Structure Formation and DM

Finally, the *real* linear theory has to be done in linearized or even full general relativity

$\Longrightarrow$ very, very complicated.

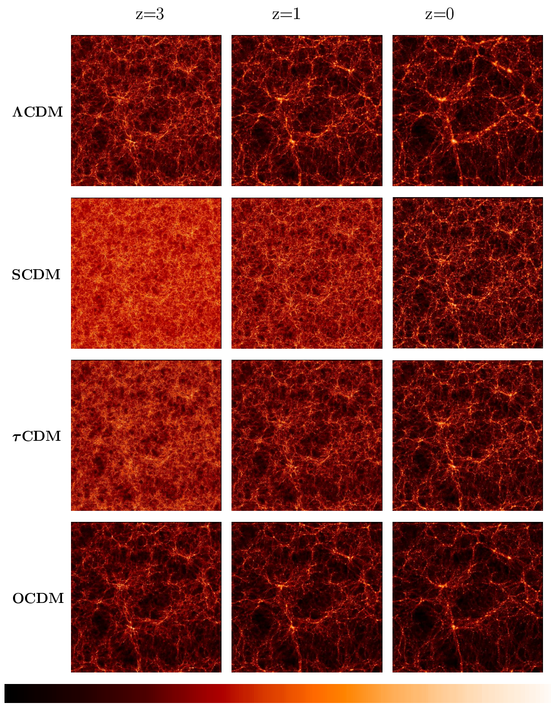
Full fledged, detailed structure formation is mainly done numerically.

N-body codes: describe particles (=galaxies) as points, compute mutual interactions in expanding universe

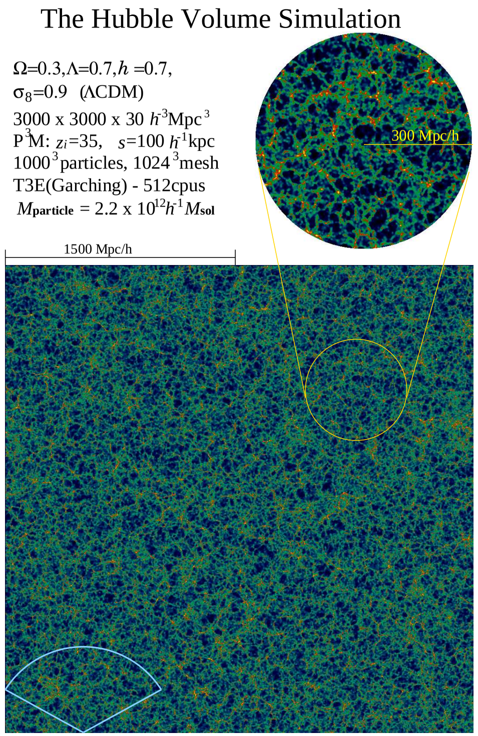
Requires massive computing power.

VIRGO consortium: USA, Canada, Germany, UK
Hubble Volume Simulation: Garching T3E (512 processors), 70 h CPU time followed by the Millenium Simulation (30 d CPU time)

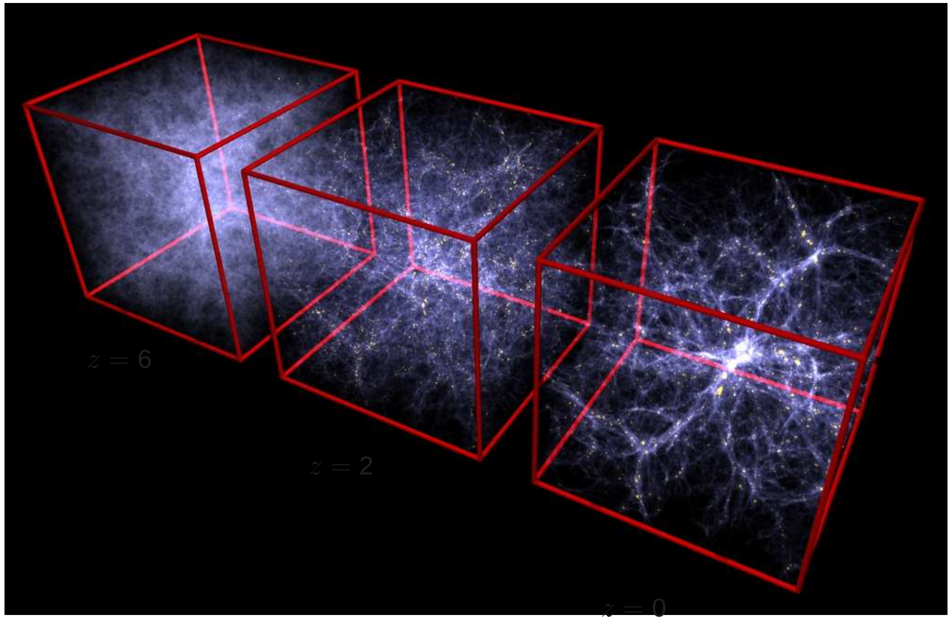
see Springel et al. (2005), Springel, Frenk & White (2006) and `http://www.mpa-garching.mpg.de/~virgo/virgo/`



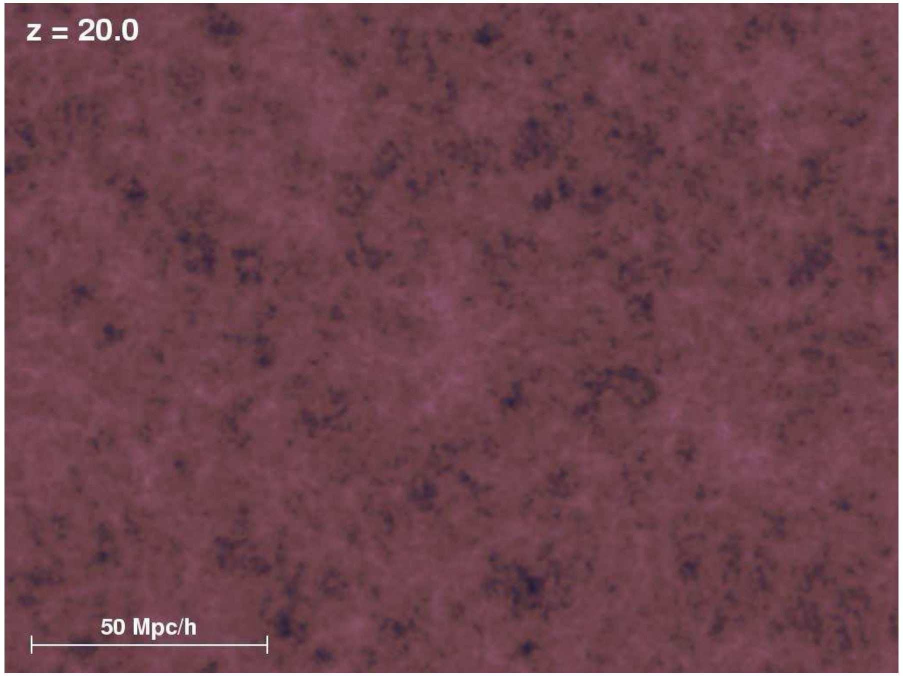
The VIRGO Collaboration 1996



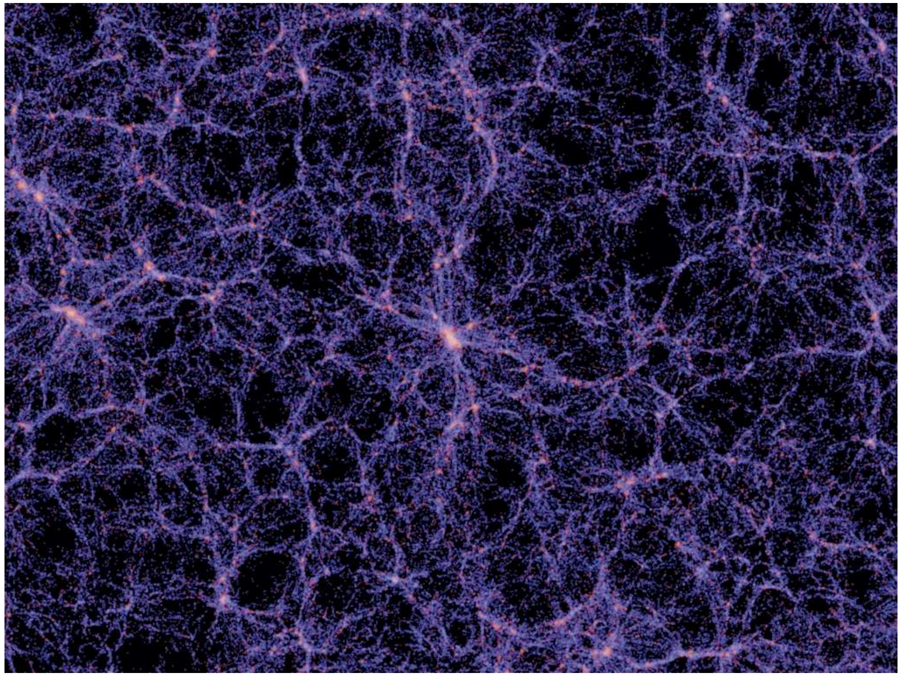
ΛDM, pie shows SDSS size



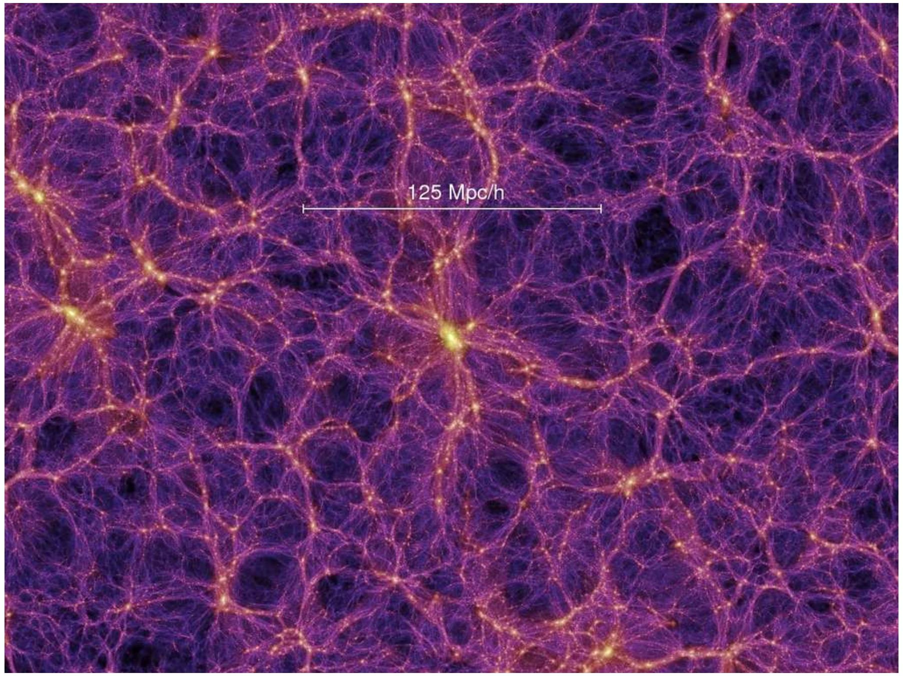
(V. Springel/MPA)



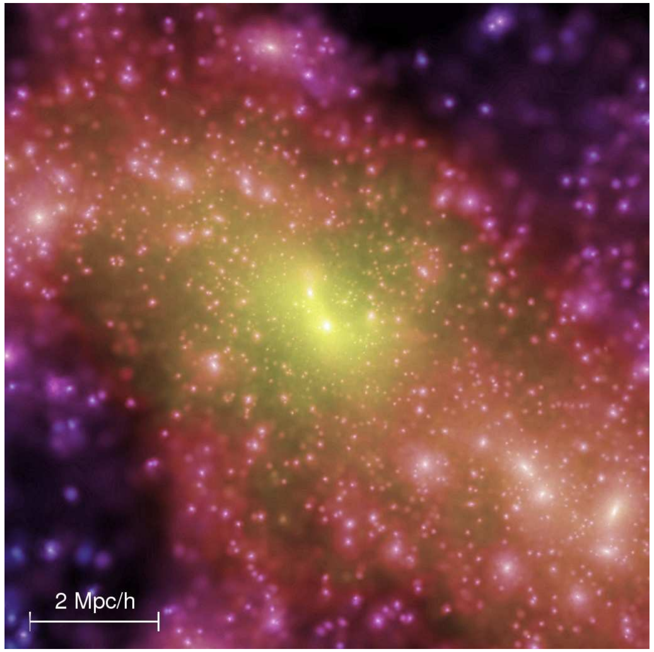
Evolution of structure in a ΛCDM Universe (MPA/V. Springel)



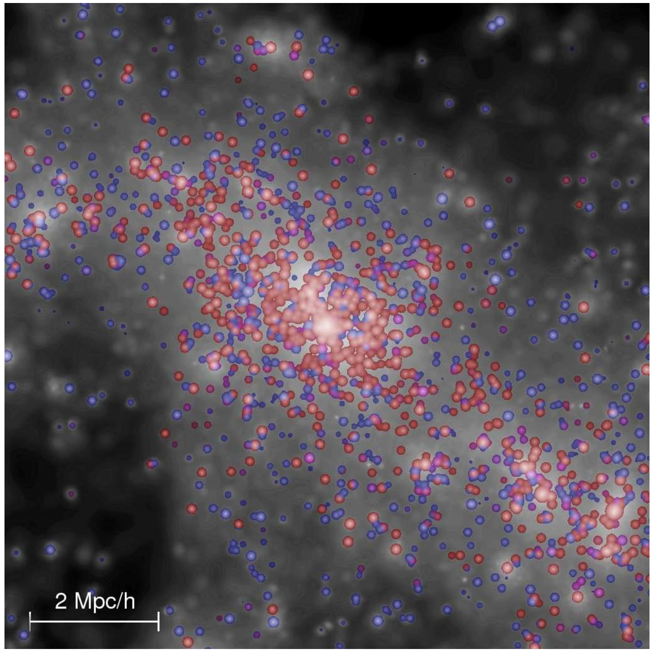
. . . and corresponding galaxy distribution (V. Springel/MPA)



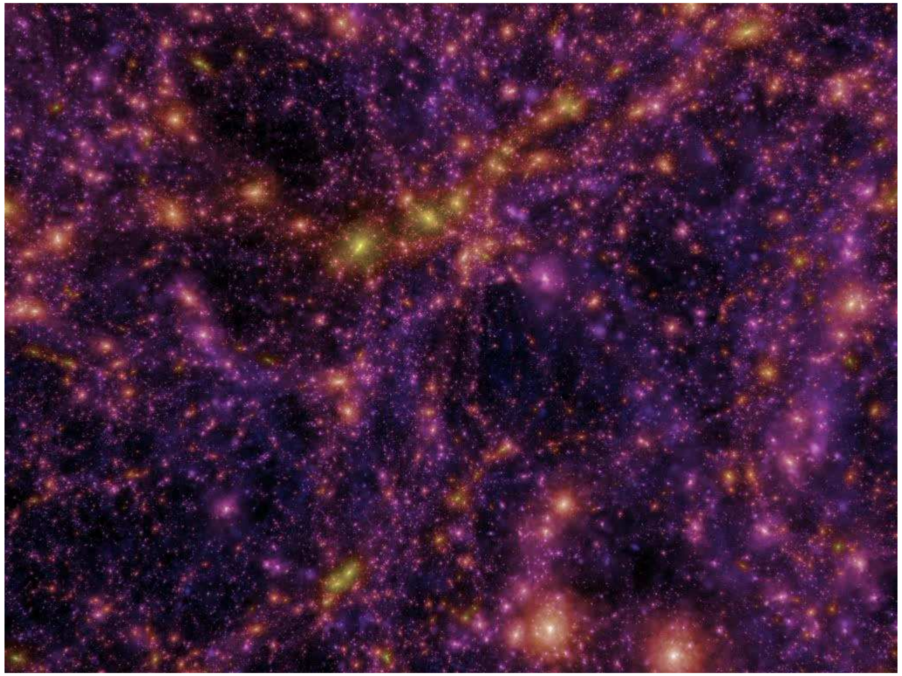
Todays dark matter distribution. . . (V. Springel/MPA)



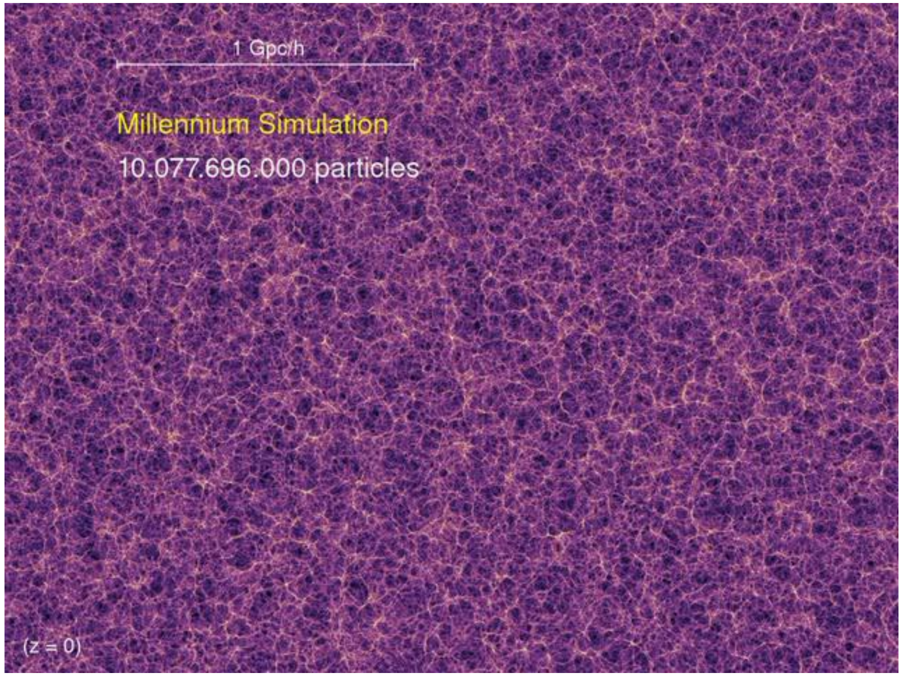
Todays dark matter distribution in a cluster. . . (V. Springel/MPA)



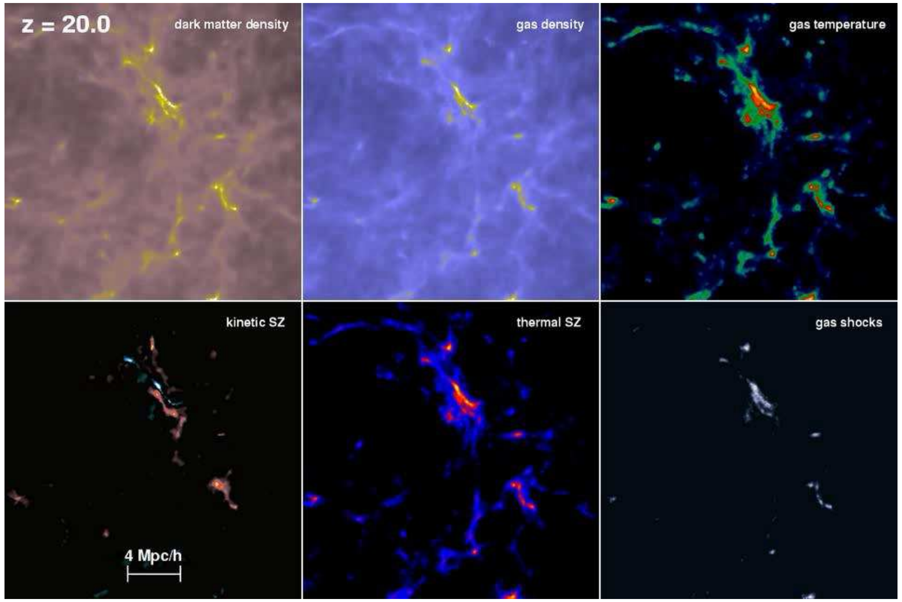
. . . and corresponding galaxy distribution (V. Springel/MPA)



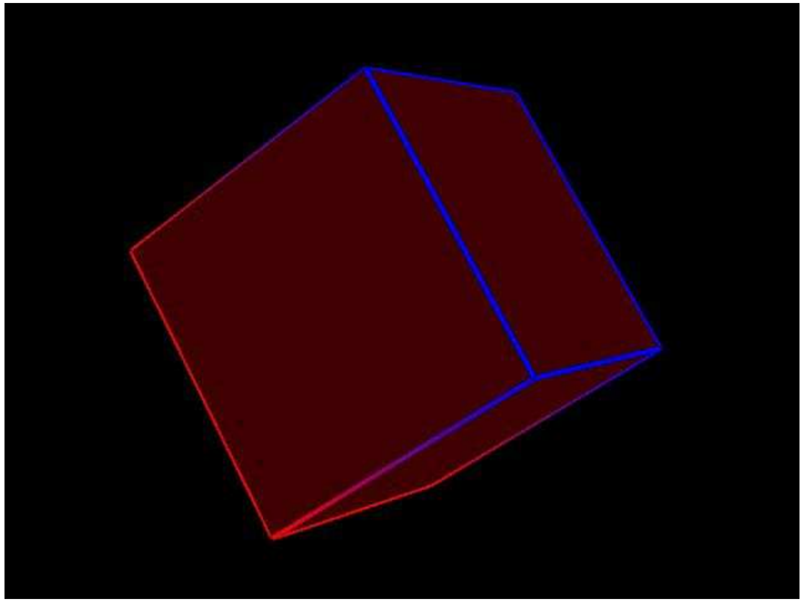
Flight through the DM structure of the Millennium Simulation (V. Springel)



Zoom into the DM structure of the Millennium Simulation



Formation of a galaxy cluster (V. Springel)



(movie courtesy N. Gnedin)

Reionization: ionization of intergalactic medium through UV radiation from the first stars

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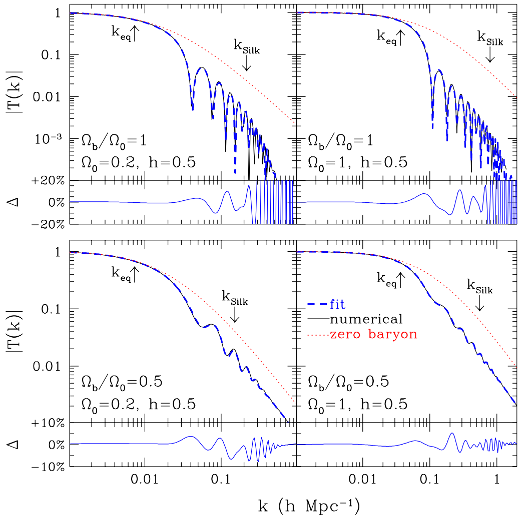
Formal Structure Formation



Calculation of real power spectra difficult: growth under self-gravitation pressure effects dissipation.

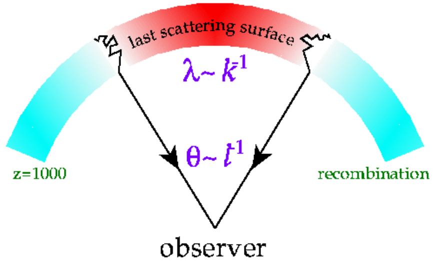
To predict observations from today: define transfer function

$$\delta_k(z=0) = D(z) T_k \delta_k(z) \qquad (9.80)$$

But: need initial conditions, $\delta_k(z)$!

(Eisenstein & Hu, 1999)

CMBR



courtesy Wayne Hu

Matter and Radiation are coupled, i.e., large mass density = high photon density.

Photons from overdense regions: gravitational redshift ⟹ observable!
(Sachs Wolfe Effect)

CMBR: Radiation from surface of last scattering ⟹ Gravitational redshift is observable as temperature fluctuation:

$$\frac{\Delta T}{T} \sim \frac{\Delta\Phi_{\mathrm{g}}}{c^2} \qquad (9.81)$$

CMBR Fluctuations trace gravitational potential at $z \sim 1100$!

CMBR

Temperature fluctuations:

$$\frac{\Delta T}{T} \sim \frac{\Delta\Phi_{\mathrm{g}}}{c^2} \qquad (9.81)$$

where

$$\Delta\Phi_{\mathrm{g}} \sim -\frac{2G\Delta M}{R} = \frac{8\pi G}{3}\bar{\rho}R^2\delta = -\delta(t)\,(H(t)R)^2 \qquad (9.82)$$

Current angle of region on sky:

$$\alpha \sim R/d_{\mathrm{A}} \qquad (9.83)$$

where the angular diameter distance

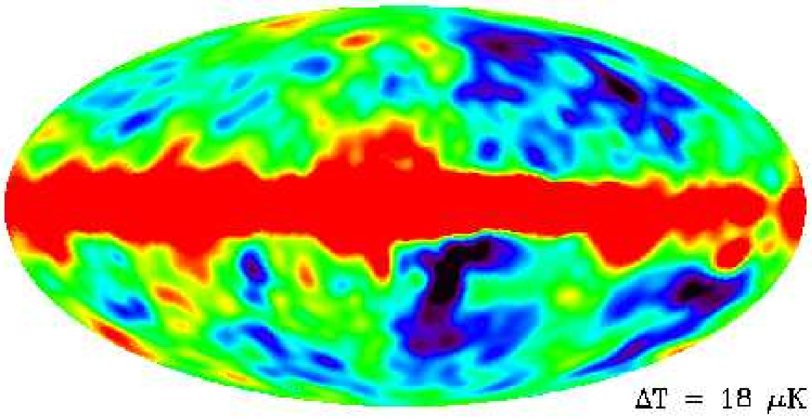
$$d_{\mathrm{A}} = d_{\mathrm{L}}/(1+z)^2 \qquad (9.84)$$

Therefore:

$$\frac{\Delta T}{T} \sim \frac{\Delta\Phi_{\mathrm{g}}}{c^2} \propto -\frac{\delta\alpha^2}{3} \qquad (9.85)$$

Quotient 3 from more detailed theory, “Integrated Sachs Wolfe effect”

CMBR



COBE: Resolution $\alpha \sim 7^\circ$ (corresponds to $\sim 10^{20}\,M_\odot$ at recombination). Temperature fluctuations imply $\delta \sim 10^{-3}$ at recombination.

This is small for pure matter dominated universe $\Longrightarrow$ Implies existence of dark matter!

CMBR

Detailed theory of fluctuations: Expand CMB fluctuations on sky in spherical harmonics:

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell,m} a_{\ell,m} Y_{\ell,m}(\theta,\phi) \tag{9.86}$$

Since rotationally symmetric, can express variation in terms of multipole coefficients, C_ℓ:

$$C(\theta) = \frac{1}{4\pi}\sum_{\ell}\sum_{m=-\ell}^{+\ell} |a_{\ell,m}| P_\ell(\cos\theta) \tag{9.87}$$

$$=: \frac{1}{4\pi}\sum_{\ell}(2\ell+1) C_\ell P_\ell(\cos\theta) \tag{9.88}$$

where $C(\theta) = \langle \Delta T/T \rangle$ and where the P_ℓ are the Legendre polynomials.

CMBR

Expect following features:

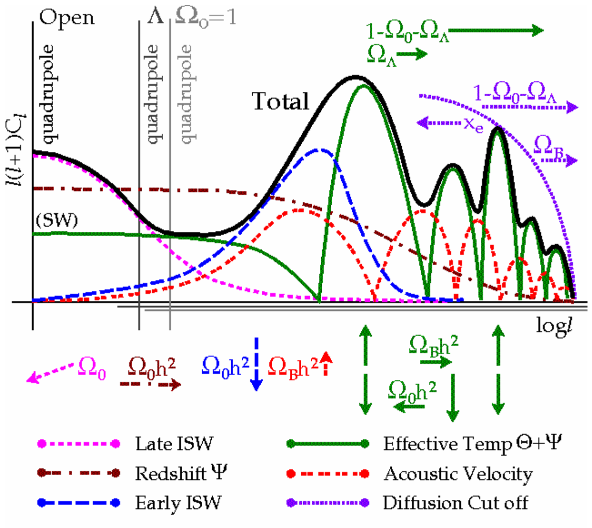
Large angle anisotropy: (small ℓ, scales $\gtrsim$ horizon at decoupling): Flat part due to Sachs-Wolfe effect

Smaller angular scales: (larger ℓ): Influenced by photon-baryon interactions:
Matter falls in potential well
$\Longrightarrow$ Pressure resists
$\Longrightarrow$ acoustic oscillations
$\Longrightarrow$ Power at selected scales!

Power from those density fluctuations which had their maximum amplitude at time of last scattering dominates $\Longrightarrow$ acoustic peak

Also damping from photon diffusion (Compton scattering; Silk damping [after Joseph Silk])

CMBR



Hu, Sugiyama, & Silk (1995)

Location and strength of acoustic peaks dependent on

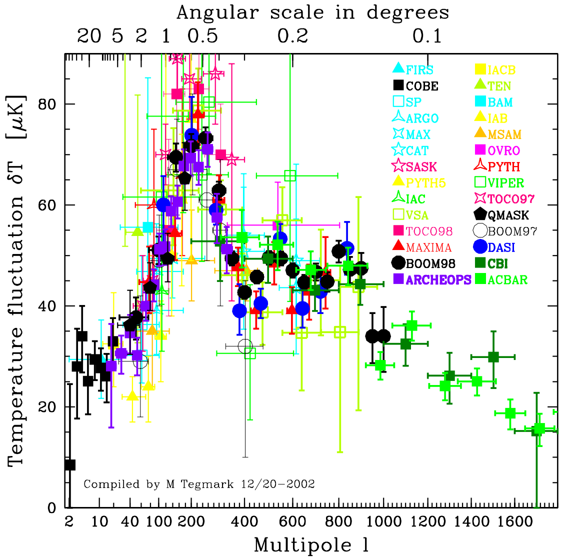
$$\Omega_b \quad H_0 \quad \Omega_0$$

Position of acoustic peak not observed with COBE (at smaller scale than 7°)

courtesy BOOMERANG team

Enter: BOOMERANG (Balloon Observations of Milimetric Extragalactic Radiation and Geophysics), Flight in Antarctica 1998 December 29 – 1999 January 9

Summary: Pre-WMAP



1st acoustic peak found by BOOMERANG in 1999

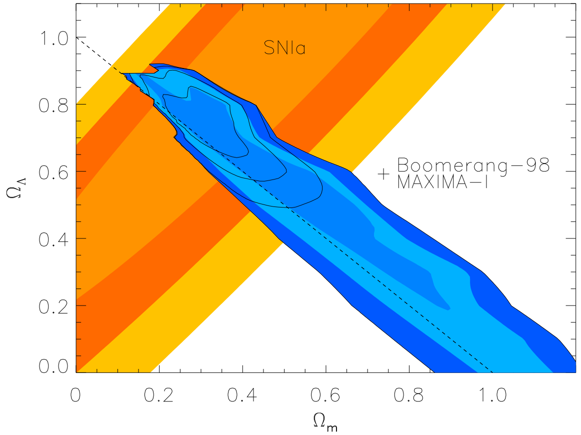
(Jaffe et al., 2000)

Courtesy M. Tegmark

BOOMERANG before Mt. Erebus; courtesy BOOMERANG team

Other balloon missions: MAXIMA-1,. . .

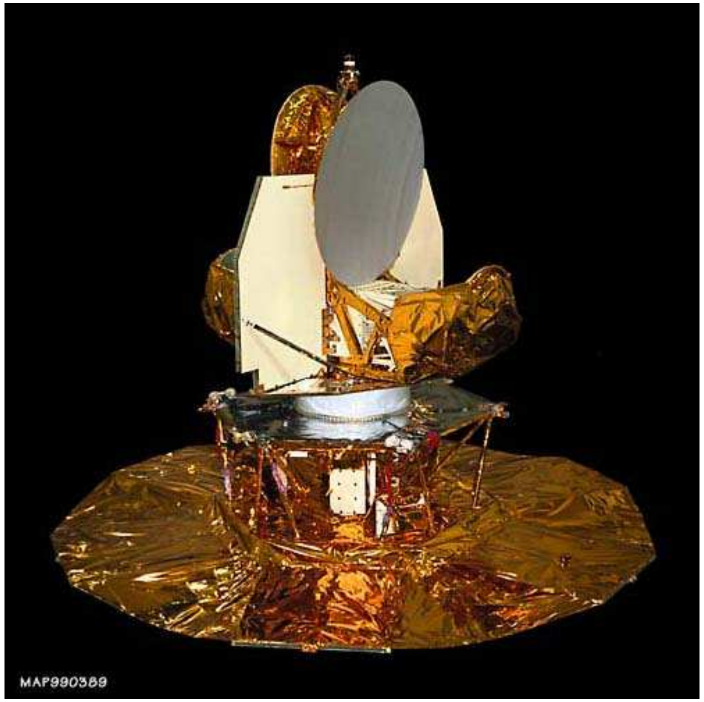
Summary: Pre-WMAP



(Jaffe et al., 2000, black contours: incl. Large Scale Structure)

Summary of CMB fluctuations pre 2000 (COBE, BOOMERANG, MAXIMA):

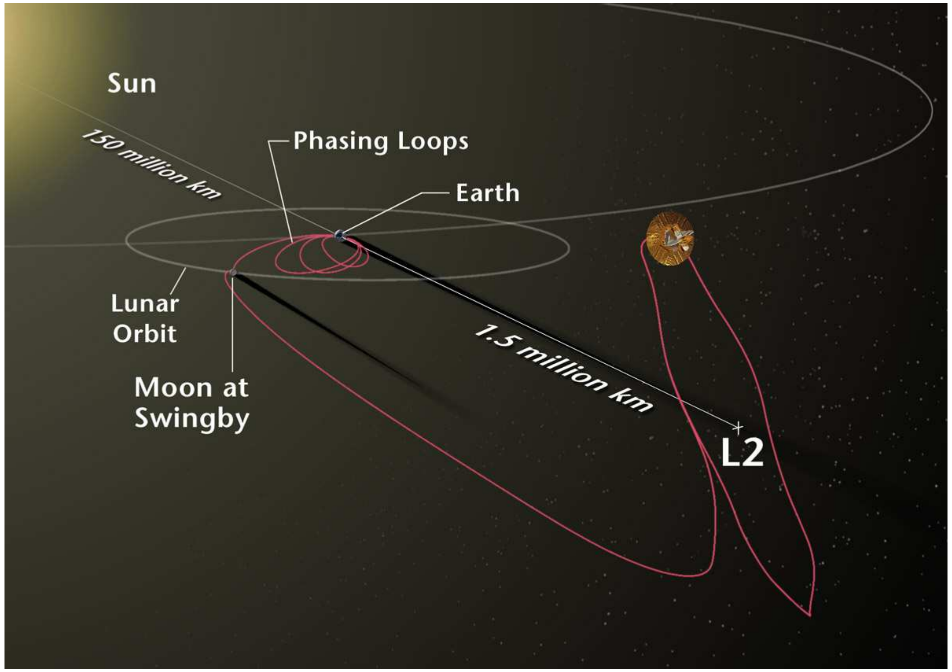
$$\Omega_{\mathrm{tot}} \simeq 1.11 \pm 0.07 \begin{pmatrix}+0.13\\-0.12\end{pmatrix} \qquad \Omega_{\mathrm{b}}h^2 \simeq 0.032^{+0.005}_{-0.004} \begin{pmatrix}+0.009\\-0.008\end{pmatrix} \tag{9.89}$$

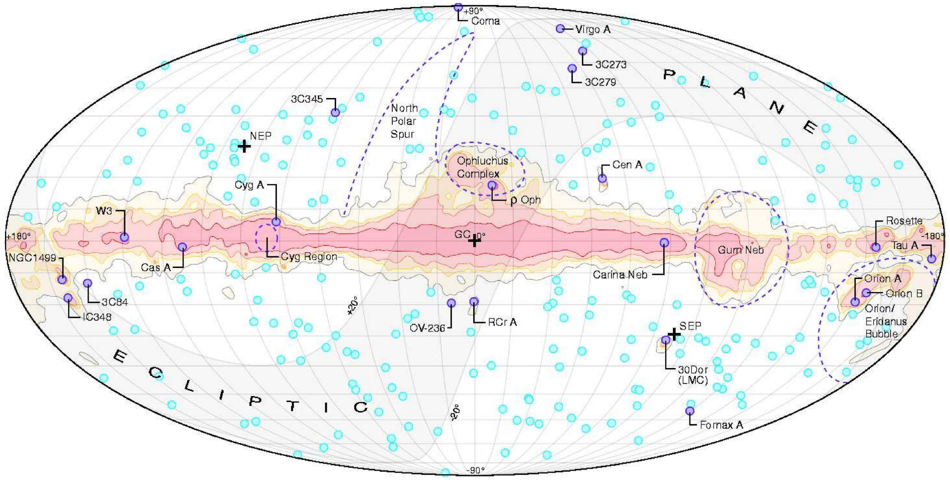


Wilkinson Microwave Anisotropy Probe (WMAP):

- Launched 2001 June 30, measurements began 2001 August 10
- Orbit around 2nd Lagrange Point of Sun-Earth System
- Highly precise radiometers of high spatial resolution (best: 0.21° FWHM in W-Band at 3.2 mm) in five wavebands

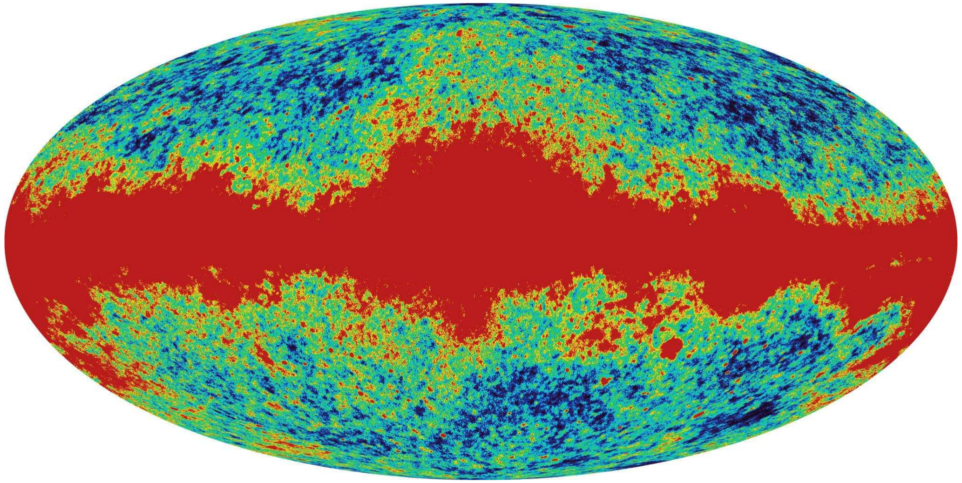
(see Bennett et al. 2003 for an overview).



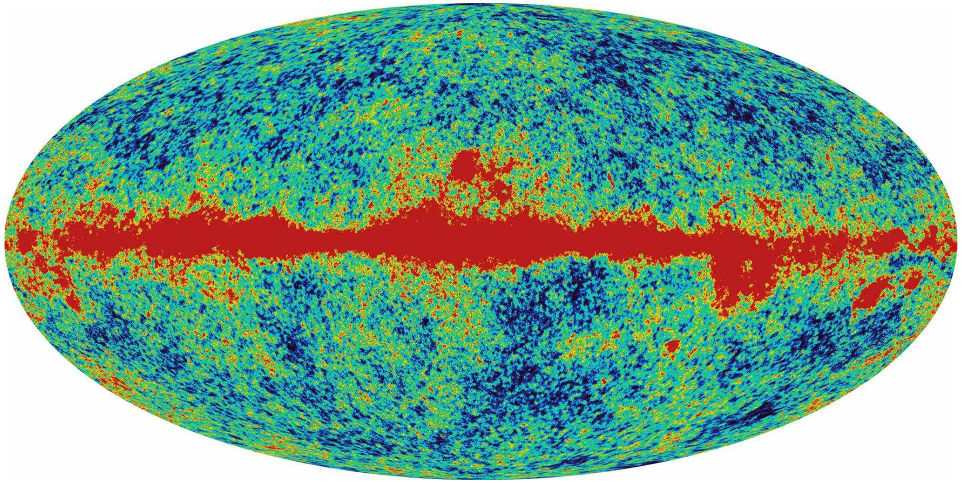


Foreground features of the microwave sky (Bennett et al., 2003).

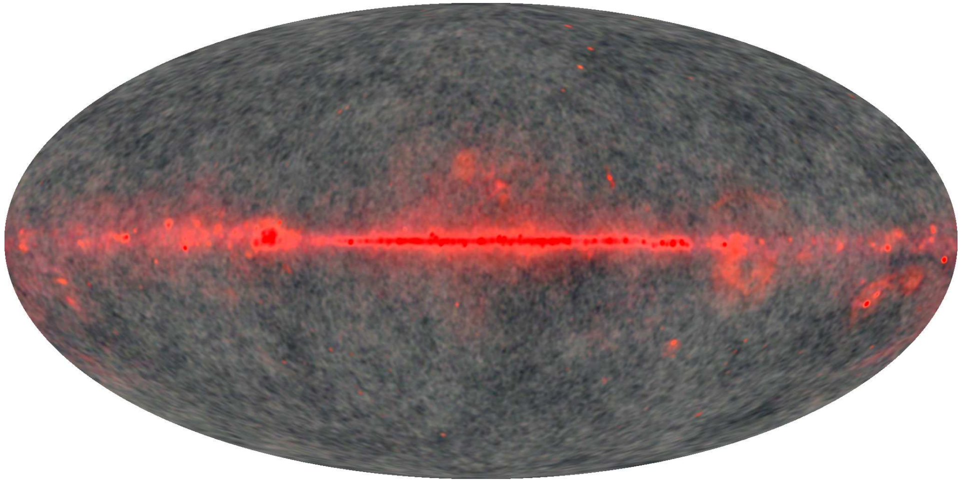
Sunyaev Zeldovich effect is expected to be strongest in Coma cluster, temperatures of $-0.34 \pm 0.18\,\mathrm{mK}$ in W and $-0.24 \pm 0.18\,\mathrm{mK}$ in K-band; barely detectable with WMAP, does not contaminate maps.



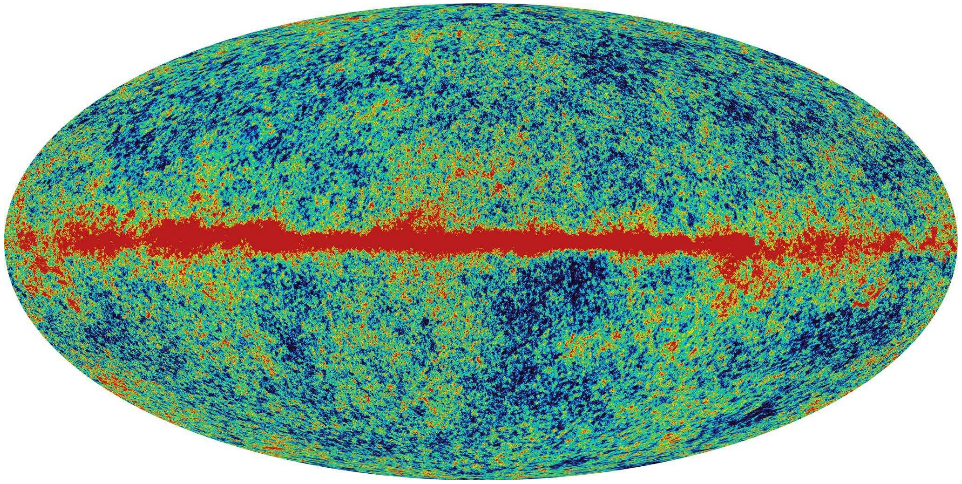
WMAP, K-Band, $\lambda = 13\,\mathrm{mm}$, $\nu = 22.8\,\mathrm{GHz}$, $\theta = 0.83^\circ$ FWHM



WMAP, Q-Band, $\lambda = 7.3\,\mathrm{mm}$, $\nu = 40.7\,\mathrm{GHz}$, $\theta = 0.49^\circ$ FWHM

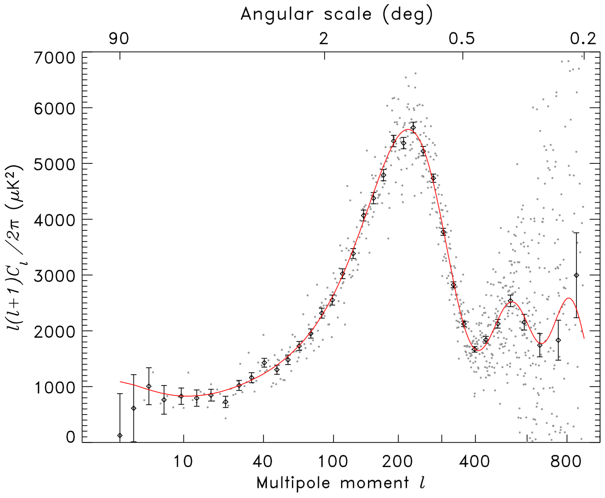


Different spectral signature enables identification of Galaxy foreground radiation



WMAP, W-Band, $\lambda = 3.2\,\mathrm{mm}$, $\nu = 93.5\,\mathrm{GHz}$, $\theta = 0.21^\circ$ FWHM

Power Spectrum, I



(WMAP, 1 year data Spergel et al., 2003, Fig. 1)

Best fit parameters for WMAP data after 3 years of measurements and assuming $\Omega = 1$ (Spergel et al., 2007):

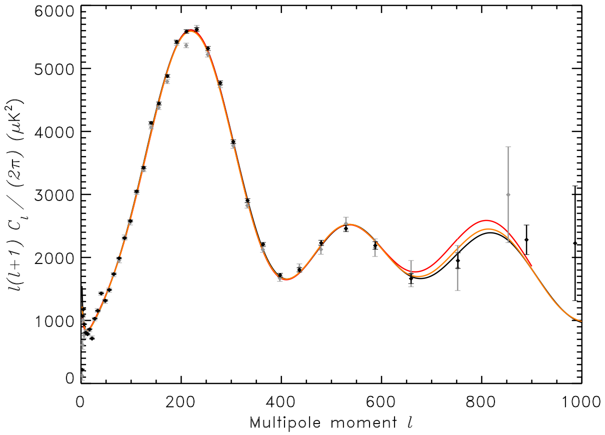
$$\begin{aligned} h &= 0.732 \pm 0.032 \\ \Omega_\mathrm{m}h^2 &= 0.1277 \pm 0.0080 \\ \Omega_\mathrm{b}h^2 &= 0.02229 \pm 0.00073 \\ \tau &= 0.089 \pm 0.030 \end{aligned}$$

and initial density fluctuations with an amplitude of $\sigma_8 = 0.761 \pm 0.049$ and slope 0.958 ± 0.016.

Power spectrum requires that Λ behaves like a cosmological constant.

$\Longrightarrow$ Very good agreement between data and theory

Power Spectrum, II



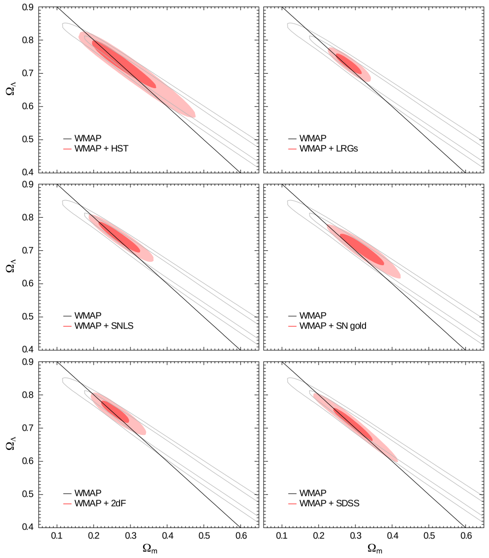
(WMAP, 3 year data Spergel et al., 2007, Fig. 2)

Best fit parameters for WMAP data after 3 years of measurements and assuming $\Omega = 1$ (Spergel et al., 2007):

$$h = 0.732 \pm 0.032$$
$$\Omega_\mathrm{m} h^2 = 0.1277 \pm 0.0080$$
$$\Omega_\mathrm{b} h^2 = 0.02229 \pm 0.00073$$
$$\tau = 0.089 \pm 0.030$$

and initial density fluctuations with an amplitude of $\sigma_8 = 0.761 \pm 0.049$ and slope 0.958 ± 0.016.
Power spectrum requires that Λ behaves like a cosmological constant.
$\Longrightarrow$ Very good agreement between data and theory

Omega



Using WMAP data alone gives

$$\Omega_\mathrm{m} = 0.415 \quad \Omega_\Lambda = 0.630 \tag{9.90}$$

Combining WMAP with other measurements generally results in $\Omega_k \sim -0.01 \pm 0.01$, i.e., measurements consistent with a flat universe.

In the year 1 data, a model with $\Omega_\Lambda = 0$ is found to be consistent with the WMAP data only if $H_0 = 32.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_\mathrm{tot} = 1.28$
$\Longrightarrow$ Ruled out by other measurements.

(Spergel et al., 2007, Fig. 21)

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The End