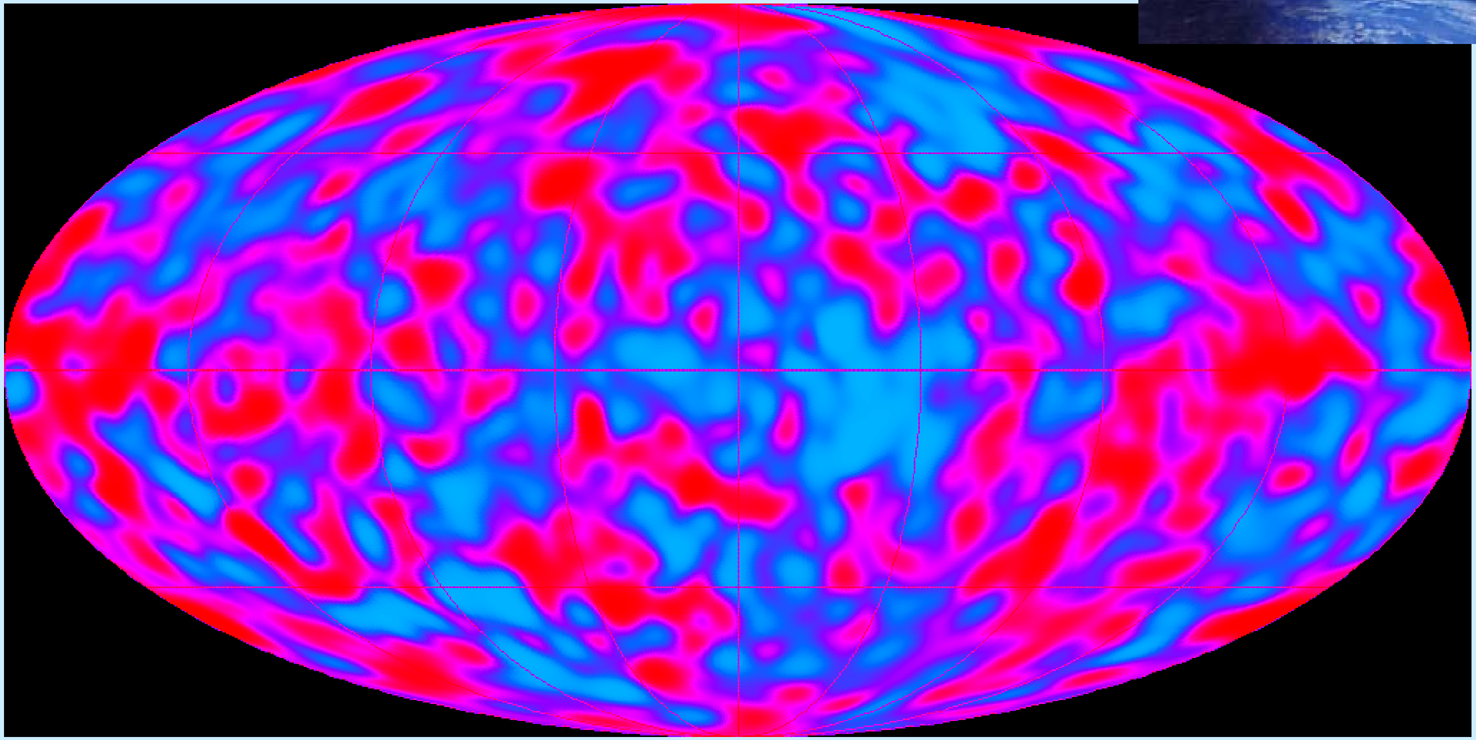
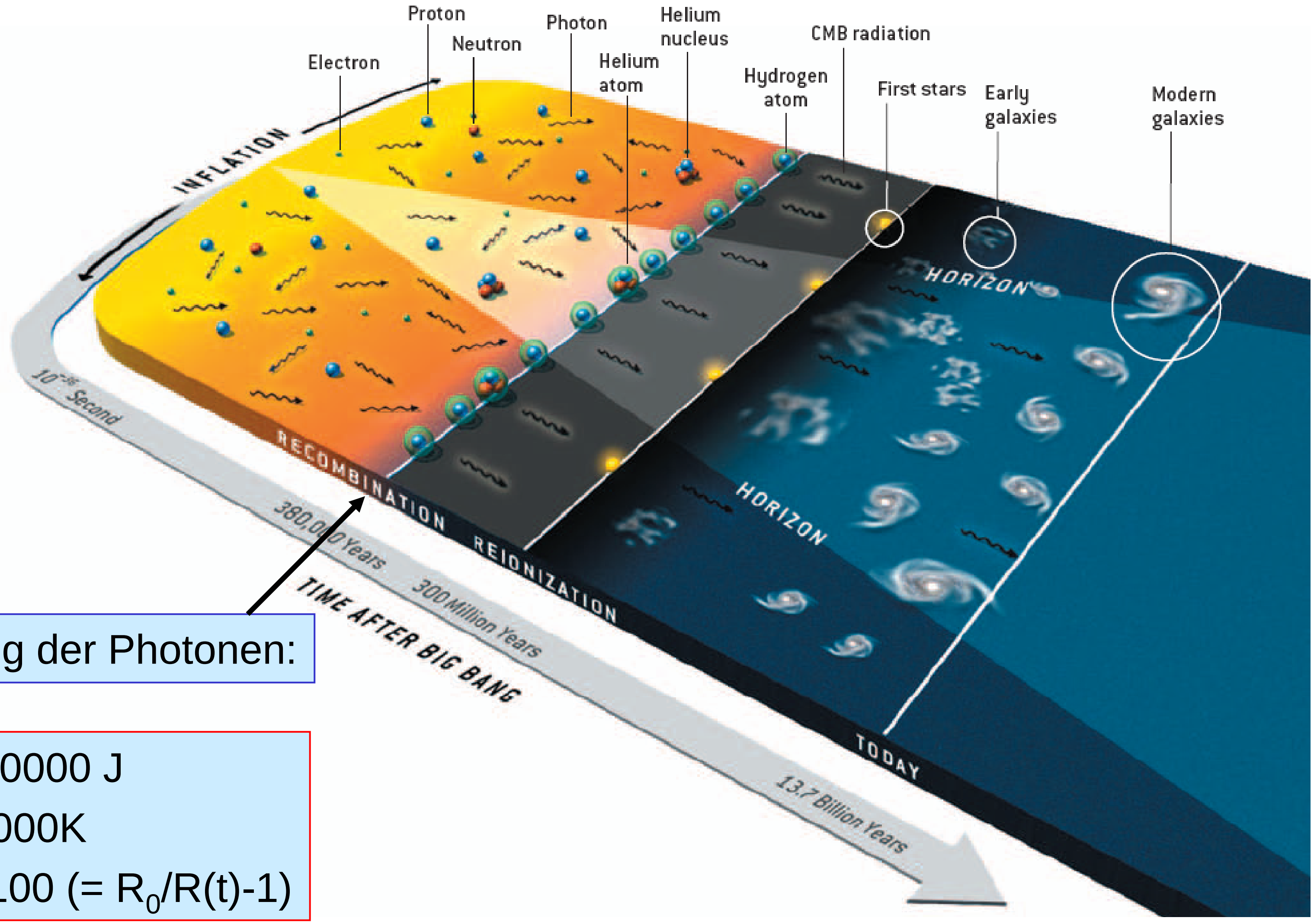
2.5 Mikrowellen-Hintergrundstrahlung (CMBR)

Entkopplung der Photonen:

- $t \approx 400000$ J
- $T \approx 3000$K
- $z \approx 1100$ $(= R_0/R(t)-1)$



Entwicklung des Universums

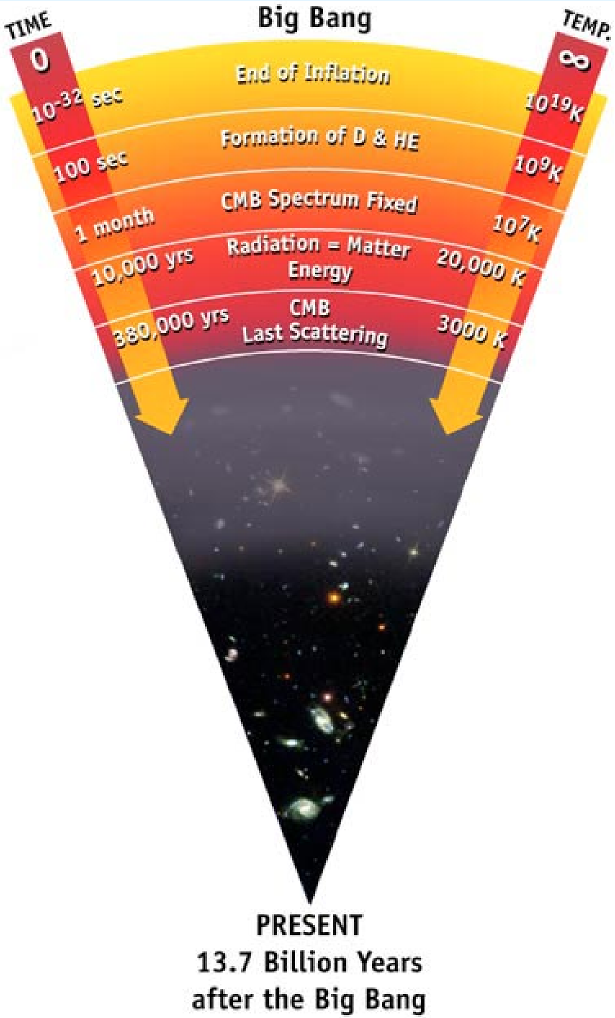


Entkopplung der Photonen:

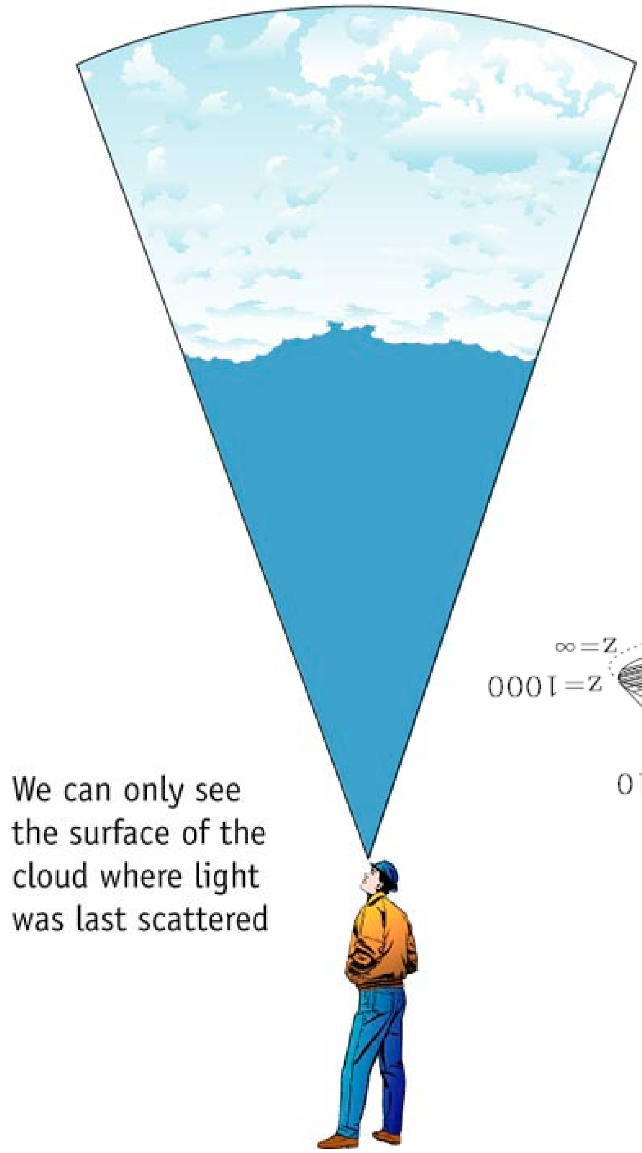
- $t \approx 400000$ J
- $T \approx 3000$K
- $z \approx 1100$ ($= R_0/R(t)-1$)

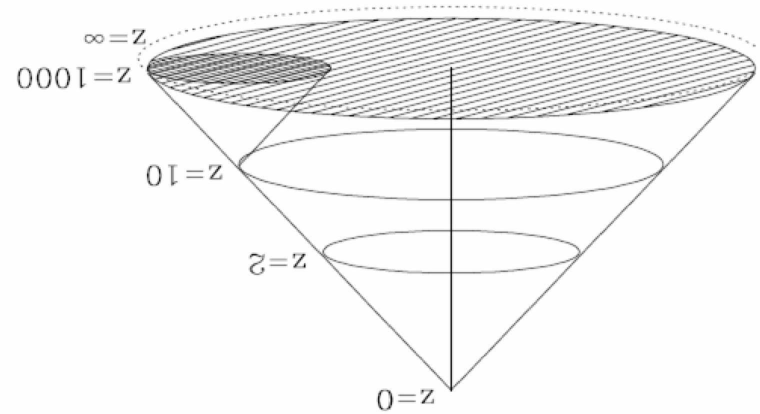
Die ‘letzte Streufläche’ der Photonen

(Last Scattering Surface)



The cosmic microwave background Radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.

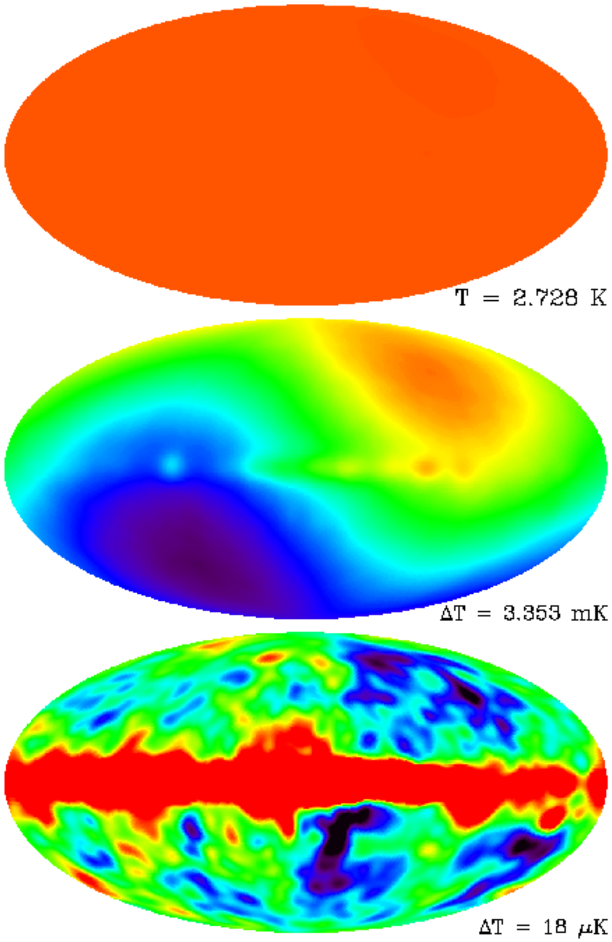


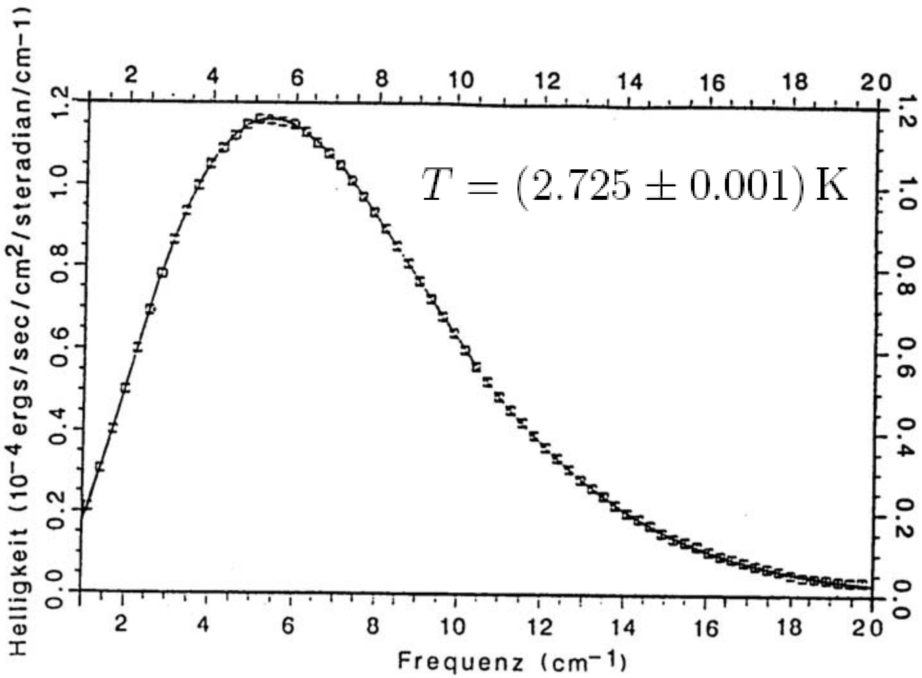


Phasen der kosmologischen Entwicklung

t [s]	E [GeV]	T [K]	R [m]	
10^{-44}	10^{19}	10^{32}	10^{-5}	Planckzeit, $\lambda_{Compton} \approx r_S$
10^{-36}	10^{15}	10^{28}	10^{-2}	$E \approx M_X$, GUT-Symmetrie-Brechung, Baryogenese
10^{-10}	10^{2}	10^{15}	10^{12}	$E \approx M_W$, $\mathrm{SU}(2)_L \times \mathrm{U}(1)$-Symmetrie-Brechung
10^{-6}	10^{0}	10^{13}	10^{14}	Quark-Confinement, $p\bar{p}$-Annihilation
10^{0}	10^{-3}	10^{10}	10^{17}	Neutrinos entkoppeln, e^+e^--Annihilation
10^{2}	10^{-4}	10^{9}	10^{18}	Bildung leichter Kerne (Nukleosynthese)
10^{12}	10^{-9}	10^{4}	10^{23}	Photonen entkoppeln, Übergang von Strahlungs- zu Materie-Dominanz, Bildung von Atomen, Sternen, Galaxien
10^{17}	10^{-13}	10^{0}	10^{26}	Bildung des Sonnensystems und von organischem Leben, heute ($t_0 \approx 2 \cdot 10^{10}$ Jahre)

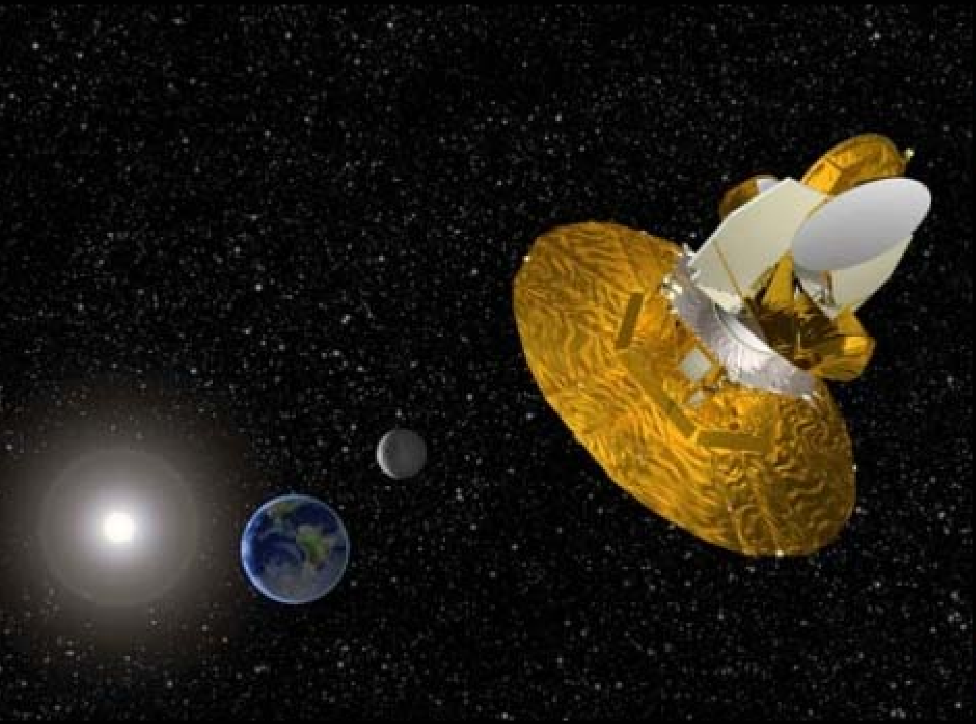
COBE-Messungen

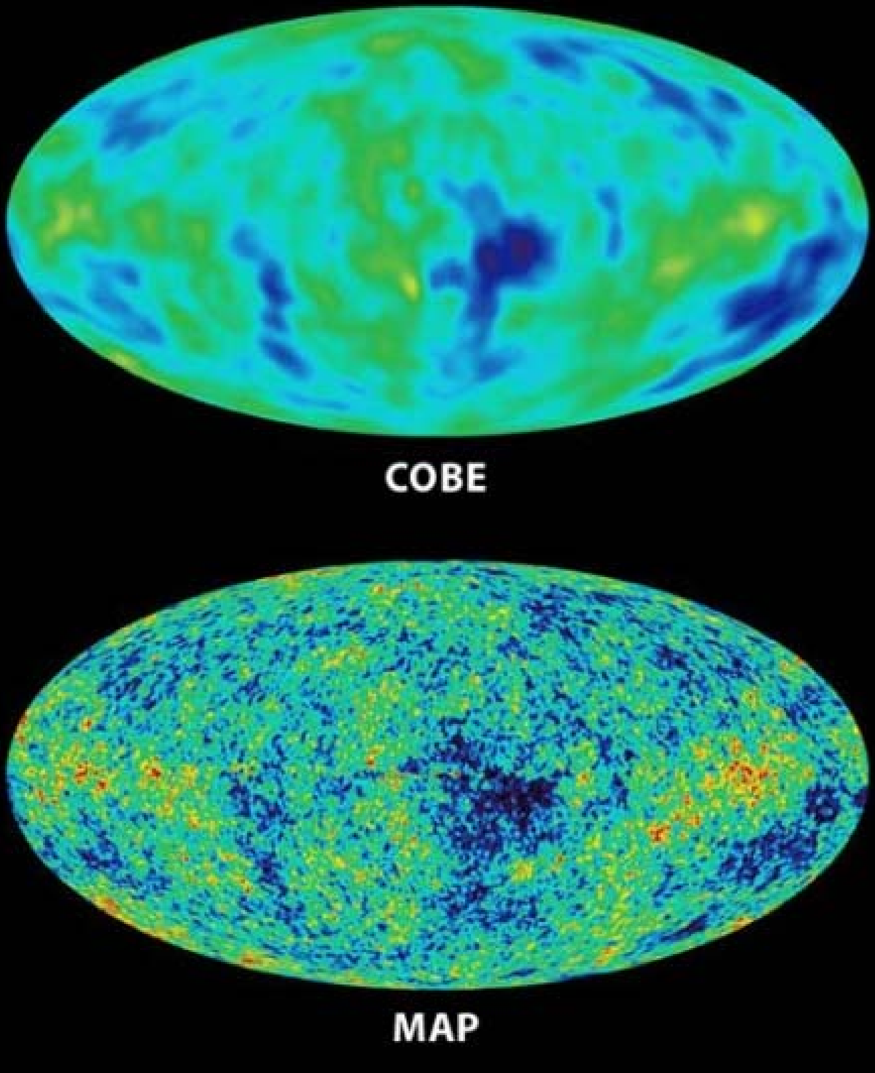




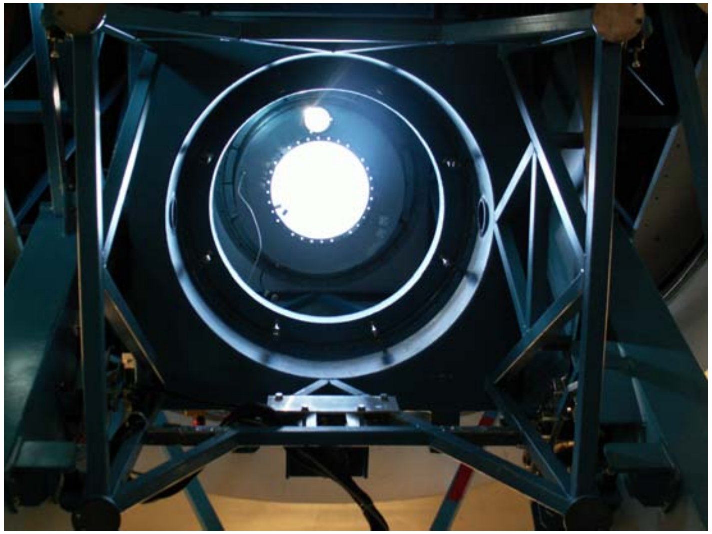
$$I(\nu)d\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}d\nu,$$

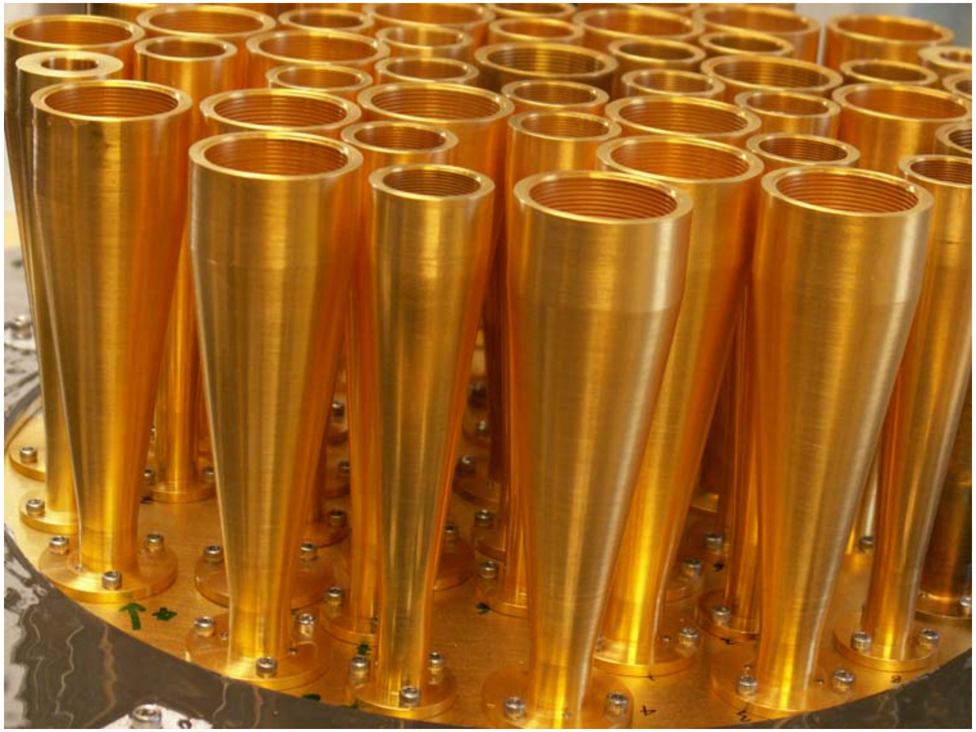
WMAP





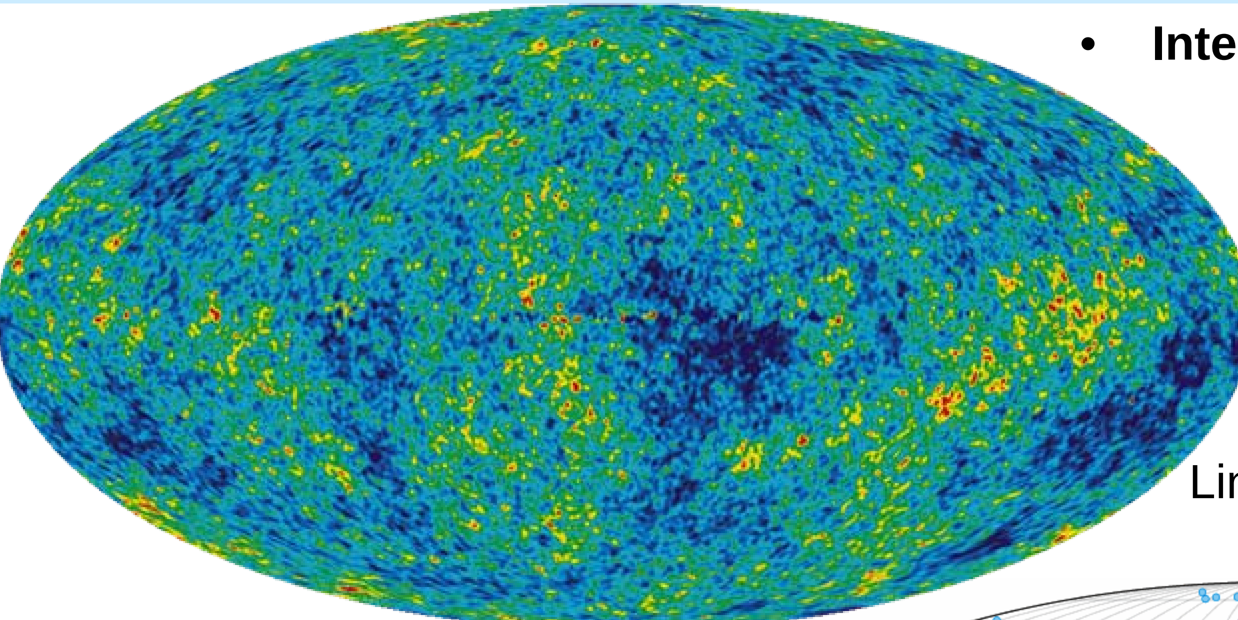
DASI-Feier am Südpol





Hörner zum Empfangen der CMBR

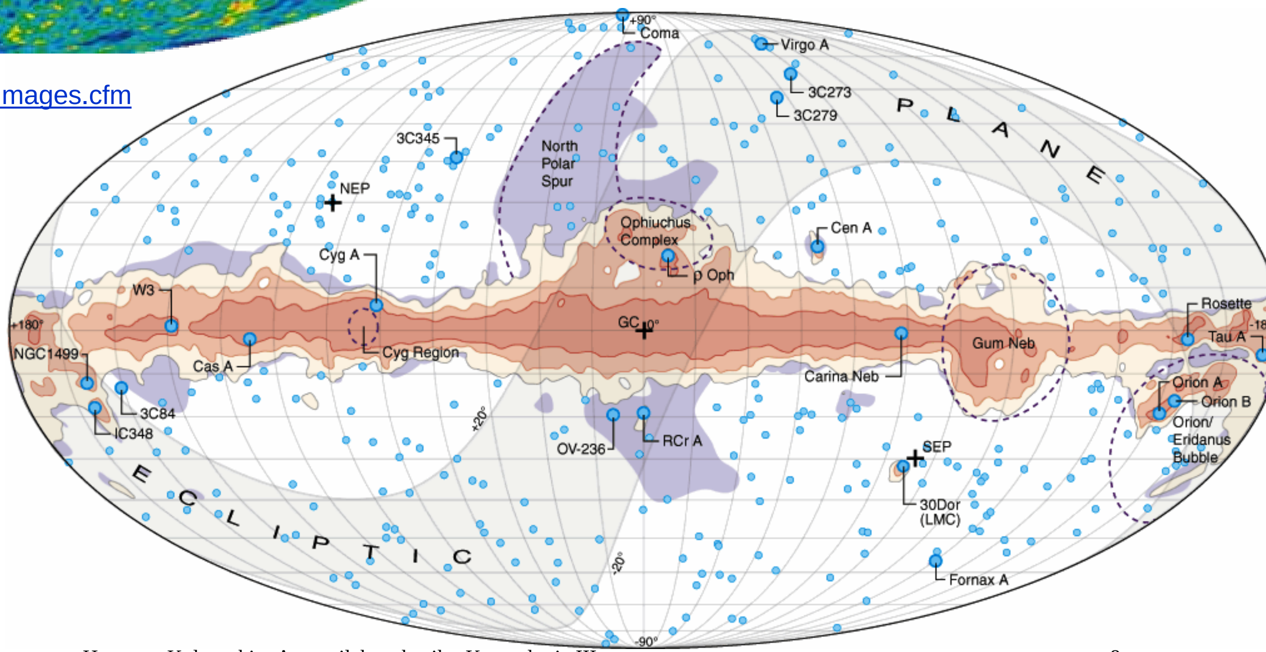
ΔT-Karte in Galaktischen Koordinaten



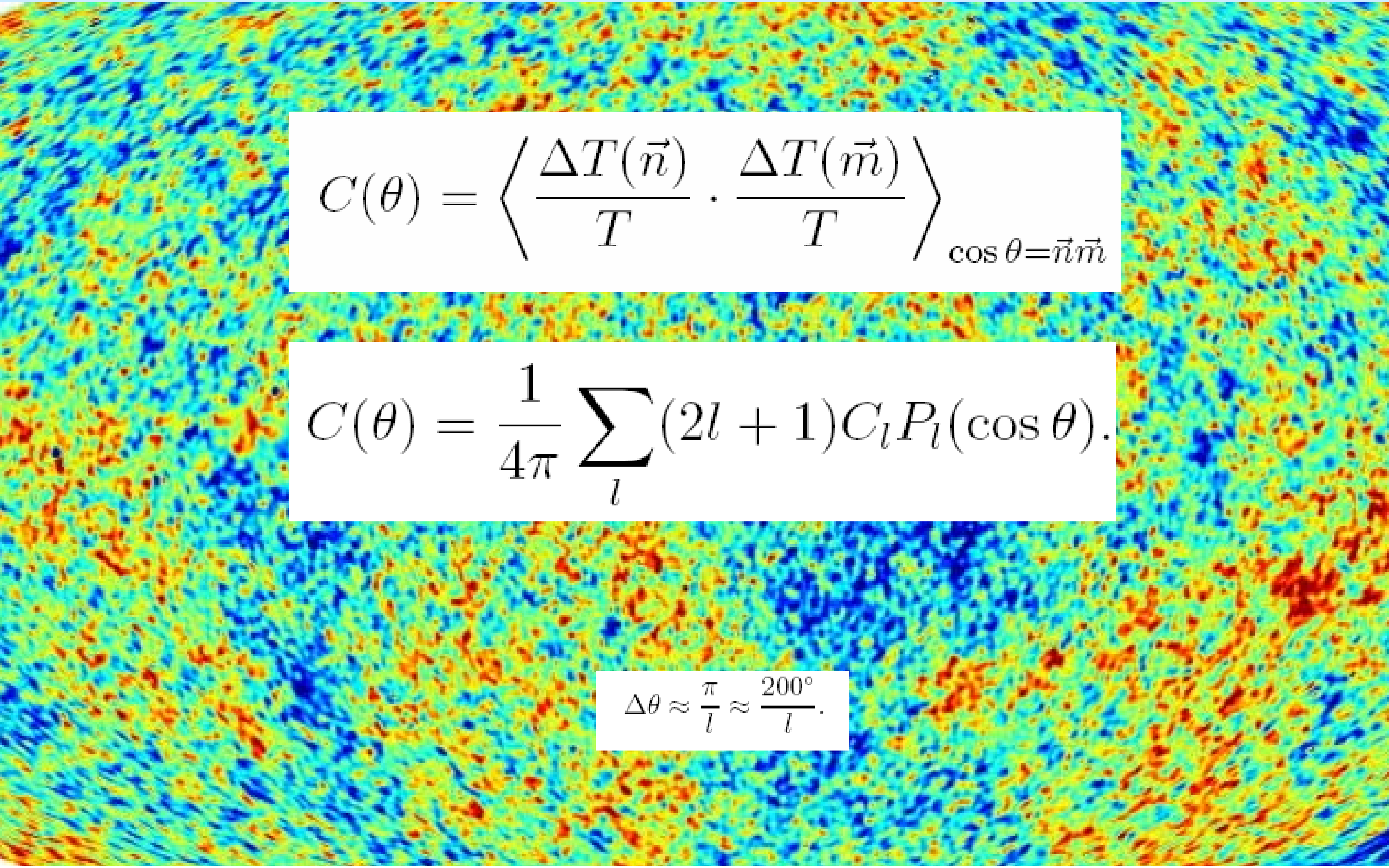
- **Internal Linear Combination Map**
  Galactic coordinates,
  Mollweide projection

Linear scale from -200 to 200 μK

http://lambda.gsfc.nasa.gov/product/map/current/m_images.cfm



Legendre-Entwicklung der CMB-Anisotropie

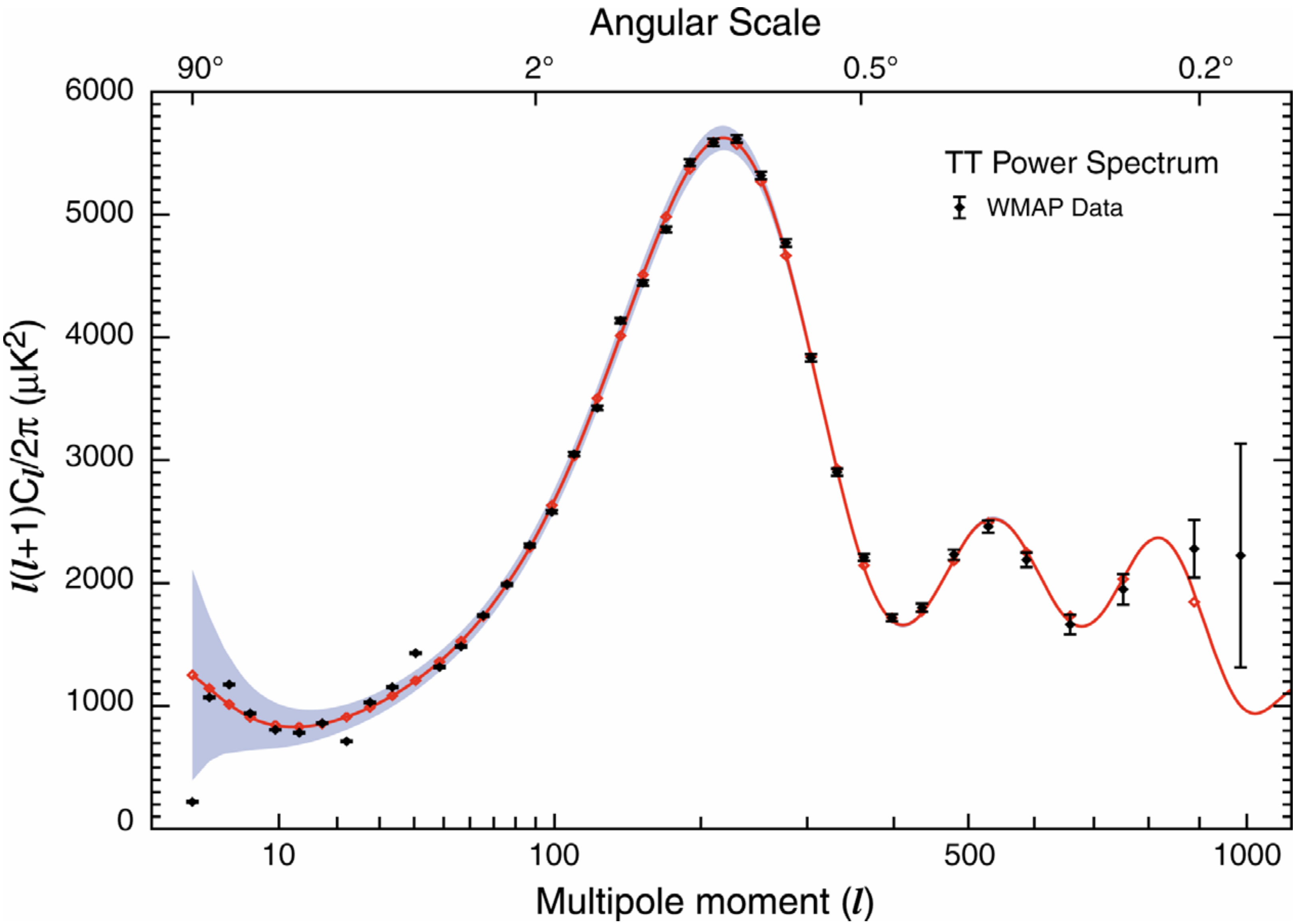


$$C(\theta) = \left\langle \frac{\Delta T(\vec{n})}{T} \cdot \frac{\Delta T(\vec{m})}{T} \right\rangle_{\cos\theta = \vec{n}\vec{m}}$$

$$C(\theta) = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\cos\theta).$$

$$\Delta\theta \approx \frac{\pi}{l} \approx \frac{200^\circ}{l}.$$

CMB-Anisotropie: Multipol-Leistungsspektrum

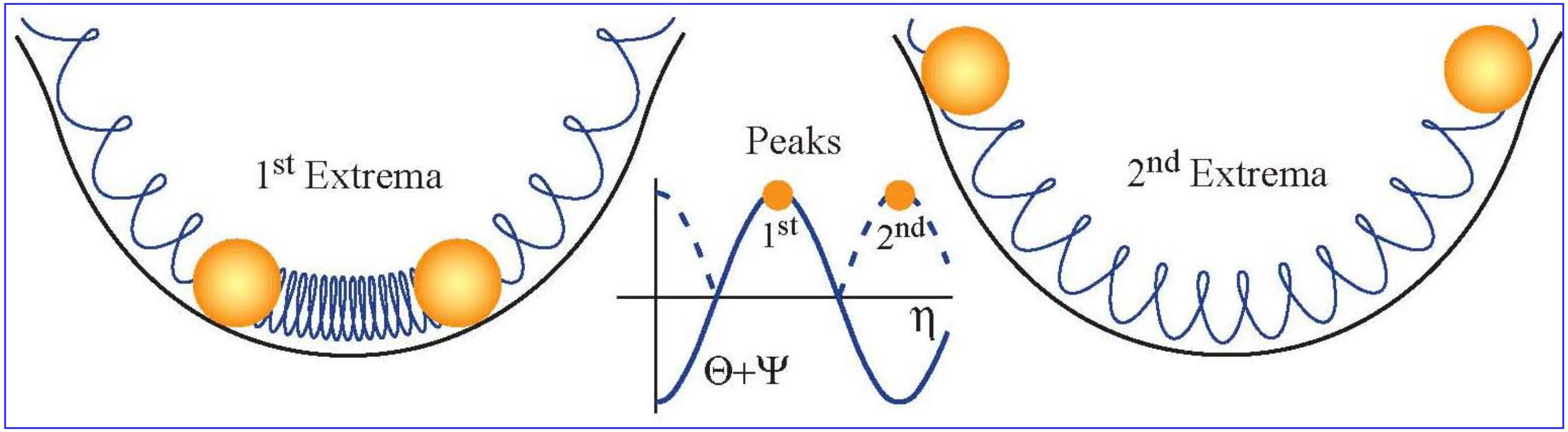


Akustische Schwingungen

Schallhorizont zur Zeit t

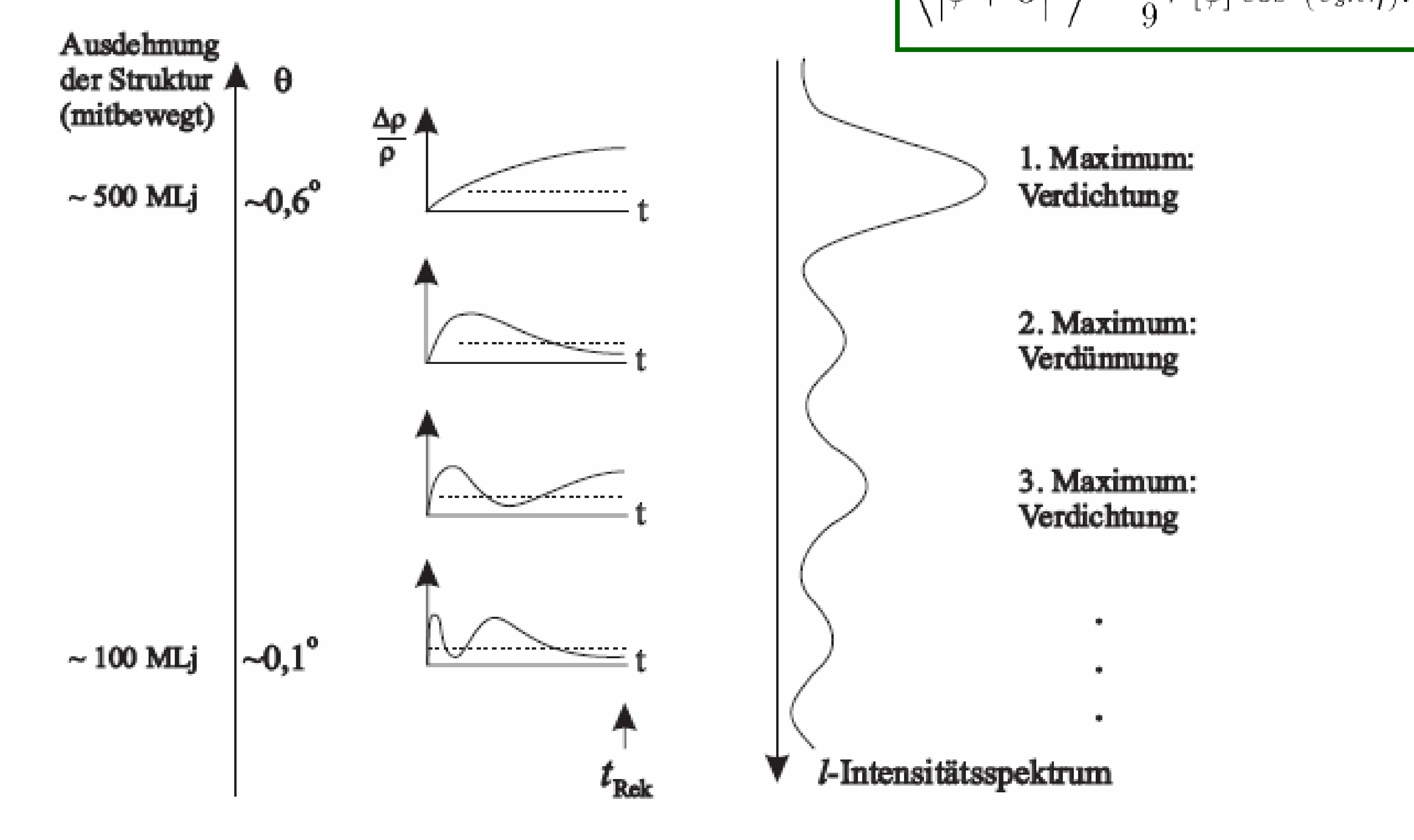
$$d_s(t) \approx \frac{v_s}{H(t)}$$

$$\left.\begin{array}{l} v_s = \sqrt{\dfrac{\partial p}{\partial \rho}}. \\[2em] p = \dfrac{1}{3}\rho\, c^2 \end{array}\right\} \Rightarrow \quad v_s = \frac{1}{\sqrt{3}}c$$



‚Acoustic Peaks‘

$$\left\langle \left| \hat{\phi} + \hat{\Theta} \right|^2 \right\rangle = \frac{1}{9} V[\hat{\phi}] \cos^2(v_s k \eta).$$

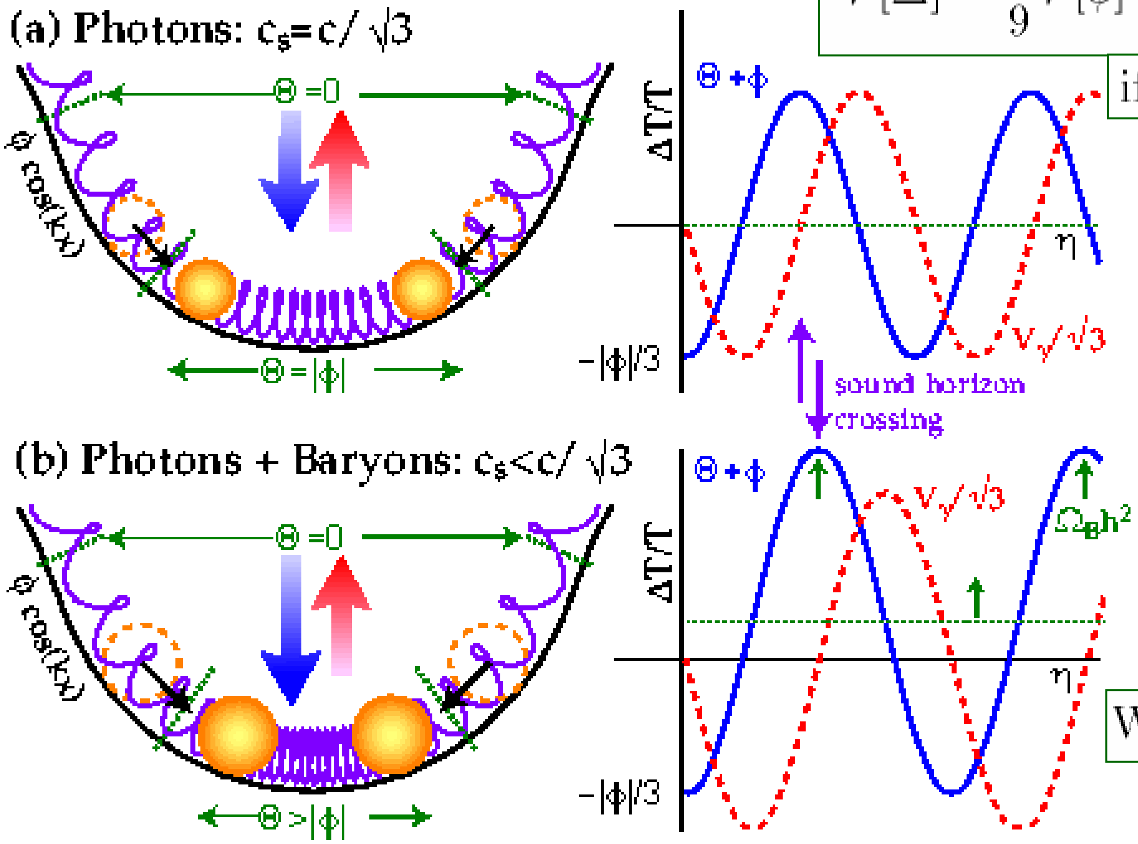


Akustische Schwingungen

Wayne Hu‘s Tutorial

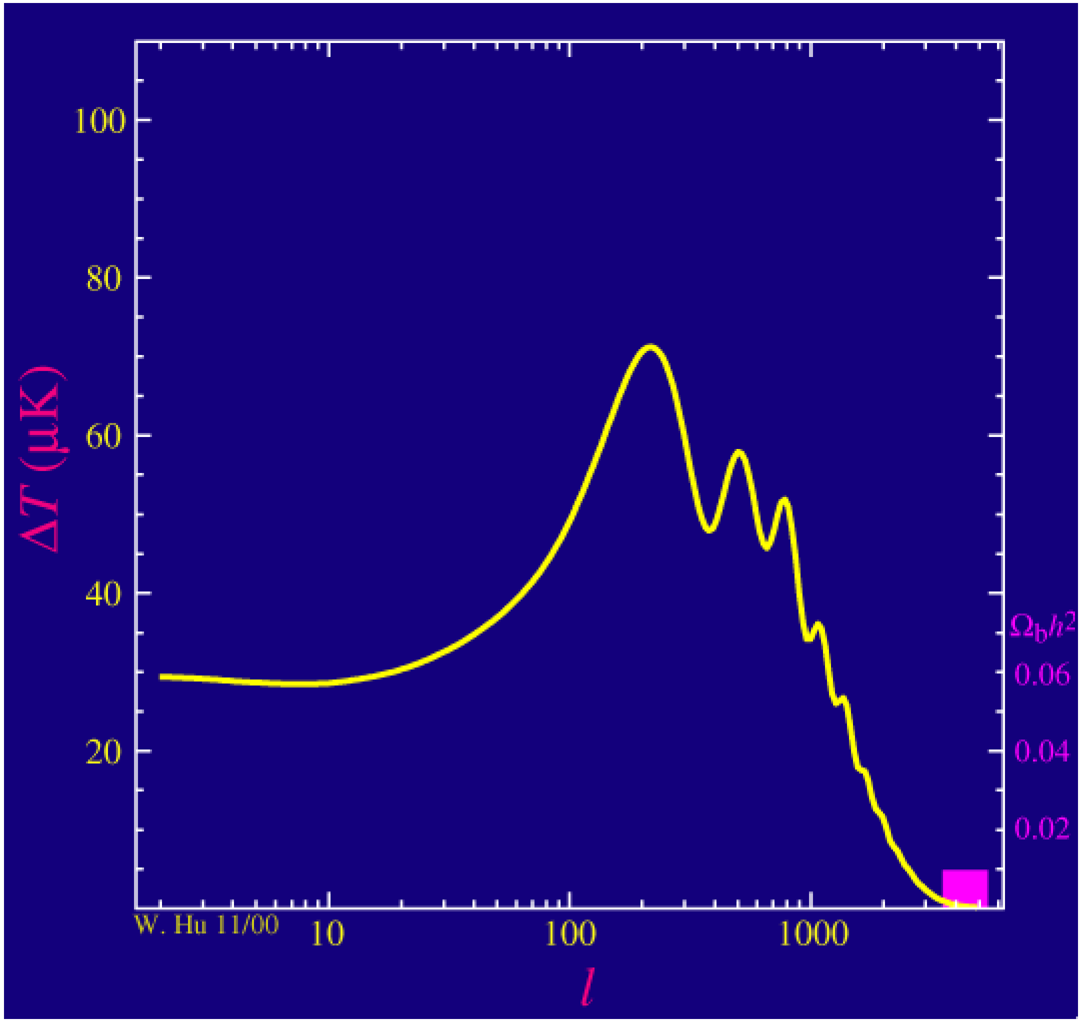
$$V[\Delta] = \frac{1}{9}V[\hat{\phi}]\left[\sin^2(v_s\eta k) + \cos^2(v_s\eta k)\right] = \frac{1}{9}V[\hat{\phi}]$$

if the sound speed v_S is exactly $c/\sqrt{3}$

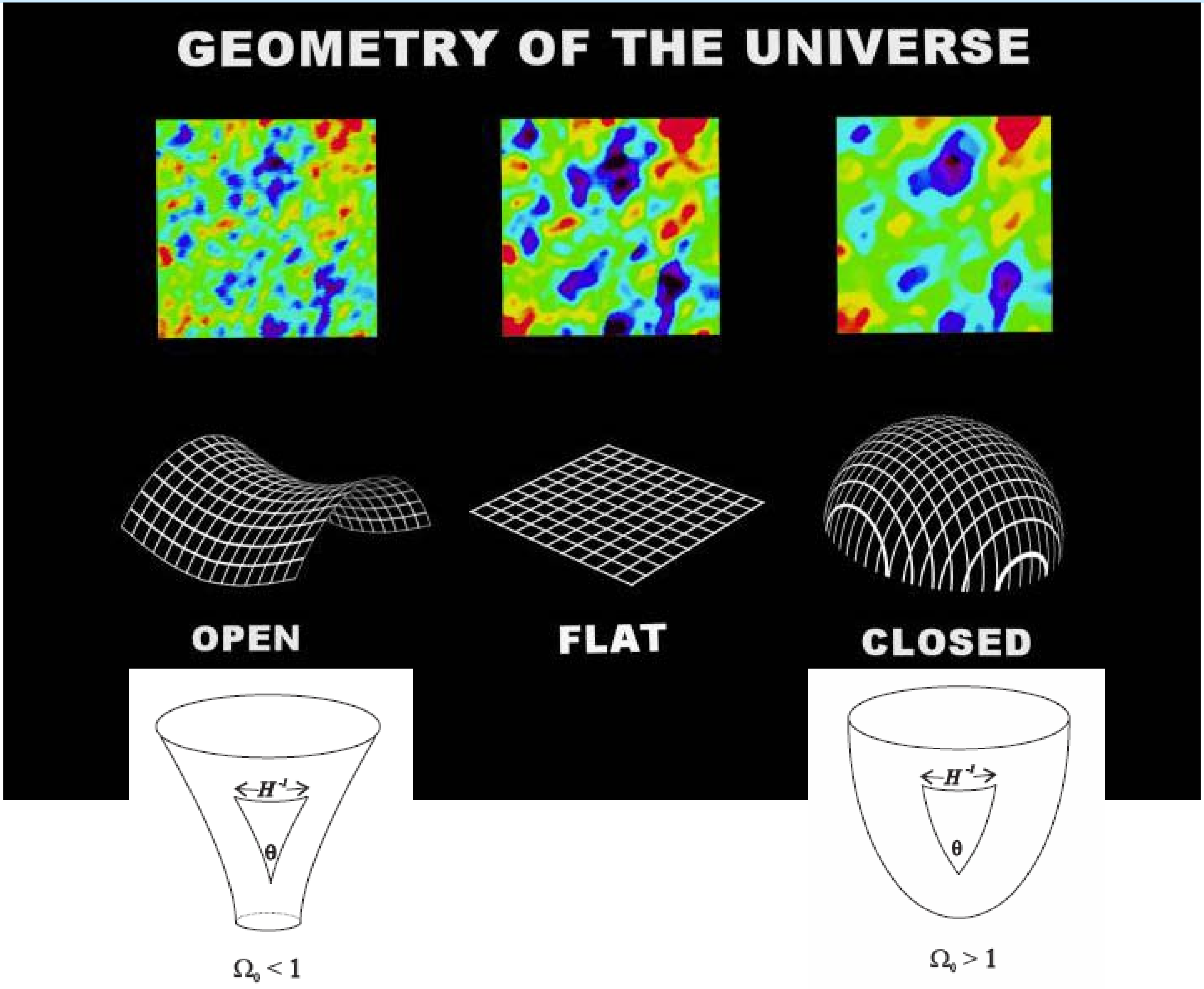


When the sound speed is lower

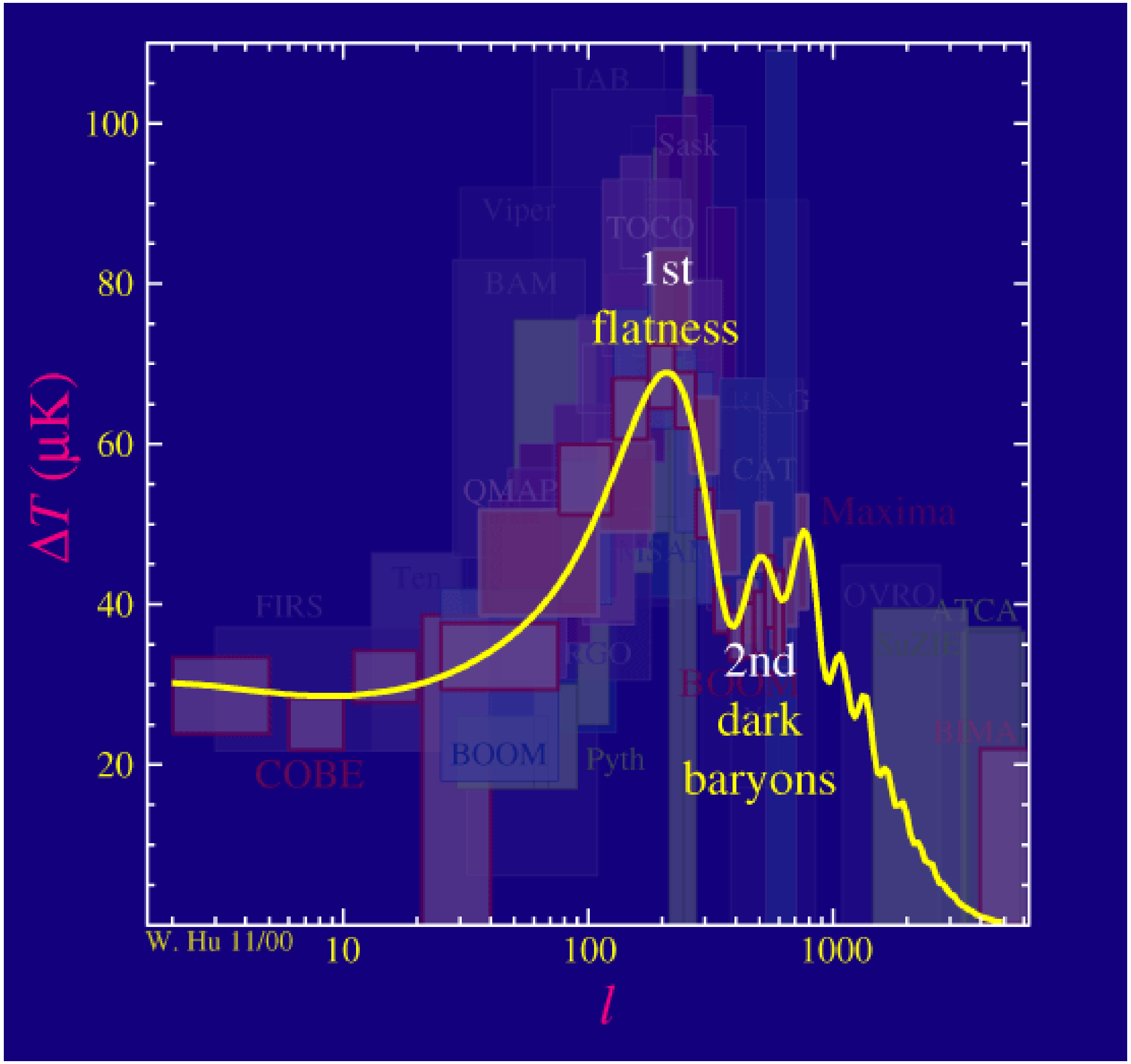
Was wäre wenn …



Raumkrümmeng



Sensitivität des Spektrums



Fitte deinen Kosmos

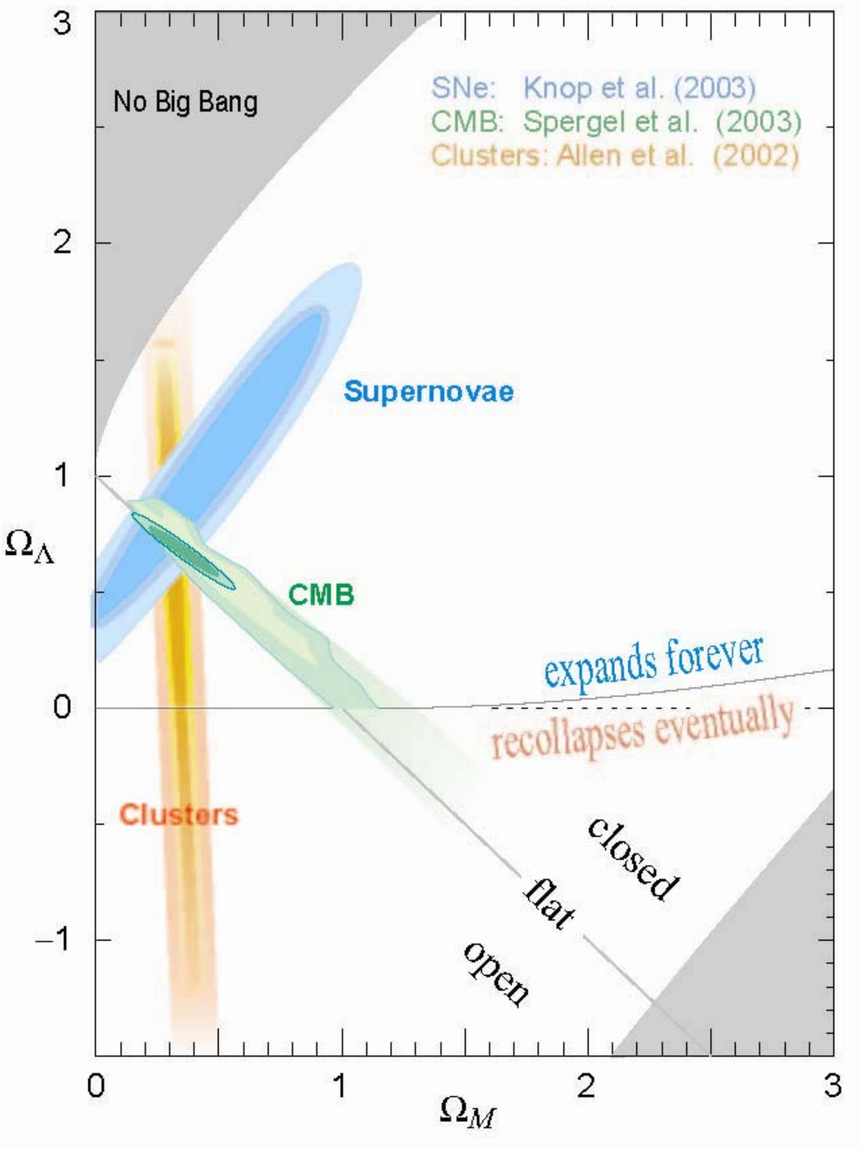
http://wmap.gsfc.nasa.gov/resources/camb_tool/cmb_plot.swf

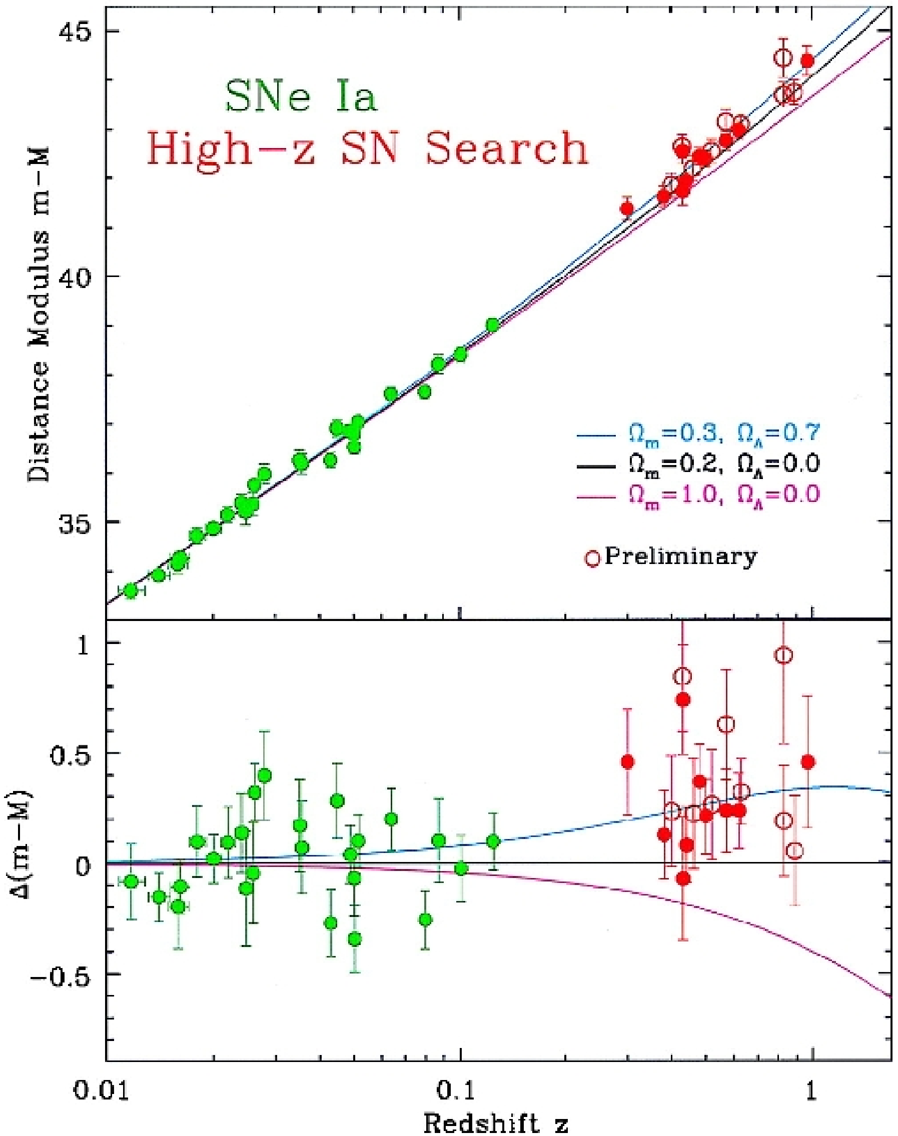
Kosmologische Parameter

Sensitivität des CMB-Multipolspektrums

Parameter	Symbol	Value
Hubble parameter	h	0.73 ± 0.03
Total matter density	Ω_{m}	$\Omega_{\mathrm{m}} h^2 = 0.128 \pm 0.008$
Baryon density	Ω_{b}	$\Omega_{\mathrm{b}} h^2 = 0.0223 \pm 0.0007$
Cosmological constant	Ω_{Λ}	See Ref. 2
Radiation density	Ω_{r}	$\Omega_{\mathrm{r}} h^2 = 2.47 \times 10^{-5}$
Neutrino density	Ω_{ν}	See Sec. 21.1.2
Density perturbation amplitude	σ_8	0.76 ± 0.05
Density perturbation spectral index	n	$n = 0.958 \pm 0.016$
Tensor to scalar ratio	r	$r < 0.65$ (95% conf)
Ionization optical depth	τ	$\tau = 0.089 \pm 0.030$
Bias parameter	b	See Sec. 21.3.4

Kosmologische Konstante





Was wir gelernt haben

- The Universe recombined at $z \simeq 1100$ and started to become ionized again at $z \simeq 10$.
- The geometry of the Universe is close to flat.
- Both Dark Matter and Dark Energy are required.
- Gravitational instability is sufficient to grow all of the observed large structures in the Universe.
- Topological defects were not important for structure formation.
- There are 'synchronized' super-Hubble modes generated in the early Universe.
- The initial perturbations were adiabatic in nature.
- The perturbations had close to Gaussian (*i.e.*, maximally random) initial conditions.