cosmic microwave background physics

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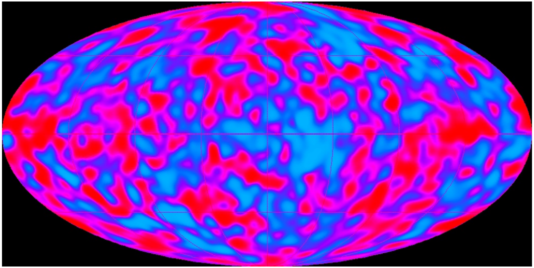
outline

1. thermal history
2. CMB
3. summary

cosmic microwave background



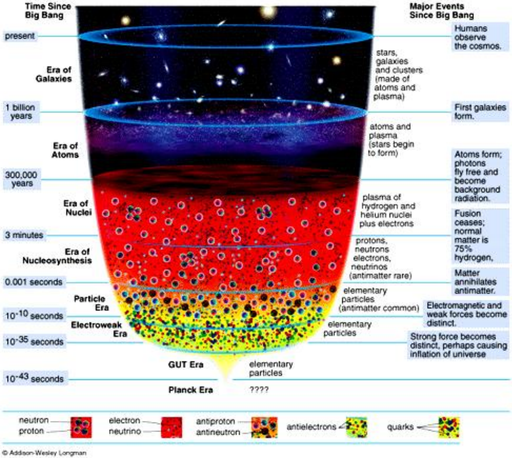
source: COBE observations

- the Universe is filled with radiation corresponding to a temperature of $2.726\mathrm{K}$
- small fluctuations of the temperature of the sky of order 10^{-5}
- radiation from the formation of the first atoms

thermal history of the universe

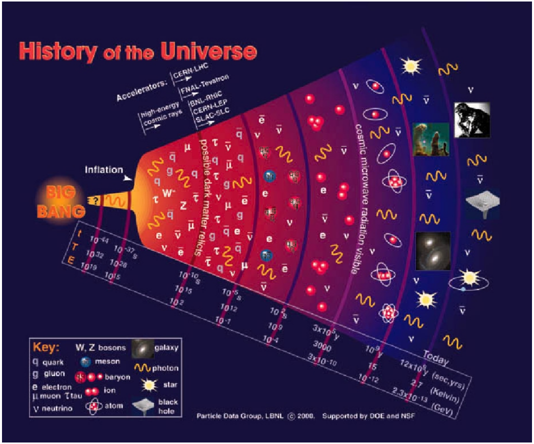
- temperature of fluids drop while universe expands
- 2 important stages
  1. temperature is high enough to allow nuclear reactions
     → big bang nucleosynthesis ($z \simeq 10^{10}$)
  2. temperature is high enough to ionise hydrogen
     → cosmic microwave background ($z \simeq 10^{3}$)

thermal history of the universe: overview



source: Addison-Wesley

thermal history of the universe: particle interactions



source: particle data group

temperature and Hubble expansion

- Hubble expansion is an **adiabatic** process $\delta Q = 0$
- adiabatic equation: $V^{\kappa-1}T$ = const with adiabatic index $\kappa \equiv c_p/c_V$
- early times: universe is filled with photons $\kappa = 4/3$ (relativistic gas)

$$T \propto V^{-1/3} \propto a^{-1} \tag{1}$$

- late times: universe is filled with (dark) matter $\kappa = 5/3$ (classical gas)

$$T \propto V^{-2/3} \propto a^{-2} \tag{2}$$

Planck-spectrum for photons

- photons in thermodynamic equilibrium are characterised by the Planck-spectrum

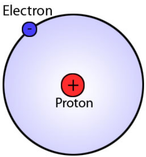
$$n(p,T) = \frac{g}{(2\pi\hbar)^3}\int_0^\infty \mathrm{d}p \frac{4\pi p^2}{\exp(\epsilon(p)/k_B T) - 1} \quad (3)$$

- Planck-spectrum depends only on temperature
- from the number density $n(p,T)$ of photons we can compute number, energy and pressure by integration

$$n_\gamma = \frac{g_\gamma \zeta(3)}{\pi^2}\left(\frac{k_B T}{\hbar c}\right)^3, u_\gamma = \frac{g_\gamma \pi^2}{30}\frac{(k_B T)^4}{(\hbar c)^3}, p_\gamma = u_\gamma/3 \quad (4)$$

- there are two polarisation states, $g_\gamma = 2$
- pure magic: $u_\gamma \propto a^{-4}$ (dilution and redshift), and at the same time: $u \propto T^4$, so $T \propto a^{-1}$ as predicted from the adiabatic equation

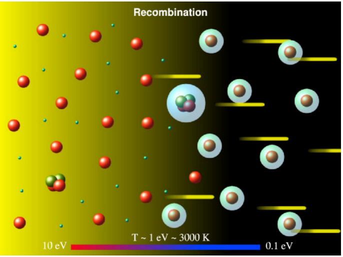
first atoms form



source: science kids

- at high temperatures, the reaction $p + e^- \leftrightarrow H + \gamma$ proceeds in **both** directions
- as the Universe expands, the temperature drops because of adiabatic cooling
- at low temperatures, the reaction only proceeds in the $\rightarrow$-direction and atoms form
- this happens at $\sim 10^4$K roughly 300000 years after the big bang

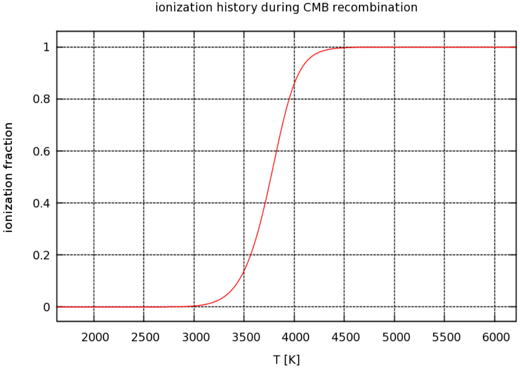
photon propagation



source: Ned Wright

- while the Universe is hot, all atoms are ionised: photons scatter off electons and can't propagate
- Universe cools and atoms form: photons can travel freely and the Universe becomes transparent
- we see this radiation redshifted by 1000 today as the microwave background

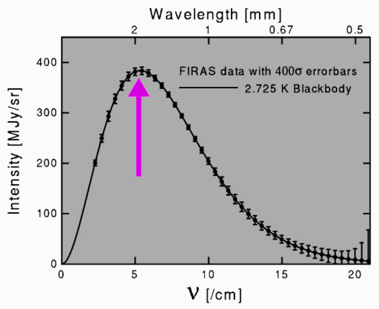
formation of atoms



source: wikipedia

- fraction of neutral atoms is a **steep** function of temperature
- while the Universe cools down, the atoms form **really fast**

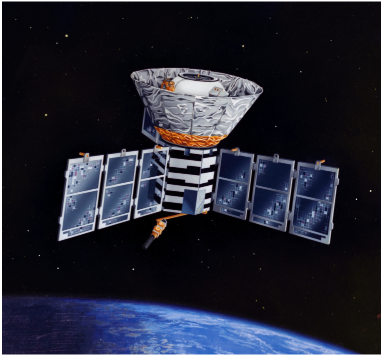
cosmic microwave background



source: FIRAS@COBE

- atoms were produced in thermal equilibrium
- photons should follow a Planck-distribution
- redshifted by 1000 since then, from optical to microwave

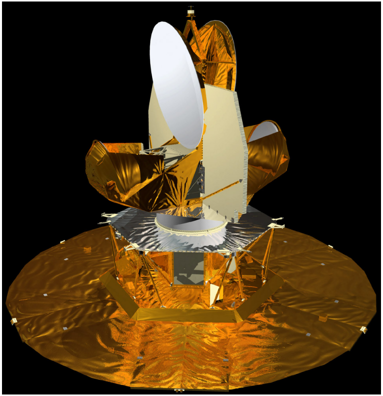
COsmic Background Explorer



source: NASA

- COBE-satellite

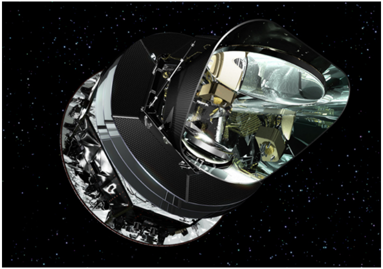
Wilkinson Microwave Anisotropy Probe



source: NASA

- WMAP-satellite

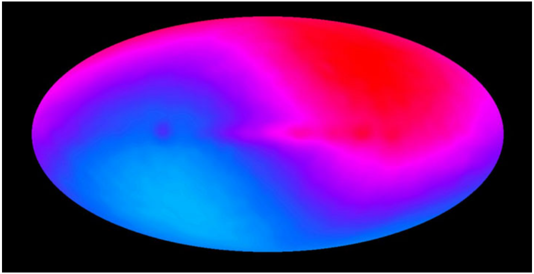
Planck-surveyor



source: ESA

- Planck-satellite

CMB motion dipole



source: COBE

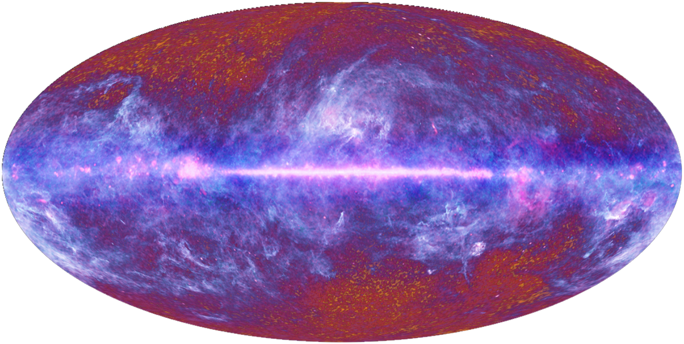
- the most important structure on the microwave sky is a dipole
- CMB dipole is interpreted as a relative motion of the earth
- CMB dispole has an amplitude of $10^{-3}K$, and the peculiar velocity is $\beta = 371\mathrm{km/s}/c$

$$T(\theta) = T_0\,(1 + \beta\cos\theta) \qquad (5)$$

cosmic microwave background

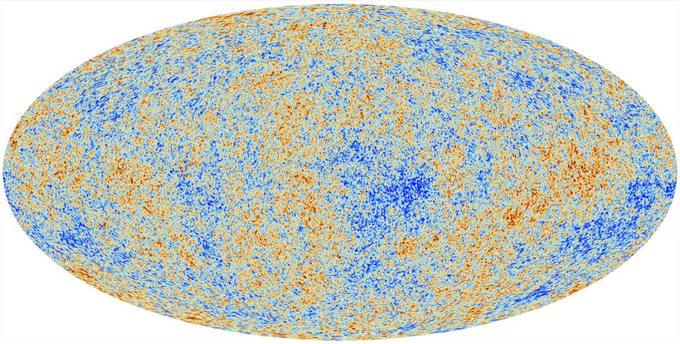
- the temperature of the sky is not constant, but there are very small fluctuations
- the hot baryon plasma feels fluctuations in the distribution of (dark) matter by gravity
- at the point of (re)combination:
    - hydrogen atoms are formed
    - photons can propagate freely
- perturbations can be observed by two effects:
    - plasma was not at rest, but flowing towards a potential well → Doppler-shift in photon temperature, depending to direction of motion
    - plasma was residing in a potential well → gravitational redshift

subtraction of motion dipole



source: PLANCK

subtraction of Milky Way emission



source: PLANCK

what...

...about those spots everywhere!?!

CMB angular spectrum

- analysis of fluctuations on a sphere: decomposition in $Y_{\ell m}$

$$T(\theta) = \sum_\ell \sum_m T_{\ell m} Y_{\ell m}(\theta) \quad \leftrightarrow \quad T_{\ell m} = \int \mathrm{d}\Omega\, T(\theta) Y^*_{\ell m}(\theta) \tag{6}$$

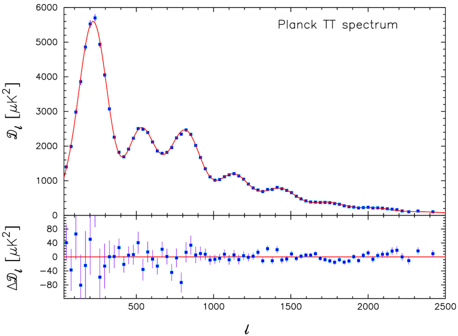
- spherical harmonics are an orthonormal basis system
- average **fluctuation variance** on a scale $\ell \simeq \pi/\theta$

$$C(\ell) = \langle |T_{\ell m}|^2 \rangle \tag{7}$$

- averaging $\langle \ldots \rangle$ is a hypothetical ensemble average. in reality, one computes an estimate of the variance,

$$C(\ell) \simeq \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=+\ell} |T_{\ell m}|^2 \tag{8}$$

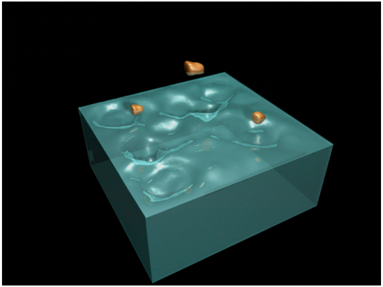
what about those spots?



measure the spot size

- we compute the Fourier transformation and measure the angular size of the object (aka the wavelength)
- there's a peak in the spectrum at 2 degree: that's the size of the spots

sound waves in the plasma



superposition of sound waves

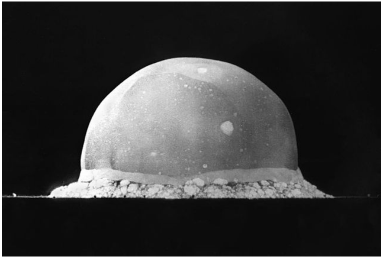
- processes in the early universe excite sound waves
- we see a superpositions of them in the cosmic microwave background
- there are temperature variations because the plasma is moving around in the sound wave

standard ruler principle

distance estimate with a sniper scope

- estimate the **distance** to an object by measuring the **angle** under which it appears
- need to know the true physical size of the object

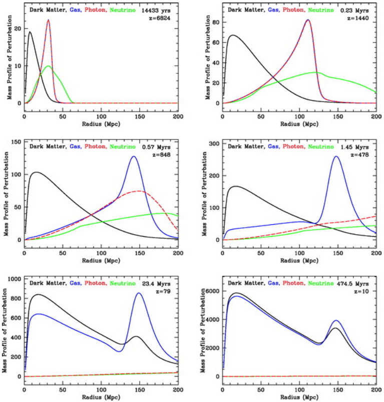
standard ruler principle



trinity nuclear test, 16 milli-seconds after explosion

- physical size: combine
  1. time since explosion
  2. velocity of fireball
- distance: combine
  1. physical size
  2. angular size

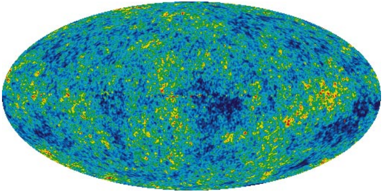
formation of baryon acoustic oscillations



evolution of a single perturbation (source: Eisenstein, Seo and Hu (2005))

- from a pointlike perturbation, a spherical wave travels in the photon-baryon-plasma
- propagation stops when atoms form

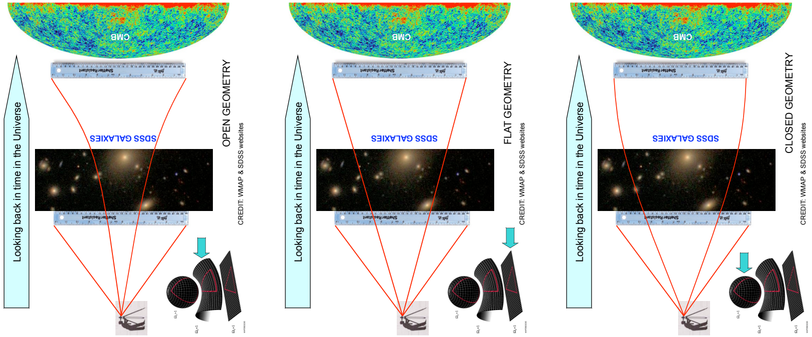
cosmic microwave background: standard ruler



all-sky map of the cosmic microwave background, WMAP

- hot and cold patches of the CMB have a typical physical size, related to the horizon size at the time of formation of hydrogen atoms
- idea: physical size and apparent angle are related, redshift of decoupling known

standard ruler: measurement principle



- curvature can be well constrained
- assumption: galaxy bias understood, nonlinear structure formation not too important

distance measures: comoving distance

- comoving distance χ is the distance on a spatial hypersurface between the world lines of a source and the observer moving with the Hubble flow
- photon geodesics are defined by $\mathrm{d}s = 0$ (Fermat's principle)
- therefore $c\mathrm{d}t = -a\mathrm{d}\chi$ (from metric), $\mathrm{d}\chi = -c\mathrm{d}a/(a^2H)$

$$\chi = c\int_{a_e}^{a_a} \frac{\mathrm{d}a}{a^2 H(a)} \tag{9}$$

- complete analogy to conformal time $\mathrm{d}\eta = \mathrm{d}a/(a^2H)$, such that $\chi = c\eta$

distance measures: angular diameter distance

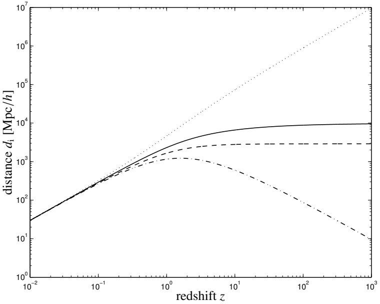
- angular diameter distance d is the distance infered from the angle under which a physical object appears
- physical cross section ΔA, solid angle $\Delta\Omega$:

$$\frac{\Delta A}{4\pi a_e^2 \chi} = \frac{\Delta\Omega}{4\pi} \tag{10}$$

- define d:

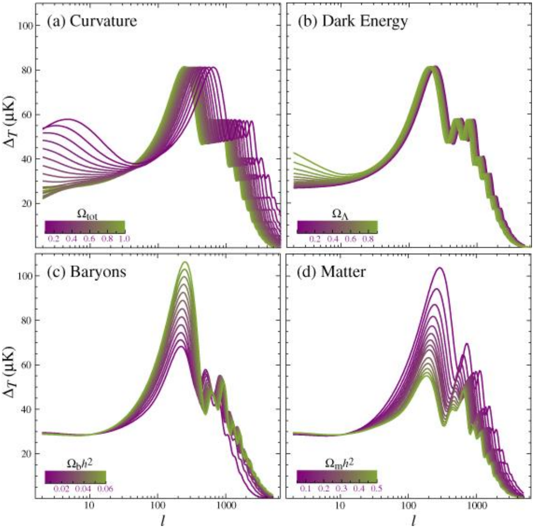
$$d \equiv \sqrt{\frac{\Delta A}{\Delta\Omega}} = a_e \chi \tag{11}$$

relation between distance and redshift



cosmological distances vs. redshift z

parameter sensitivity of the CMB spectrum



source: Wayne Hu

CMB simulator

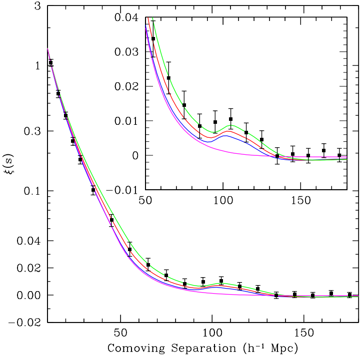
CMB simulator

http://www.strudel.org.uk/planck/

Planck paper model

http://planck.cf.ac.uk/news/make-your-own-planck-model

baryon acoustic oscillations in the galaxies



pair density $\xi(r)$ of galaxies as a function of separation r

- baryon acoustic oscillations: the (pair) density of galaxies is enhanced at a separation of about $100\mathrm{Mpc}/h$ comoving
- idea: angle under which this scale is viewed depends on redshift

summary: microwave background

- we can today observe the radiation from the formation of atoms
- the atoms formed at a temperature of 3000K at a redshift of 1000, and today
  1. temperature is 3K
  2. frequency is 160GHz
  3. wave length is 3mm
- the optical light is shifted to microwaves by cosmological redshifting
- redshifting corresponds to adiabatic cool-down in the expansion

summary: spots in the CMB

- the temperature has tiny fluctuations: there are spots in the CMB
- sound waves are excited in the plasma in the early Universe
- the sound waves travel **until** atoms form
- a **standard ruler** of size $c_s \times \Delta t$ is established
- we observe this standard ruler under an angle of $1 \ldots 2$ degrees
- we know how far the cosmic microwave background is away, and have an **integrated measure** of the Hubble function