Particles and Universe: Evolution of the Universe (2)

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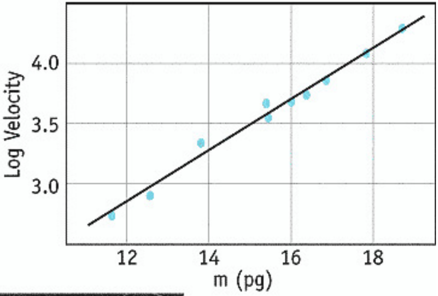
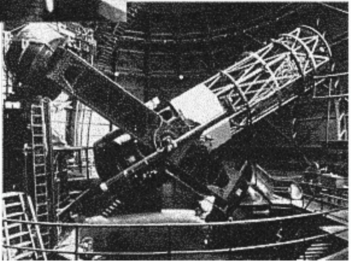
Hubble's Law

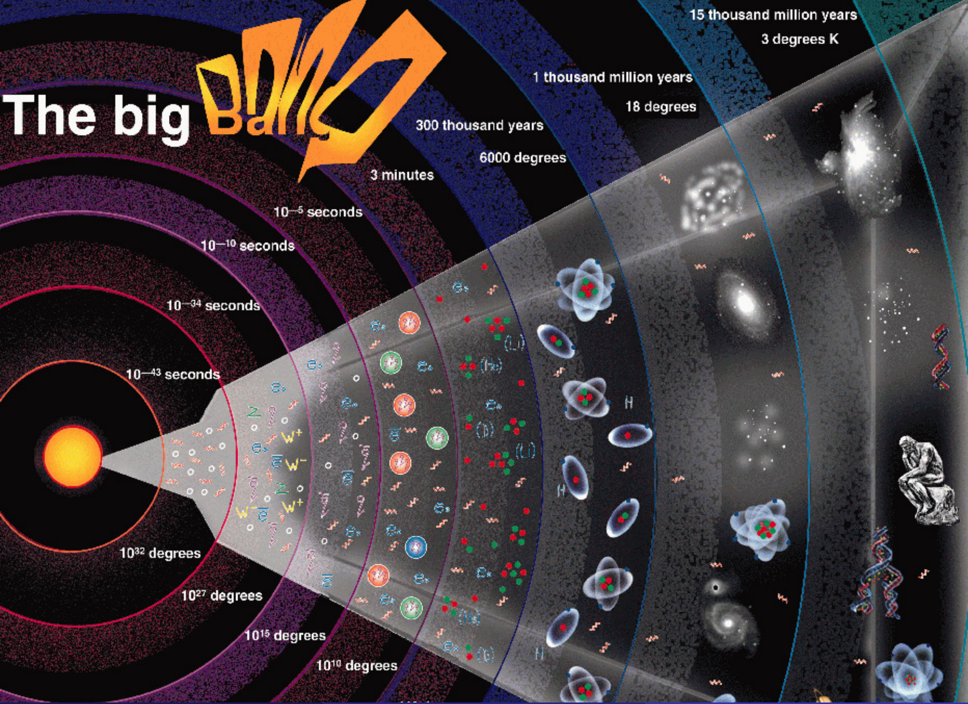
DISCOVERY OF EXPANDING UNIVERSE

Edwin Hubble





Mt. Wilson
100 Inch
Telescope


The big Bang
15 thousand million years
3 degrees K
1 thousand million years
18 degrees
300 thousand years
6000 degrees
3 minutes
10−5 seconds
10−10 seconds
10−34 seconds
10−43 seconds
1032 degrees
1027 degrees
1015 degrees
1010 degrees

Critical density

Friedmann equations give dependence between matter density in the Universe and curvature of space.

Critical density:

$$\rho_c \quad = \quad \frac{3H^2}{8\pi G} \sim 10^{-26}\frac{kg}{m^3} \sim 10\frac{GeV}{c^2/m^3}$$

Density parameters (density in units of ρ_c):

$$\Omega_m \quad = \quad \frac{\rho}{\rho_c}$$

$$\Omega_\Lambda \quad = \quad \frac{\Lambda}{3H^2}$$

If $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$
$\Rightarrow$ Universe is 'flat' (euclidean)
curvature $k = 0$

If $\Omega_{tot} < 1$
$\Rightarrow$ Universe is 'open'
curvature $k = -1$

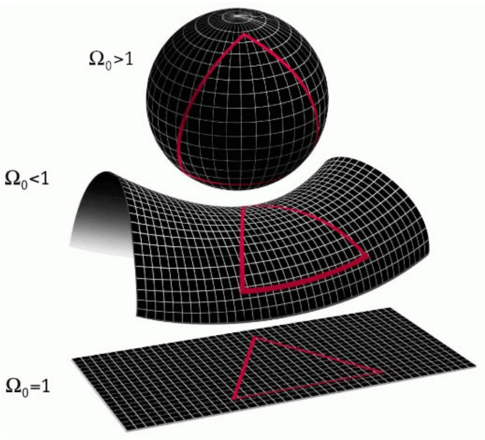
If $\Omega_{tot} > 1$
$\Rightarrow$ Universe is 'closed'
curvature $k = +1$

Evolution of the Universe

Total matter/energy density in the Universe determines the space curvature on cosmological scales

Locally we know, that space is flat (sum of triangle angles is 180°).

But it is very hard to check on large distances...



How to estimate the density of matter in the Universe? $\Omega \equiv \rho/\rho_c$

Many possible approaches:

- looking at radiation of stars and interstellar matter
  $\Rightarrow$ luminous matter $\Omega_{lumi} \sim 0.006$
- from the abundance of light elements + Primordial nucleosynthesis model (BBN)
  $\Rightarrow$ baryonic matter $\Omega_b \sim 0.04 - 0.05$
- measurement of gravitational interactions and structure formation
  $\Rightarrow$ "gravitational" matter (total ?)
  $\Omega_m \sim 0.3$

Comparison of different results indicate, that in addition to "ordinary" (baryonic) matter the Universe consists also of the so called Dark Matter...

Evolution of the Universe

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- from fitting ΛCDM model to CMB measurements (today)

Comparison of different results indicate, that in addition to "ordinary" (baryonic) matter the Universe consists also of the so called Dark Matter...

Dark Matter

We know that dark matter:

- is "cold" (non-relativistic)
- is non-baryonic
- is stable (does not decay)
- interacts very weakly (gravitational only?)
- contributes to about 1/4 of critical density (5$\times$ baryon matter)

We do not know:

- What it consists of (one or more paricles)?
- How to observe it directly?

One of the candidates is the Lightest Supersymmetric Particle (LSP), which we hope to find at LHC...

Predictions

While the Universe expanded, average particle energies (temperatures) decreased. Heavier particles were no longer reproduced and disapeared...

In few hours after the Big Bang the Universe was filled with nuclei of light elements (including protons), electrons and photons. Atoms were not stable, as they could be easily disintegrated by energetic photons.

$$e^- + p^+ \quad \longleftrightarrow \quad H + \gamma$$

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$$e^- + p^+ \quad \longrightarrow \quad H + \gamma$$

Only after about 300'000 years after the Big Bang photons were no longer energetic enough. Electrons are captured by nuclei creating neutral atoms.

The Universe starts to be transparent for photons.

Photons still fill the space, but their energies decrease (wavelengths increase) with the expansion of the Universe.

Predictions

In 1948, George Gamow, Ralph Alpher and Robert Herman came to the conclusion that photons emitted 300'000 years after the Big Bang should still fill the Universe.

Only their energy is so small, that we are not able to detect them.

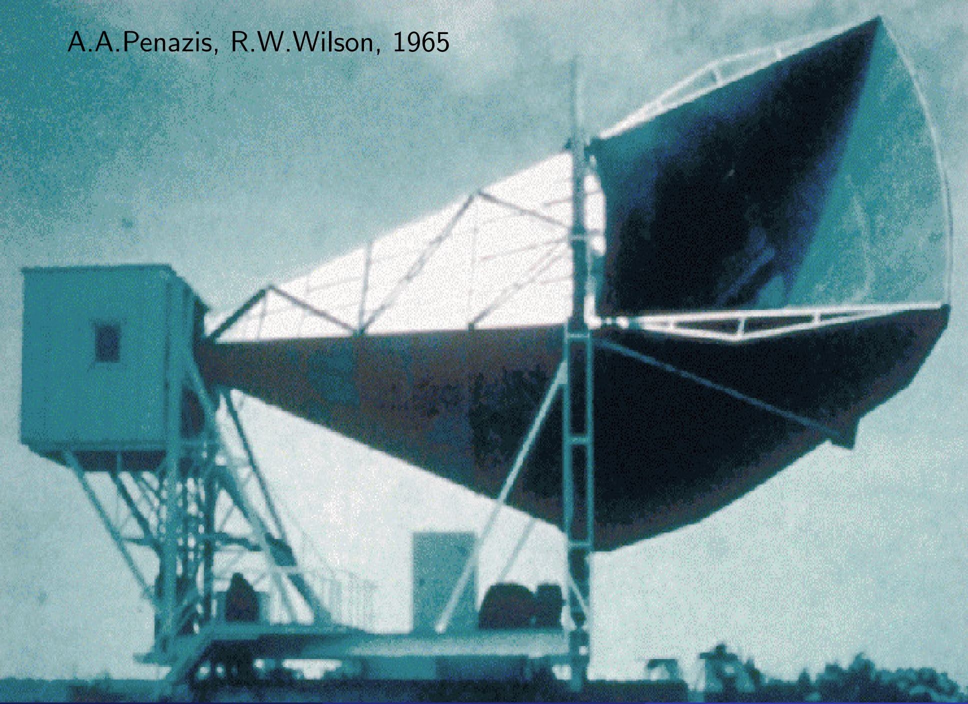
This is the so called Cosmic Microwave Background (CMB)
also known as relic radiation

Spectral distribution of the radiation should correspond to the black body radiation at temperature

$$T \sim 5\,K$$

Observation of CMB was the final argument for the Big Bang theory,
it could not be explained in the model of static Universe.

A.A.Penazis, R.W.Wilson, 1965



Discovery

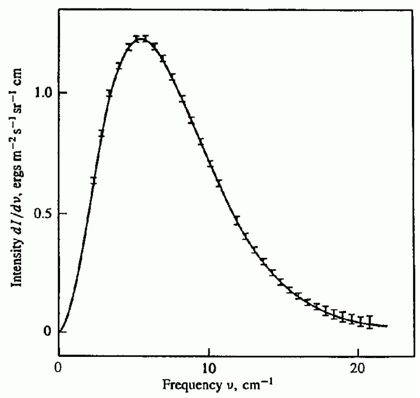
Cosmic Microwave Background was discovered by A.A.Penazisa and R.W.Wilsona in 1965.

It was more and more studied in the next decades, but it was difficult.

Precise measurements became possible with satellite detectors - it was confirmed that the spectra corresponds to the black body radiation at

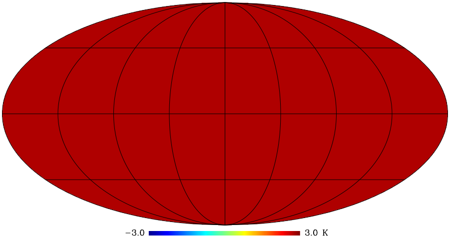
$$T = 2.725 \pm 0.002\ K$$

COBE satellite results (1999)

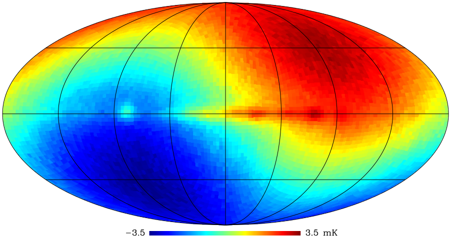


Angular distribution

To the first approximation ($\Delta T \sim 1K$) radiation is isotropic:



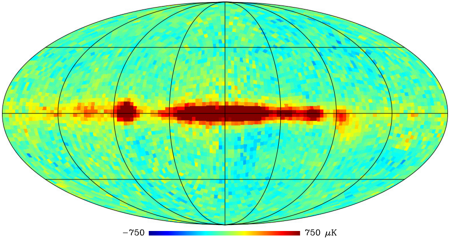
But when we look closer ($\Delta T \sim 1mK$):



we see the effect of Earth motion with respect to the 'global' frame ?

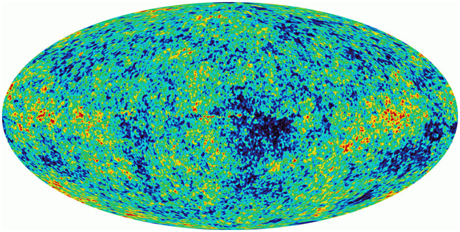
Angular distribution

Correcting for Doppler effect ($\Delta T \sim 200 \mu K$):

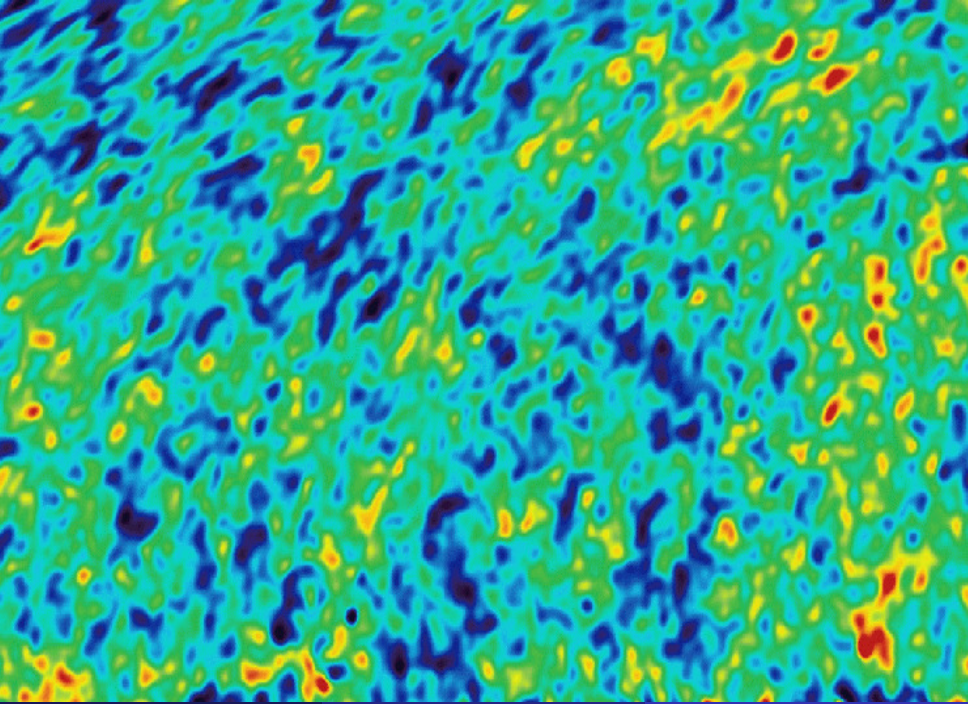


⇒ we see radiation of our galaxy (Milky Way)...

Subtracting radiation coming from the Galaxy and other known sources ($\Delta T \sim 100 \mu K$):



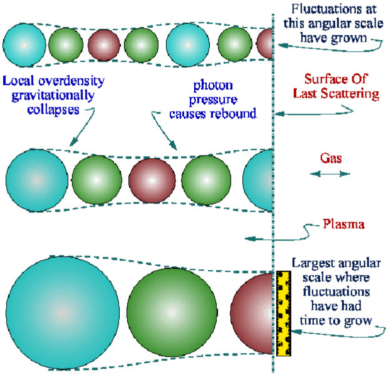
⇒ starts to be interesting !!!



Fluctuations

Temperature fluctuations are due to the fact that the Universe was not "static" when CMB was emitted

It 'oscillated' around the equilibrium state, where the radiation pressure is balanced by gravitational attraction ⇒



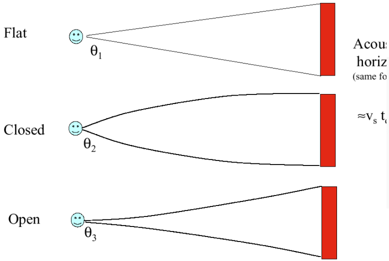
Angular size of these fluctuations depends on the size of the Universe at the time of CMB decoupling...

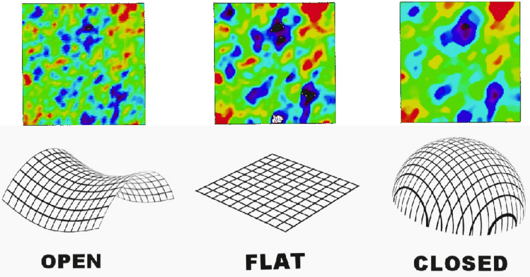
⇒ it depends on the cosmological parameters

Fluctuations

Observed angular sizes of CBM fluctuations depend strongly on the curvature of the Universe

Simulation results:





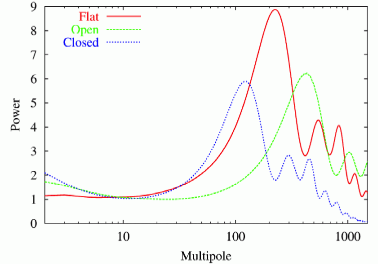
Fluctuations

Observed pattern of fluctuations can be described by calculating correlations between pixels at given angular distance.

Formally, we can describe it as the image decomposition into the so called spherical harmonics (Legendre polynomials) in $\cos\theta_{ij}$ (angular distance).

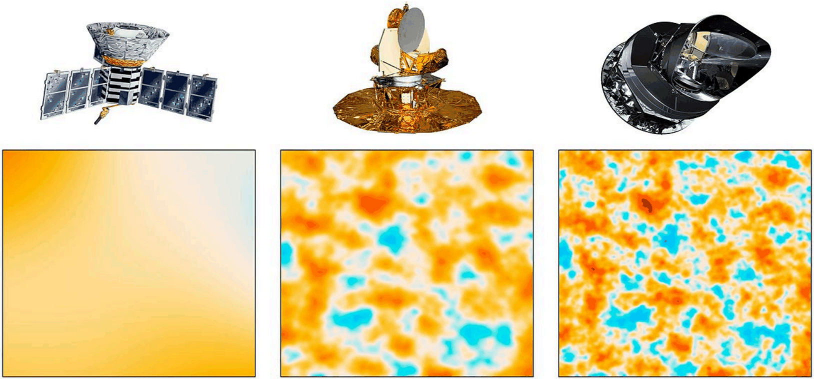
The power spectra (power distributions between different "multipoles" - fluctuations at different angular scales) depend on the model parameters.

Results of simulation for different model parameters:



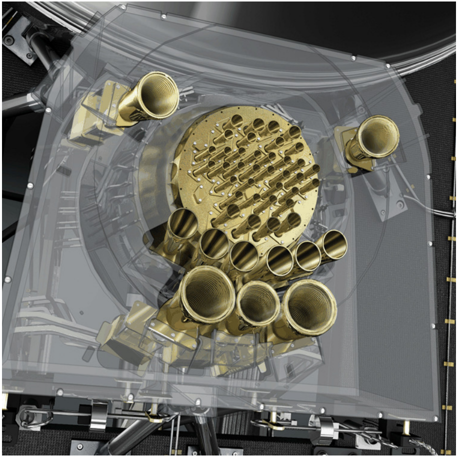
eg. for flat Universe $(\Omega = 1)$ we would expect dominant contribution (main peak) at $l \sim 200$

CMB satellites Best for precise fluctuation measurements



COBE	WMAP	Planck
1989	2001	2009

Planck Satellite



CMB detected by 75 sensors
in 9 frequency bands
from 30 to 857 GHz

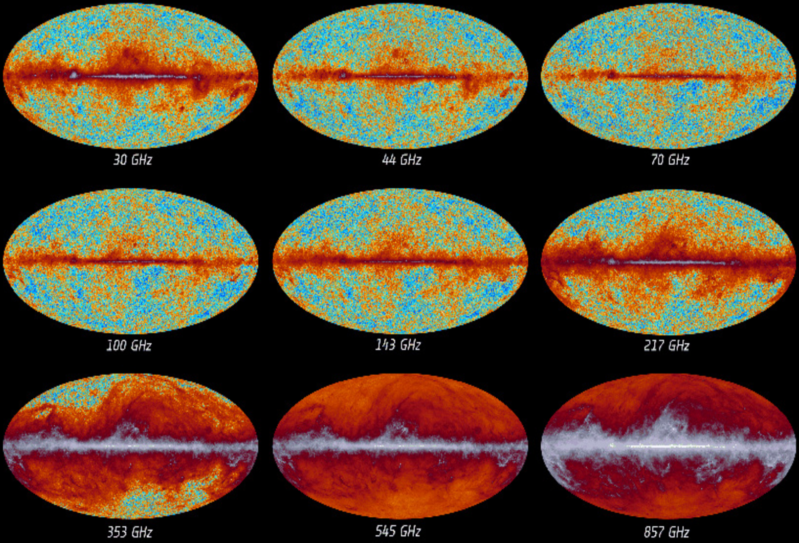
Low frequency sensors at 20 K

High frequency sensors at 0.1 K !!!

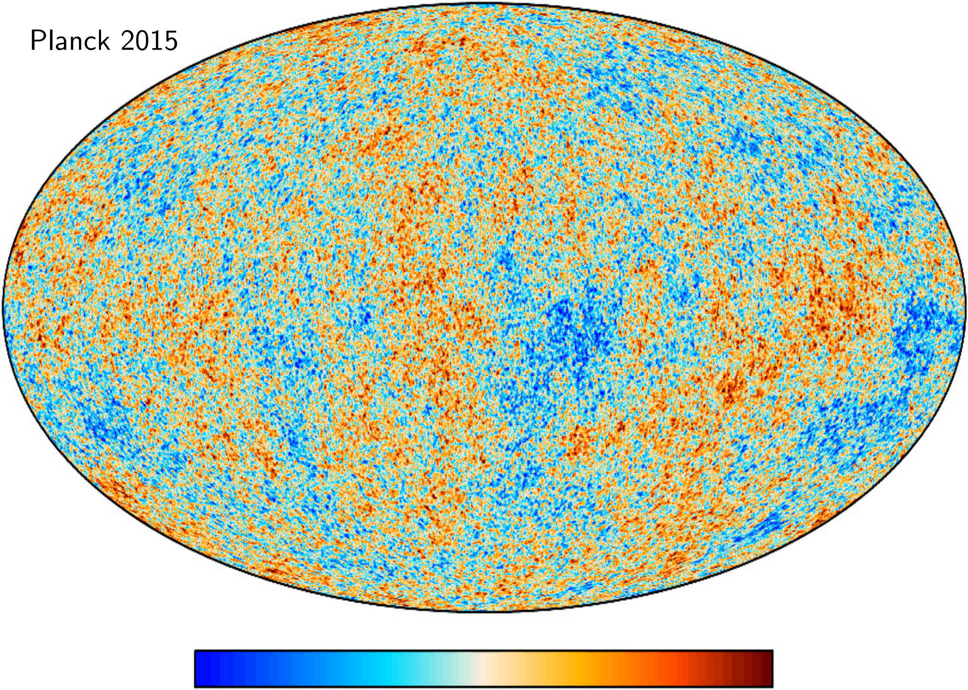
Scan of the whole sky in 6 month

Sensitivity increased by factor of 25, compared to WMAP

The sky as seen by Planck



Planck 2015



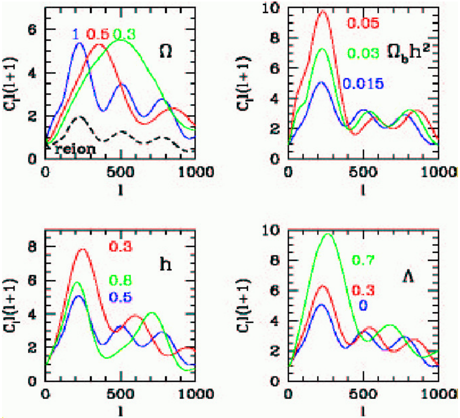
Model fitting

CMB power spectrum depends not only on the total density, but also on other cosmological parameters.

Model used in the Planck data analysis includes densities for:

- photons (⇒ CMB)
- baryons
- neutrinos
- cold dark matter (CDM)
- cosmological constant (Λ)

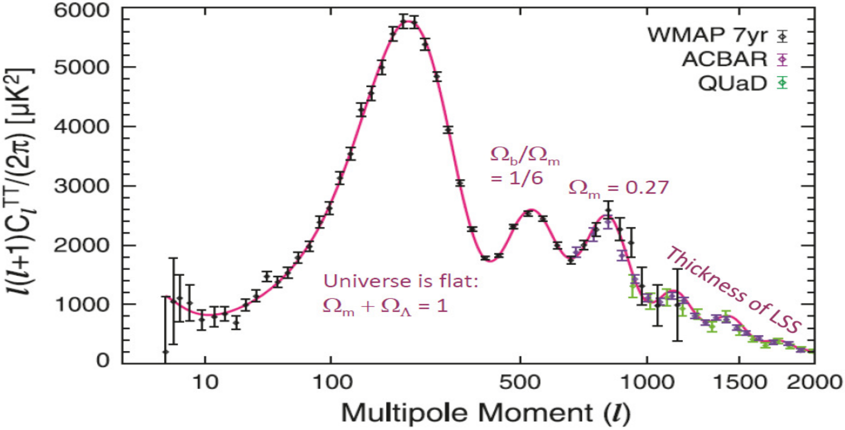
Simulation results:



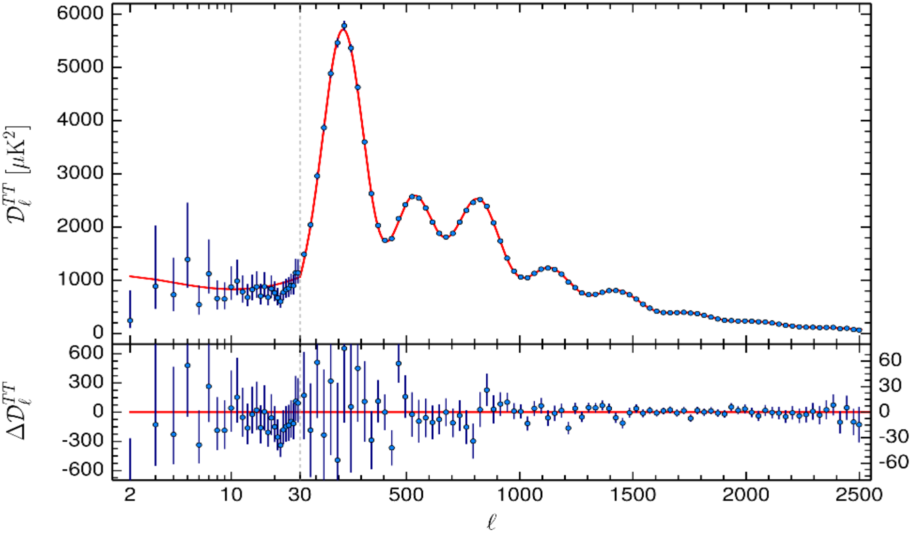
⇒ Universe evolution can be described by 6 independent parameters

Model fitting

By fitting the full power spectra, most parameters can be constrained



Results (2015) Consistent with flat Universe: $\Omega_{tot} \approx 1$ ± 0.0025



Fit results

The Universe seems to be flat within 0.25% accuracy ($\Omega \approx 1$)

Total matter contribution is about 31% of the critical density (Ω_m)

$\Rightarrow$ we need to include contribution from the cosmological constant Λ (dark energy?)

Only about 5% comes from atoms, baryonic matterii (Ω_b)
$\Rightarrow$ rest of matter must be "invisible" dark matter

Parameter	*Planck* TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

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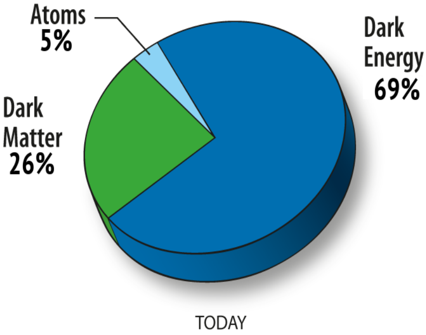
dark matter

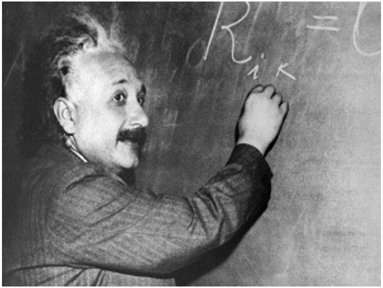


$$T_U = 13.799 \pm 0.038 \; Gy$$

General Relativity, as introduced by Einstein in 1916, describes evolution of the Universe.

We assume that the Universe is uniform and isotropic at largest scales.

But what about smaller scales?
We know the Universe is not uniform...



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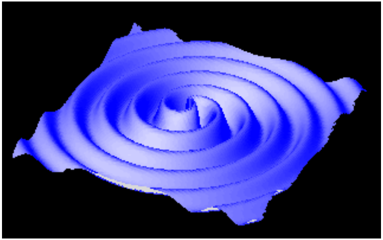

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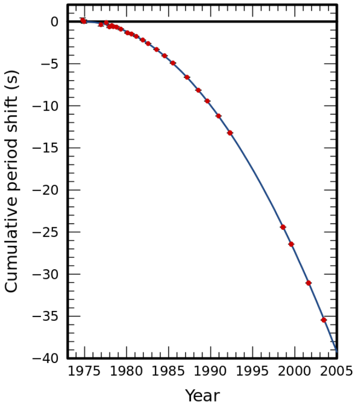
We know the Universe is not uniform...

If masses accelerate, they can emit gravitational waves, similar to electromagnetic waves for accelerating charges, but much, much weaker...

Indirect evidence

In 1974 Joseph Taylor and Russell Hulse discovered pulsar PSR 1913+16.

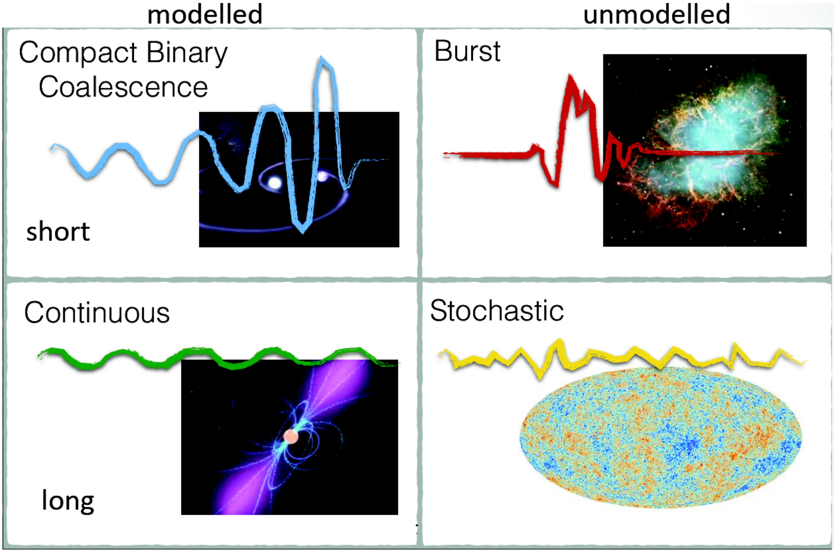
They noticed regular changes in its primary period (59 ms), which were interpreted as being due to the Doppler effect.
⇒ pulsar is circulating around another star in a binary system (7.75 h period)



Longer observations indicated that the period of circulation was decreasing
⇒ binary system rotates faster and faster
⇒ explained by energy loss with radiation

Very good agreement with GR ⇒ Nobel 1993

Possible sources



Properties

Gravitational waves behave very similar to electromagnetic waves:

- propagate with the same velocity (speed of light)
- follow curvature of space (gravitational lensing)
- frequency depends on relative motion (Doppler effect)
- carry energy, momentum and angular momentum

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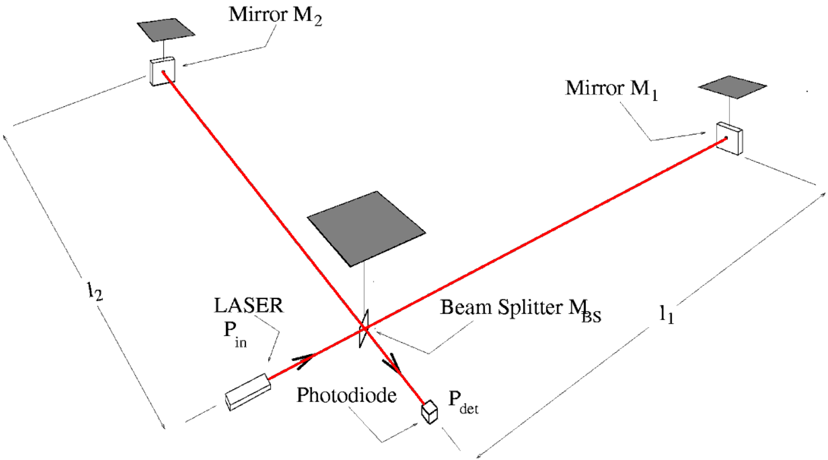
However, gravitational waves are extremely weakly absorbed in matter
$\Rightarrow$ very difficult to observe by direct interaction

Passing wave deforms space: rest state (or motion) of objects is not affected, but distances between them are!
$\Rightarrow$ can be measured using interferometers

Interferometers

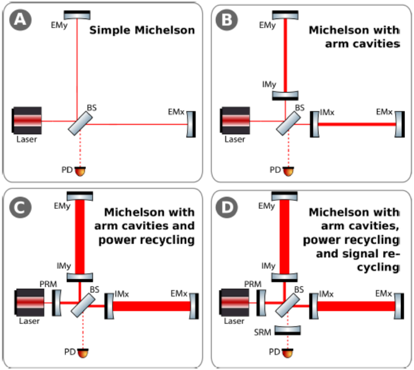
Very simple idea: repeat the Michelson-Morley experiment.
Look for the periodic variations in the speed of light...

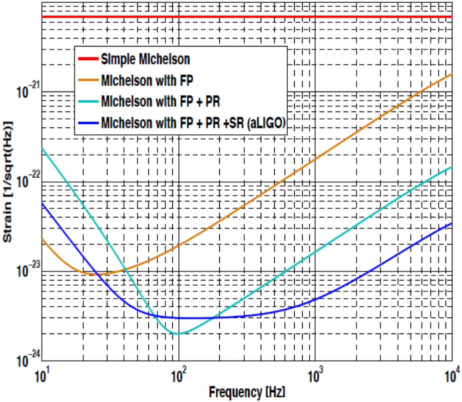


Interferometers

We need to be sensitive to extremely tiny displacements! $\Delta L/L \sim 10^{-21}$

$\Rightarrow$ use resonant cavities to increase laser power and effective arm length





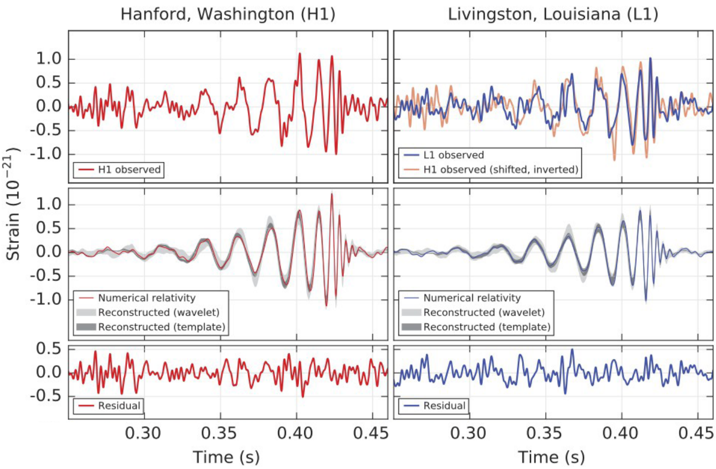
VIRGO (Italy) 3 km arms

LIGO (Hanford, USA)   4 km arms

LIGO (Livingston, USA) 4 km arms

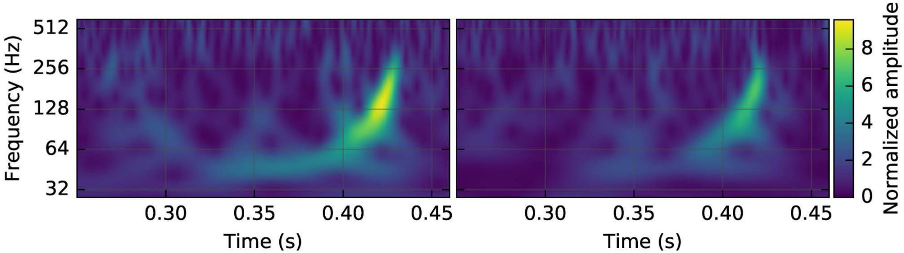
Discovery

On September 14, 2015, at 09:50:45 UTC, seen by both LIGO detectors
"found" by an algorithm looking for close binary coalescence



Discovery

Very strong signal, clearly visible in time-frequency power distribution

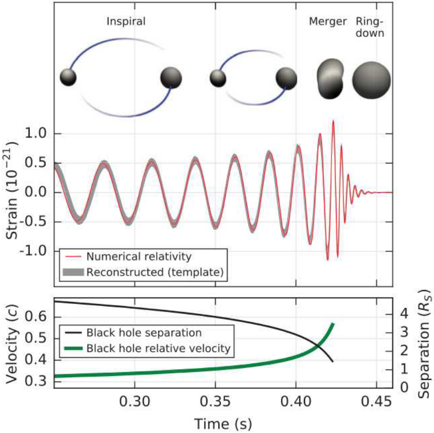


Expected background at this signal level:

1 event in 203'000 years !

Description

GW150914 looks like coalescence of two massive black holes.



Very good description by GR

Initial masses:

$$M_1 = 36^{+5}_{-4}\ M_\odot$$
$$M_2 = 29^{+4}_{-4}\ M_\odot$$

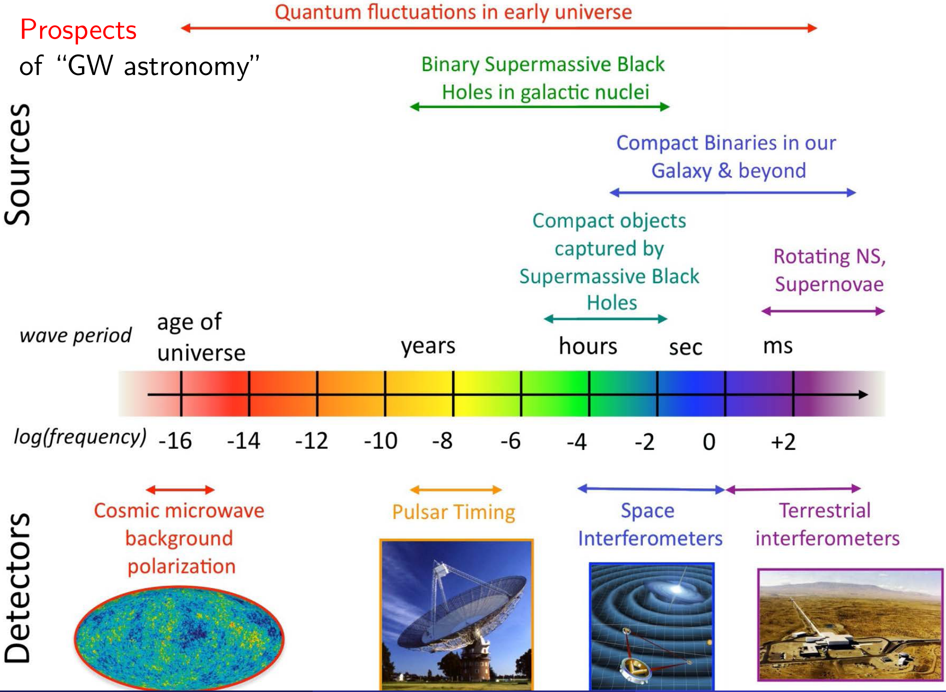
Final black hole:

$$M_f = 62^{+4}_{-4}\ M_\odot$$

Distance:

$$d = 410^{+160}_{-180}\ Mpc$$
$$z = 0.09^{+0.03}_{-0.04}$$

Prospects
of "GW astronomy"



Summary

Recent years brought many new results of interest to both particle physics, astronomy, astrophysics and cosmology

$\Rightarrow$ new field of research: Astroparticle physics

We are still trying to find answers to many questions:

- Dark Matter — we still do not know what it is composed of, even if we have few theories (eg. supersymmetric particles)
- Dark Energy — Einsteins "mistake" which turned out to be true absolute mystery...
- Baryon Asymmetry — we do not understand how matter-antimatter symmetry was broken...
- UHECR — Ultra High Energy Cosmic Rays, with energies up to 10^{20} eV, where do they come from?...

We do hope LHC will find some answers,
but there are also many other dedicated experiments...