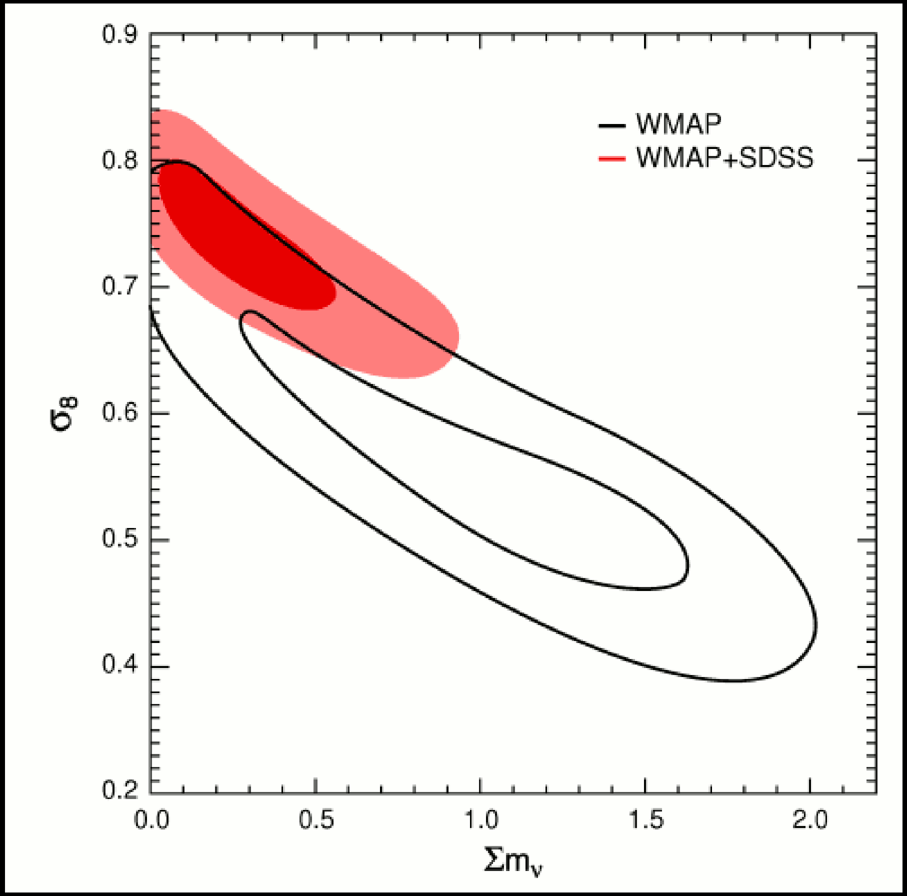
What is Dark Energy?

$$w = 0.915^{+0.049}_{-0.075}$$



What's New #1b :
Neutrinos

Total Mass (in eV):



More massive neutrinos damp out smaller-scale fluctuations, slow structure growth.

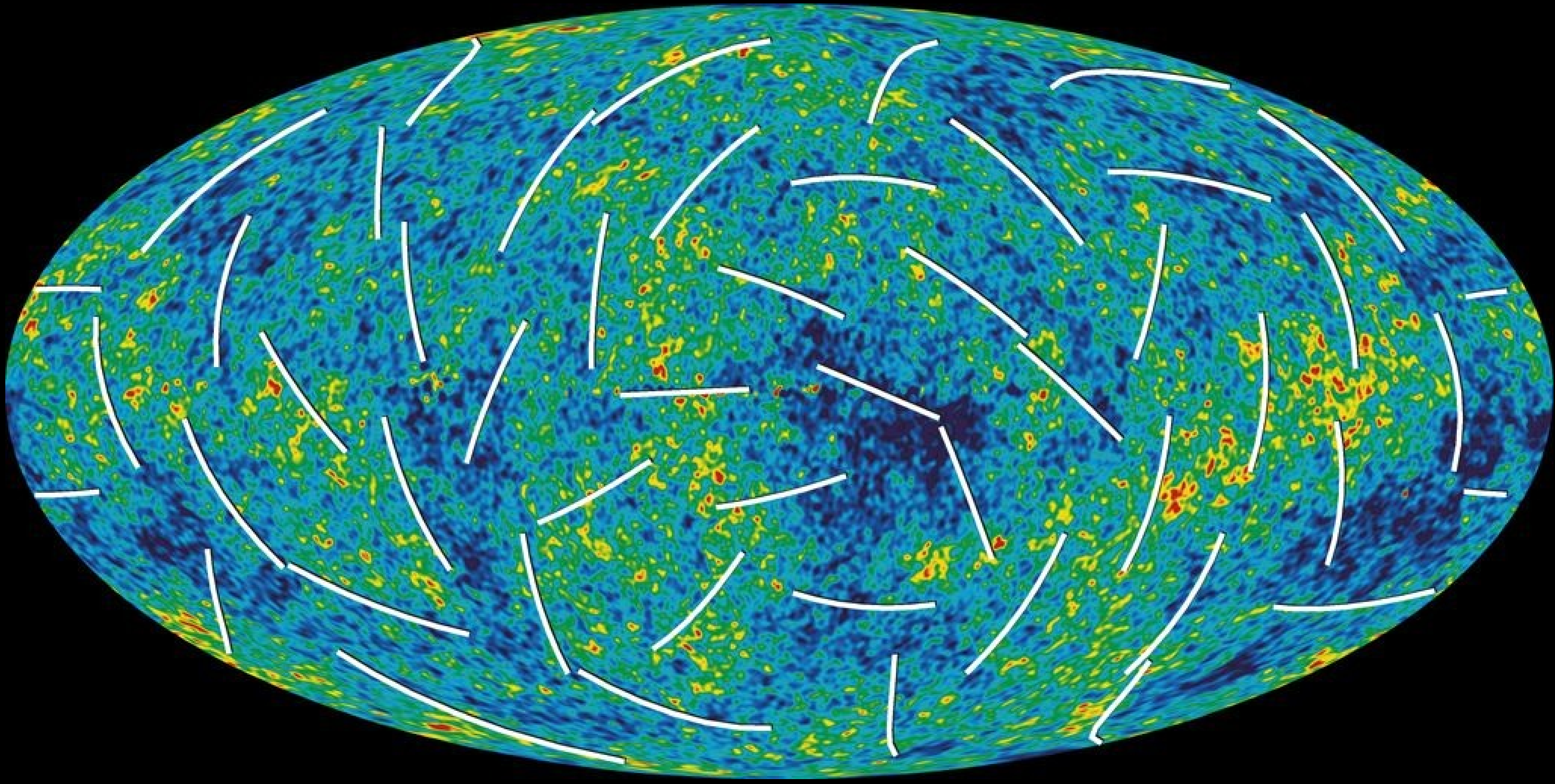
Number of Relativistic Species:

$$N_\nu = 3.29^{+0.45}_{-2.18}$$

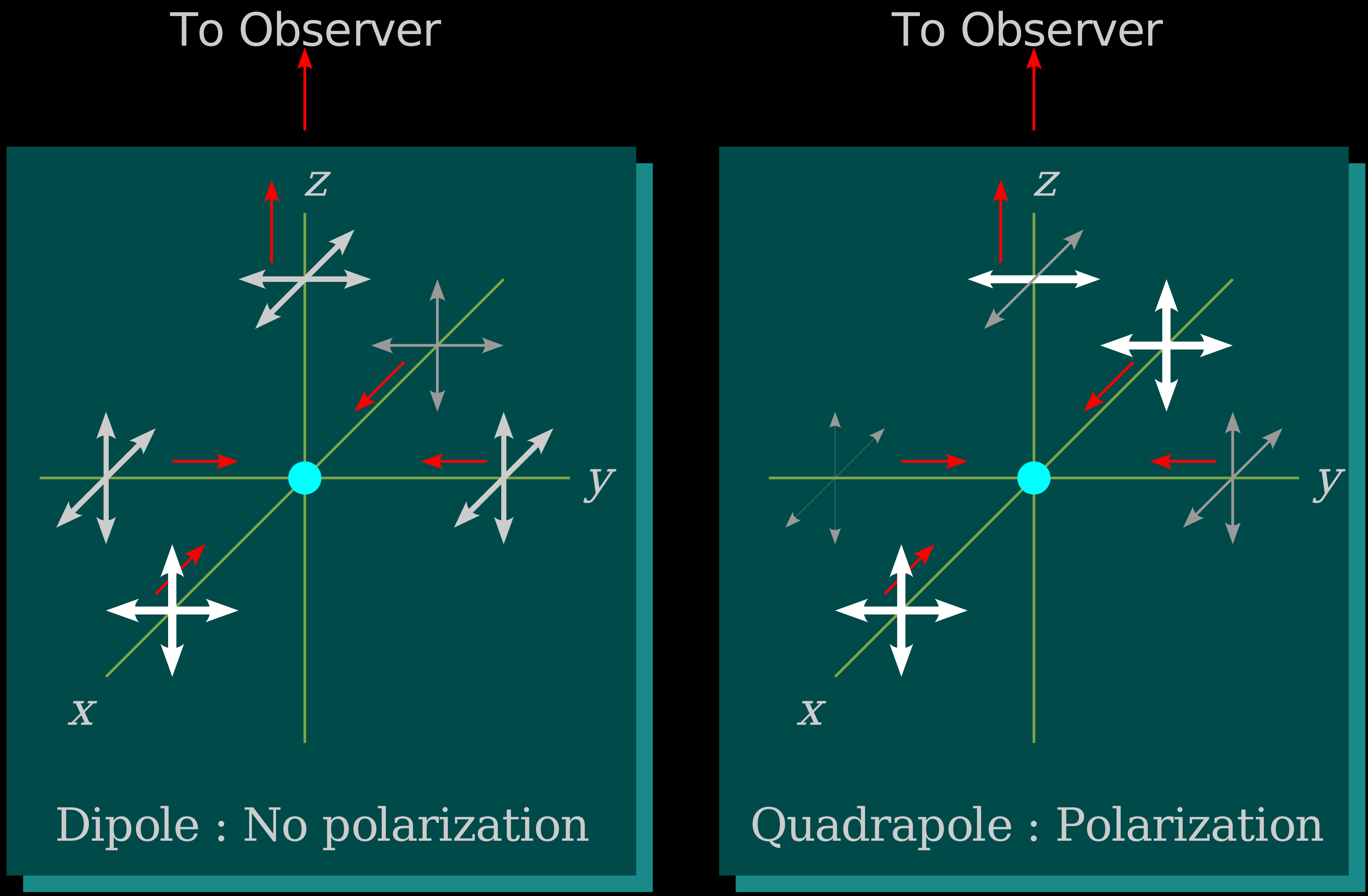
CMB fluctuations sensitive to epoch of matter/radiation equality ; more ν's needs more CDM, which in turn effects structure growth.

(Question : only light neutrinos??)

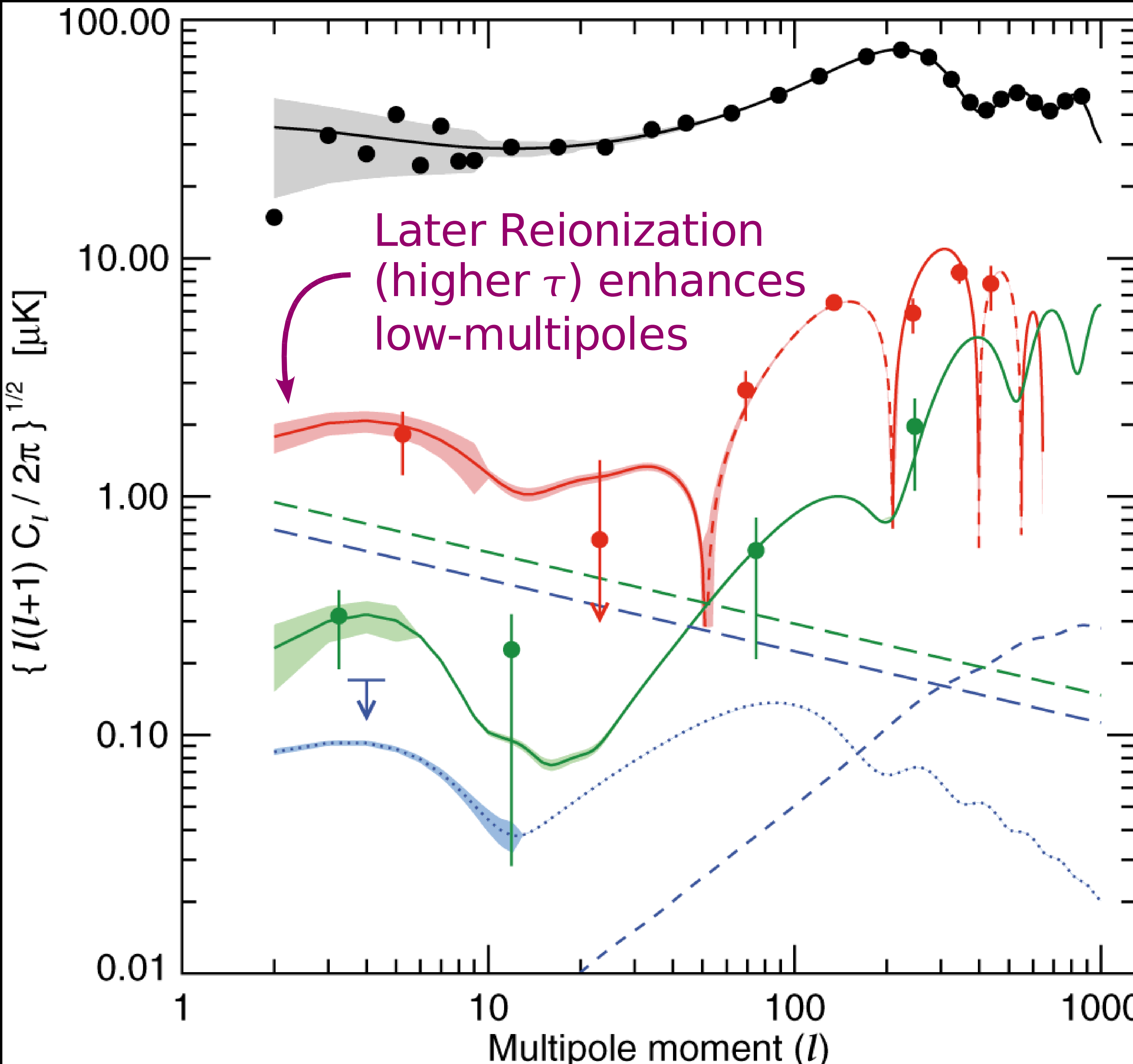
What's New #2:
Polarization



Polarization from Compton Scattering off electrons

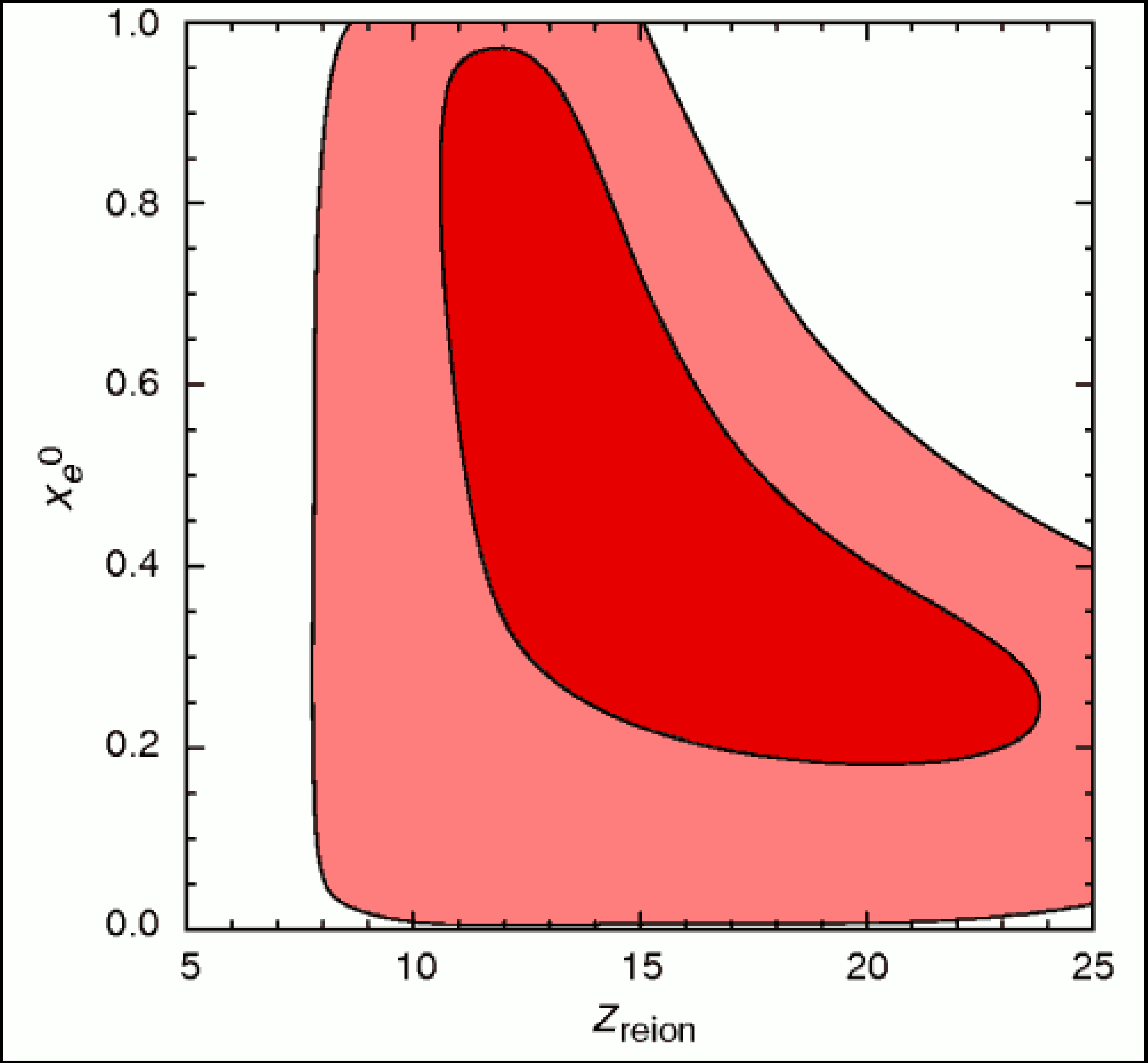


(After Dodelson)



Later Reionization
(higher τ) enhances
low-multipoles
{ l(l+1) C_l / 2π }^1/2 [μK]
Multipole moment (l)
100.00
10.00
1.00
0.10
0.01
1
10
100
1000

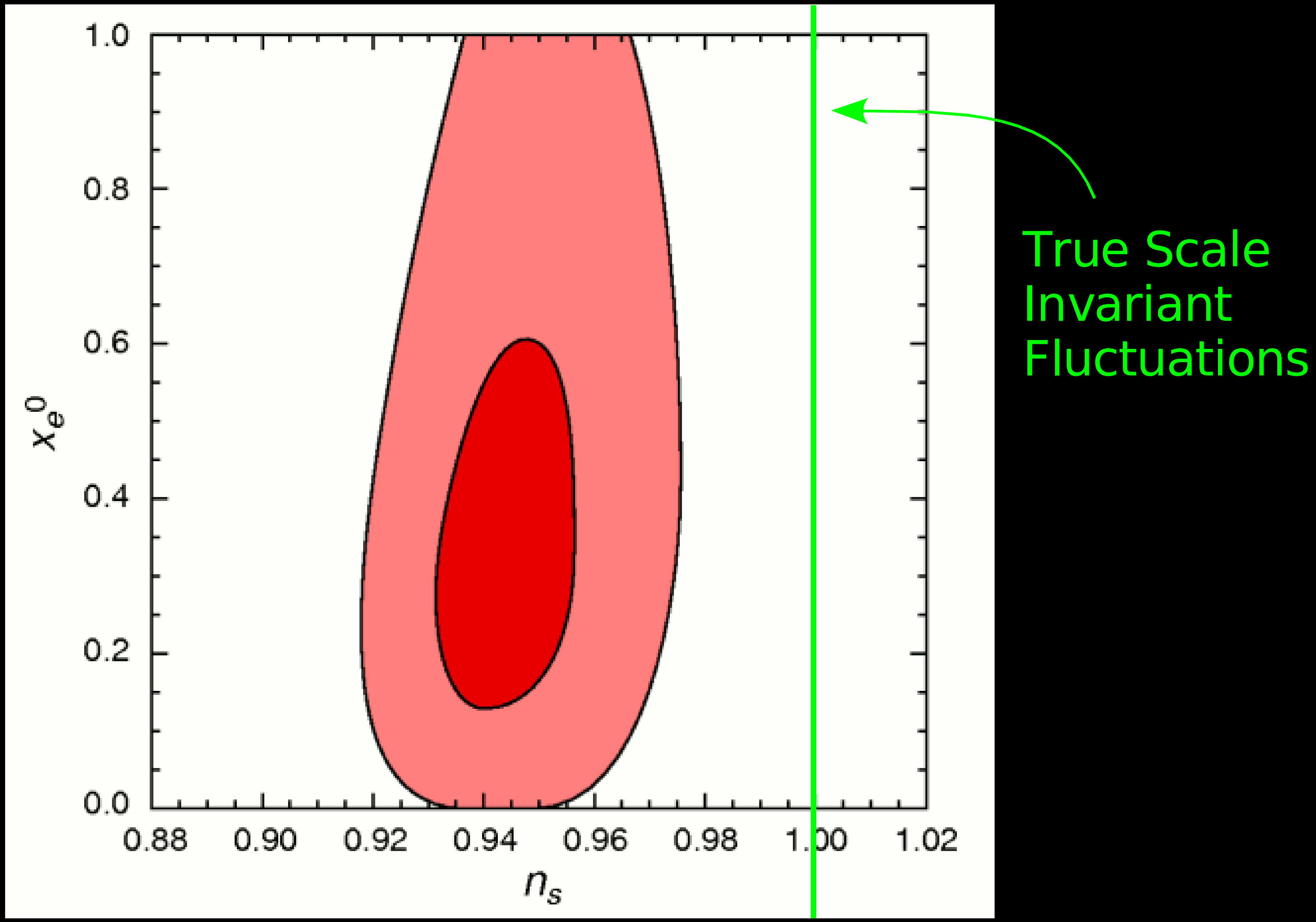
Ionization Fraction & Redshift of Reionization



Simple Model

$$x_e = 0 \qquad z > z_{reion}$$
$$= x_e^0 \qquad z_{reion} > z > 7$$
$$= 1 \qquad z < 7$$

What's New #4:
Inflation's Smoking Something



Conclusions

The Big Bang's smoking gun?
- That happened decades ago!

Inflation's smoking gun?
- Maybe. The inflation paradigm still stands up!

Reionization
- Maybe later (lower z) than we thought?
- Becoming accessible for Galaxies/GRBs/Quasars.

Precision Cosmology
- Precise parameters, damn good agreement with the Big Bang model and other observations.