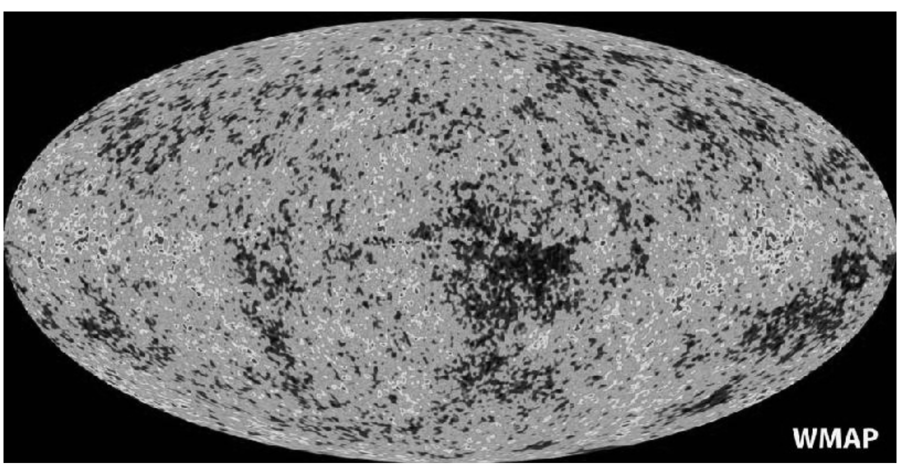
Cosmic Microwave Background

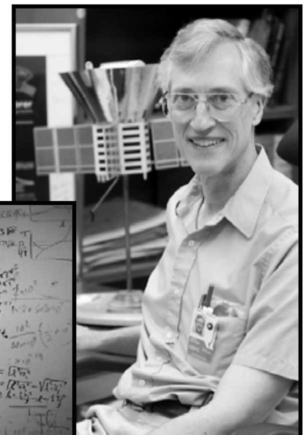


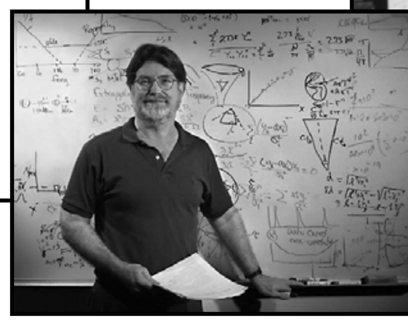
Echo of the Big Bang

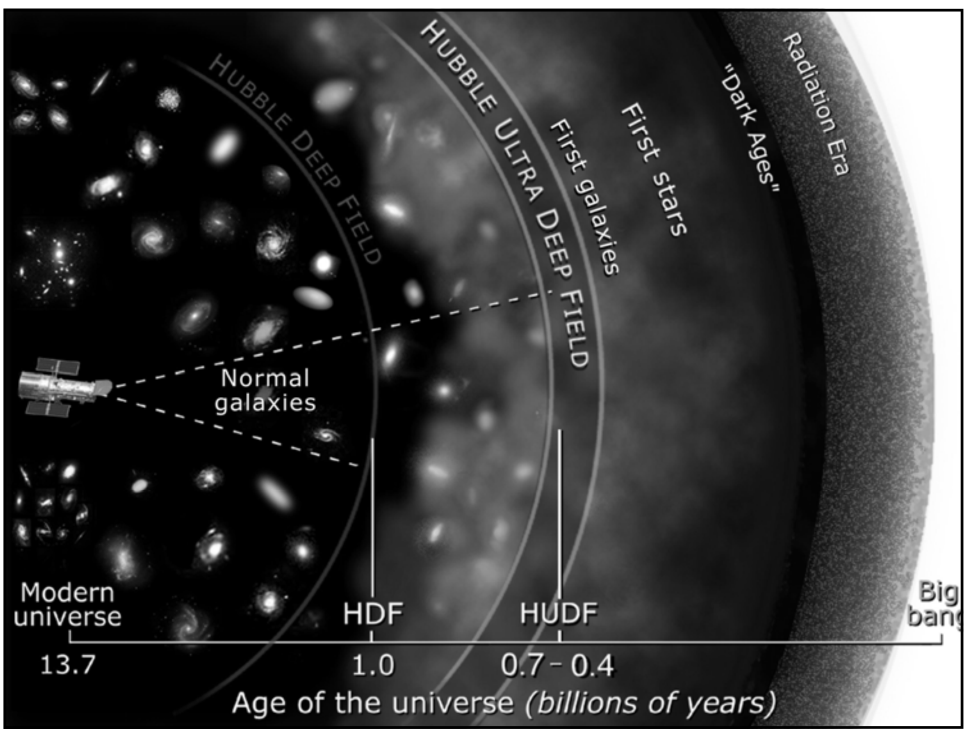
Nobelprijs Natuurkunde 2006

COBE (1992):

- John Mather
  - DIRBE: temperature, blackbody
- George Smoot
  - DMR: fluctuations, embryonic structure







Cosmic Microwave Background: Some Facts

Radiation Field of the Universe:

0) Discovered in 1965 (serendipitously) by Penzias & Wilson,
Nobelprize 1978 !!!!!

- Thermal radiation pervading throughout the whole Universe
- As yet it has a temperature of

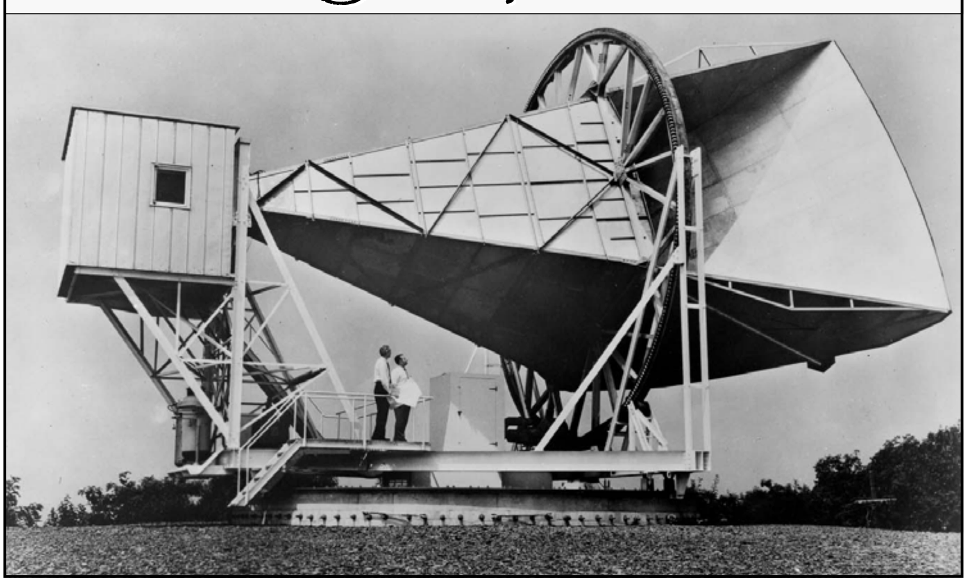
$$T_\gamma = 2.725 \text{ K}$$

1) By far CMB photons represent the most abundant species in the Universe:

$$n_\gamma \sim 415 \text{ cm}^{-3}$$

- For comparison: $n\gamma / n_B \sim 1.9 \times 10^9$!!!! (second: cosmic neutrino's)
- Stellar photons: negligible !!!! (integrated over all stars at all times !)

Cosmic Microwave Background: Some Facts



Cosmic Microwave Background: Some Facts

7) CMB highly (impressively) Isotropic:

- in each direction on the sky the radiation has almost exactly the same temperature/intensity
- temperature anisotropies VERY SMALL, in the order of

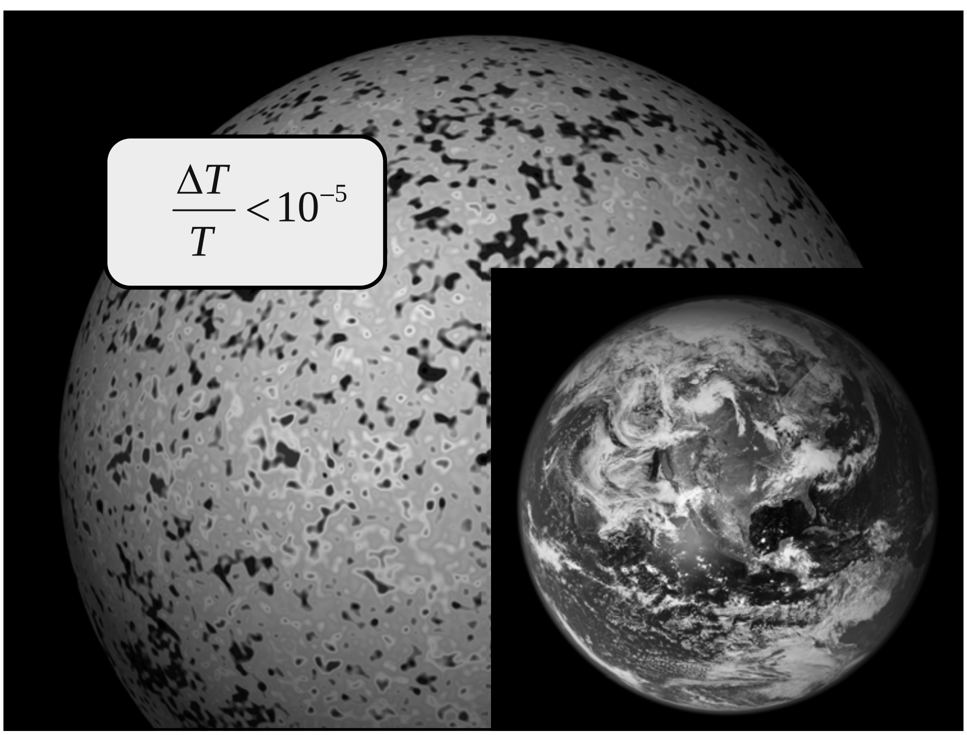
$$\frac{\Delta T}{T} < 10^{-5}$$

- for comparison:

  Planet Earth's highest mountain would be in the order 10-25 m !!!!!!!

8) The electromagnetic spectrum of the CMB PERFECTLY Thermal Blackbody (most accurately measured BB spectrum ever):

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



Cosmic Microwave Background: Some Facts

6) CMB photons Last Scattered

379,000 yrs. after Big Bang

at a redshift z=1089 (ie. expansion factor a(t)=1/1089)

7) Following the - Decoupling of Radiation and (Baryonic) Matter

- Recombination Hydrogen Atoms

(as protons and electrons combine)

8) At recombination T ~ 3000 K: the (CMB) sky would look red

Since then, gradual cooling of radiation through expansion Universe:

- cosmic redshift photons

9) The CMB photons created at much earlier epoch !!!

Last surge: positron-electron annihilation,

1 min. after Big Bang, redshift $z \sim 10^9$

Cosmic Microwave Background

COBE (1992):

Accurate measurement Planck spectrum CMB

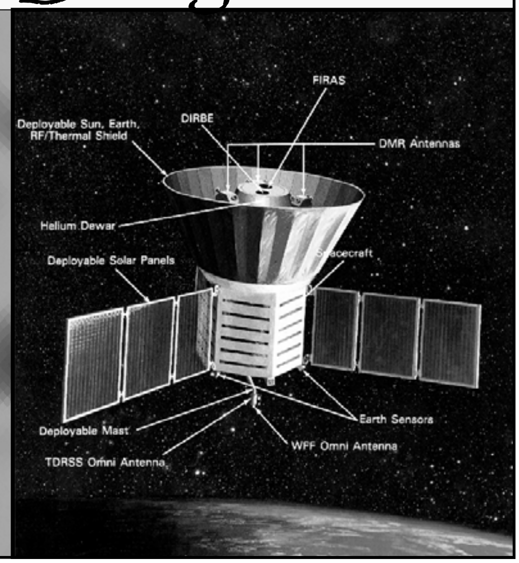
First detection angular temperature perturbations ($\theta \sim 7^o$): Sachs-Wolfe effect

Cosmic Microwave Background

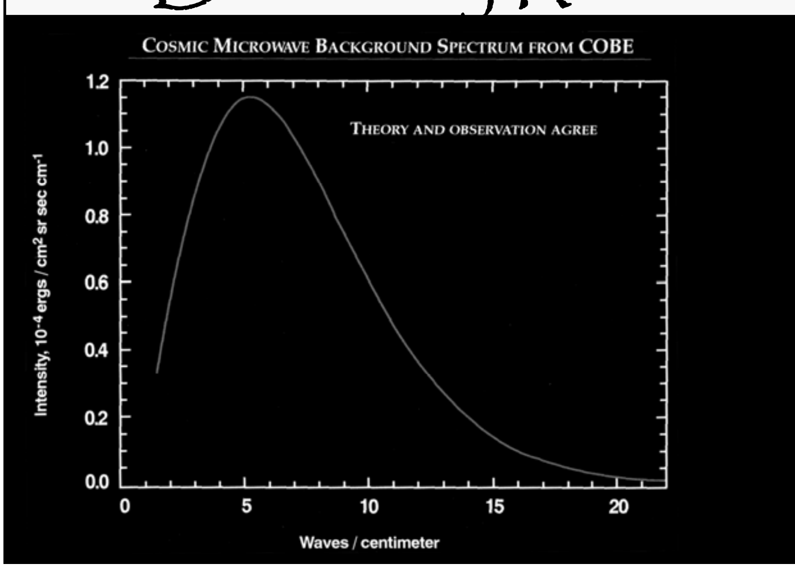
COBE (1992):

Three instruments:

- FIRAS: Mather
  - Far-Infrared Absolute Spectrophotometer
- DIRBE: Hauser
  - Diffuse Infrared Background Experiment
- DMR: Smoot
  - Differential Microwave Radiometer



Spectrum Blackbody Radiation



her

-DIRBE:
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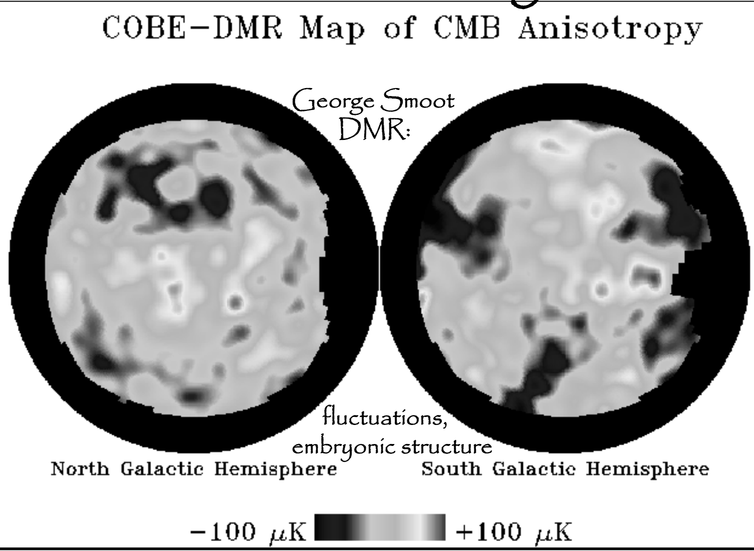
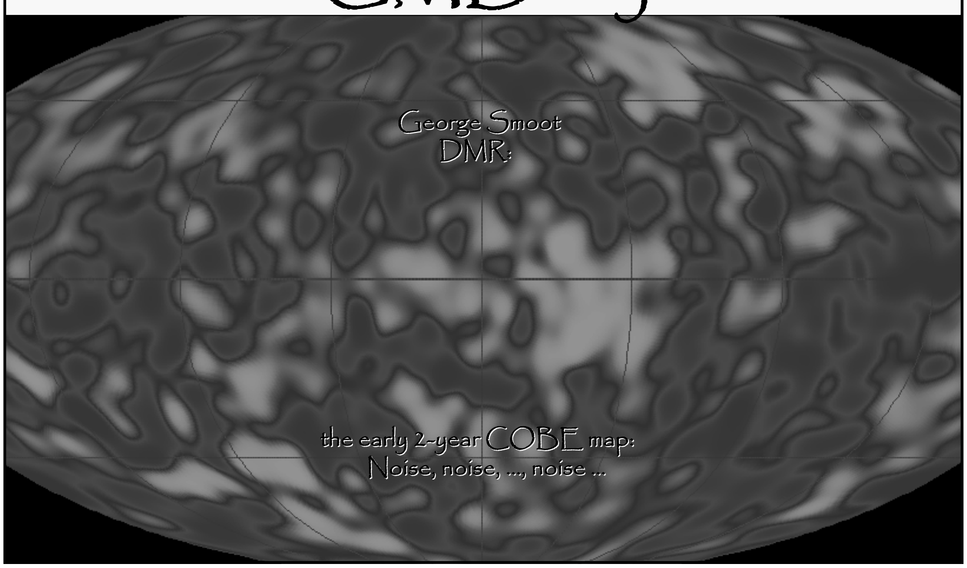
dy Spectrum

Primordial Anisotropies
CMB sky



Primordial Anisotropies
CMB sky



Key to the Universe

CMB Radiation, the cosmic radiation field of the Universe,
Cosmic Treasure Trove:

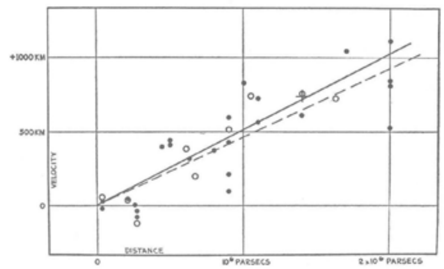
1) Direct probe of Thermal State of the early primordial Universe, the Universe before Decoupling:
Ultimate Proof Reality of Hot Big Bang
2) Direct reflection of Primordial Structure of the Universe, the Embryonic State of all Structure in today's Universe
3) Through its simplicity (linearity) the ultimate diagnostic tool for measuring the Universe:
Cosmic Parameters
4) Link on early decisive hypothetical/theoretical ($t \approx 10^{-36} - 10^{-34}$ sec)
Inflationary Epoch

The Simple Universe:

Cosmic
Geometry & Expansion

Hubble Expansion

[redacted]



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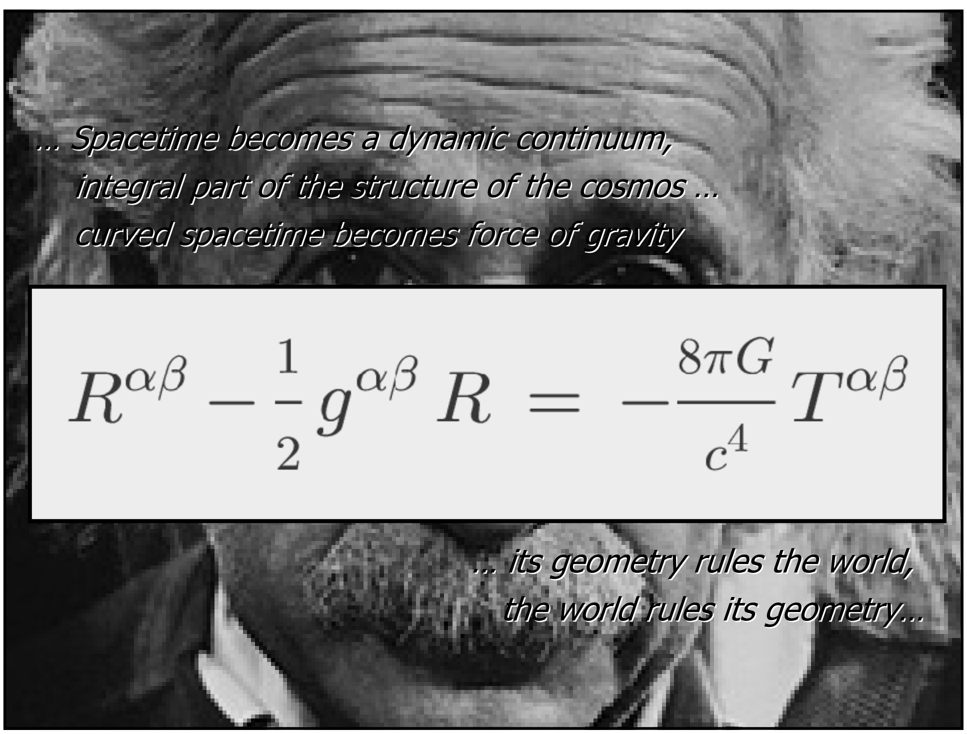
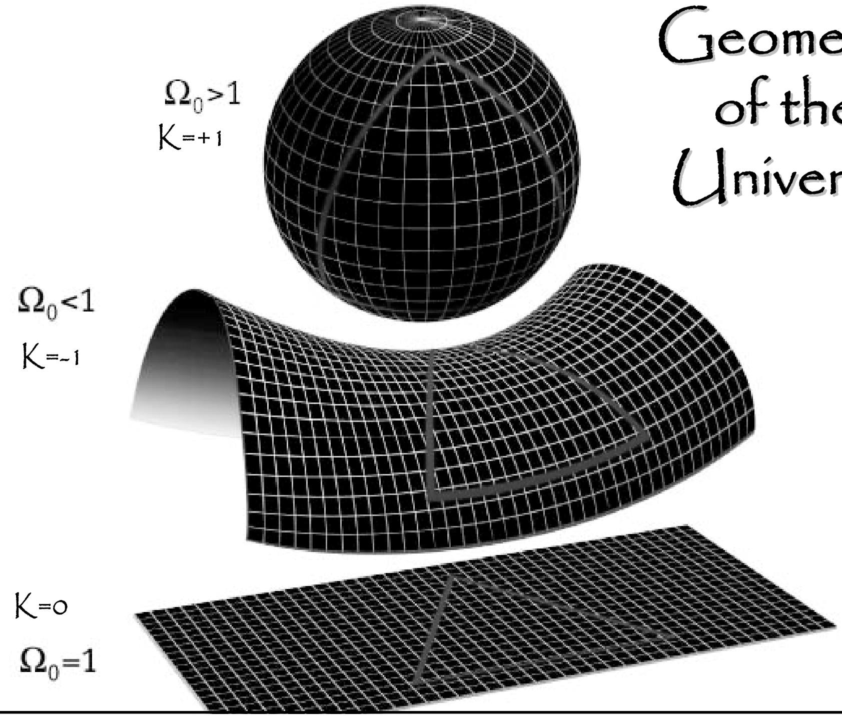


… Spacetime becomes a dynamic continuum,
integral part of the structure of the cosmos …
curved spacetime becomes force of gravity

$$R^{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} R = -\frac{8\pi G}{c^4} T^{\alpha\beta}$$

… its geometry rules the world,
the world rules its geometry…

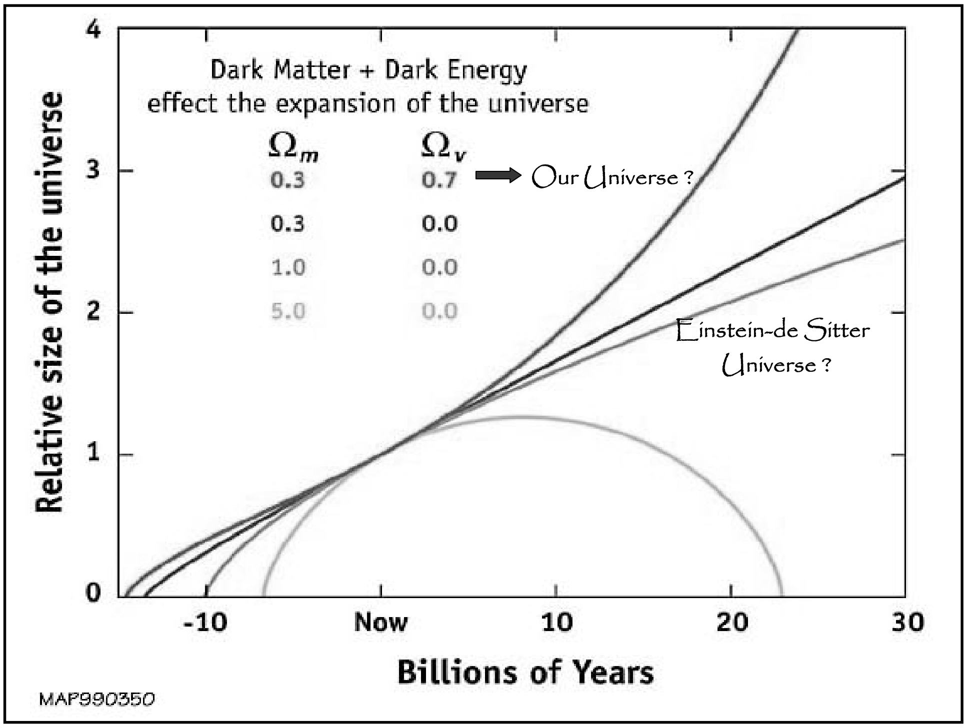
Geometry of the Universe



Friedmann-Robertson-Walker-Lemaitre Universe

$$\ddot{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) R + \frac{\Lambda}{3} R$$

$$\dot{R}^2 = \frac{8\pi G}{3}\rho R^2 + \frac{\Lambda}{3} R^2 - kc^2$$



Geometry & Dynamics:

Friedmann-Robertson-Walker-Lemaitre Universe

Three factors (interrelated) determine Evolution & Fate Universe:

1) The energy content of the Un iverse:
   cosmic (energy) density: $\rho(t)$
2) The curvature k
3) The cosmological constant Λ

Dynamics:
Friedmann-Robertson-Walker-Lemaitre Universe

Cosmological (energy) densities are typically in the order of that of the critical energy density of Universe. Currently,

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} = 1.8791h^2 \times 10^{-29}\,\mathrm{g\ cm^{-3}}$$

Geometry & Dynamics:
Friedmann-Robertson-Walker-Lemaitre Universe

Evolution & Fate of the universe determined by one major factor:

$$\Omega \equiv \frac{\rho}{\rho_{crit}} = \frac{8\pi G\,\rho}{3H^2}$$

Curvature determined by the Energy Density .

$$k = \frac{H^2 R^2}{c^2}(\Omega - 1)$$

Geometry & Dynamics:
Friedmann-Robertson-Walker-Lemaitre Universe

Evolution & Fate of the universe determined by one major factor:

$$\Omega \equiv \frac{\rho}{\rho_{crit}} = \frac{8\pi G\,\rho}{3H^2}$$

Total energy density the sum of various contributions,

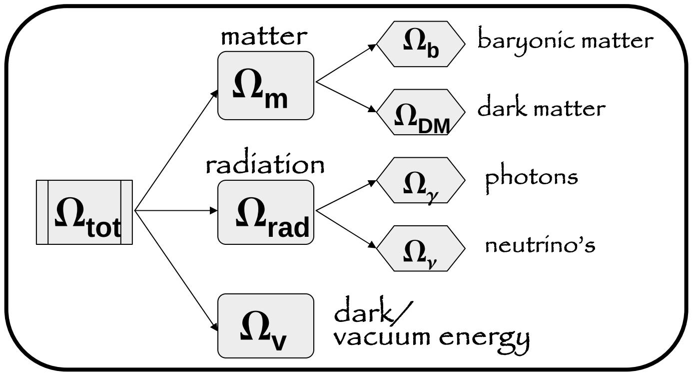
$$\Omega_{tot} = \Omega_{matter} + \Omega_{rad} + \Omega_{\Lambda}$$

Cosmology:
"quest for two issues":

Content & Parameters

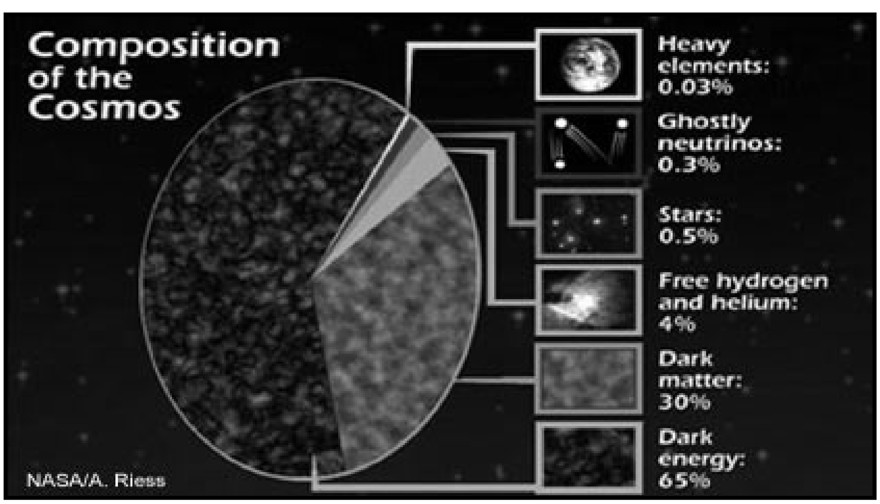
The Universe; What it consists of

The total energy content of Universe made up by various constituents, main ones:



In addition to the constituents mentioned in the diagram, there are contributions by e.g. gravitational waves, magnetic fields, etc. However, given the poor constraints on their contribution henceforth we will not take them into consideration.

The Universe; What it consists of



Cosmic Energy Inventory

1	dark sector			0.954 ± 0.003
1.1	dark energy		0.72 ± 0.03	
1.2	dark matter		0.23 ± 0.03	
1.3	primeval gravitational waves		$\lesssim 10^{-10}$	
2	primeval thermal remnants			0.0010 ± 0.0005
2.1	electromagnetic radiation		$10^{-4.3\pm0.0}$	
2.2	neutrinos		$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy		$-10^{-4.1\pm0.0}$	
3	baryon rest mass			0.045 ± 0.003
3.1	warm intergalactic plasma		0.040 ± 0.003	
3.1a	virialized regions of galaxies	0.024 ± 0.005		
3.1b	intergalactic	0.016 ± 0.005		
3.2	intracluster plasma		0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges	0.0015 ± 0.0004	
3.4		disks and irregulars	0.00055 ± 0.00014	
3.5	white dwarfs		0.00036 ± 0.00008	
3.6	neutron stars		0.00005 ± 0.00002	
3.7	black holes		0.00007 ± 0.00002	
3.8	substellar objects		0.00014 ± 0.00007	
3.9	HI + HeI		0.00062 ± 0.00010	
3.10	molecular gas		0.00016 ± 0.00006	
3.11	planets		10^{-6}	
3.12	condensed matter		$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes		$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy			$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies		$-10^{-7.2}$	
4.2	clusters		$-10^{-6.9}$	
4.3	large-scale structure		$-10^{-6.2}$	

Fukugita & Peebles 2004

Cosmic Constituents

The energy content of the Universe may be broadly divided into various classes, dependent on how their energy density evolves in time. The three most important ones are:

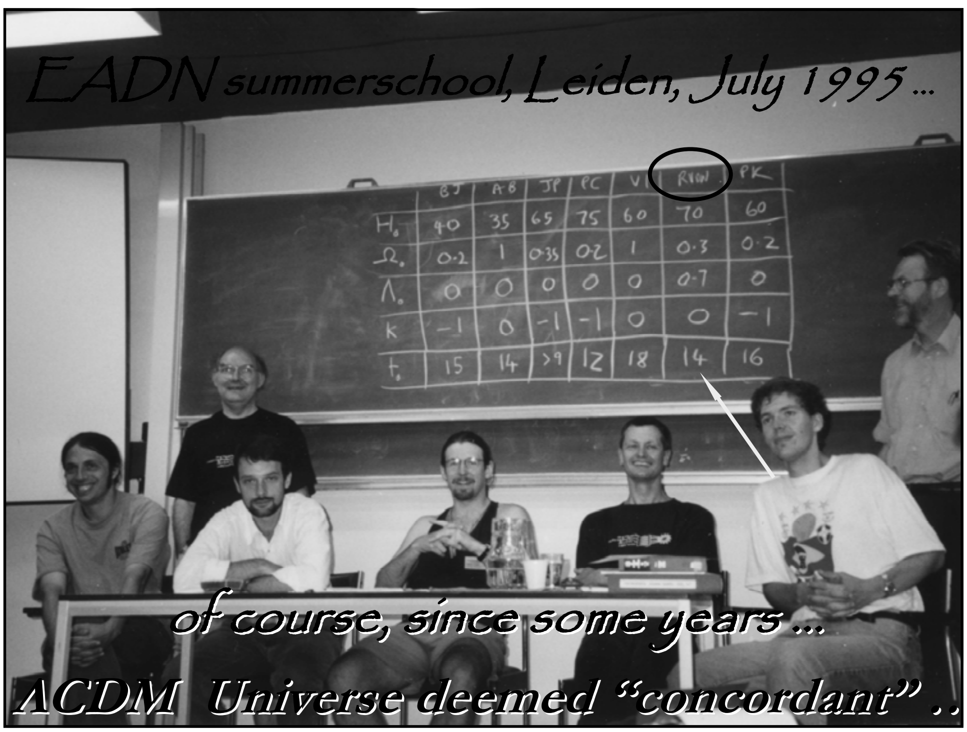
- Matter: $\rho_m \propto a(t)^{-3}$
- Radiation: $\rho_{rad} \propto a(t)^{-4}$
- Dark Energy:

$$\rho_v = a(t)^{-3(1+w)} \quad \Longleftarrow \quad p = w\,\rho_v$$
$$\Downarrow \; w = -1$$
$$\rho_\Lambda = cst.$$

Concordance
“Vanilla”
Cosmology

(WMAP3
parameters)

Parameter	Value	Description
Basic parameters		
H_0	$70.9^{+2.4}_{-3.2}$ km s^{-1} Mpc^{-1}	Hubble parameter
Ω_b	$0.0444^{+0.0042}_{-0.0035}$	Baryon density
Ω_m	$0.266^{+0.025}_{-0.040}$	Total matter density (baryons + dark matter)
τ	$0.079^{+0.029}_{-0.032}$	Optical depth to reionization
A_s	$0.813^{+0.042}_{-0.052}$	Scalar fluctuation amplitude
n_s	$0.948^{+0.015}_{-0.018}$	Scalar spectral index
Derived parameters		
ρ_0	$0.94^{+0.06}_{-0.09} \times 10^{-26}$ kg/m^3	Critical density
Ω_Λ	$0.732^{+0.040}_{-0.025}$	Dark energy density
z_{ion}	$10.5^{+2.6}_{-2.9}$	Reionization red-shift
σ_8	$0.772^{+0.036}_{-0.048}$	Galaxy fluctuation amplitude
t_0	$13.73^{+0.13}_{-0.17} \times 10^9$ years	Age of the universe



The Hot Big Bang:

Cosmic Timeline

Adiabatic Expansion

From the Friedmann equations, it is straightforward to appreciate that cosmic expansion is an adiabatic process:

$$\dot{\rho} + 3\left(\rho + \frac{p}{c^2}\right)\frac{\dot{a}}{a} = 0$$

$$\Downarrow$$

$$dU = -p\,dV \quad \Longleftarrow \begin{cases} U = \rho c^2 V & \text{internal energy} \\ V \propto a^3 & \text{cosmic volume} \end{cases}$$

In other words, there is no ``external power" responsible for "pumping" the tube ...

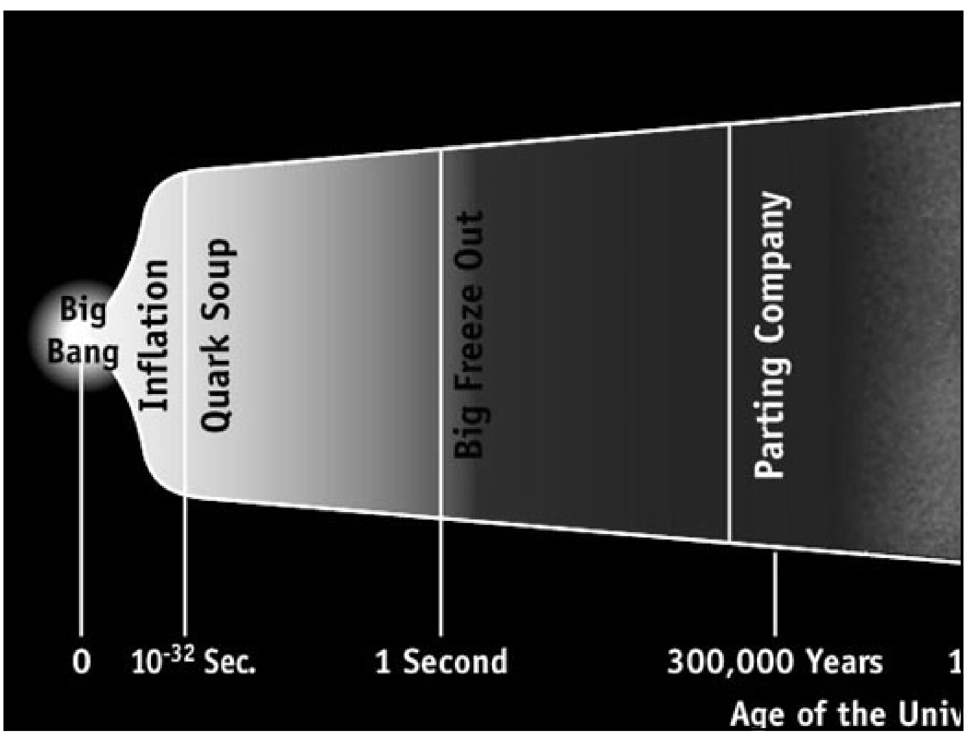
Adiabatic Expansion

$$p \propto \rho^{\gamma} \quad \Longrightarrow \quad T V^{\gamma-1} = cst.$$

$$\begin{cases} \gamma = \frac{5}{3} & \Longrightarrow \quad T_b \propto V^{-2/3} \propto a^{-2} \\ \gamma = \frac{4}{3} & \Longrightarrow \quad T_{rad} \propto V^{-1/3} \propto a^{-1} \end{cases}$$

Cosmic expansion is Adiabatic: Temperature History

Hot Big Bang



Episodes Thermal History

Era	Episodes	Time
Planck Epoch		$t < 10^{-43}$ sec
Phase Transition Era	GUT transition electroweak transition quark-hadron transition	10^{-43} sec < t < 10^{5}sec
Hadron Era		$t \sim 10^{-5}$ sec
Lepton Era	muon annihilation neutrino decoupling electron-positron annihilation primordial nucleosynthesis	10^{-5} sec < t < 1 min
Radiation Era	radiation-matter equivalence recombination & decoupling	1 min < t <379,000 yrs
Post-Recombination Era	Structure & Galaxy formation Dark Ages Reionization Matter-Dark Energy transition	t > 379,000 yrs

Hot Big Bang: What it explains

- Olber's paradox:
  the night sky is dark
  ➡ finite age Universe (13.7 Gyr)
- Hubble Expansion
  uniform expansion, with
  expansion velocity ~ distance: $v = H r$
- Explanation Helium Abundance 24%:
  light chemical elements formed (H, He, Li, ...)
  after ~3 minutes ...
- The Cosmic Microwave Background Radiation:
  the 2.725K radiation blanket, remnant left over
  hot ionized plasma ➡ neutral universe
  (379,000 years after Big Bang)
- Distant, deep Universe indeed looks different ...

The Hot Big Bang:

Inflationary Universe

FRW Big Bang: What it cannot explain

- Flatness Problew
  the Universe is remarkably flat, and was even (much) flatter in the past
- Horizon Problem
  the Universe is nearly perfectly isotropic and homogeneous, much more so in the past
- Monopole Problem:
  There are hardly any magnetic monopoles in our Universe
- Fluctuations, seeds of structure
  Structure in the Universe: origin

FRW Big Bang extended: Inflationary Universe

- Essential Ingredient/Extension Standard Cosmology

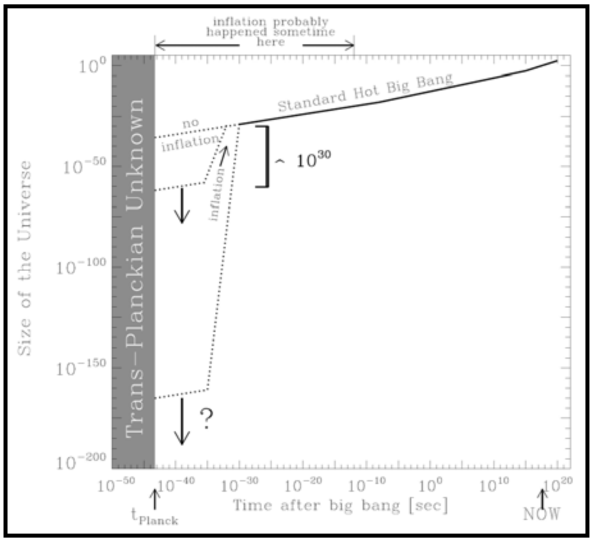
Inflationary Universe

- Phase transition Early Universe

- GUT transition : $t \sim 10^{-36}$ sec ??

- (false) vacuum potential induces exponential (de Sitter) expansion

- Universe blows up by factor $N > 10^{60}$



FRW Big Bang extended: Inflationary Universe

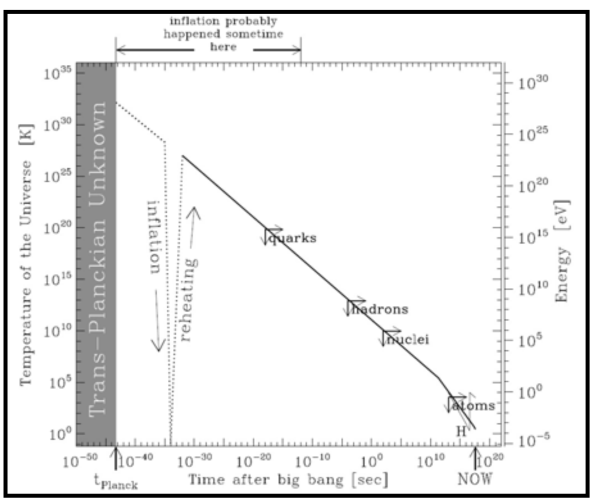
Inflationary Universe

Explains:

- Horizon Problem
- Flatness Problem
- Monopole Problem

And ...

- Origin of Structure



Radiation/ Relativistic

Cosmic Radiation

Most ubiquitous, most pervasive, constituent of the Universe: Radiation.

- photons γ
- neutrinos ν

Two major components of relativistic (massless) species:

Cosmic Radiation

1) Number Density CMB photons:

$$n_\gamma(T) = \frac{8\pi}{c^3}\int_0^\infty \frac{\nu^2\,d\nu}{e^{h\nu/kT}-1} = 60.4\left(\frac{kT}{hc}\right)^3$$

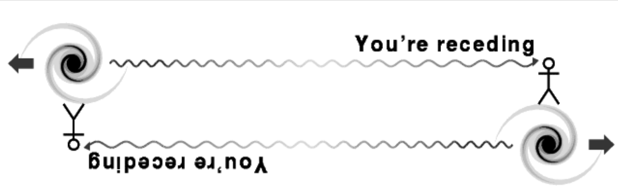
$$n_\gamma = 60.4\left(\frac{kT}{hc}\right)^3 \approx 410\,(1+z)^3\ \mathrm{cm}^{-3}$$

Present Number Density: ⇨ $n_\gamma \sim 410\,\mathrm{cm}^{-3}$

Cosmic Redshift

$$1+z=\frac{1}{a} \Longleftarrow \begin{cases} \lambda_{em}=\lambda_0 \\ \lambda_{obs}=\dfrac{a(t_{obs})}{a(t_{em})}\lambda_0 \end{cases}$$

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



Cosmic Radiation

2) Number photons/neutrinos conserved

- photon number density $n_{rad} \propto a(t)^{-3}$

3) As a result of the cosmic expansion, wavelength of a photon redshifts:

- photon energy $\varepsilon_{rad} \propto a(t)^{-1}$

4) Energy Density Radiation evolves:

$$\rho_{rad} \propto a(t)^{-4} \propto (1+z)^4$$

Cosmic Radiation

5) Energy Density ➡ at present negligible:

$$\Omega_{rad} \approx 10^{-5}$$

6) Dynamically increasingly important in early Universe, dominant over Matter before

$z > z_{eq}$: $\rho_{rad} > \rho_m$

$z < z_{eq}$: $\rho_{rad} < \rho_m$

⇩

$z > z_{eq}$: $a(t) \propto t^{1/2}$

$z < z_{eq}$: $a(t) \propto t^{2/3}$

Equivalence Epoch

$$1 + z_{eq} = 4.0 \times 10^4 \, \Omega_m h^2$$

Cosmic Radiation

7) In terms of Number Density,
Cosmic Photons have ALWAYS been dominant,
Most abundant species in the Universe. By FAR !!!!!!!!!

$$n_B(z) = n_{B,0}\,(1+z)^3$$

$$n_\gamma(z) = n_{\gamma,0}\,(1+z)^3$$

$$\Downarrow$$

$$\eta(z) = \frac{n_B(z)}{n_\gamma(z)} = \frac{n_{B,0}}{n_{\gamma,0}} = \eta_0$$

5) Ratio Baryons to Photons
Entropy Universe

$$\frac{n_\gamma}{n_B} \approx 10^9$$

Fundamental Property !!!!!!
Universe very Peculiar Physical System

CMB

Thermalization

Electron-Positron Annihilation

$T < 10^9$ K $t \sim 1$ min, $z \sim 10^9$	At this redshift the majority of photons of the Cosmic Microwave Background are generated

- Before this redshift, electrons and photons are in thermal equilibrium. After the

$$e^+ + e^- \rightleftharpoons 2\gamma$$

temperature drops below $T \sim 10^9$ K, the electrons and positrons annihilate, leaving a sea of photons.

- As they absorb the total entropy s of the e^+, e^-, γ plasma, the photons acquire a temperature $T_\gamma >$ neutrino temperature T_ν .

Electron-Positron Annihilation

- At the onset certainly not thermally distributed energies
- Photons keep on being scattered back and forth until $z \sim 1089$, the epoch of recombination.
- Thermal equilibrium (blackbody spectrum) of photons reached within 2 months after their creation

Blackbody Spectrum produced through three scattering processes

- Compton scattering
- Free-free scattering
- Double Compton scattering

CMB Thermalization

- Thermalization through three scattering processes
  - Compton scattering + dominant energy redistribution
  - Free-free scattering + creates new photons to
  - Double Compton scattering adjust spectrum to Planck

- While Compton scattering manages to redistribute the energy of the photons, it cannot adjust the number of photons. Free-free scattering and Double Compton scattering manage to do so ...

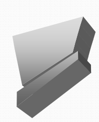
- But ...
  only before $z < 10^5$, after that the interaction times too long ....

CMB Thermalization

- Following this thermalization, a perfect blackbody photon spectrum has emerged:

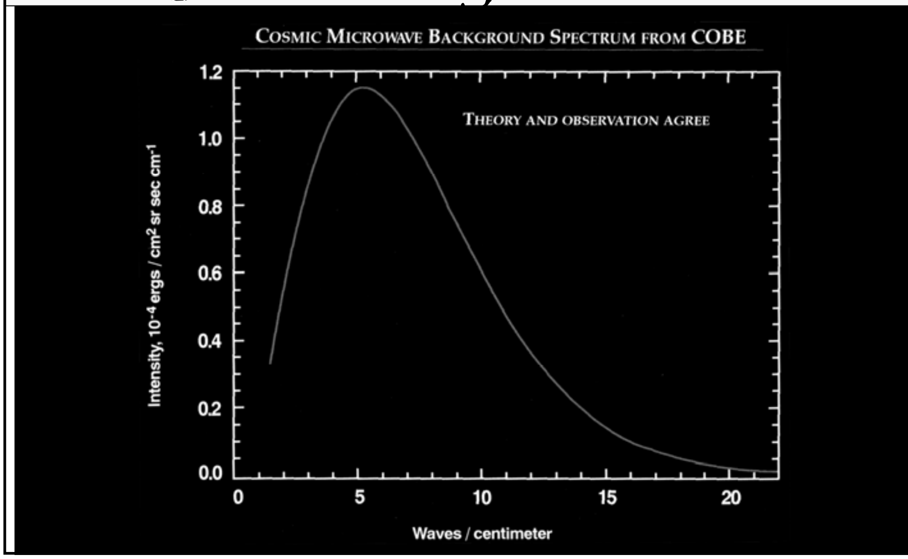
$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- This is the ULTIMATE proof of the HOT BIG BANG



- Note: after $z \sim 105$ till recombination, the interaction between electrons and photons exclusively by Thomson Scattering

Spectrum
Blackbody Radiation



CMB

Recombination & Decoupling

Recombination & Decoupling

T ~ 3000 K

z_{dec}=1089 (Δz_{dec}=195); t_{dec}=379.000 yrs

- Before the "Recombination Epoch
  Radiation and Matter are tightly coupled through Thomson scattering.

- The events surrounding "recombination" exist of THREE major (coupled, yet different) processes:

• Recombination	protons & electrons combine to H atoms
• Decoupling	photons & baryonic matter no longer interact
• Last scattering	meaning, photons have a last kick and go …

Recombination & Decoupling

T ~ 3000 K

z_{dec}=1089 (Δz_{dec}=195); t_{dec}=379.000 yrs

- Before this time, radiation and matter are tightly coupled through
  Thomson scattering:

$$e^- + \gamma \rightleftharpoons e^- + \gamma$$

  Because of the continuing scattering of photons, the universe is a "fog".

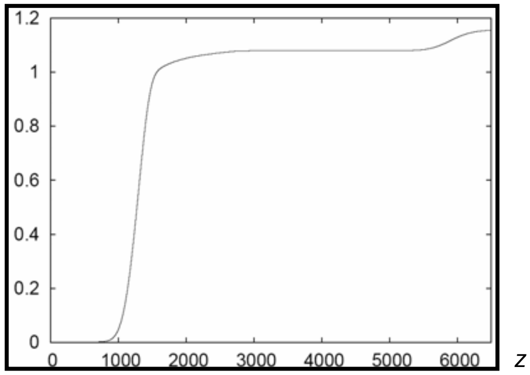
- A radical change of this situation occurs once the temperature starts to drop below T~3000 K. and electrons. Thermodynamically it becomes favorable to form neutral (hydrogen) atoms H (because the photons can no longer destory the atoms):

$$p + e^- \rightleftharpoons \mathrm{H}$$

- This transition is usually marked by the word "recombination", somewhat of a misnomer, as of course hydrogen atoms combine just for the first time in cosmic history. It marks a radical transition point in the universe's history.

Recombination history

$$x_e = \frac{n_e}{n_H}$$



As temperature changes:

- shifting ionization can be followed through Saha equation (note: on "wrong" premise of equilibrium)
- Recombination should happen at T ~ 4000 K
- But: far too many CMB photons, it is not equilibrium process !!!!

Recombination & Decoupling

- Note that the decoupling transition occurs rather sudden at T~3000 K, with a "cosmic photosphere" depth of only Δz_{dec}~195 (at z~1089).
- The cosmological situation is highly exceptional. Under more common circumstances the (re)combination transition would already have taken place at a temperature of T~10^4 K.
- Due to the enormous amount of photons in the universe, signified by the abnormally high cosmic entropy,

$$\frac{n_\gamma}{n_B} \approx 10^9$$

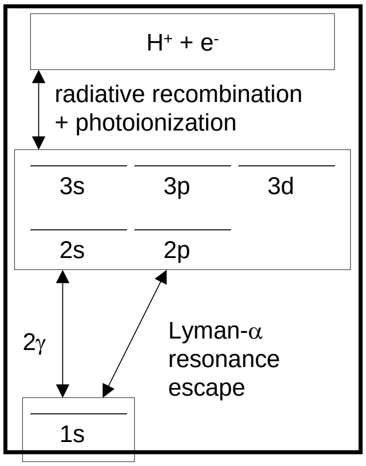
even long after the temperature dropped below T~ 10^4 K there are still sufficient photons to keep the hydrogen ionized (i.e. there are still plenty of photons in the Wien part of the spectrum).

- Recombination therefore proceeds via a 2-step transition, not directly to the groundstate of hydrogen. The process is therefore dictated by the rate at which Lyα photons redshift out of the Lyα rest wavelenght. For n_γ/n_B~10^9 this occurs at

$$T \sim 3000\,\mathrm{K}$$

Standard theory of H recombination

(Peebles 1968, Zel'dovich et al 1968)



Recombination Process
not entirely trivial:

- ground state could be reached via Lya transition (2P-1S)

DOES NOT WORK !!!!!

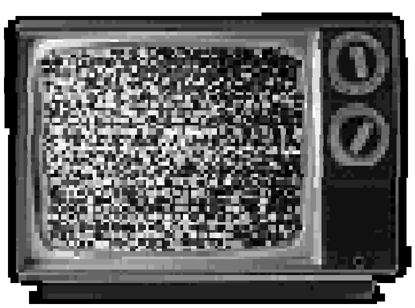
large abundance Lya → Ionization

- Recombination in parts: forbidden transition =2-photon emission: 2S – 1S

- Takes 8.23 s^{-1} → much slower than 'direct', and thus

recombination occurs late …
at T ~ 3000 K

Cosmic Photons



Note:

far from being an exotic faraway phenomenon, realize that the CMB nowadays is counting for approximately 1% of the noise on your tv set …

Courtesy: W. Hu

Recombination & Decoupling

- In summary, the recombination transition and the related decoupling of matter and radiation defines one of the most crucial events in cosmology. In a rather sudden transition, the universe changes from

Before z_{dec}, $z>z_{dec}$

- universe fully ionized
- photons incessantly scattered
- pressure dominated by radiation:

$$p = \frac{1}{3} a T^4$$

After z_{dec}, $z<z_{dec}$

- universe practically neutral
- photons propagate freely
- pressure only by baryons:

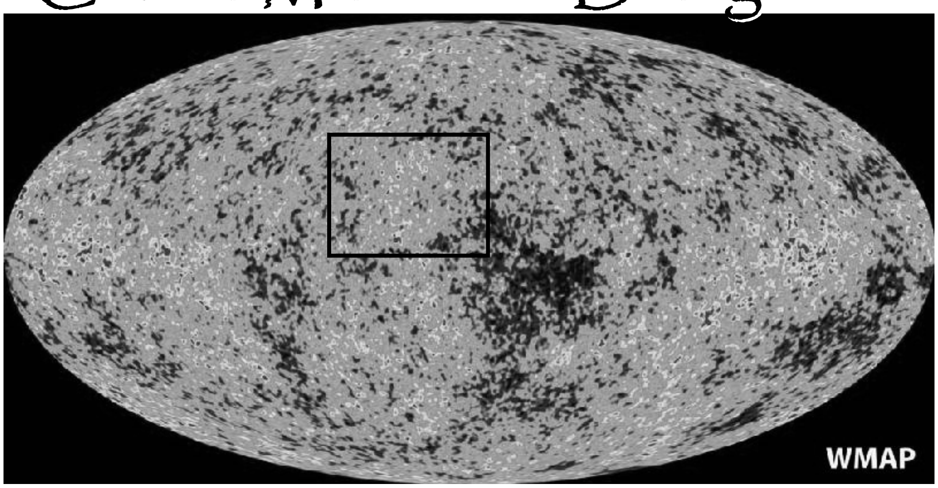
$$p = n k T$$

- (photon pressure negligible)

Ripples in the Universe

Structure in the Universe

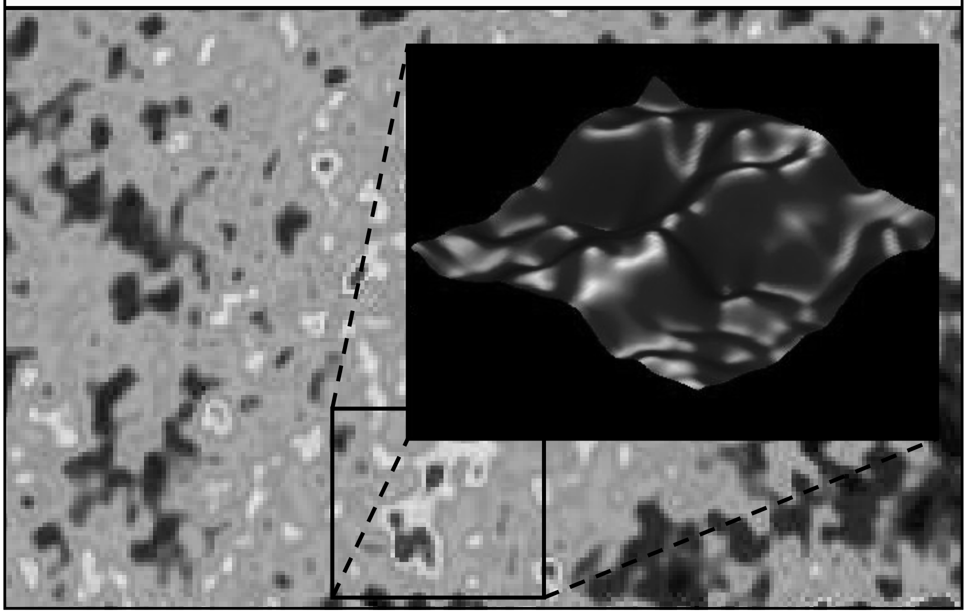
Cosmic Microwave Background



Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T < 10^{-5}$

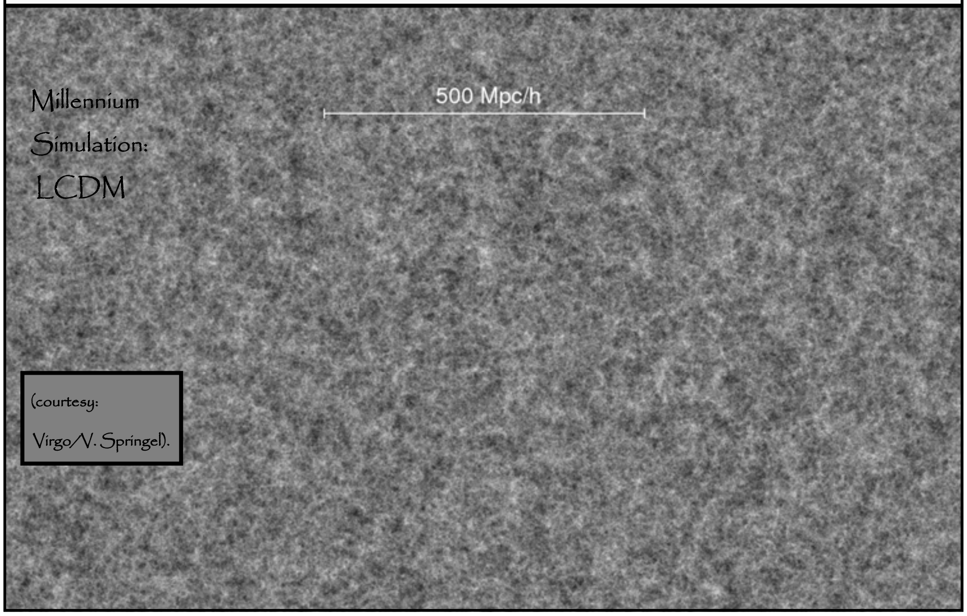
Primordial Gaussian Perturbations



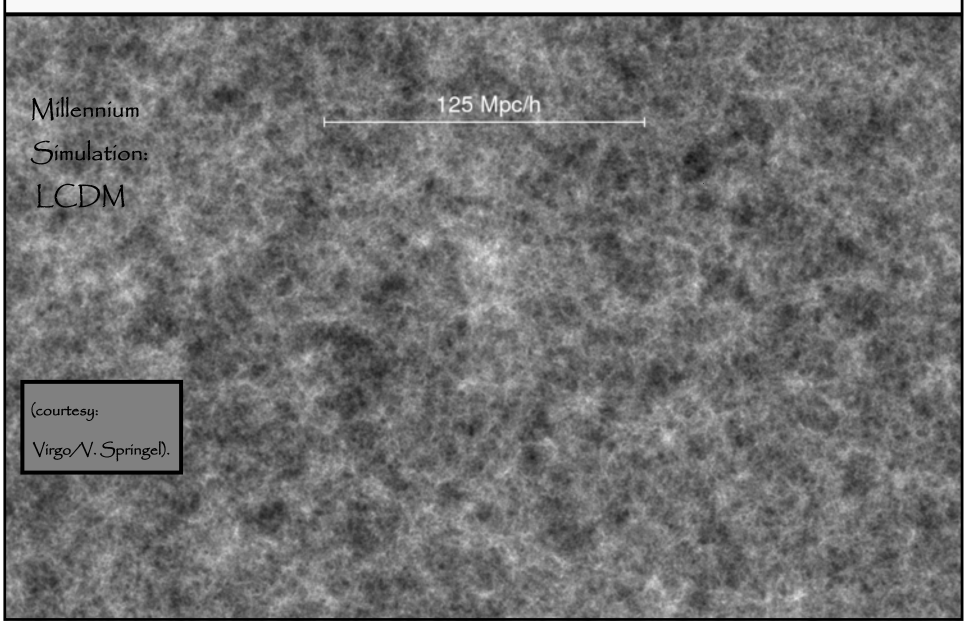
Gravitational Instability

$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Millennium Simulation



Millennium Simulation



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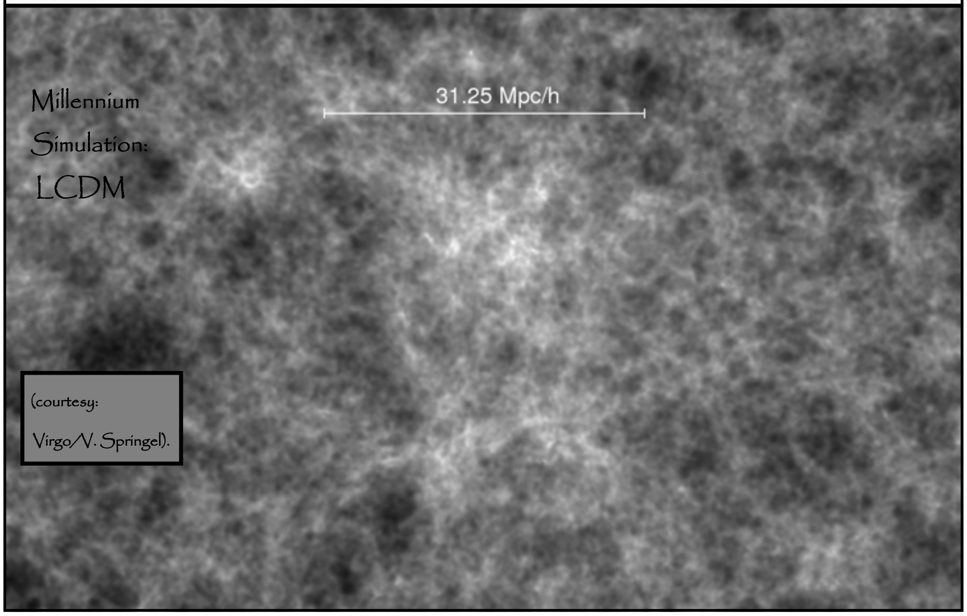

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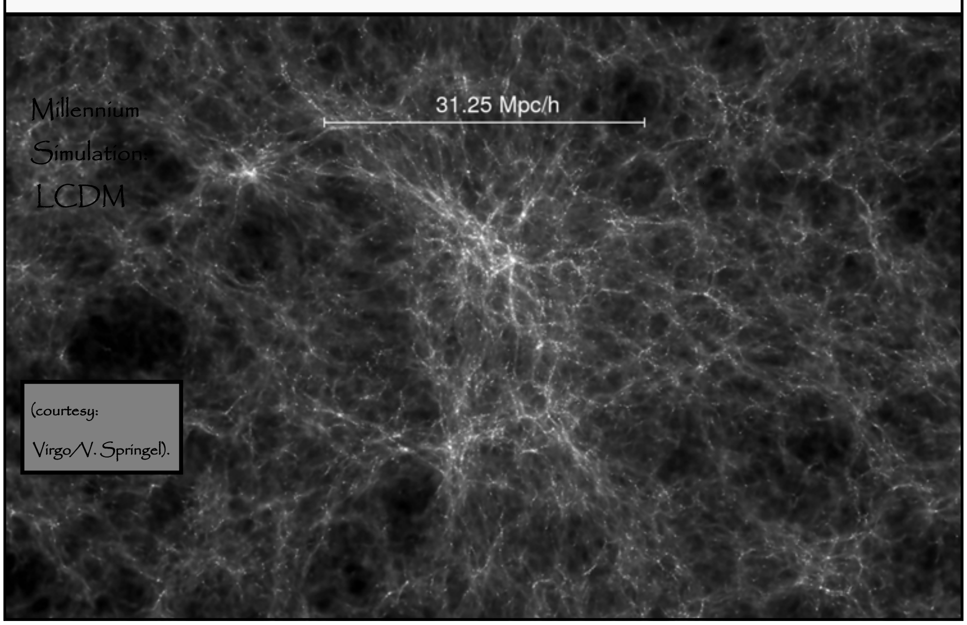

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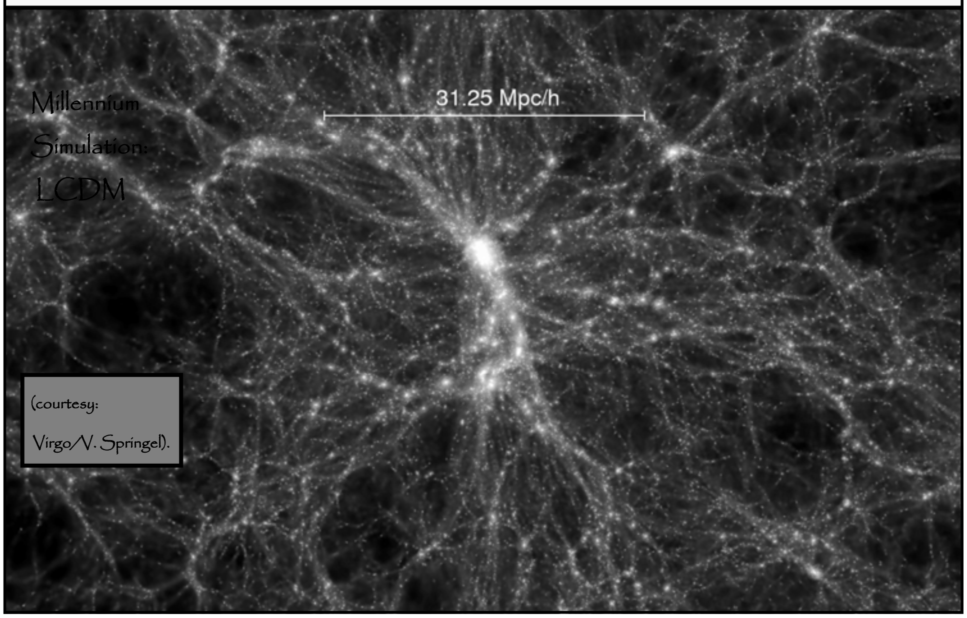

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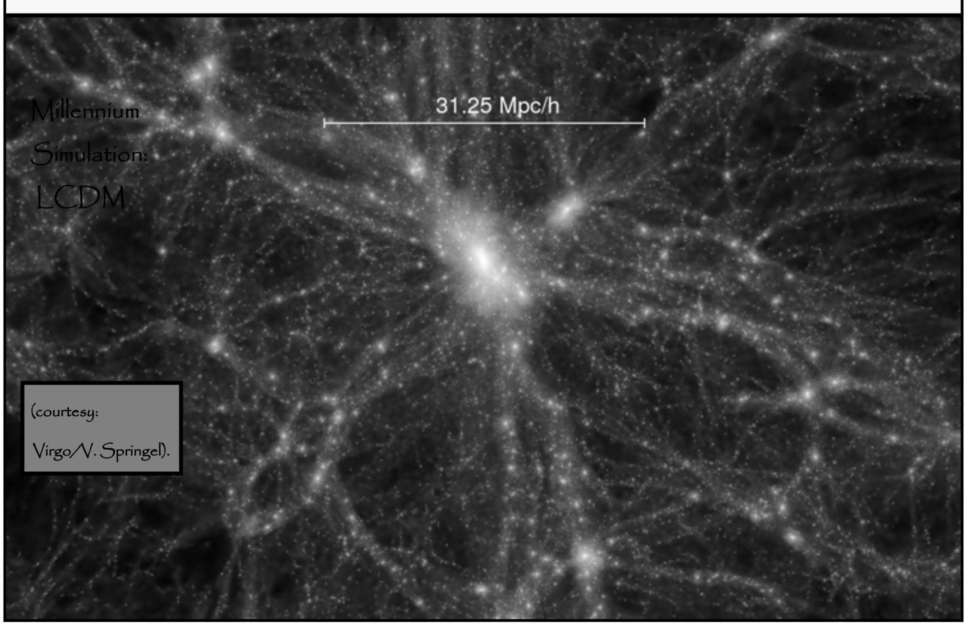

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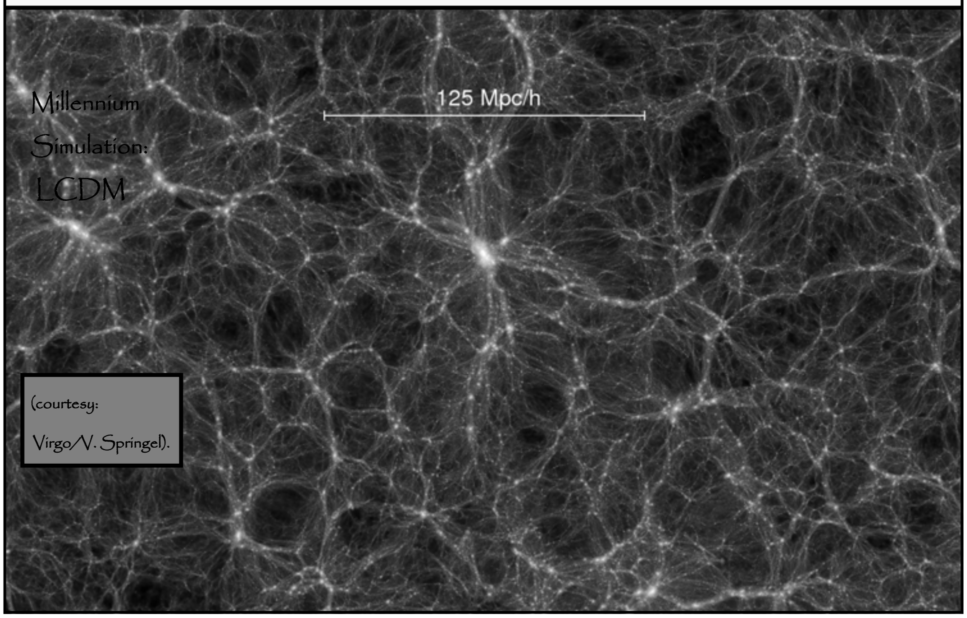

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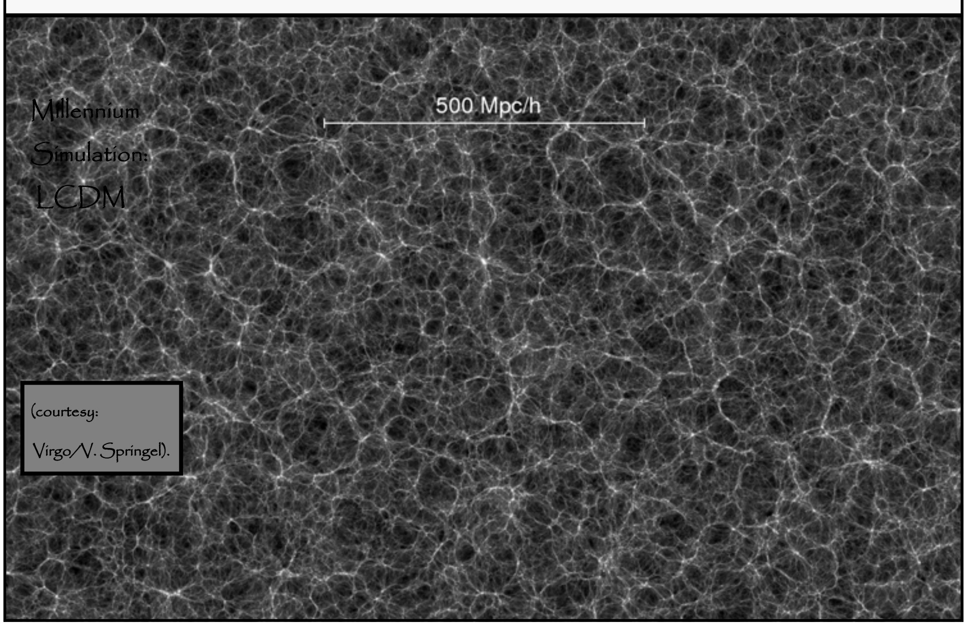


Rippling Origins

Inflationary Origins

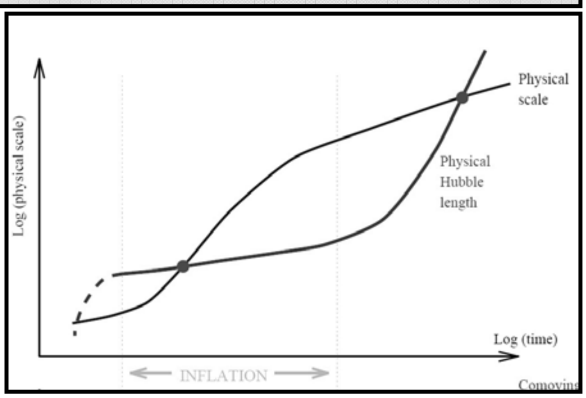
Inflationary Origin of Cosmic Structure:
- Primordial Quantum Noise (due to uncertainty principle)
- becomes seeds for structure today
- at inflation the fluct's expanded to superhorizon size

Predictions:

- Gaussian fluctuations
- Adiabatic fluctuations (radiation & matter equally perturbed)
- Near scale-free potential perturbations:

$P(k) \sim k^n$

$n \approx 0.96$



Primordial Perturbation Growth

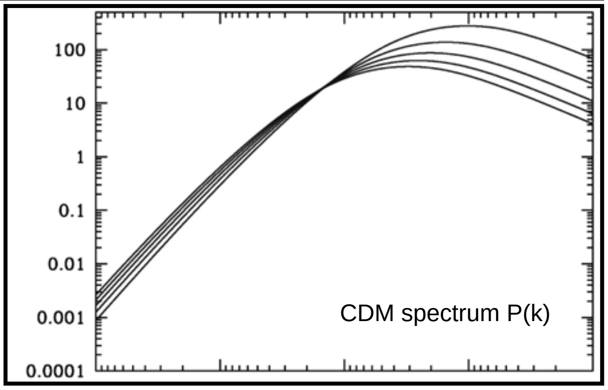
Once fluctuations "entered" the cosmic horizon,
they can start growing ...

Growth dependent on a series of modulating processes, eg.:

Baryon perturbations
held up by pressure (Jeans !)

Dark Matter:
- starts growth at
horizon entrance
- damps below
free-streaming:
CDM vs. HDM

Cosmic Expansion regime:
- radiation dominance:
no growth DM pert.
- matter dominance



Cold Dark Matter Cosmologies

$$P_{\rm CDM}(k) \propto \frac{k^n}{[1 + 3.89q + (16.1q)^2 + (5.46q)^3 + (6.71q)^4]^{1/2}} \times \frac{[\ln 1 + 2.34q]^2}{(2.34q)^2}$$

$$q = k/\Gamma$$

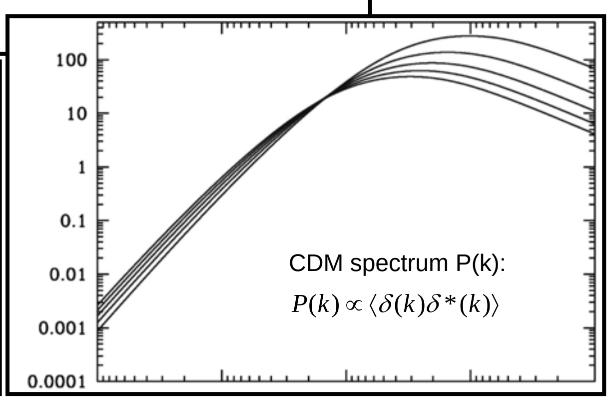
$$\Gamma = \Omega_{m,\circ} h \exp\left\{-\Omega_b - \frac{\Omega_b}{\Omega_{m,\circ}}\right\}$$

Standard Scenario:

Perturbations in medium of
Cold Dark Matter particles

- axions, neutralino's ...

Results in a hierarchical
scenario of structure formation...



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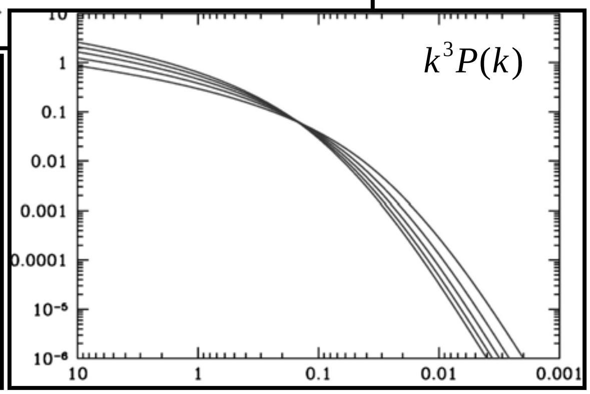
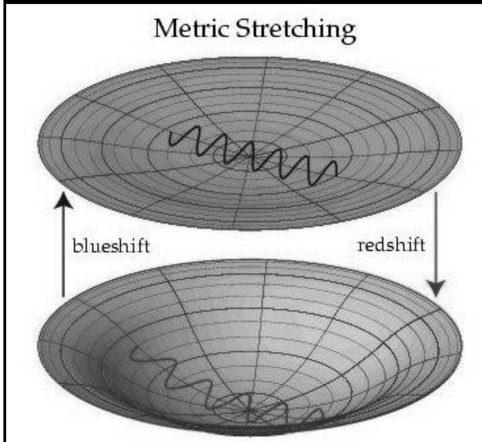


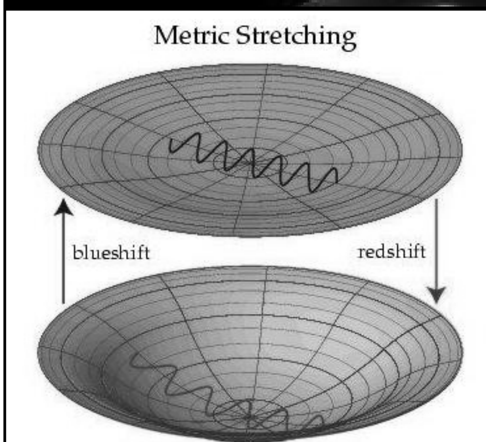
Rippling The Photons

CMB Perturbations



- As a result of perturbations in Gravitational potential photons experience frequency shift
- While travelling through perturbation:
  - Gravitational Redshift +
  - (Relativistic) Time Dilation
- Combined effect: Sachs-Wolfe Effect

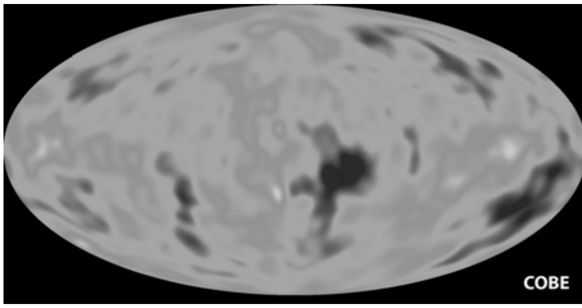
Sachs-Wolfe Effect

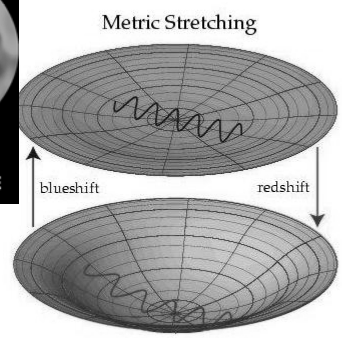


Sachs-Wolfe Effect

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta \Phi}{c^2}$$

Cosmic Microwave Background

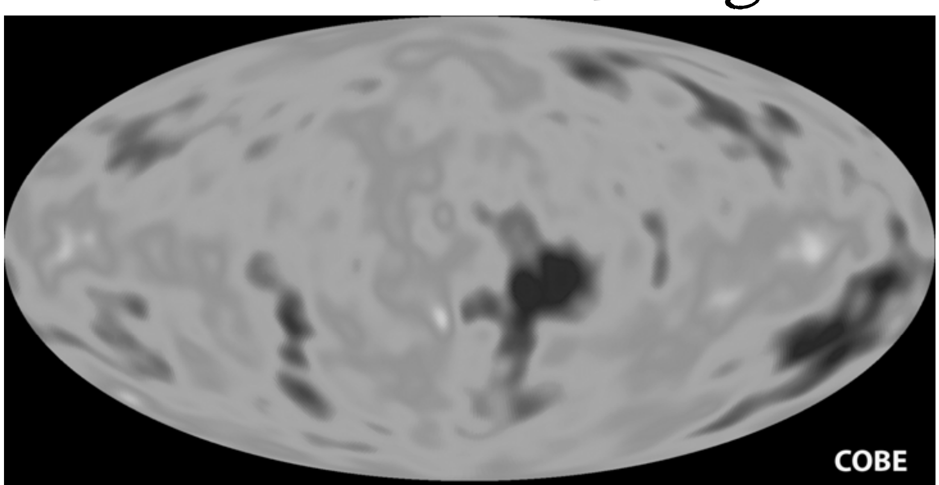




Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Superhorizon perturbations in gravitational potential (Sachs-Wolfe)
- $\Delta T/T < 10^{-5}$

Cosmic Microwave Background



Map of the Universe at Recombination Epoch:

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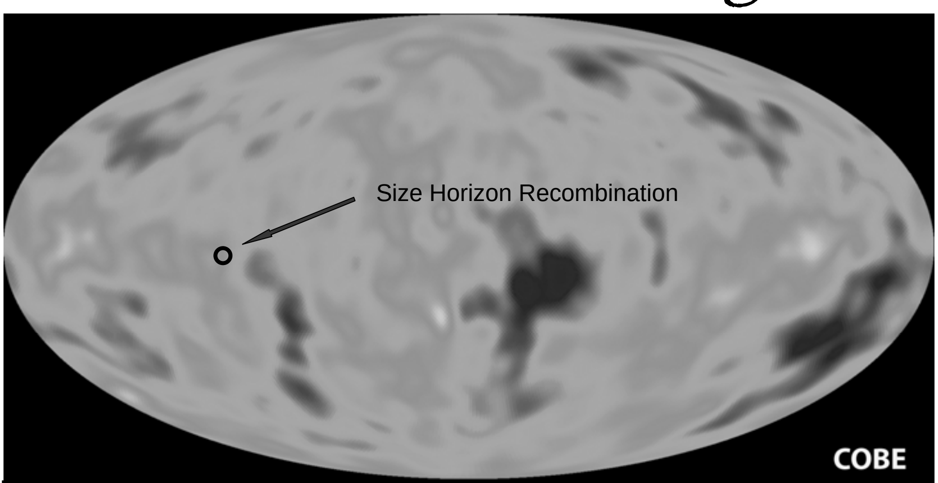
Horizon Problem Illustrated

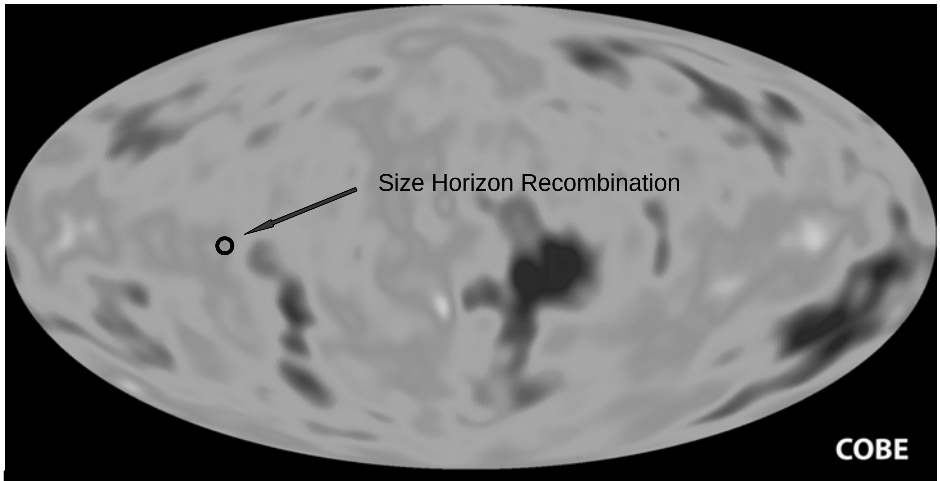
Cosmic Microwave Background



COBE measured fluctuations: > 7°
Size Horizon at Recombination spans angle ~ 1°

How can it be that regions totally out of thermal contact,
would have the same temperature ?

Cosmic Microwave Background

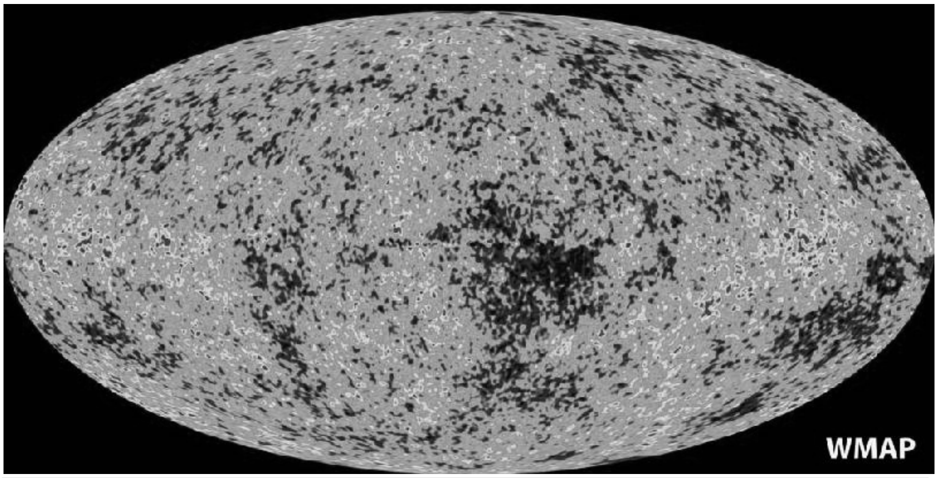


COBE measured fluctuations: > 7°
Size Horizon at Recombination spans angle ~ 1°

COBE proved existence superhorizon fluctuations: Inflation prediction !!!!!

Resolving Fluctuations

Cosmic Microwave Background



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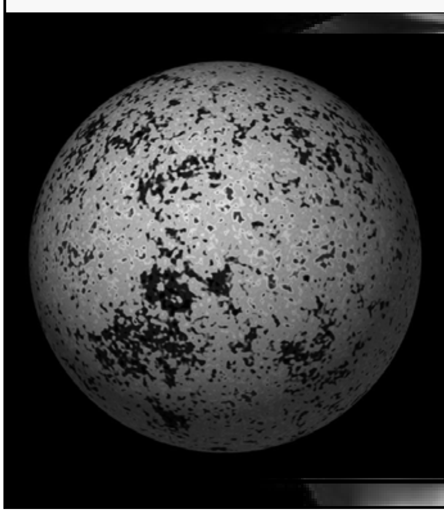
Temperature Anisotropies

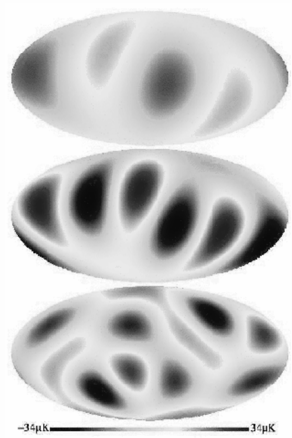


Temperature Perturbations in terms of Spherical Harmonics:

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

$$\phi \sim \frac{\pi}{l} \sim \frac{180^\circ}{l}$$

Temperature Anisotropies



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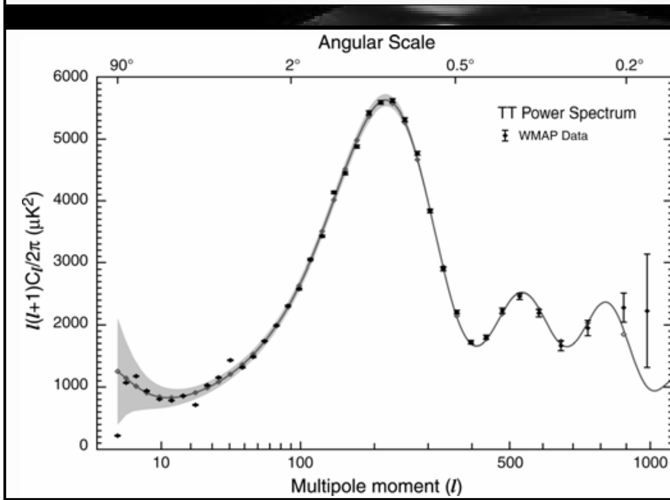
CMB Power Spectrum



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

Angular power spectrum

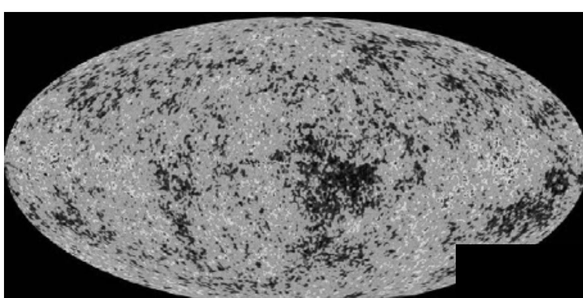
$$C_l \propto \langle a_{lm} a^*_{lm} \rangle$$

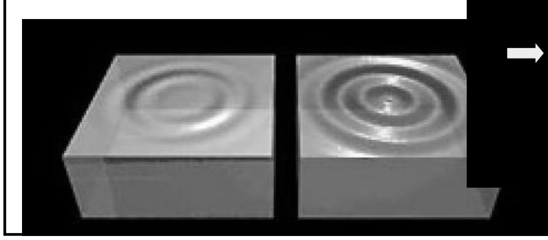
$$C_l \propto l(l+1)$$

$$P(k) \propto k$$

Music of the Spheres

Cosmic Microwave Background





Seeing Sound

For graphics & science see website Wayne Hu

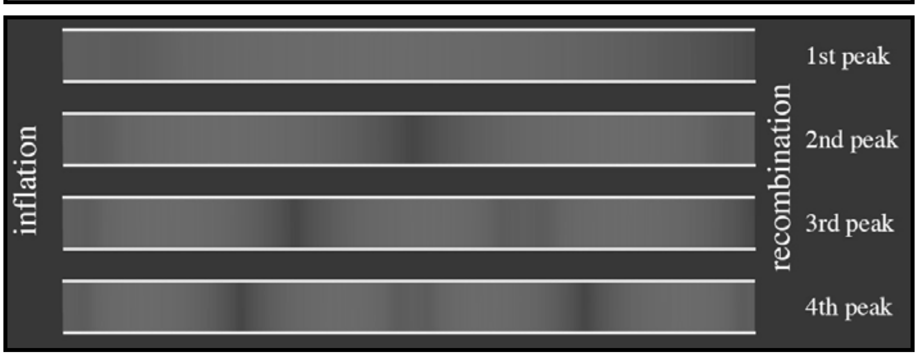
- Colliding electrons, protons and photons forms a plasma
- Acts like a gas
- Compressional disturbance propagates in the plasma through collisions

- Unlike sound in the air:
  - air molecules travel ≈ 10^{-5} cm before colliding
  - in primordial plasma, photons travel 10^{4} pc
- Unlike sound in the air:
  - we do not hear it but see it in the CMB
  - compression heats the gas resulting in a hot spot in the CMB

Piper at the Gates of Dawn

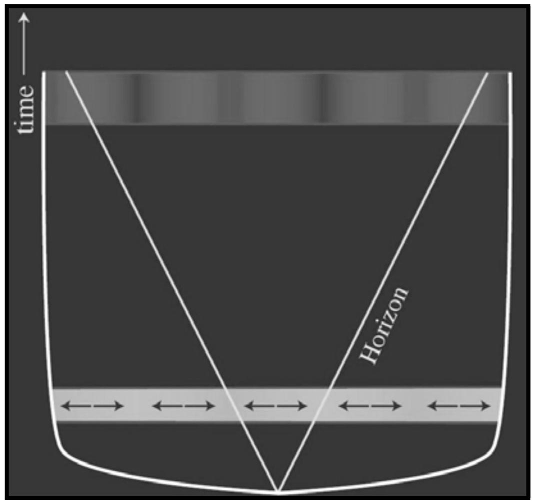
- Like blowing into a flute or an open pipe
- Spectrum of sound contains a

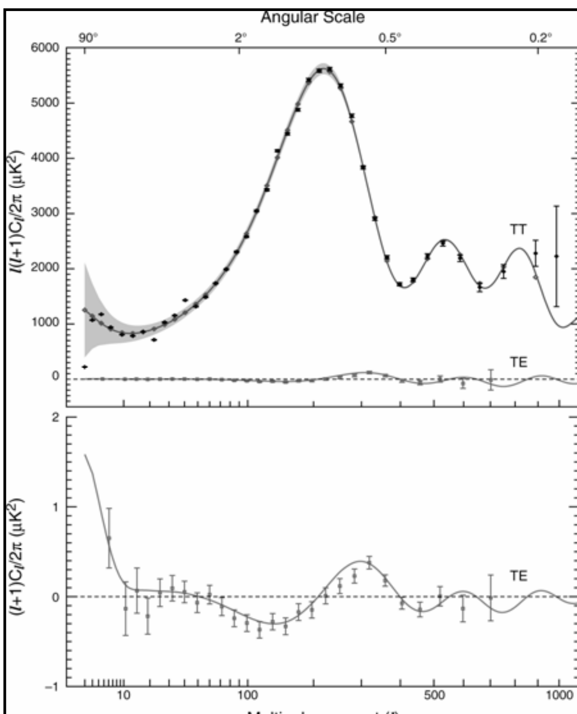
Fundamental frequency & Harmonic overtones



Piper at the Gates of Dawn

- Inflation is the source of sound waves at the beginning of time
- Sound waves are frozen at recombination, yielding a harmonic spectrum of frequencies that reach maximum displacement





CMB

Angular power spectrum

WMAP3

Temperature fluctuations

Temperature-Polarization

$$C_l \propto \langle a_{lm} a^*_{lm} \rangle$$

$$C_l \propto l(l+1)$$

$$P(k) \propto k$$

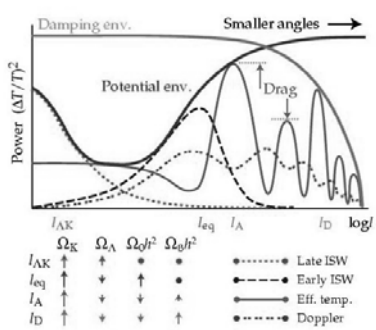
Harmonic Signature

- Identify structure and composition of the Universe
  - through detailed examination of the pattern of overtones on the fundamental frequency
  - much like using them for a music instrument

- Observed frequency spectrum consistent with inflationary origin:
  - spectrum of cosmic sound has harmonics at integer ratios of fundamental

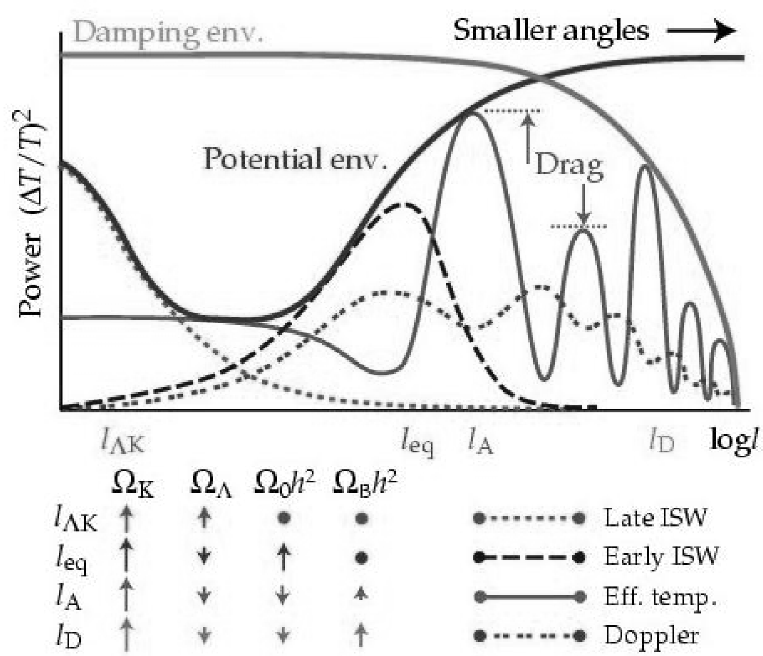
- Without inflation, fluctuations should have been generated at intermediate times
- This would have destroyed the harmonic structure of the peaks (like drilling holes in an organ pipe)

Music of the Spheres



Total Angular CMB Spectrum modulated by combination of several effects, the Primary Perturbations

1) Sachs-Wolfe potential fluctuations,
2) Acoustic perturbations
   as the corresponding potential fluct. enter horizon and start to collapse
3) Integrated Sachs-Wolfe potential perturbations:
   - Early ISW: matter/radiation at recomb.
   - Late ISW: expansion influence curvature & cosmological constant
4) Doppler perturbations
   velocity fluct. accompanying potential pert.
5) Silk Damping
   radiation damping of fluctuations



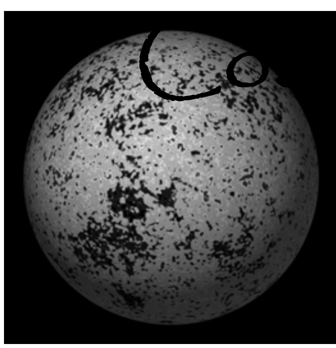
Modulating Influences

- Silk Damping:
  - photons diffuse out of matter perturbations
  - fluctuations with size < photon free-streaming length get suppressed
  - harmonic structure beyond third peak seriously damped

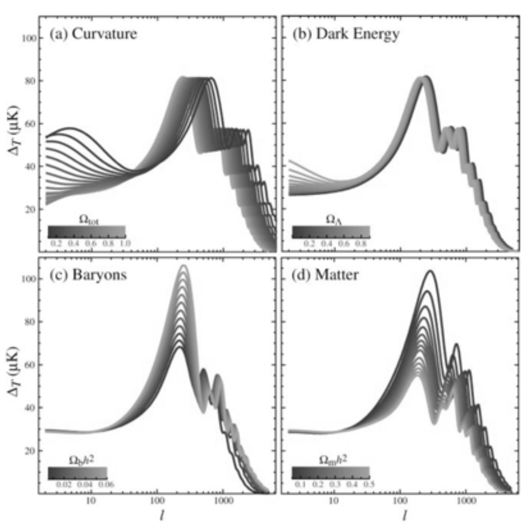
- Integrated Sachs-Wolfe effect:
  - damping/boosting temperature fluctuations due to decay/growth potential perturbations:
    - Early ISW: while still radiation-dominated, potential DM fluct's grow less, suppression of temp. fluct.
    - Late ISW: as Dark Energy takes over universe, potential wells decay (due to accelerated expansion)

Universe Measured

Cosmic Parameters



The WMAP CMB temperature
power spectrum



Friedmann-Robertson-Walker-Lemaitre Universe

Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$	$n_s = 0.93^{+0.03}_{-0.03}$
$w < -0.78$ (95% CL)	$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$	$r < 0.71$ (95% CL)
$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$	$z_{dec} = 1089^{+1}_{-1}$
$\Omega_b = 0.044^{+0.004}_{-0.004}$	$\Delta z_{dec} = 195^{+2}_{-2}$
$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}	$h = 0.71^{+0.04}_{-0.03}$
$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$	$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr
$\Omega_m = 0.27^{+0.04}_{-0.04}$	$t_{dec} = 379^{+8}_{-7}$ kyr
$\Omega_\nu h^2 < 0.0076$ (95%CL)	$t_r = 180^{+220}_{-80}$ Myr (95% CL)
$m_\nu < 0.23$ eV (95% CL)	$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K	$z_{eq} = 3233^{+194}_{-210}$
$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}	$\tau = 0.17^{+0.04}_{-0.04}$
$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$	$z_r = 20^{+10}_{-9}$ (95% CL)
$\Omega_b\Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$	$\theta_A = 0.598^{\circ}{}^{+0.002}_{-0.002}$
$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc	$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
$\sigma_8\Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$	$l_A = 301^{+1}_{-1}$
$A = 0.833^{+0.086}_{-0.083}$	$r_s = 147^{+2}_{-2}$ Mpc

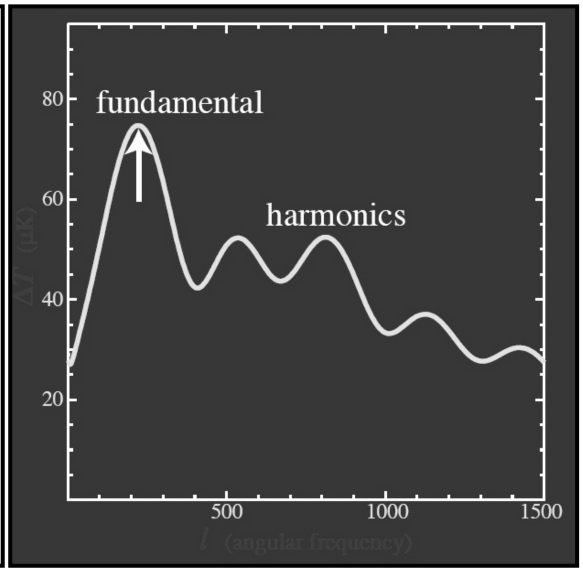
Curvature Measured

Harmonic Signature

Spectrum cosmic sound:

-integer ratios fundamental

- competition between
  gravity vs. pressure:
  dependent on phase
- fundamental + odd mode:
  gravity along sonic motio
- even multiples:
  gravity fights sonic motion

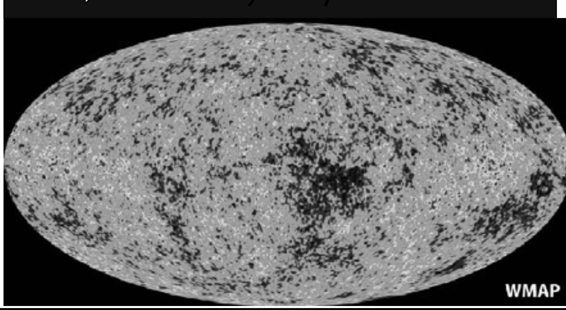


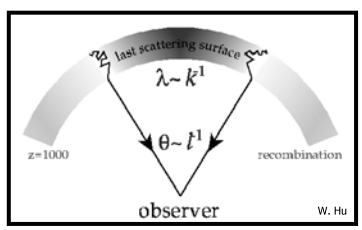
Geometry of the Universe: Music of the Spheres

Measuring the Geometry of the Universe:

- Object with known physical size, at large cosmological distance
- Measure angular extent on sky
- Comparison yields light path

→ *Geometry of space*





"Physical Object":

- Sound waves in primordial matter-radiation plasma: wavelength λ_s
- observable at surface of epoch recombination, at which photons were last scattered

Geometry of the Universe: Music of the Spheres

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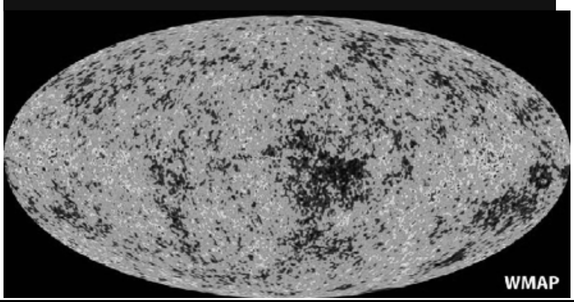
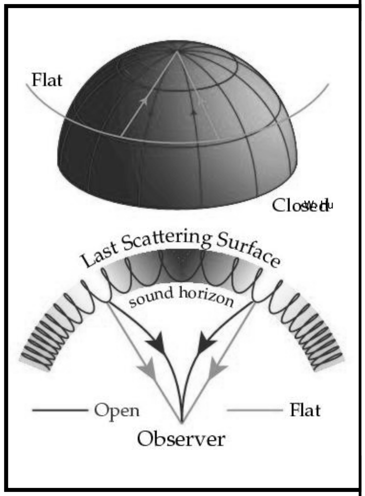
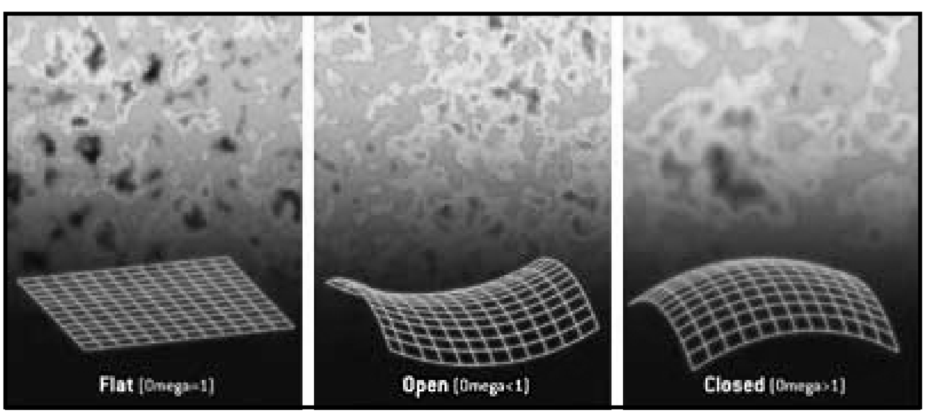
⇒ *Geometry of space*



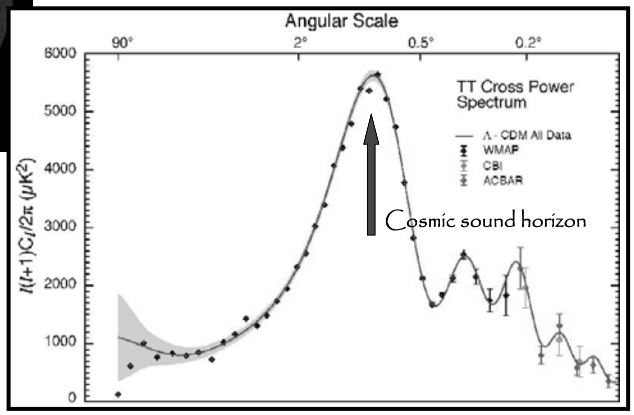


Friedmann-Robertson-Walker-Lemaitre Universe



Music of the Spheres

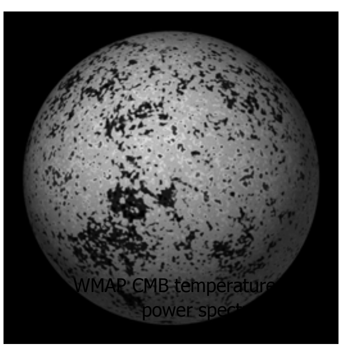
The Cosmic Tonal Ladder

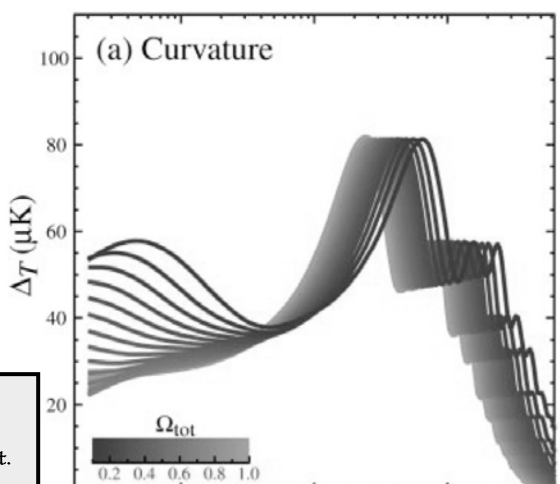


The WMAP CMB temperature power spectrum

The Cosmic Microwave Background Temperature Anisotropies: the Embryonic Universe

Curvature: CMB





Curvature influences:
- angular scale of given physical fluct.
- evolution potential wells

Matter

Cosmic Constituents: Matter

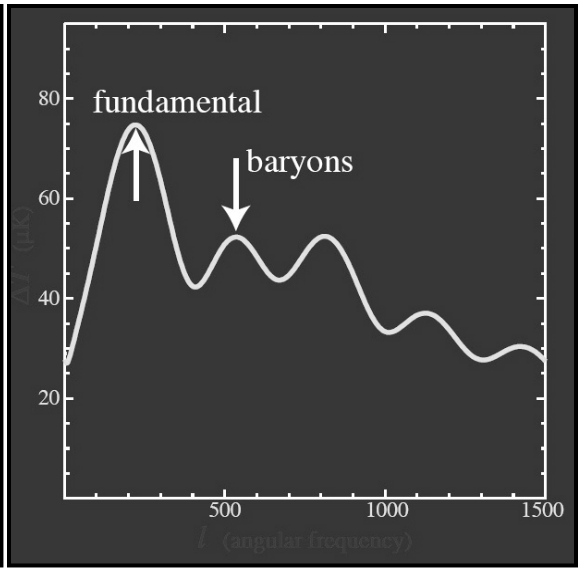
- Baryonic Matter
- Nonbaryonic Dark Matter

Baryonic Matter

Baryonic Matter:

- Baryonic "drag" suppresses fluctuation

- low second peak: baryon density comparable to photon density



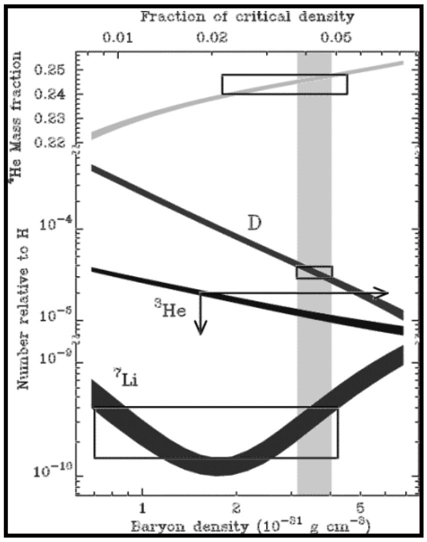
Baryonic Matter

Note:

- STARS are but a fraction of the total amount of baryonic matter
- There is still a large amount of undetected baryonic matter:
  - hiding as warm Intergalactic Gas (WHIM) ?

3	baryon rest mass				0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003	
3.1a	virialized regions of galaxies		0.024 ± 0.005		
3.1b	intergalactic		0.016 ± 0.005		
3.2	intracluster plasma			0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges		0.0015 ± 0.0004	
3.4		disks and irregulars		0.00055 ± 0.00014	
3.5	white dwarfs			0.00036 ± 0.00008	
3.6	neutron stars			0.00005 ± 0.00002	
3.7	black holes			0.00007 ± 0.00002	
3.8	substellar objects			0.00014 ± 0.00007	
3.9	HI + HeI			0.00062 ± 0.00010	
3.10	molecular gas			0.00016 ± 0.00006	
3.11	planets			10^{-6}	
3.12	condensed matter			$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1+\epsilon_n)$	

Baryonic Matter: primordial nucleosynthesis

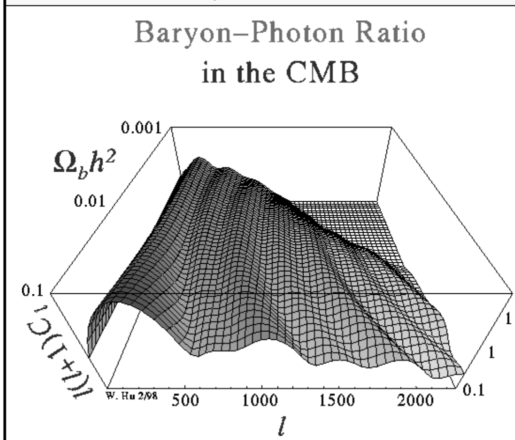


From measured light element abundances:

$$\eta \equiv \frac{n_B}{n_\gamma}$$

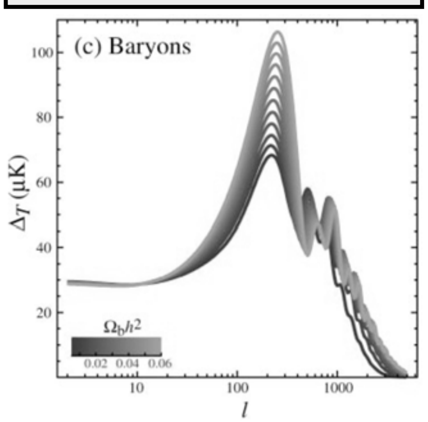
$$0.005 \lesssim \Omega_b h^2 \lesssim 0.026$$

Baryonic Matter: CMB



$$\Omega_b h^2 \approx 0.0224 \pm 0.0009$$
$$\Omega_b \approx 0.044 \pm 0.004$$

Due to baryon drag in the primordial baryon-photon gas, 2nd peak in CMB spectrum is suppressed:

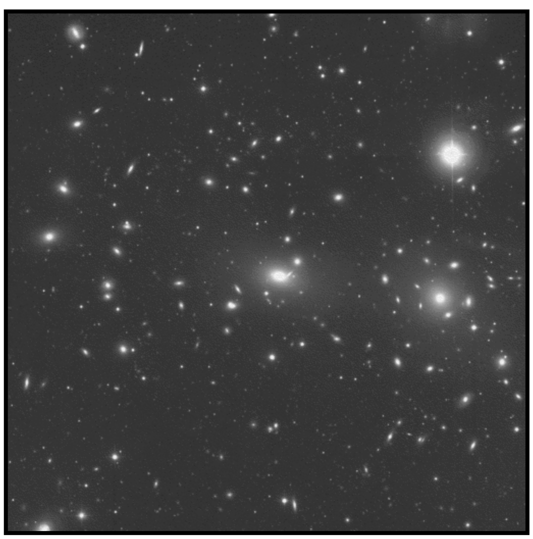


Dark Matter

It is the nonbaryonic Matter that is responsible for the existence of Structure in the Universe !!!

If it had not been there: no substantial structure

Clusters of Galaxies



Courtesy:
O. Lopez-Cruz

Coma Cluster

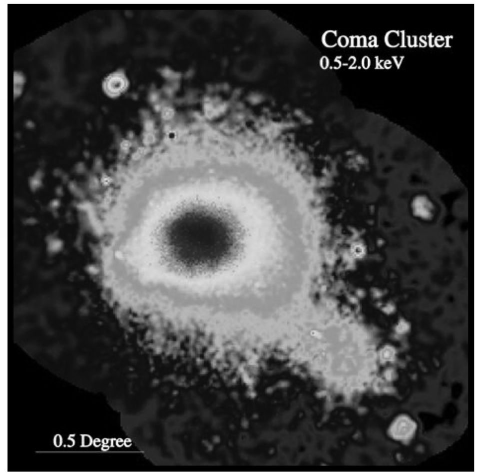
Clusters: X-ray intracluster gas

Hydrostatic Equilibrium:

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

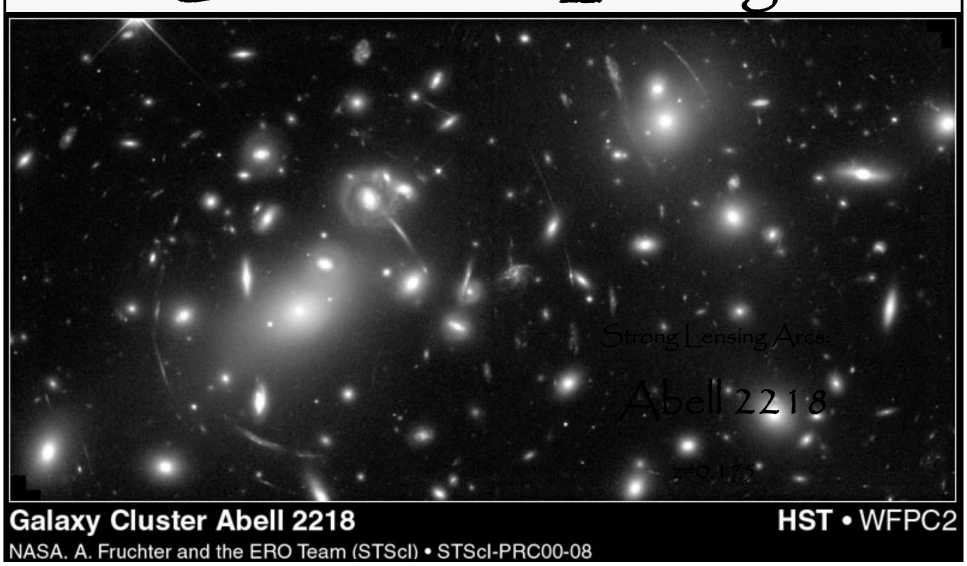
Emission:

Bremsstrahlung: $L \sim \rho^2$



ROSAT X-ray image Coma Cluster

Clusters: Gravitational Lensing



Nonbaryonic Dark Matter

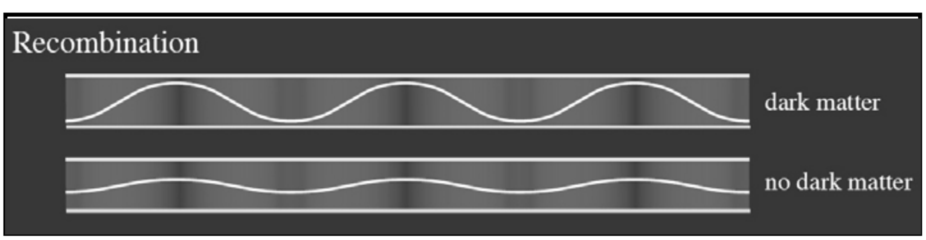
Two major classes of Dark Matter:

MACHOs massive compact halo objects
- brown dwarfs
- stellar remnants (black holes, neutron stars)
- primordial black halos

WIMPs weakly interacting massive particles:
- hot dark matter e.g. massive neutrinos
- cold dark matter axions, neutralinos
- warm dark matter

Dark Matter

Dark Matter:
-Retains the gravitational potential,
- while baryonic matter oscillates as stable sound wave
- otherwise, decay gravitational potential

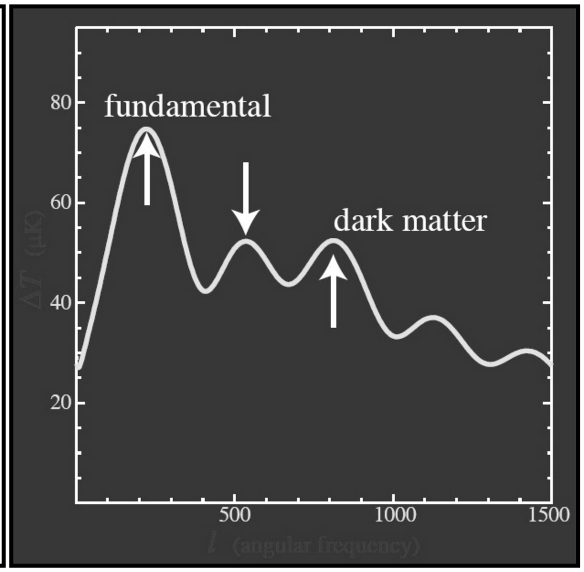


Dark Matter

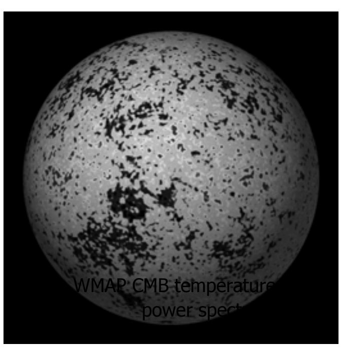
Dark Matter:

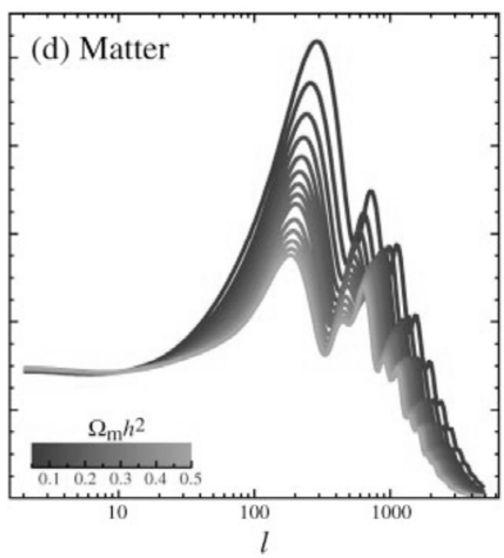
-Responsible for keeping up gravitational potential perturbations

- third peak:
  dark matter density



Matter: CMB





(Dark) Matter determines the depth of the potential wells, influencing the amplitude of the acoustic fluctuations

Dark Energy/ Cosmological Constant

Cosmic Acceleration

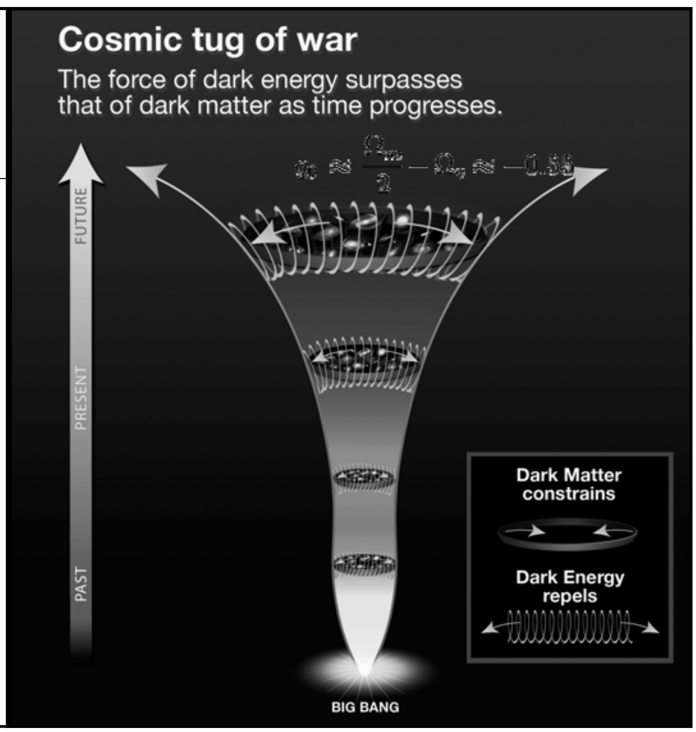
Our Universe

Present:

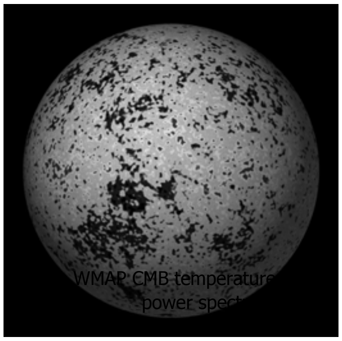
ACCELERATES

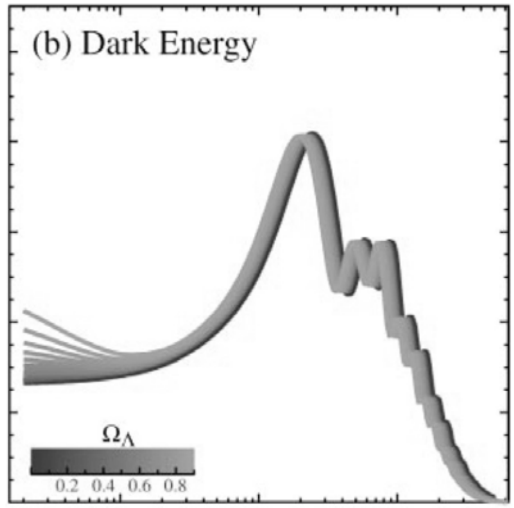
Past:

DECELERATED



Dark Energy: CMB





Dark Energy modifies evolution potential wells

Secondary Effects

- Sunyaev-Zel'dovich Effect
- Gravitational Lensing CMB
- Reionization: polarization
- Integrated Sachs-Wolfe Effect
- Rees-Sciama Effect
- Vishniac Effect
- ....

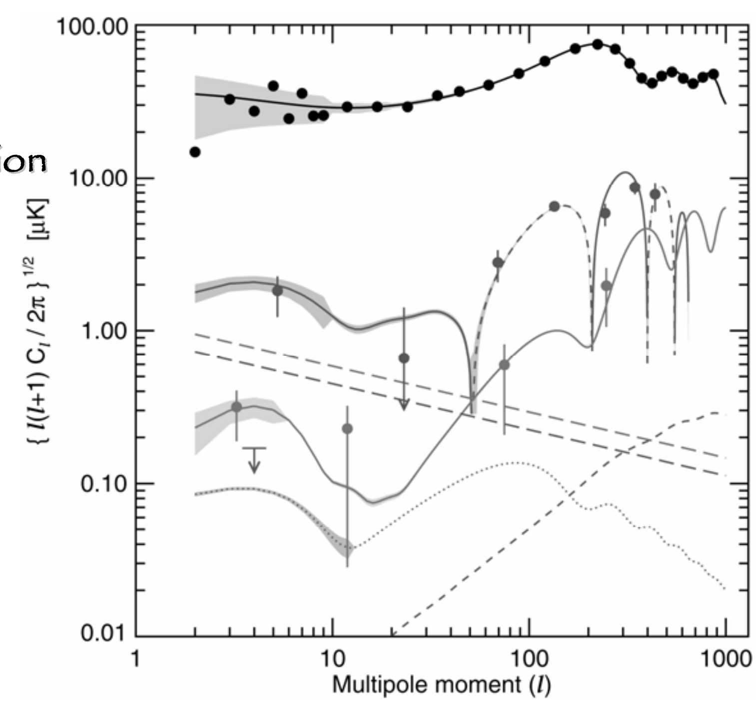
Polarization CMB

Richest Source of Information on Primordial Universe:

Two modes:

E-mode:	Doppler motions recombination
	Reionization
B-mode:	Gravitational Lensing
	Primordial (Inflationary) Gravitational Waves

CMB Polarization



Cosmic Microwave Background

Lifted Cosmology into

the realm

Of Precision Cosmology