Dark Matter Search – 1

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The Dark Side of the Universe

- First evidence and confirmations:

1933 F. Zwicky: velocity dispersion of Coma galaxies too high to be explained by luminous matter

1936 S. Smith: velocity dispersion of the Virgo cluster

1974 two groups: systematical analysis of *mass density* vs *distance from center* in many galaxies

Zwicky writes (1933): "If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter. From these considerations it follows that the large velocity dispersion in Coma (and in other clusters of galaxies) represents an unsolved problem."

The Dark Side of the Universe

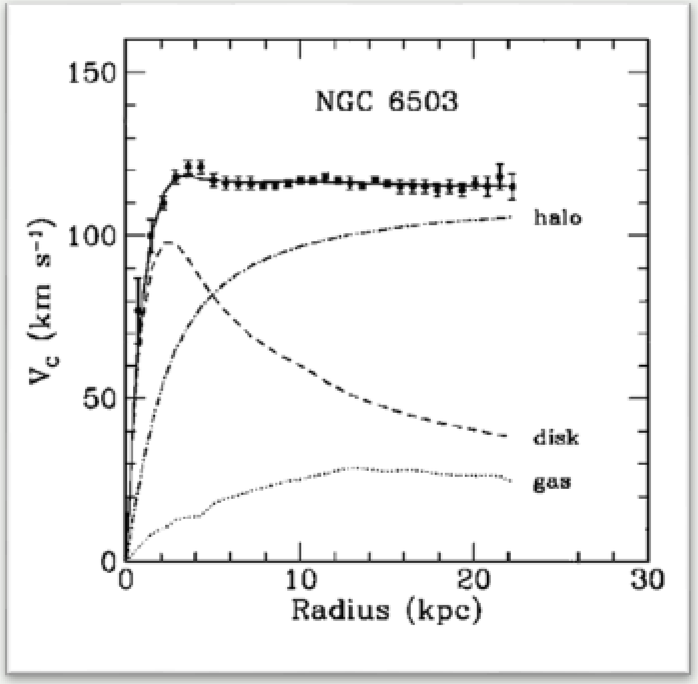
- First evidence and confirmations:

  1933 F. Zwicky: measuring dispersion velocity of Coma galaxies; larger than expected from luminous matter

  1936 S. Smith: studying the Virgo cluster

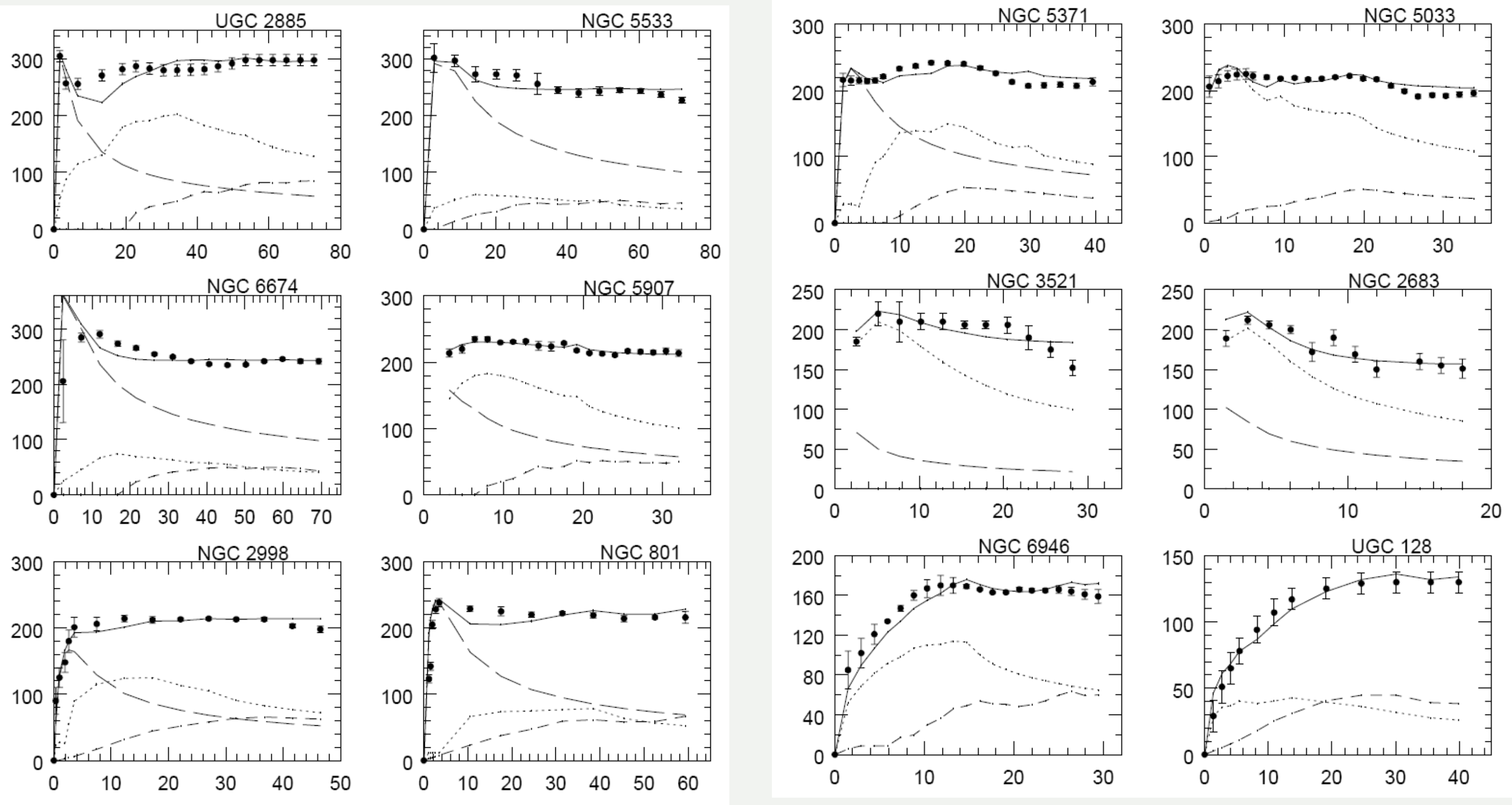
  1974 two groups: systematic analysis of *mass density* vs *distance from center* in many galaxies

  - Spectroscopic Optical observation of HII region (ionized hydrogen) inside the Galaxy (V. Rubin)
  - Radio emission at 21-cm from Hydrogen (hyperfine transition of neutral H atom) for large radii of Galaxies



- Typical rotation speed: ~200 km/s
- Visible disk size 10 kpc
- Dark Halo extends 10 times

The rotational Curves



In particular, spherical symmetry; mass inside a sphere:

$$M(r) = \int_V \rho dV$$

$$\frac{GM(r)m}{r^2} = m\frac{v^2}{r}; \qquad \Rightarrow \qquad v^2 = \frac{GM(r)}{r}$$

$M(r) = M_0$ constant for r>R

$$v \propto \frac{1}{\sqrt{r}}$$

In Galaxies $\boldsymbol{v}$ about flat:

$$M(r) \propto r; \qquad \Rightarrow \qquad \rho \propto \frac{1}{r^2}$$

The Dark Side of the Universe

- Some other experimental evidences
    - LMC motion around Galaxy: LMC velocity is close to or above the escape speed one would expect if the Milky Way contained only its visible baryonic matter (stars, gas, dust)
    - from X-ray emitting gases surrounding elliptical galaxies
    - hot intergalactic plasma velocity distribution in clusters is too high to be gravitationally bound by visible matter alone.
    - from gravitational lensing
    - bullet cluster 1E0657-558

The inferred gravitational mass is typically **5–10 times larger** than the luminous (baryonic) mass.

Dark Matter in Clusters

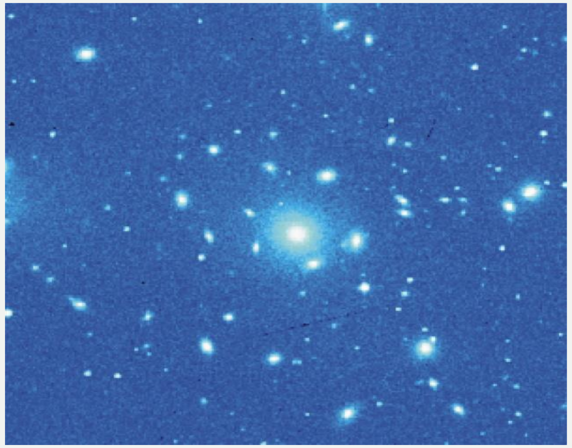
- Clusters can be studied in the **optical**
- It is possible to observe them in the **X-ray**

Hot Gas (>10^7 K) ⇒ X-Ray Emission for Thermal Bremsstrahlung

Surface Brightness Profile	Gas Density Distribution
Spectral Analysis	Temperature, Metal Enrichment

If the gas is in hydrostatic Equilibrium

From ρ and T it is possible to estimate Matter distribution and contribution in the cluster



Optical image of Coma cluster

X-Ray image of Coma cluster

X-ray Galaxy clusters

Assuming that the gas is spherically distributed and in hydrostatic equilibrium, we can use it as a tracer of the whole matter distribution:

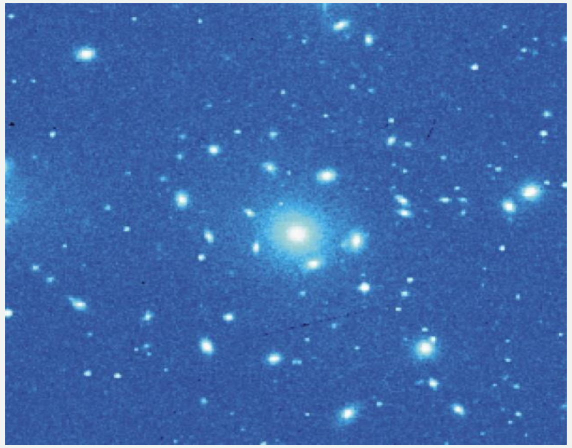
$$\frac{dP_{gas}}{dr} = -\rho_{gas}\frac{d\phi}{dr} = -\rho_{gas}\frac{GM(<r)}{r^2}$$

Assuming an equation of state for the gas:

$$M(<r) = -\frac{r}{G}\frac{k_B T}{\mu m_p}\left(\frac{d\ln\rho_{gas}}{d\ln r}+\frac{d\ln T}{d\ln r}\right)$$

The gas density profile ρ can be directly obtained from the X-ray surface brightness, while the temperature T can be derived from a spectral analysis

Results: the baryonic mass in galaxies and in the diffuse intra-cluster medium is only the 15% of the total mass!
Dark matter dominates also at cluster scales!

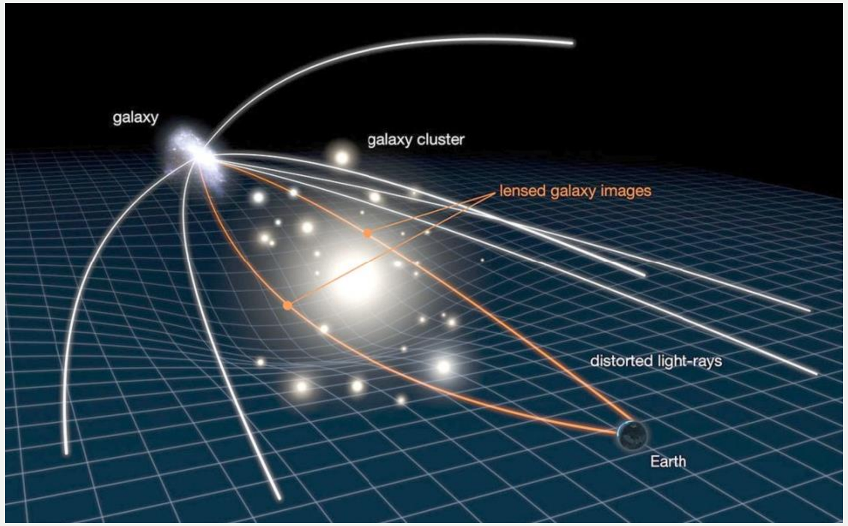


Optical image of Coma cluster

X-Ray image of Coma cluster

Gravitational lensing

- The curvature of space–time due to gravitating mass (including dark matter) deflects the light, distorting the images of background galaxies.
- Measurements of such effects provide constraints on the mean density of dark matter and its density relative to baryonic matter.



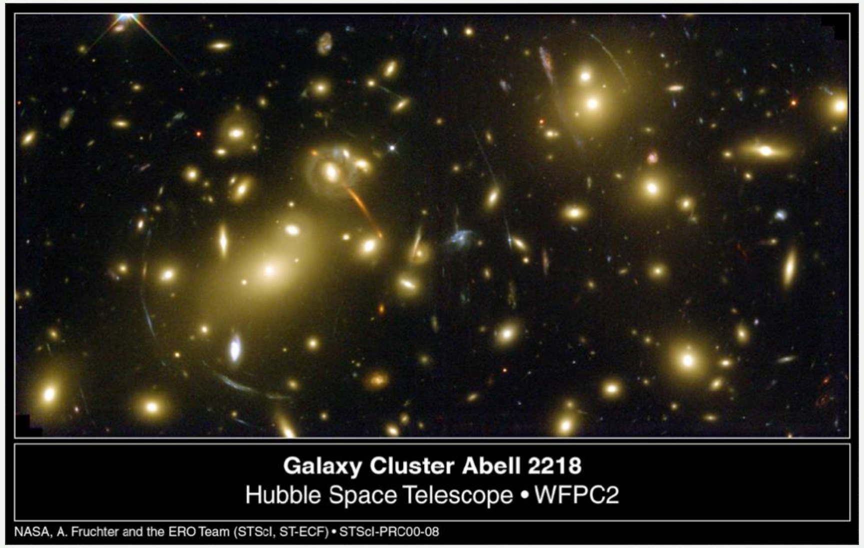
Deflection angle in general relativity: $\gamma = \frac{4GM}{c^2 b}$

Mass of the lens

Impact parameter

See Chapter 9 of «Cosmology», S. Weinberg

Gravitational lensing (**strong lensing**) in the galaxy cluster Abell 2218 reveals highly elongated arcs produced by background sources. The strength of the lensing signal requires a mass distribution far exceeding the luminous component, providing robust evidence for a dominant dark matter halo within the cluster.



Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

A direct empirical proof of the existence of dark matter

A Cosmic Collision: the Bullet cluster 1E0657−558, z=0.296

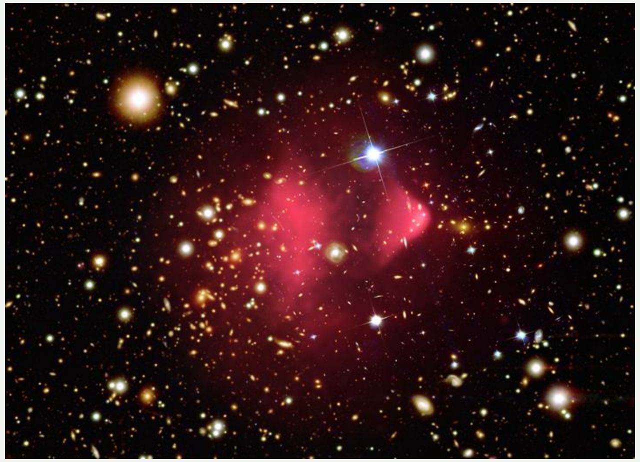
Astrophys. J. **648**, L109-L113 (2006)

- Collision of two clusters of galaxies
- the galaxies' nuclei collided about 100Myr ago

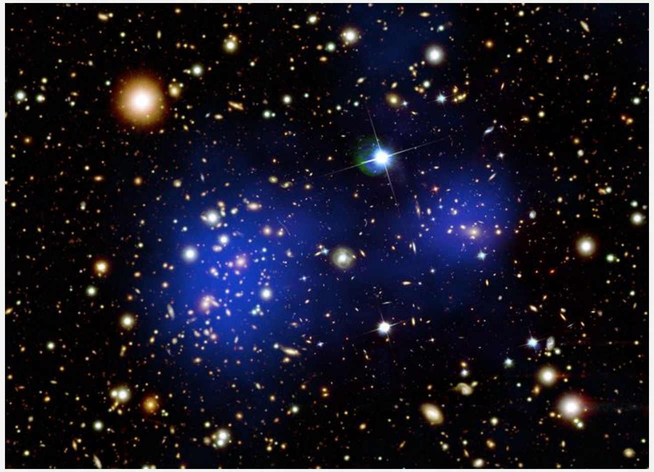
The largest part of the matter in the system is not luminous

The Bullet cluster

Observation Method	Component Detected	Key Findings in the Bullet Cluster
X-Ray Wavelengths (e.g., Chandra)	**Normal (Baryonic) Matter** (Hot Gas/Plasma)	• Reveals vast amounts of hot, X-ray emitting gas and plasma (the dominant baryonic mass component). • This gas was stripped from the two colliding clusters, appearing as **pink clumps/red.** • The gas slowed down due to **drag forces** (ram pressure) during the collision. • The collision occurred at great speeds, around **5,000 km/s.**
Gravitational Lensing (Weak Lensing)	**Total Mass Distribution** (Gravitational Potential)	• Gravitational lensing is determined **solely by mass**, measuring how light from background sources is bent and distorted by the mass present along the line of sight. • Weak lensing is typically used for mass reconstruction in galaxy clusters.
Composite View (X-Ray + Lensing)	**Spatial Separation** (Mismatch)	• The map of the total mass distribution (reconstructed via lensing, shown in **blue**) follows the distribution of the galaxies, **not** the hot gas (pink). • This demonstrates a **clear and extraordinary mismatch** between where the mass signal is located and where the normal matter (dominant baryons) is located.



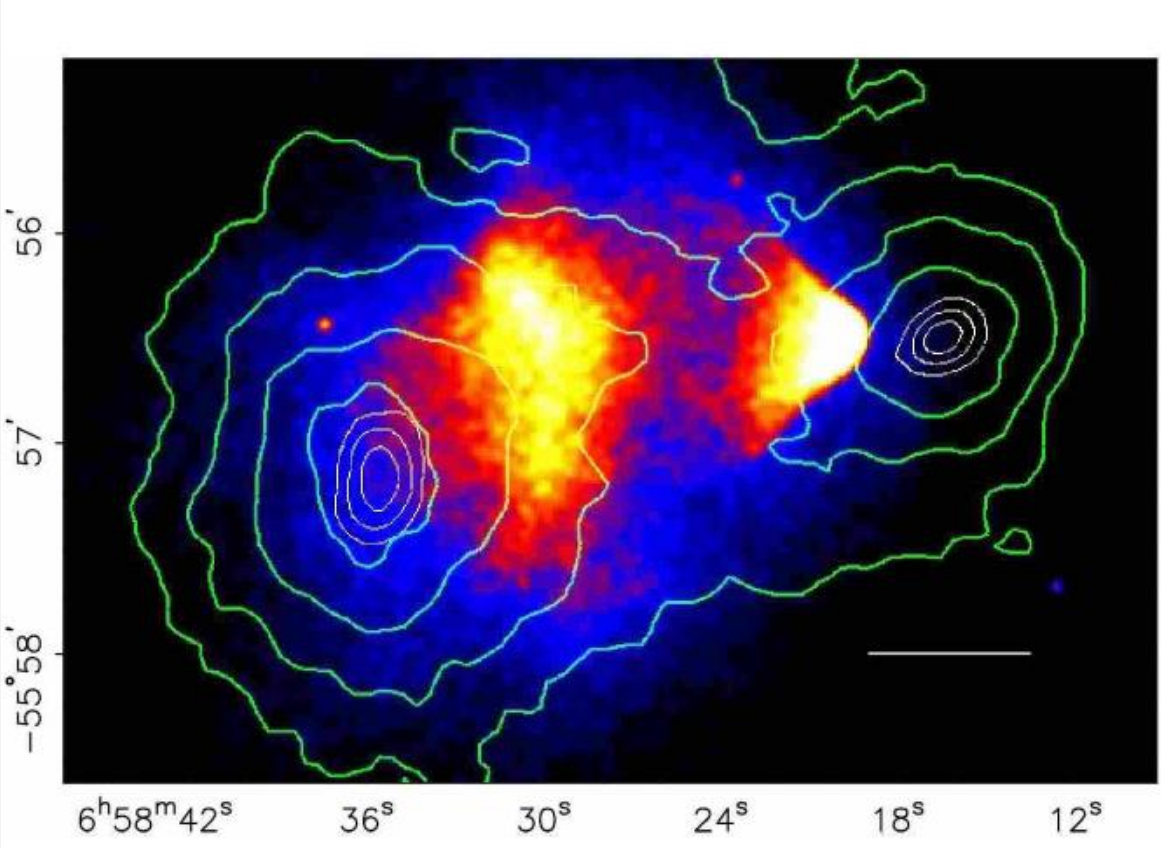
X-ray



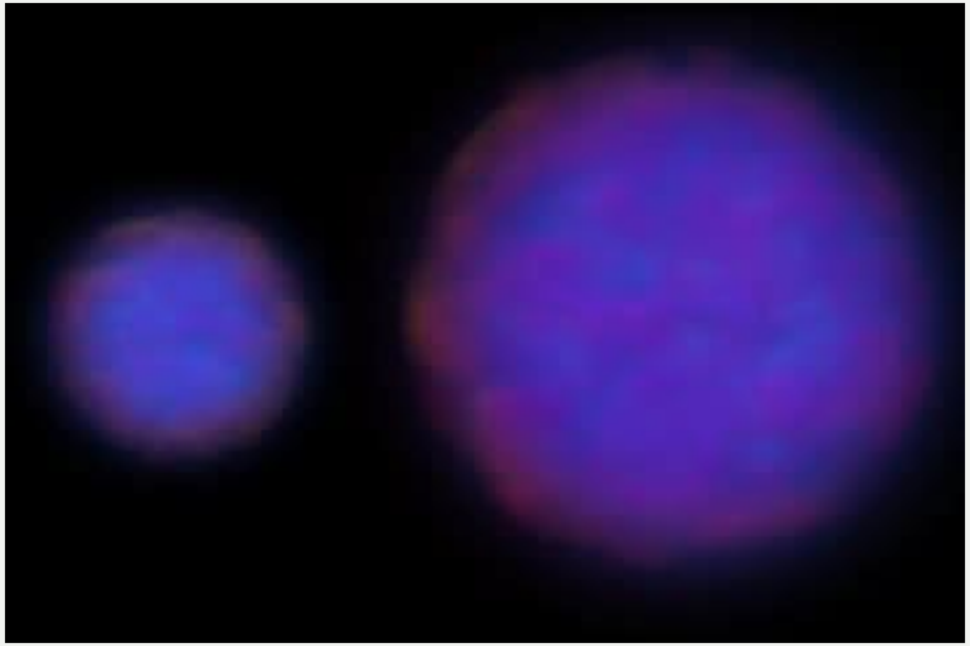
Weak lensing

The Bullet cluster

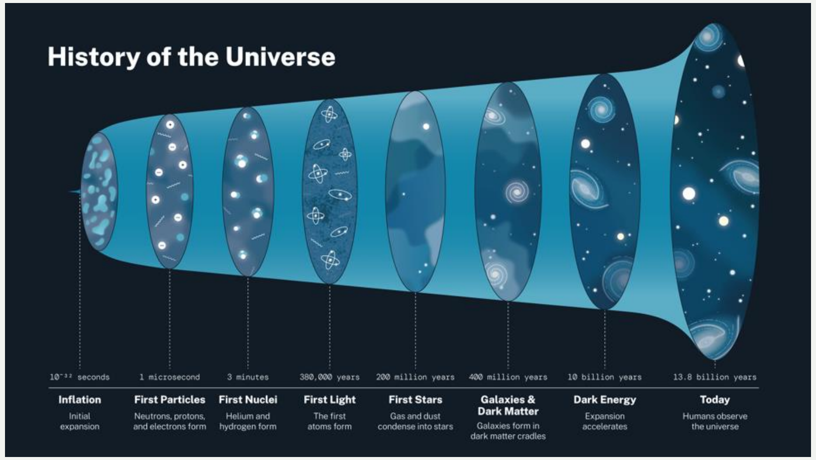
clear and extraordinary mismatch between where the mass signal is located and where the normal matter (dominant baryons) is located.



The Bullet cluster

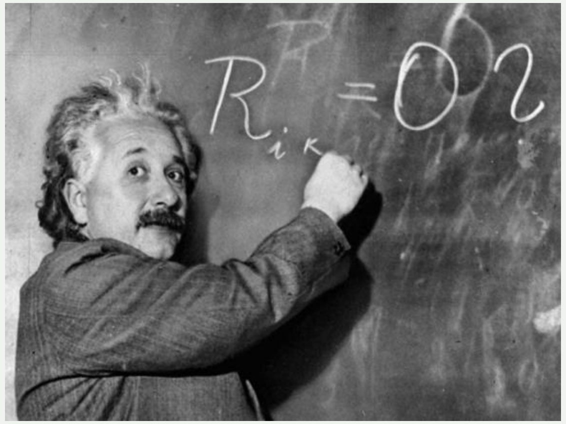


The Standard Big Bang Model



Big Bang, big initial "explosion"

The origin of all was an initial "singularity"



The basis of the Big Bang model are:

- The theory of the General Relativity

  The gravity is a distortion of the space-time

  "Matter tells space how to curve, and space tells matter how to move. How do gravity waves fit in this?" – J. Wheeler

- The Cosmological Principle

  The Matter in the Universe is homogeneously and isotropically distributed on large scale

  Experimental evidences e.g. from the distribution of a large number of galaxies

The Universe is assumed to be a perfect fluid with equation of state:

$$p=w\rho c^2$$

The Einstein field equations: the expansion of the Universe

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\mathcal{R} = 8\pi G_{\mathrm{N}} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

It is common to assume that the matter content of the Universe is a perfect fluid, for which

$$T_{\mu\nu} = -p g_{\mu\nu} + (p+\rho)\, u_\mu u_\nu$$

The metric: $d = a(t)\chi$ $\quad \dot{d} = \left(\frac{\dot{a}}{a}\right) d + a(t) v_{pec}$ Hubble-Lemaitre law

The observed homogeneity and isotropy enable us to describe the overall geometry and evolution of the Universe in terms of two cosmological parameters accounting for the spatial curvature and the overall expansion of the Universe. These two quantities appear in the most general expression for a space-time metric known as the Robertson-Walker metric:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

By rescaling the radial coordinate, we can choose the curvature constant k to take only the discrete values $+1, -1$, or 0 corresponding to closed, open, or spatially flat geometries. In this case, it is often more convenient to re-express the metric as:

$$ds^2 = dt^2 - a^2(t)\left[d\chi^2 + S_k^2(\chi)\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

$$S_k(\chi) = \begin{array}{ll} \sin\chi & k=+1 \\ \chi & k=0 \\ \sinh\chi & k=-1 \end{array}$$

The Friedmann equations

Combining the Einstein field equation and the metric, Friedmann obtained 2 independent equations, describing the evolution of the space-time [e.g. the scale factor a(t)]:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

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

acceleration equation

a(t): scale factor
ρ(t): energy density
p(t): pressure [p=wρ]

- The geometry of the universe is given by the metric curvature ***k***, which receives contributions from all energy components in the universe: matter, radiation, vacuum, etc.
- $H = \left(\frac{\dot{a}}{a}\right)$: its present value is the Hubble constant

We need to estimate the total energy density of the Universe.

- Usually, they are expressed in terms of a critical value for the energy density:

$$\rho_{crit} = \frac{3H^2}{8\pi G} \approx 10^{-29} g/cm^3$$

$$\Omega_i \equiv \frac{\rho_i}{\rho_{crit}}$$

≈ 6 hydrogen atoms per m^3

The Friedmann equations at present time (today)

- First Friedmann equation (c=1):

$$H_0^2 = \left(\frac{\dot{a}}{a}\right)^2 (today) = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \quad \rightarrow \quad \boxed{1 = \frac{8\pi G}{3H_0^2}\rho - \frac{k}{a^2 H_0^2} + \frac{\Lambda}{3H_0^2}}$$

$$\rho_{crit} = \frac{3H^2}{8\pi G} \approx 10^{-29} g/cm^3$$

- Normalizing with the critical density, we define:

$$\boxed{\Omega_m = \frac{8\pi G}{3H_0^2}\rho} \qquad \boxed{\Omega_k = -\frac{k}{a^2 H_0^2} \quad \text{(Improper use)}} \qquad \boxed{\Omega_\Lambda = \frac{\Lambda}{3H_0^2}}$$

$$\boxed{\Omega_{tot} = 1 - \Omega_k = \Omega_m + \Omega_\Lambda}$$

- Considering $p \approx 0$ in a matter dominated Universe, from the second Friedmann equation:

$$\frac{\ddot{a}}{a}(today) = -\frac{4\pi G}{3}\rho + \frac{\Lambda}{3} \quad \rightarrow \quad q_0 = -\frac{1}{H_0^2}\frac{\ddot{a}}{a}(today) = \frac{1}{2}\frac{8\pi G}{3H_0^2}\rho - \frac{\Lambda}{3H_0^2}$$

- So that the deceleration parameter, q_0, is:

$$q_0 > 0 \implies \ddot{a} < 0$$

$$\boxed{q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda}$$

The deceleration parameter is a measurable quantity

The Universe is either flat, open or closed?

The structure of the space-time can have three possible geometries

$$\boxed{\Omega_{tot} = 1 - \Omega_k \qquad \Omega_k = -\frac{k}{a^2 H_0^2}}$$

- ✖ Density > Critical density ($\Omega_{tot}>1$)

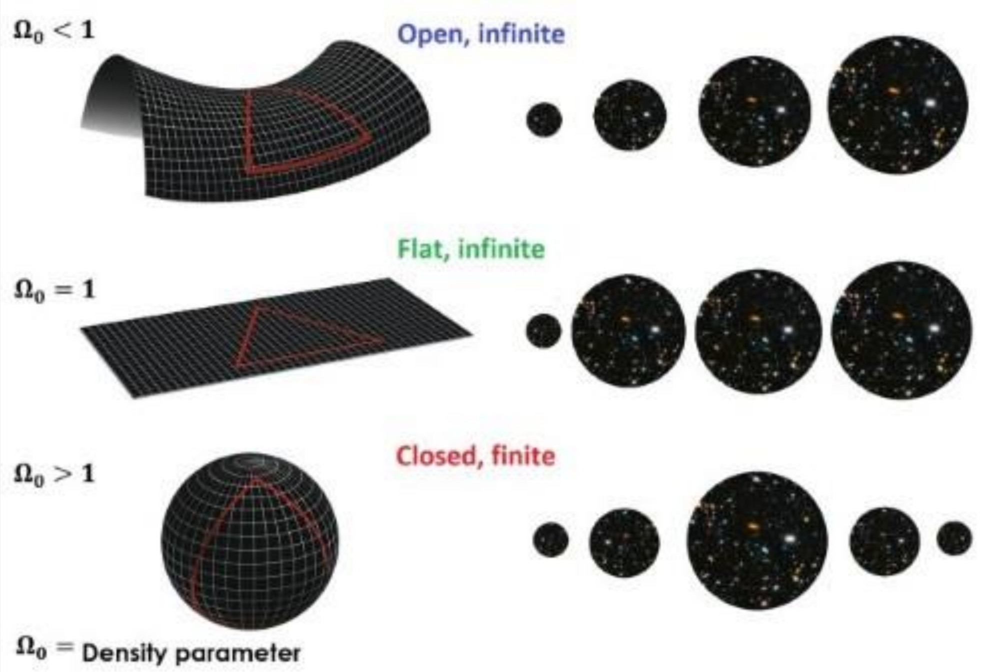
$\Omega_k < 0;$ $k = 1$ → Close Universe, Positive Curvature, Finite Volume

- ✖ Density = Critical density ($\Omega_{tot}=1$)

$\Omega_k = 0;$ $k = 0$ → Flat Universe, Zero Curvature, Infinite Volume

- ✖ Density < Critical density ($\Omega_{tot}<1$)

$\Omega_k > 0;$ $k = -1$ → Open Universe, Negative Curvature, Infinite Volume



The Universe can change size but NOT the geometry

The Cosmic Microwave Background (CMB)

Discovered by Penzias and Wilson (1965)

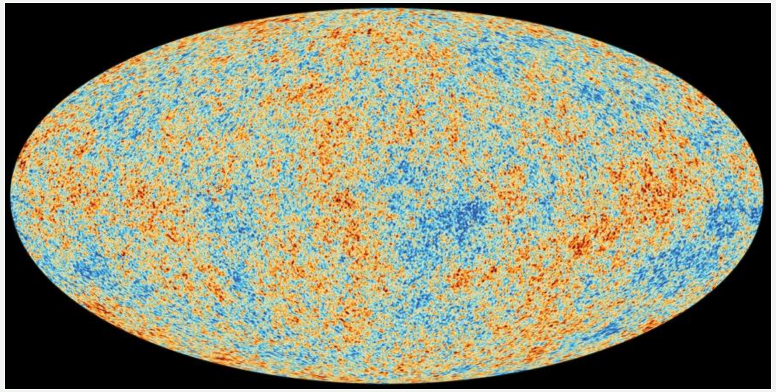
The measured temperature of the radiation was

3 K → -270 °C

it appears on the microwave band

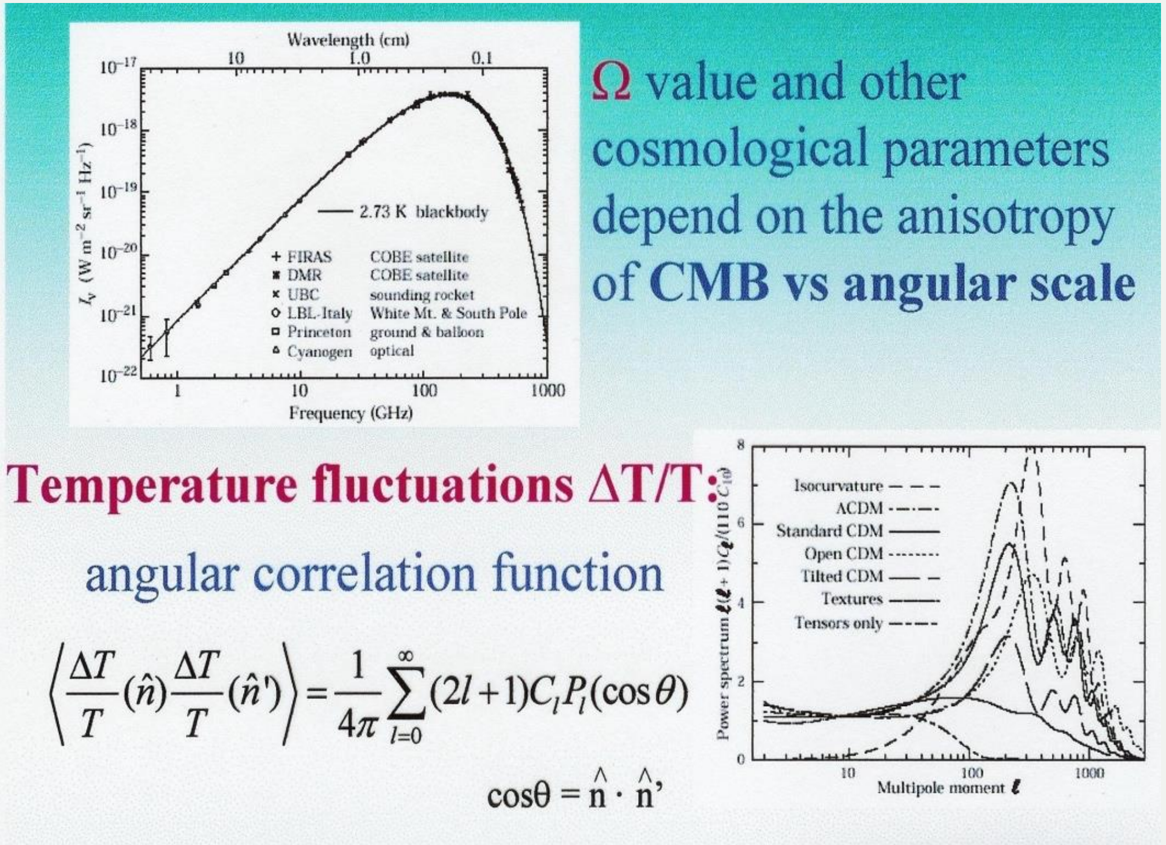
microwave antenna

- 380.000 years after Big Bang the Universe becomes transparent for the light and the electromagnetic radiation starts propagating "freely"
- The relic radiation holds "memory" of the Universe when it was 0.003% of present age
- The CMB temperature fluctuations (CMB anisotropy) are the trace of the density fluctuations of matter: the galaxies' seeds that will grow up through the gravitational amplification



$(T_2-T_1)/T_1=3\times10^{-5}$

Anisotropy of CMB



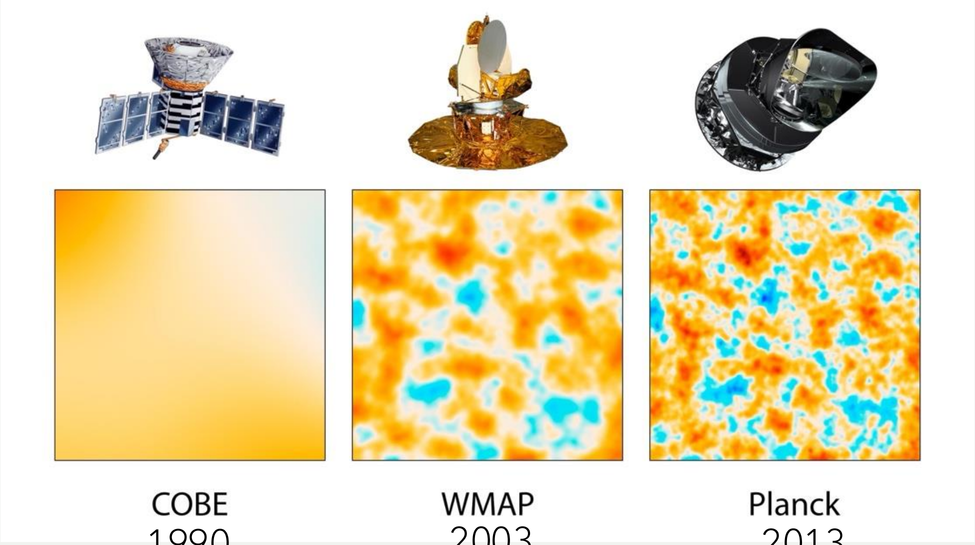
Ω value and other cosmological parameters depend on the anisotropy of **CMB vs angular scale**

Temperature fluctuations ΔT/T:

angular correlation function

$$\left\langle \frac{\Delta T}{T}(\hat{n})\frac{\Delta T}{T}(\hat{n}')\right\rangle = \frac{1}{4\pi}\sum_{l=0}^{\infty}(2l+1)C_l P_l(\cos\theta)$$

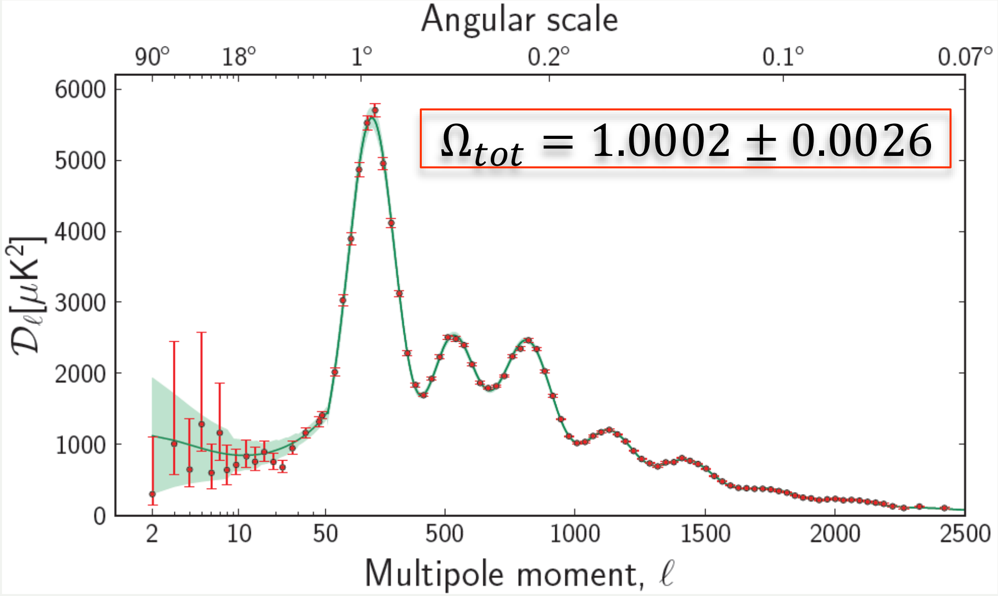
$$\cos\theta = \hat{n}\cdot\hat{n}'$$



COBE 1990

WMAP 2003

Planck 2013



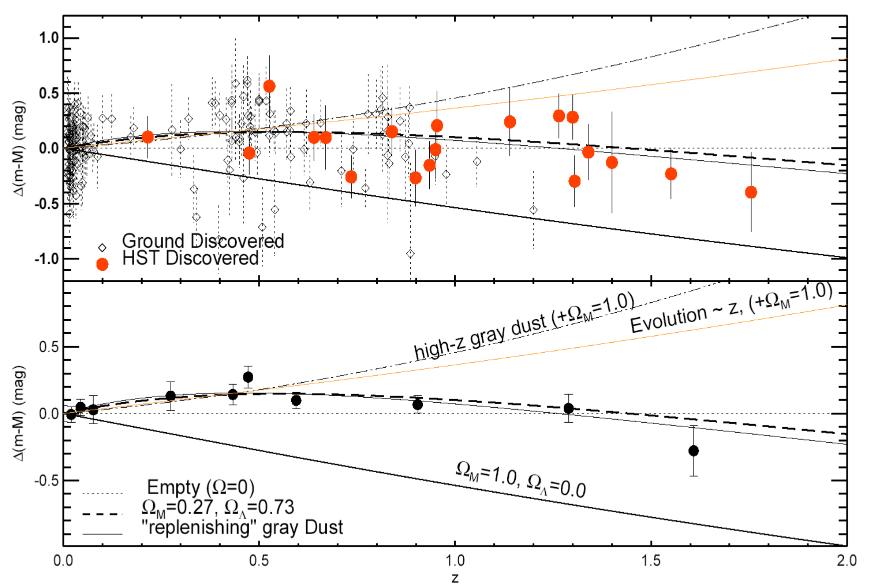
$$\Omega_{tot} = 1.0002 \pm 0.0026$$

→ First peak at $l \simeq 220\ \Omega^{-1/2}$

Peaks at l>220 give information on baryon density

The expansion of the Universe

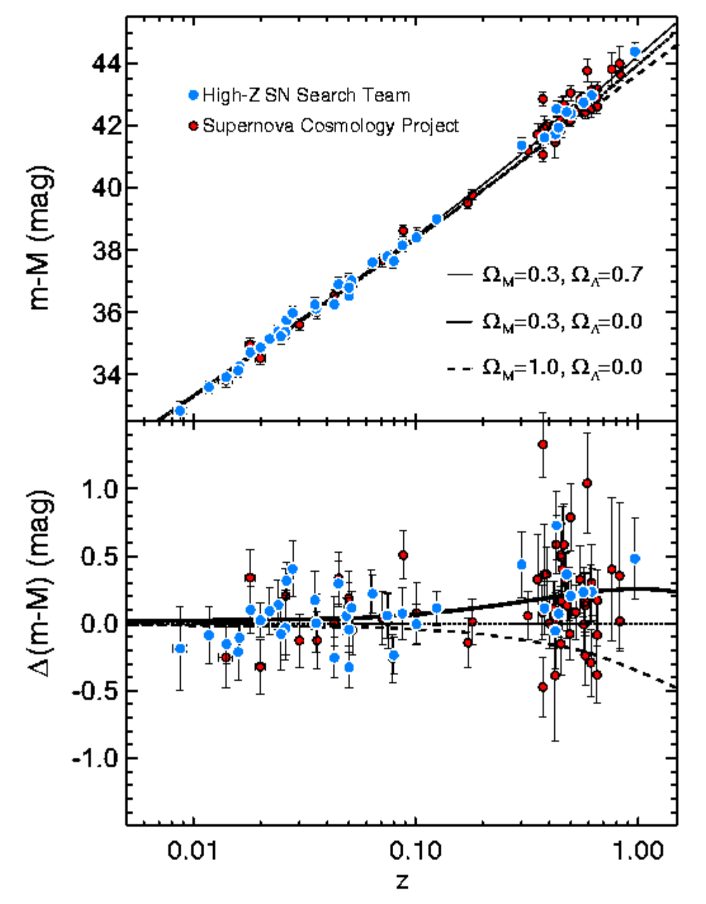
The observed luminosities of a special subclass of supernovae type 1A can be used as standard candles up to large distances (luminosity distance) to study the expansion of the Universe



The result was that the expansion of the universe is accelerating

$$\Omega_\Lambda \approx 0.7$$

S. Perlmutter, B.P. Schmidt and A.G. Riess, Nobel laureates on 2011



Baryons component in the Universe

Comparison of nucleosynthesis theory with observations of light elements abundance allows to estimate baryon density

Considering:

a) the present abundance of light nuclei

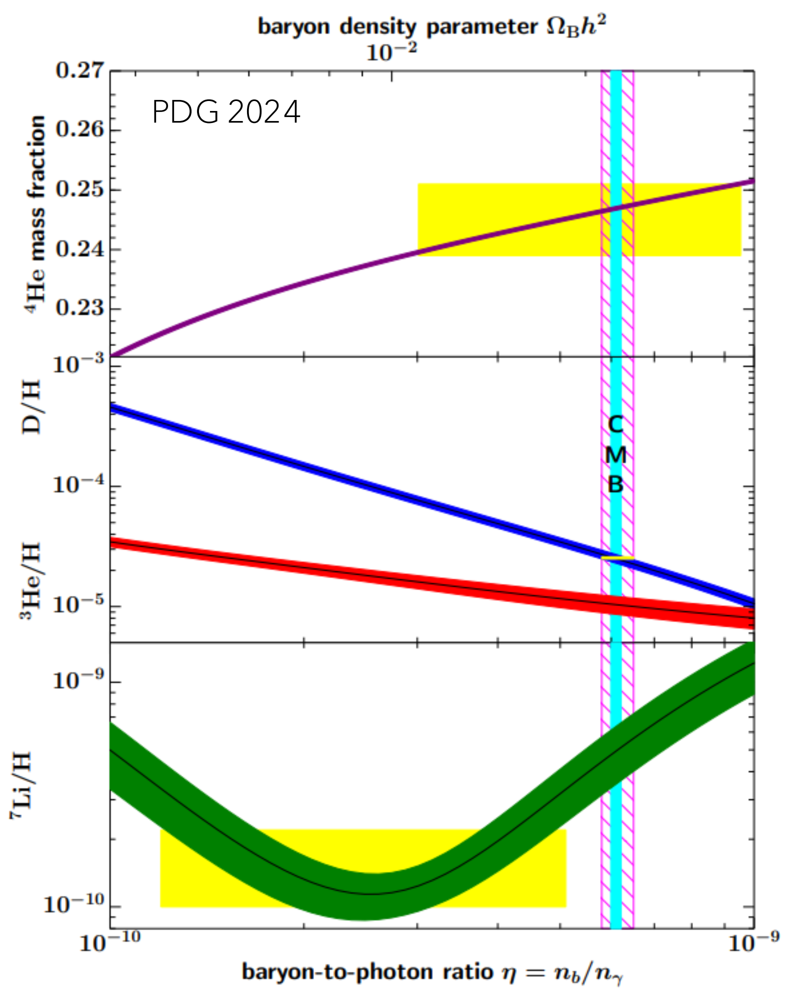
b) The density of CMB photons

$5.8 \leq \eta_{10} \leq 6.6$ (95% CL)

$$\boxed{0.01 \leq \Omega_B \leq 0.06 << \Omega_m}$$

$$\boxed{\Omega_B = 4\%}$$

Baryons give a small contribution to Ω_m



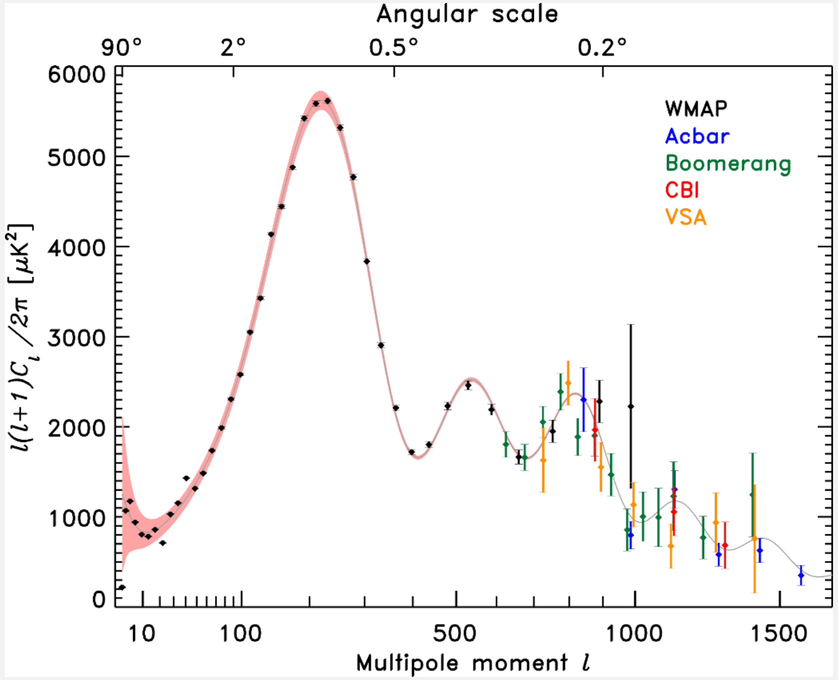
CMB peaks as a baryometer

- The photon–baryon fluid is sitting in the gravitational potential wells that are the seeds of the structure in the universe. As gravity tries to compress the fluid, radiation pressure resists resulting in acoustic oscillations.
- Baryons load down the photon–baryon plasma and add inertial (and gravitational) mass to the oscillating system.
- Since the odd acoustic peaks (I, III, V, ⋯) are associated with the plasma compression, they are enhanced by the amount of baryons. Viceversa the even peaks (II, IV, VI, ⋯) are associated with plasma rarefaction and consequently they are relatively suppressed.

→ The difference between the amplitudes of odd and even peaks allows to measure the baryon density

$$\boxed{\Omega_b = 0.044^{+0.001}_{-0.001}}$$

Present CMB data



Dark Matter in Cosmology (ΛCDM)

Concordance Model: the Universe is flat: $\boldsymbol{\Omega = \Omega_\Lambda + \Omega_M = 1}$

$$\Omega_\Lambda \approx 0.74 \qquad \Omega_M \approx 0.26$$

Primordial **Nucleosynthesis**

Observations on:
- **light nuclei** abundance
- **microlensings**
- **visible** light

Structure formation in the Universe

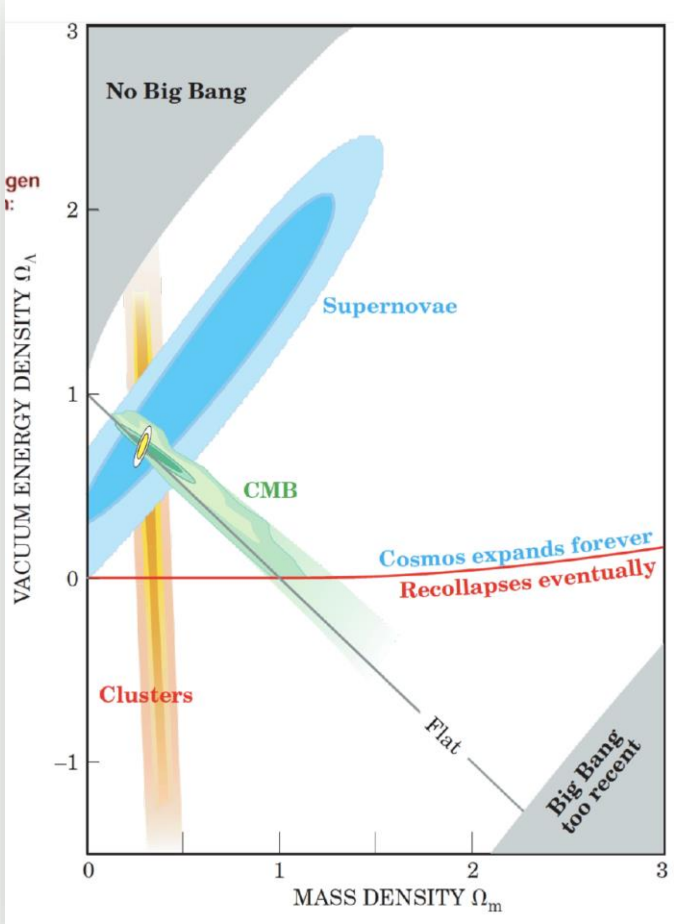
The **baryons** give “too small” contribution

$\Omega_b \sim 4\%$

Non baryonic Cold Dark Matter is dominant

$\Omega_{CDM} \sim 22\%,$
$\Omega_{HDM,\nu} < 1\ \%$

Non baryonic Cold Dark Matter particles are dominant matter and are not **SM particle**



Ω = density/critical density

6 atoms of H/m^3

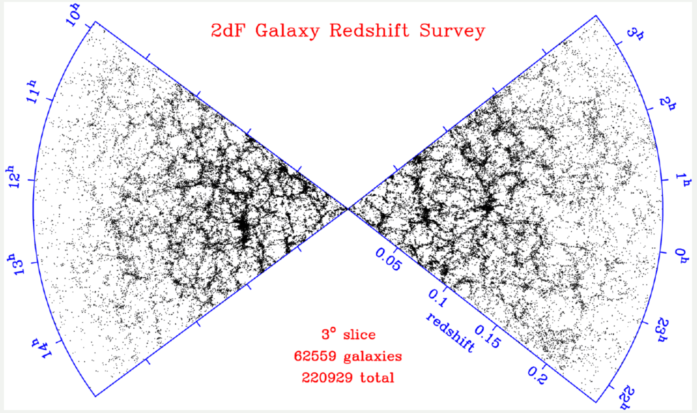
Dark Matter: hot (HDM) vs cold (CDM)

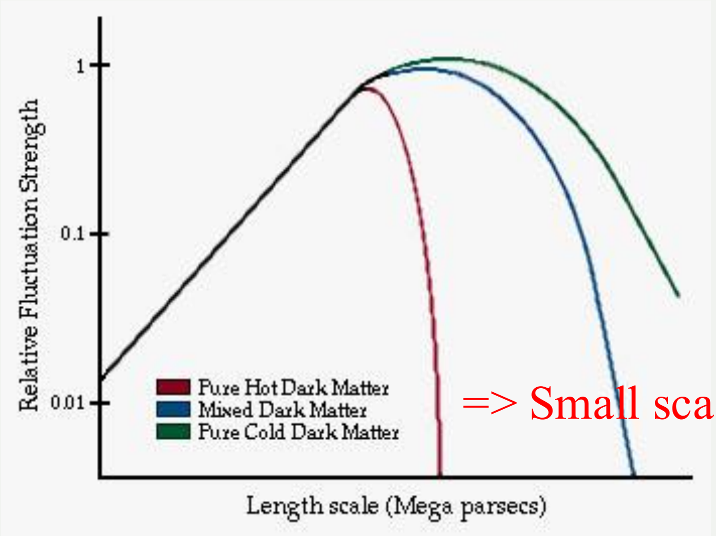
Hot dark matter (HDM).
Candidates: neutrino
It is still relativistic when it decouples from thermal background, so free-streaming affects also large scales

First objects are very large (superclusters); smaller objects like galaxies form later by fragmentation.
Top-down scenario

Cold dark matter (CDM).
Candidates: neutralinos, axions, axinos, mirror DM, etc…
It is no more relativistic when it decouples from thermal background, so free-streaming affects only small scales

First objects are small (globular clusters?); larger objects (galaxies, clusters) form later by hierarchical merging.
Bottom-up scenario

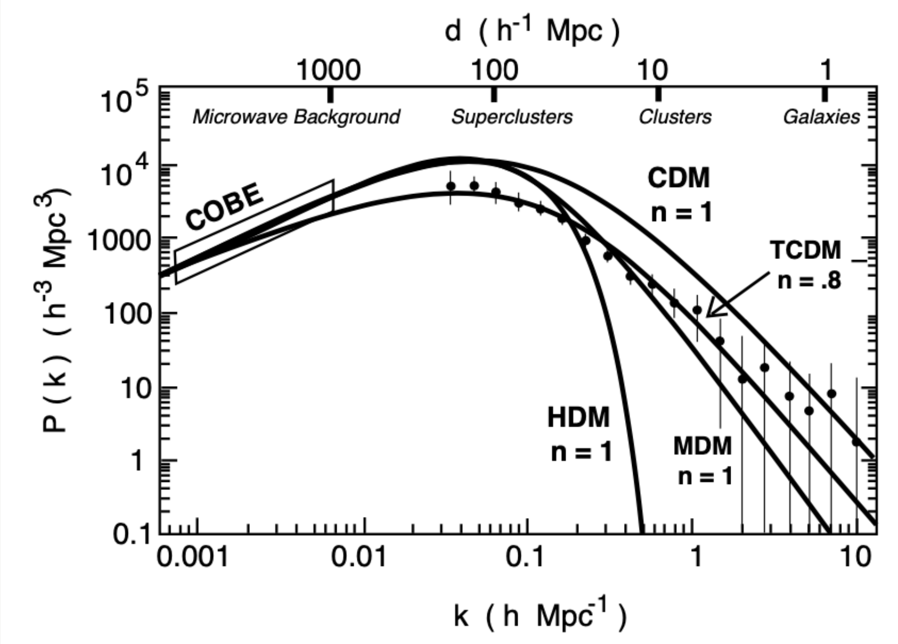


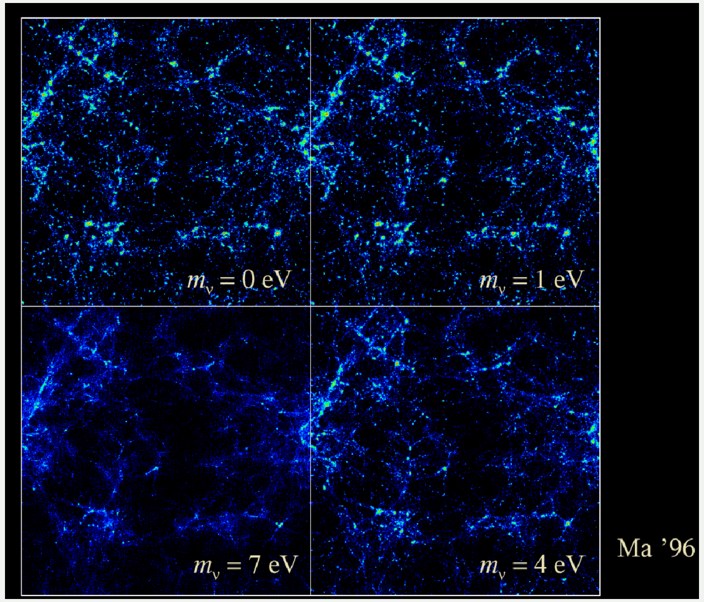


=> Small scales

Dark Matter: hot (HDM) vs cold (CDM)

- Starting from late ’80s, we have evidences in favour of a **bottom-up** structure formation (hierarchical) model, where objects formed first at small scales.
- Now this is confirmed by observational data. A **cold** (i.e. non-relativistic when it decoupled from the thermal background) **dark matter** (CDM) component is strongly favoured



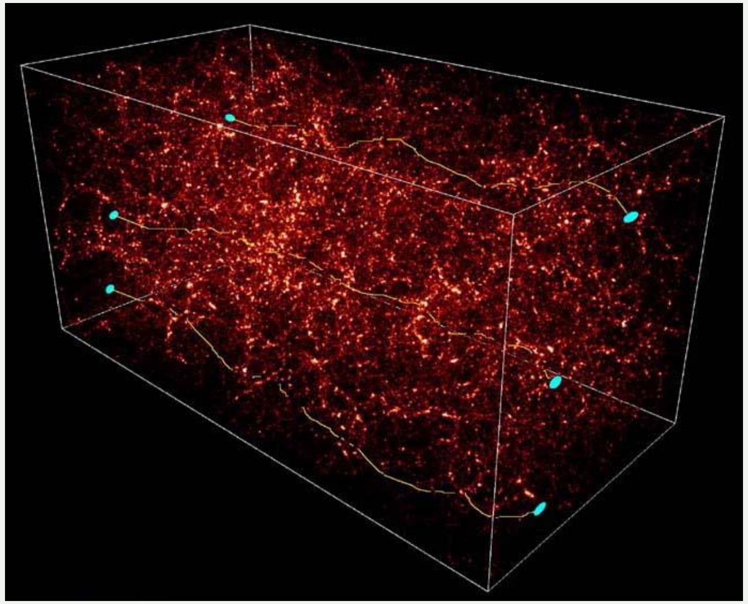


N-body simulation

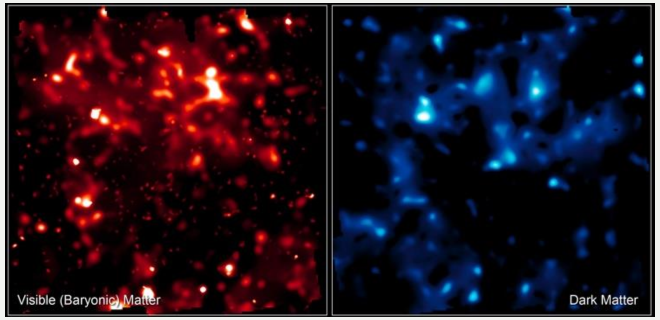
There is less clustering in models with massive neutrinos

dark matter cannot be dominated by neutrinos!

The Dark Matter in the Universe



- A large part of the Universe is made of Dark Matter and Dark Energy
- The so-called "baryonic" matter is only ≈4% of the total budget
- (Concordance) ΛCDM model and precision cosmology
- Non-baryonic Cold Dark Matter (≈27%) is the dominant component (≈87%) among the matter.
- The Dark Matter is fundamental for the formation of the structures and galaxies in the Universe
- CDM particles, possibly relics from Big Bang, with no em and color charges → beyond the SM



Dark Matter Candidates

Requirements for a good DM candidate:

- must have lifetime $t_{DM} >> t_U$
- must be electrically neutral (otherwise not dark)
- must have correct relic density: $\Omega_{DM} \simeq 0.27$
- must have mass for gravitational interaction
- must be trapped in the gravitational well of the galaxies
- non-relativistic velocities
- can be either or not thermally produced by "elementary" particles in the early Universe

Relic abundance of Dark Matter particles

Boltzmann equation for DM density calculation

- Assumptions: binary interactions of particle X in the thermal bath
- $X + X \leftrightarrow$ thermal bath particles $\quad l = (e^{\pm}, \mu^{\pm}, \tau^{\pm}, u, d, s, c, b, t, W^{\pm}, Z^{0})$
- Early hot universe, X effectively massless ($T \gg m_X$), in thermal equilibrium with SM particles
- Annihilation rate: $\Gamma_{XX \to l\bar{l}} = \langle \sigma_{XX \to l\bar{l}}\, v \rangle n_X$; expansion rate of the Universe H
- If $\Gamma \ll H$, the number of particles conserved (equation of continuity, Boltzmann equation):

$$\frac{dn}{dt} + 3Hn = 0 \qquad \rightarrow \qquad n \propto a^{-3}$$

- If $\Gamma \gg H$, the number of particles follows the equilibrium (non-relativistic particles):

$$n_{eq} = g \left(\frac{mT}{2\pi}\right)^{3/2} exp\left(-\frac{m}{T}\right)$$

quadratic for binary processes

- If $\Gamma \sim H$:

$$\boxed{\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma v \rangle \left(n_X^2 - n_{eq}^2\right)}$$

Early Universe

$d^3p = 4\pi p^2 dp = 4\pi p E dE$

In the early Universe particles in thermal equilibrium:

- n_i: equilibrium number density of Fermi (Bose) particles i
- ρ_i: equilibrium energy density

$$\rho_i = \frac{g}{2\pi^2}\int_0^\infty \frac{\sqrt{E^2 - m_i^2}\, E^2\, dE}{e^{\frac{E-\mu_i}{kT_i}} \pm 1}$$

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{\sqrt{E^2 - m_i^2}\, E\, dE}{e^{\frac{E-\mu_i}{kT_i}} \pm 1}$$

$\zeta(3) = 1.202$ ($\zeta(n)$ is the Riemann zeta function)

In the ultra-relativistic case $kT_i \gg m_i$, μ_i

$$n_i = \frac{\zeta(3)}{\pi^2} g_i\,(kT_i)^3 \text{ (Bose)}, \quad n_i = \left(\frac{3}{4}\right)\frac{\zeta(3)}{\pi^2} g_i\,(kT_i)^3 \text{ (Fermi)}$$

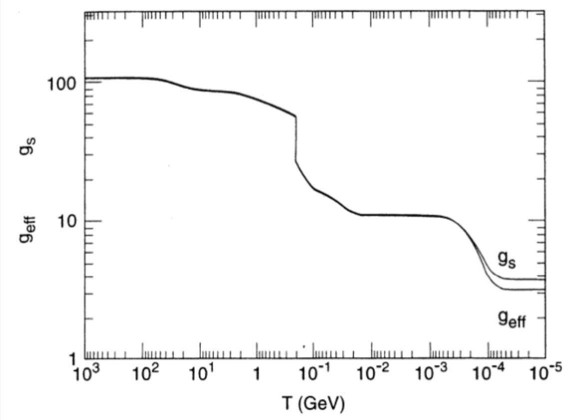
$$\rho_i = \frac{\pi^2}{30} g_i\,(kT_i)^4 \text{ (Bose)}, \quad \rho_i = \left(\frac{7}{8}\right)\frac{\pi^2}{30} g_i\,(kT_i)^4 \text{ (Fermi)}$$

$$g_* = \sum_{\text{bosons}} g_i \left(\frac{T_i}{T}\right)^4 + \left(\frac{7}{8}\right)\sum_{\text{fermions}} g_i \left(\frac{T_i}{T}\right)^4$$

Effective number of degrees of freedom of ultra-relativistic particles

The total energy density

$$\rho = \sum_i \rho_i = \frac{\pi^2}{30} g_* (kT)^4$$



Neutrino decouples from plasma at $T \approx 1$ MeV. When the temperature drops, $e^\pm$ begin to annihilate. The released energy heats up only γ's because neutrinos are decoupled. Thus, after the decoupling of photons their temperature will be higher than the neutrino temperature.

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T$$

$$n_\gamma = \frac{\zeta(3)}{\pi^2} g_\gamma (kT)^3, \quad g_\gamma = 2.$$

$$n_\nu = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_\nu (kT_\nu)^3, \quad g_\nu = 6.$$

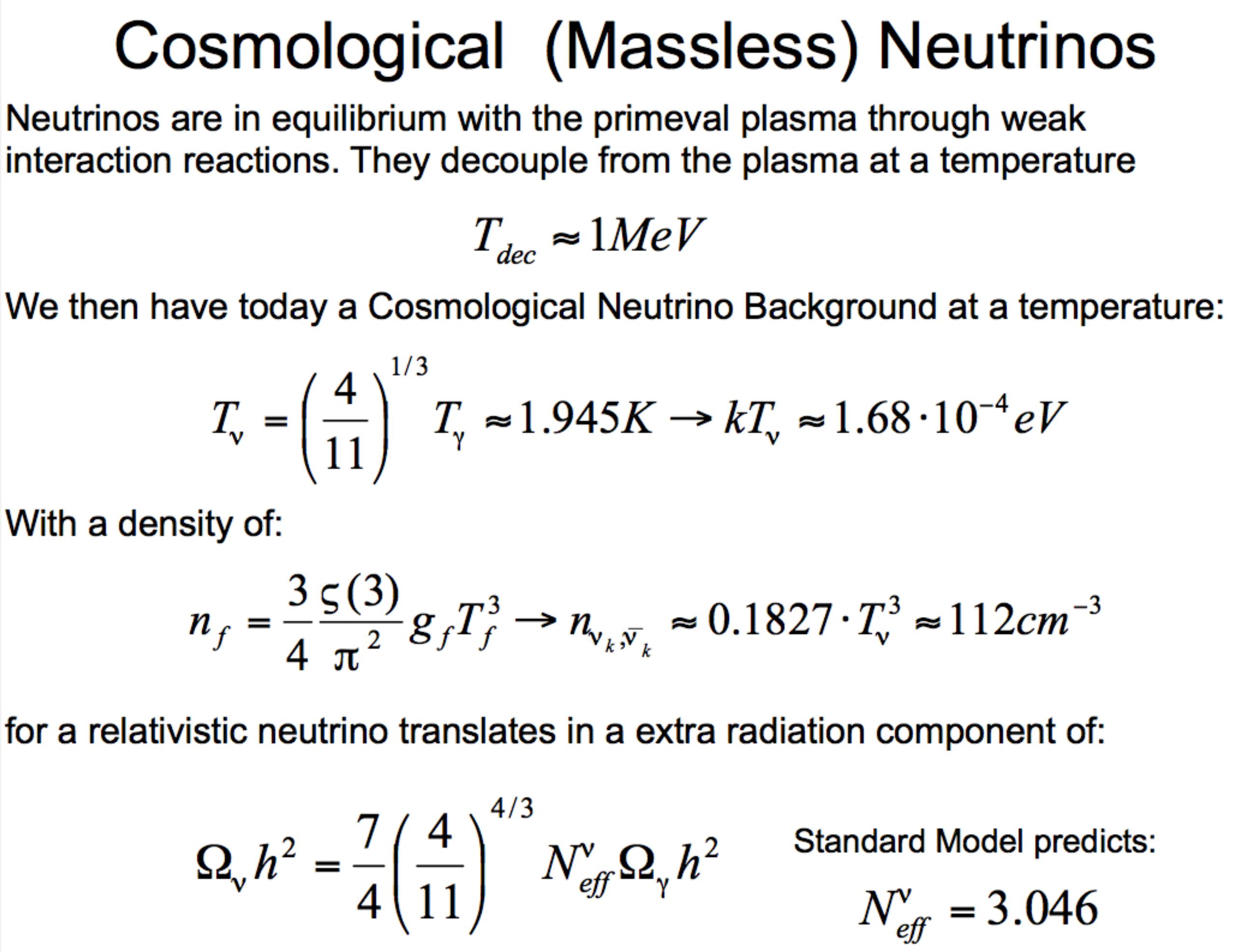
$$\longrightarrow n_\nu = \frac{9}{11} n_\gamma$$

$$n_\gamma = 410.5 \text{ cm}^{-3}$$

$$n_\nu = 336 \text{ cm}^{-3}$$

$n_B = 2.5 \cdot 10^{-7}$ cm^{-3}

photons and neutrinos are the most abundant particles in the Universe



Cosmological (Massless) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

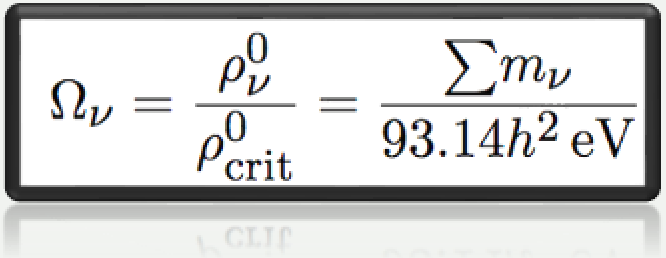
$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

for a relativistic neutrino translates in a extra radiation component of:

$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^\nu \Omega_\gamma h^2$$

Standard Model predicts:

$$N_{eff}^\nu = 3.046$$



$$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\text{crit}}^0} = \frac{\sum m_\nu}{93.14 h^2 \text{ eV}}$$

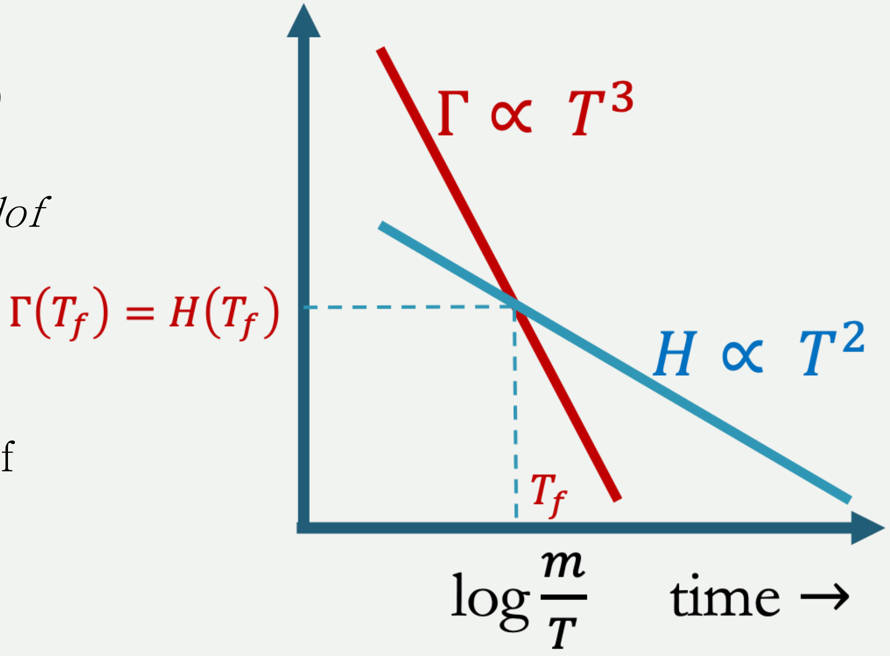
$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8}\frac{g_\nu}{g_\gamma}\left(\frac{T_\nu}{T_\gamma}\right)^4$$

Measurements on Ω_ν give info on $m_{cosmo} = \sum m_\nu$

Relic abundance of Dark Matter particles

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma v\rangle\left(n_X^2 - n_{eq}^2\right)$$

- $\Gamma = \langle\sigma v\rangle n \propto T^3$ (number density of Fermi or Boson particles $\propto T^3$)
- $H = \sqrt{\frac{8\pi G}{3}\rho} = \sqrt{\frac{4\pi^3}{45}g_*}\,T^2/m_{pl}$, where g_* represents the number of *dof*
- In hot early Universe: $\Gamma \geq H$
- As the universe expands, temperature drops, and eventually when $\Gamma(T_f) = H(T_f)$ the freeze-out occurs and the thermal bath of particles becomes nearly transparent to dark matter X



- The freeze-out implies:

$$\sqrt{\frac{4\pi^3}{45}g_*}\frac{T_f^2}{m_{pl}} = \langle\sigma v\rangle\, g\left(\frac{mT_f}{2\pi}\right)^{3/2} exp\left(-\frac{m}{T_f}\right) \Longrightarrow \text{Solving the equation in } x_f = m/T_f \text{ one find (numerically)} \boxed{\boldsymbol{T_f \approx m/30}}$$

Relic abundance of Dark Matter particles

- We now want to compute the dark matter abundance $\Omega_{X,0}h^2 = \frac{m_X n_X h^2}{\rho_0}$, where h^2 is the reduced Hubbel constant (H_0 in units of $100\, km\, s^{-1}\, Mpc^{-1}$).

To do so, we evaluate the abundance relative to that of photons, which is known.

At the freeze-out epoch: ← From the freeze-out condition

$$\frac{n_X(a_f)}{n_\gamma(a_f)} \sim \frac{n_{eq}(T_f)}{T_f^3} \sim \sqrt{\frac{4\pi^3}{45} g_*(T_f)}\,\frac{T_f^2}{m_{pl}}\,\frac{1}{T_f^3\langle\sigma v\rangle} \sim \sqrt{g_*(T_f)}\,\frac{1}{T_f\, m_{pl}\langle\sigma v\rangle} \sim \sqrt{g_*(T_f)}\,\frac{30}{m_{pl} m\langle\sigma v\rangle}$$

Recalling that:

- $n_X \sim n_{eq}(T)$ $\Gamma \gg H$
- $n_X\, a^3 \sim \text{constant}$ $\Gamma \ll H$
- $T_f \sim \frac{m_X}{30}$
- $n_\gamma \sim T^3$

The photon density today is $n_{\gamma,0} \approx 413\ \mathrm{cm}^{-3}$, and neglecting the evolution of the number of degrees with the scale factor, of freedom we get

$$n_X \propto \frac{413\ \mathrm{cm}^{-3}}{m_{pl}\frac{m}{30}\langle\sigma v\rangle} \longrightarrow \boxed{\Omega_X h^2 = \frac{m_X n_X}{(\rho_c/h^2)} \approx \left(\frac{2.5\times 10^{-10} GeV^{-2}}{\langle\sigma v\rangle}\right)}$$

For a more accurate derivation see e.g. arXiv: 1803.00070

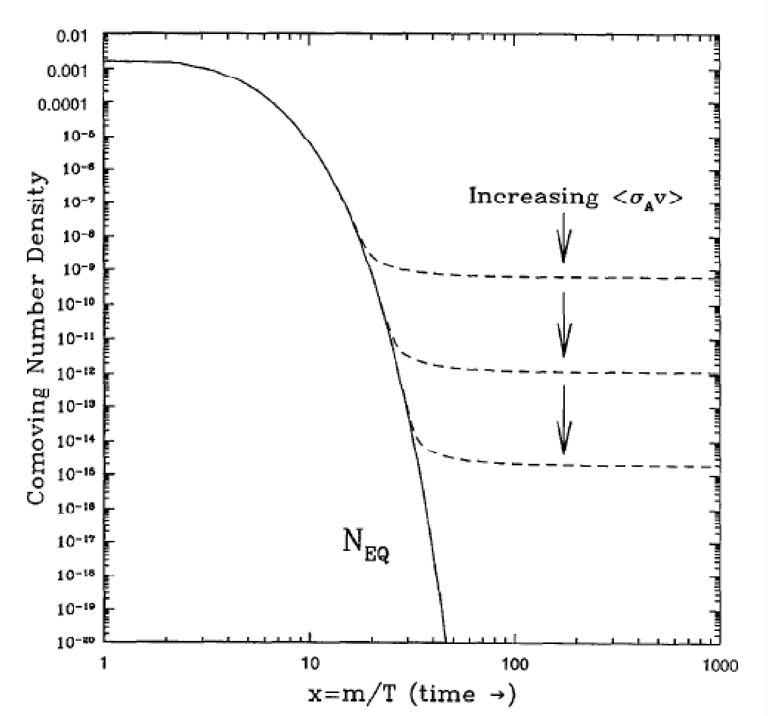
Relic abundance of Dark Matter particles

- $\Omega_X h^2 \approx \frac{0.1\,pb}{\langle\sigma v\rangle}$
- We remind this is for non-relativistic X –particles
- Increasing annihilation cross section, the X –particles remain in equilibrium for more time and decouple later. Their abundance decreases
- Hence very interesting results:
  - ✓ X –particles are well within non-relativistic regime
  - ✓ A value of the relic density corresponding to that estimated for CDM ($\Omega_X h^2 \approx 0.1$) implies an annihilation cross section on the order of the weak interaction
  - ✓ dimensionally, for electroweak scale masses and couplings:

$$\rightarrow \langle\sigma v\rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,pb \left(\frac{200\,GeV}{m}\right)^2$$

  - ✓ New physics at electroweak scale with stable neutral particle $\Longrightarrow$ CDM candidate
  - ✓ Sometimes dubbed “WIMP-miracle”

Numerical solution for the Boltzmann equation



Relic abundance of Dark Matter particles

Relativistic Freeze-out – $\Gamma(T_f) = H(T_f)$

- Relativistic particles at the decoupling time
- HDM particles
- The mass dependence does NOT drop down: $\rho\, a^4 = const$, which translates into $\Omega \propto m_X$ when the particles become non-relativistic due to the expansion of the universe
- For neutrinos: $\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{94\ eV}$

Non-relativistic Freeze-out – $\Gamma(T_f) = H(T_f)$

- Non-relativistic particles at the decoupling time
- CDM particles
- The mass dependence does drop down, i.e. Ω is not dependent on m_X
- For CDM particles: $\Omega_X h^2 \approx \frac{0.1\ pb}{\langle \sigma v \rangle}$

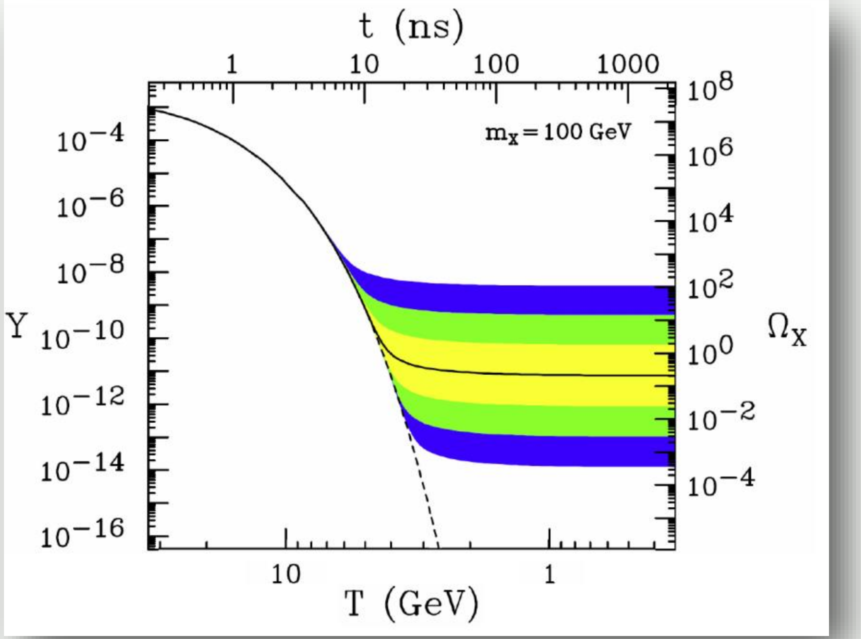
The Dark Matter Particles

- **WIMP** a particle many candidates (sub GeV to multi TeV): neutral, massive, non-relativistic, stable, weakly interacting (neutralino in SUSY, …)
- **Axion, ALPs**: pseudoscalar particles with interaction given by

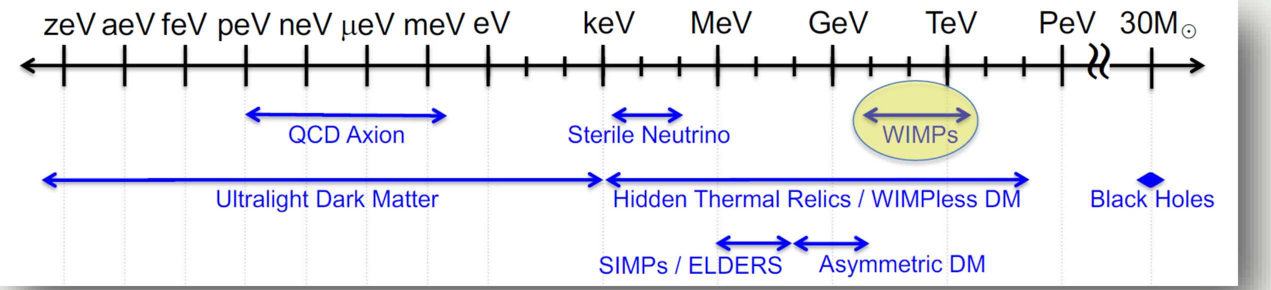
$$-\sum_{f=e,p,n} g_{af}\, a\bar{\psi}_f\gamma_5\psi_f - \frac{1}{4}g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- **Others**: Heavy neutrino, Mirror particles, sterile-ν, sneutrino, Kaluza-Klein particles, Elementary Black holes, Planckian objects, Daemons, electron interacting

The "WIMP miracle" (new physics for M ~m_W and g~1)



J.L. Feng, arXiv:2212.02479



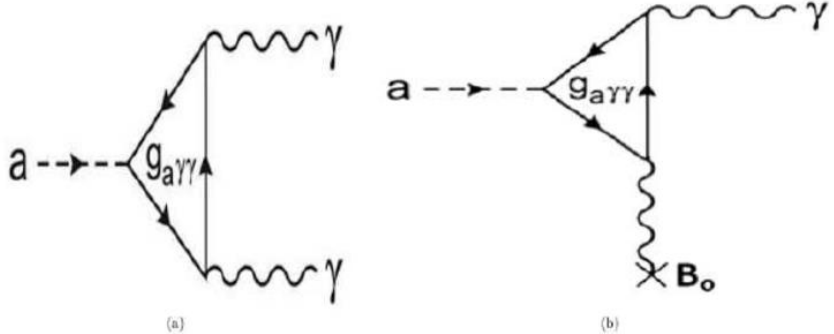
AXIONS

- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP problem
- The piece in the Lagrangian responsible for CP violation in QCD: $\mathcal{L}_{\theta QCD} = \frac{\theta_{QCD}}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$
- G is the gluon field strength tensor and $\tilde{G}$ its dual: $\tilde{G}^{\mu\nu} = \varepsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}$
- This term is called topological since it is a total derivative and does not affect the classical equations of motion.
- However, it has important effects on the quantum theory. This term is odd under CP, and produces a neutron electric dipole moment (EDM): $d_n \approx 3.6 \times 10^{-16}\,\theta_{QCD}\,e\,cm$
- Experimentally: $|d_n| < 3.0 \times 10^{-26} e\,cm$ → $\boldsymbol{\theta_{QCD} < 10^{-10}}$
- If there were only QCD, then θ_{QCD} can be set to zero by symmetry.
- In the real world, the weak interactions violate CP. The physically measurable parameter is $\theta_{QCD} = \tilde{\theta}_{QCD} + others$, where $\tilde{\theta}$ is the "bare" quantity. Thus, the smallness of θ_{QCD} is a fine-tuning problem since it involves a precise cancellation between two dimensionless terms generated by different physics.
- Peccei Quinn: Global symmetry $\mathrm{U(1)_{PQ}}$ spontaneously broken by a scalar field. The Goldstone boson is the axion

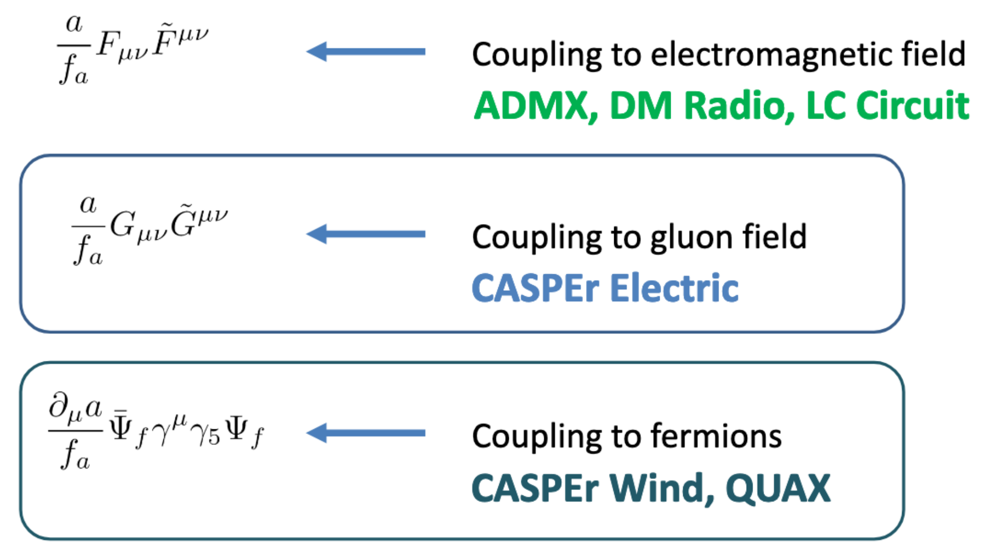
AXIONS

- ☐ Light pseudoscalar particles in many theories Beyond Standard model
- ☐ Peccei-Quinn Axion (QCD) solves strong CP problem $\theta_{QCD} < 10^{-10}$ from limits on the neutron's EDM.
- ☐ Dark matter candidate
- ☐ Production in the stars (i.e. Sun)

The Primakoff effect



$$m_a \sim \frac{\Lambda^2}{f_a}$$



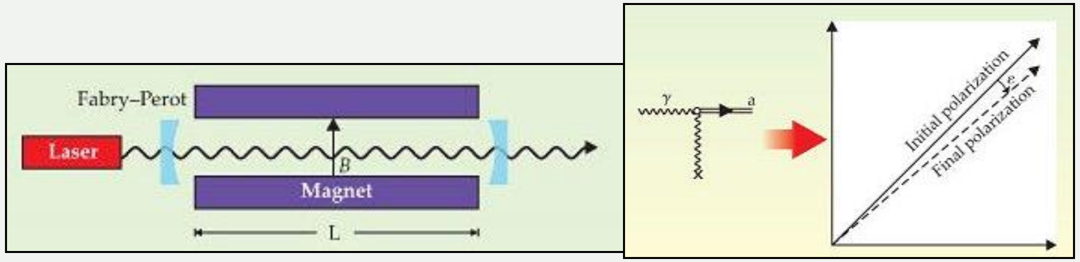
$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$ ← Coupling to electromagnetic field **ADMX, DM Radio, LC Circuit**

$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$ ← Coupling to gluon field **CASPEr Electric**

$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$ ← Coupling to fermions **CASPEr Wind, QUAX**

AXIONS

- **Axions as Dark Matter**
  - Haloscopes: Microwave cavities in solenoid magnet
  - Look for dark matter axions (low mass) converting to photons in B-Field PRL 51:1415 (1983)
  - **New techniques being explored: NMR, LC-circuit, Axion Wind**
- Axions from the Sun
  - Helioscopes: Axions generated from the sun
    - — PRL 51:1415 (1983), PRD 39:2089 (1989)
    - — **CAST, IAXO**
  - Bragg scattering on crystals, noble liquids (g_{ae})
- Axions in the Lab
  - Photon regeneration and polarization changes
    - — **PVLAS, ALPS**
  - Modifications to short range forces
    - — **ARIADNE, Torsion-balance**



···to be continued

- A significant component of the Universe consists of Dark Matter, observed across different scales
- Cosmology provides precise estimates of its total density and strong constraints on its nature
- Cold Dark Matter is the dominant component, made of unknown particles.
- Theories extending the Standard Model of particle physics predict viable Dark Matter candidates.
- Dedicated particle detectors can reveal these particles, shedding light on their cosmic origin and fundamental properties.