The Homogeneous Universe

The energy density budget

Which FRW model better corresponds to the reality?

To answer this question, we need to **determine the values of its parameters**
H_0, Ω_i, w_i

Then we will be able to:

determine the global geometry, dynamics, future behaviour (expansion, big bang, big crunch)

and also to:

determine the evolution of the universe - thermal history, transition epochs, structure formation

find out what energy forms exist in the universe (dark matter, dark energy, neutrinos)

Direct measurements

The best way to find the cosmological parameters is to estimate them from measurements of "cosmological functions", i.e., quantities like distances or power spectra that depend on the cosmological model.

Before presenting that approach in detail (based on model-dependent **indirect measurements** of cosmological properties), we will discuss an alternative approach, which is based on making **direct measurements** of some astrophysical properties that may provide good approximations to the values of the cosmological parameters.

Examples of these direct measurements are:

Determination of baryonic matter density

Big Bang Nucleosynthesis

Cosmic budget → measuring all the baryonic mass in the Universe should provide a good approximation to Ω_b

Determination of total mass and Mass-to-Light ratio (M/L)

Galaxy mass (from rotation curves)

Cluster mass (from various methods: kinematic, X-ray gas, strong gravitational lensing, weak gravitational lensing)

Determination of radiation density

CMB Temperature → directly gives the energy distribution of primordial CMB photons

Determination of the age of the universe

Nuclear chrono-cosmology (decay of radioactive elements)
Age of oldest stars (globular clusters) → lower-bound to the age of the Universe
Cooling of White Dwarfs

Determination of the Hubble constant (independently of the values of the density parameters)

Redshift drift → The redshift is a ratio between the scale factor at two different times. In a second observation of the same object, this ratio will be changed (because of acceleration) → **the redshift of a comoving object changes with time** → Measuring the redshift at different times gives information on H(z).

Calibration of the distance ladder
Gravitational lensing time-delays in double images of variable sources
Cosmic Chronometers

Let us now discuss the direct measurements of the density parameters.

We will not discuss here the direct measurements of the Hubble parameter (which have recently become an active field again due to the so-called Hubble tension).

Radiation

$$\Omega_r = \Omega_\gamma + \Omega_\nu \text{ (relativistic)}$$

The main contribution to the cosmological radiation are the **CMB photons**.

The **energy density of the CMB photons** is found by summing up the energy of all photons. The CMB has a blackbody spectrum and so the energy distribution of the photons is well-known and is determined by the temperature.

The energy density is then the integral of hv with a window function (the Bose-Einstein distribution):

$$\rho_{CMB} = \frac{2}{(2\pi)^3} \int d^3p \; \hbar\nu \; \frac{1}{e^{\hbar\nu/kT} - 1} \qquad c=1$$

2 d.o.f. — Bose-Einstein distribution

(here h is the Planck constant)

$$\rho_{CMB} = \frac{1}{c^2} \frac{\pi^2}{15} \frac{(k_B T_{CMB})^4}{(\hbar c)^3} \simeq 4.5 \times 10^{-34} \, g/cm^3$$

using T_CMB = 2.725 K

Dividing by the critical density, $\rho_c = 3 H_0^2 / 8\pi G = 1.88 \times 10^{-29}\, h^2$ g cm^{-3} ,

the dimensionless radiation density is $\Omega_\gamma = 2.4 \times 10^{-5}\, h^{-2}$

The **massless neutrinos** also give an important contribution to the radiation of the Universe. The **energy density of massless neutrinos** is computed in the same way, but using the Fermi-Dirac distribution instead and a different number of degrees-of-freedom:

... Add massless neutrinos

Fermi-Dirac   Fermion factor

$$\rho_\nu = \frac{6}{(2\pi)^3} \int d^3E \; E \, \frac{1}{e^{E/kT_\nu}+1} = 6\, \frac{7}{8}\, \frac{\pi^2}{30}\, T_\nu^4 = 3 \cdot \frac{7}{8} \left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_{CMB}$$

6 d.o.f.

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

From the thermal history of the Universe, we know that neutrinos decouple before the CMB, when the temperature was higher, such that:

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

So, their density is $\rho_\nu = 0.68\ \rho_\gamma$

$$\rho_{r_{total}} = \left(1 + 3 \cdot \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right)\rho_{CMB} = 1.68\ \rho_{CMB}$$

and in terms of the dimensionless density parameter: $\Omega_r = \Omega_\gamma + \Omega_\nu$ **~ 0.00004 h^{-2}**
(a negligible contribution to the density of the Universe today).

Note however, that **neutrinos are massive**, and the massless neutrinos scenario is only a good approximation when the temperature of the Universe is $T \gg M_\nu$.
Later in the Universe, neutrinos become non-relativistic fermionic particles and the **density of massive neutrinos** is computed as:

$$\rho_\nu = n_\nu m_\nu = m_\nu \frac{6}{(2\pi)^3}\int d^3E \frac{1}{e^{E/kT}+1}$$

using again:

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

The result is:

$$\Omega_\nu = m_\nu \frac{1}{94\ eV} h^{-2}$$

The density depends on the neutrino mass (here M_ν is the sum of the masses of the 3 neutrinos) and is no longer fully determined by the temperature.

For example, a neutrino mass of 0.1 eV would give a small but non-negligible contribution to the total energy density of $\Omega \sim 0.001$

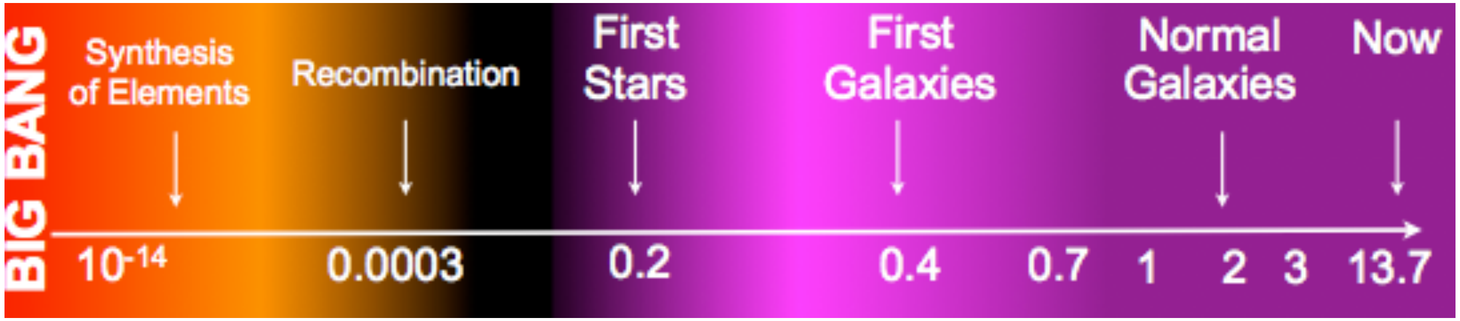
Neutrinos then contribute both to the radiation density and to the matter density.

An additional cosmological parameter N_eff (effective number of relativistic species) was introduced to model what fraction of neutrino density is considered relativistic and contributes to the radiation density, and what fraction is non-relativistic and contributes to the matter density affecting structure formation on small scales.

Baryonic matter

Ω_b

Its total density is determined by nucleosynthesis and also by cosmological probes (such as CMB anisotropies)

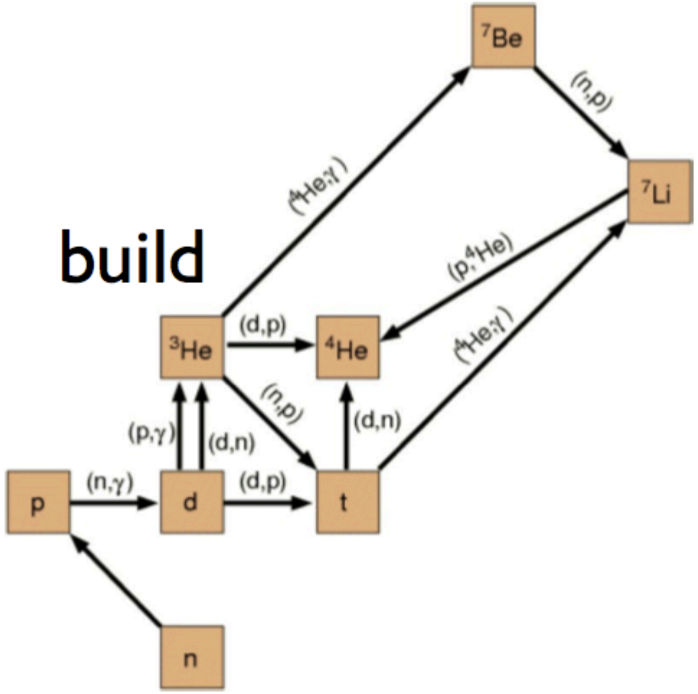


“Direct” measurement of Ω_b: nucleosynthesis

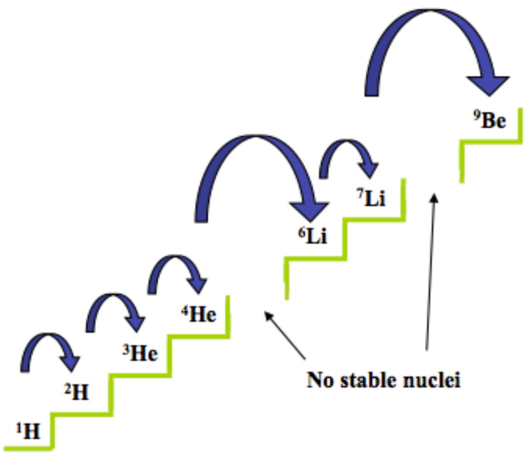
(nuclear fusion in early Big Bang)

The formation of elements during the first 2-5 minutes of the Universe

build

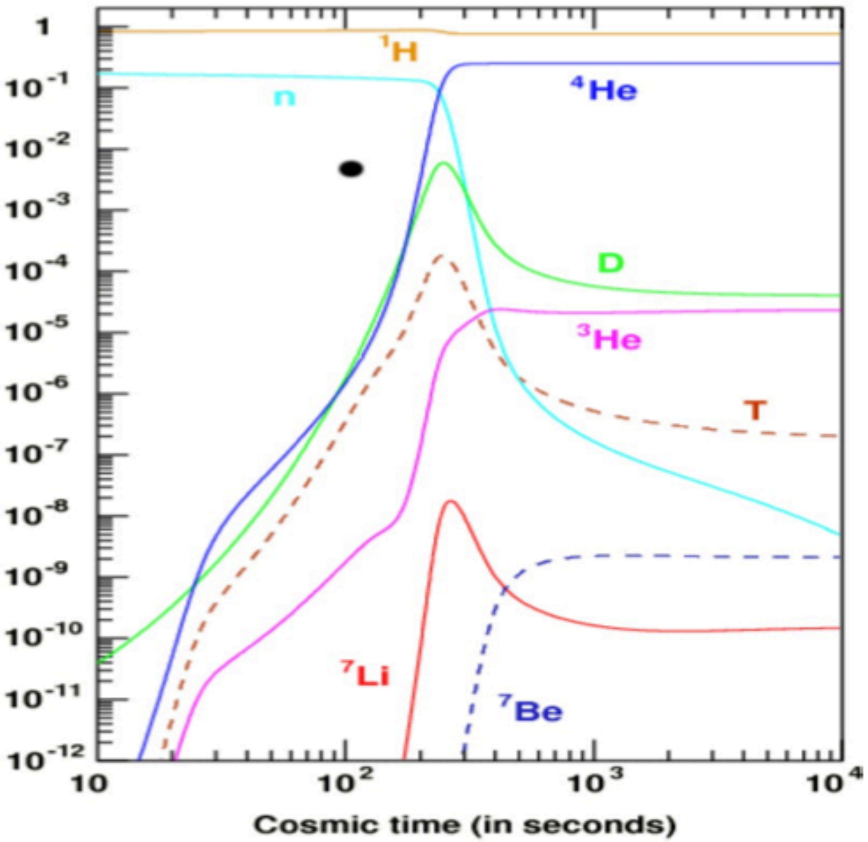


The lack of stable elements with masses 5 and 8 make it more difficult for nucleosynthesis to progress beyond Lithium and even Helium

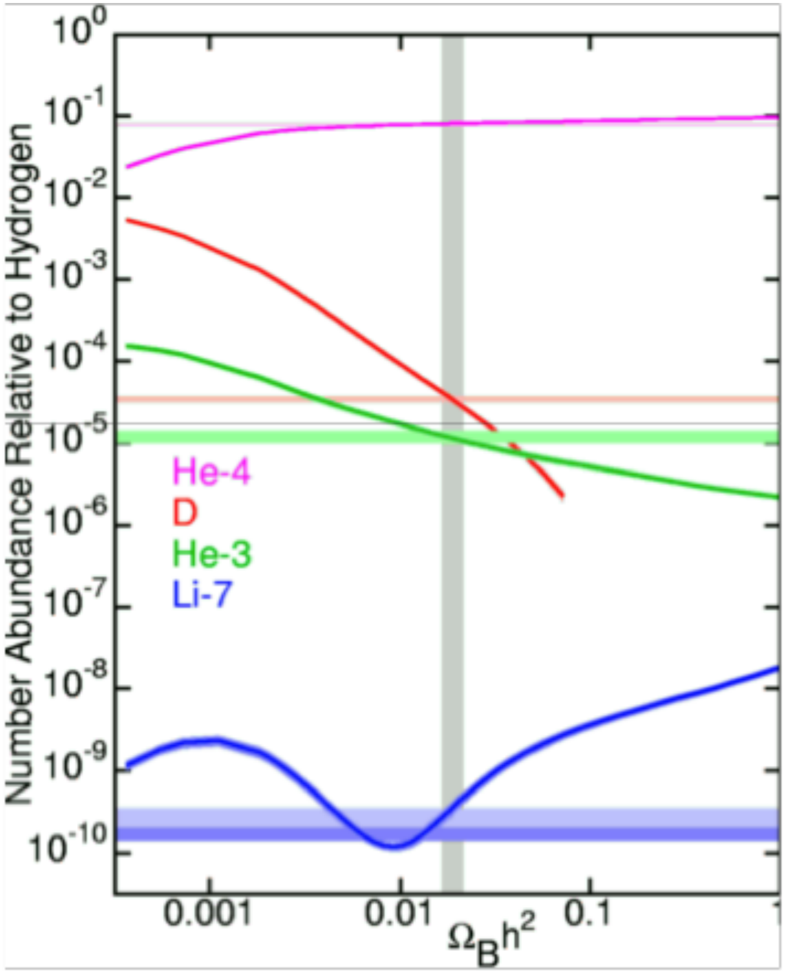


The **evolution of the abundances with time** (shown as M_element/M_H)

Formation of these elements is finished before 1000 s of cosmic time.



The interesting point is that **the reaction rate for element formation depends on the total amount of baryons present in the Universe** (before nucleosynthesis they are mainly in the form of protons and neutrons)



higher Ω_b → more He4 forms (the most stable species)

higher Ω_b → less D ou He3 form (because He4 is formed instead)

This provides a powerful way to estimate Ω_b : we just need to be able to measure the total amount of one of these species.

But this is difficult because **the abundances of the species do not remain constant**.

After star formation, stars destroy some elements and create others:

Deuterium → destroyed in stars from fusion

He 4 → produced from fusion

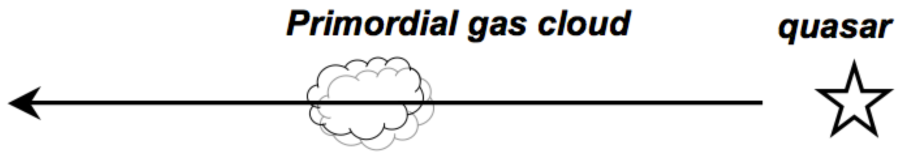
Li 7 → destroyed in stars from fusion and
also created in the interstellar medium from impact of cosmic-rays (spallation)

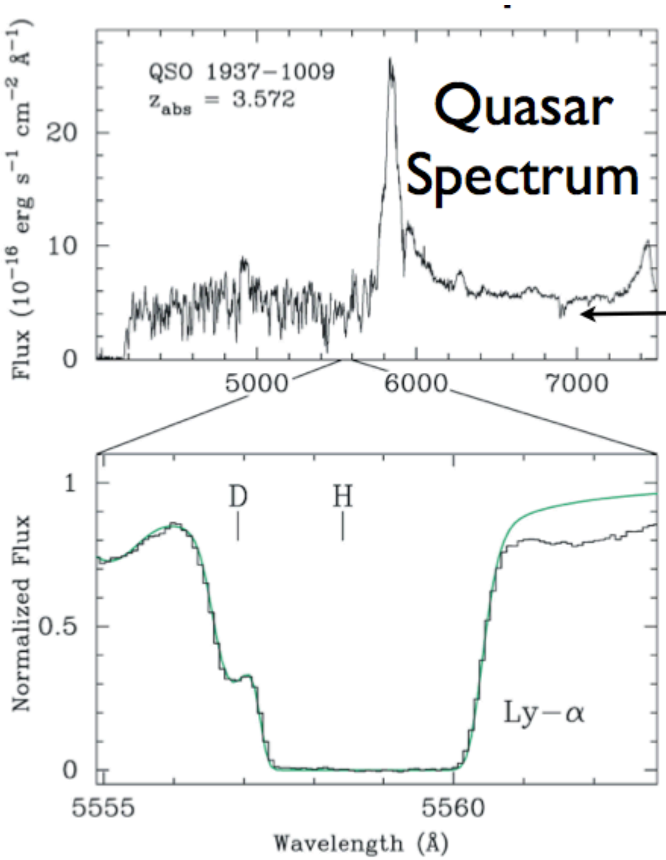
He 3 → produced by burning deuterium and
also destroyed to produce He 4

Measuring the abundances

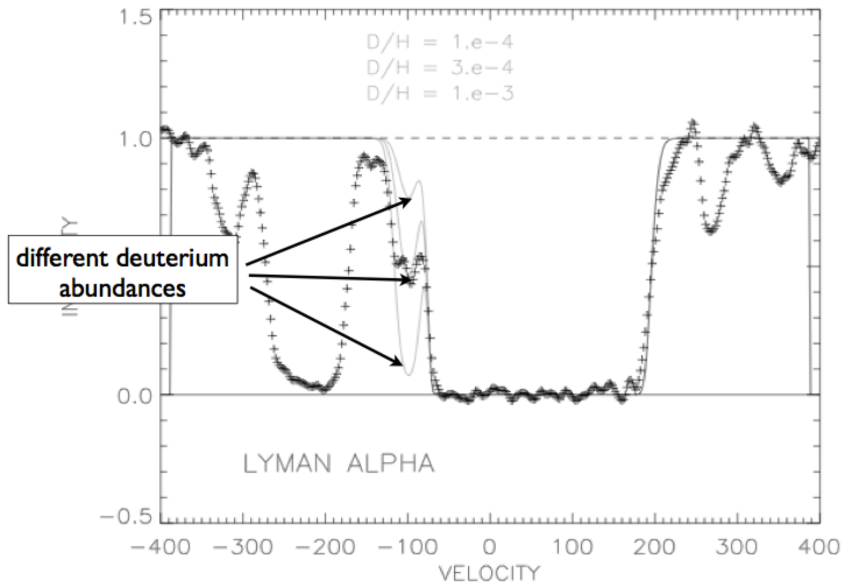
Deuterium

Observe gas clouds in the early universe (where stars have not yet formed), looking for absorption features of rare elements (deuterium) on the spectrum of background bright sources (quasars)





to control, check if there are heavier elements



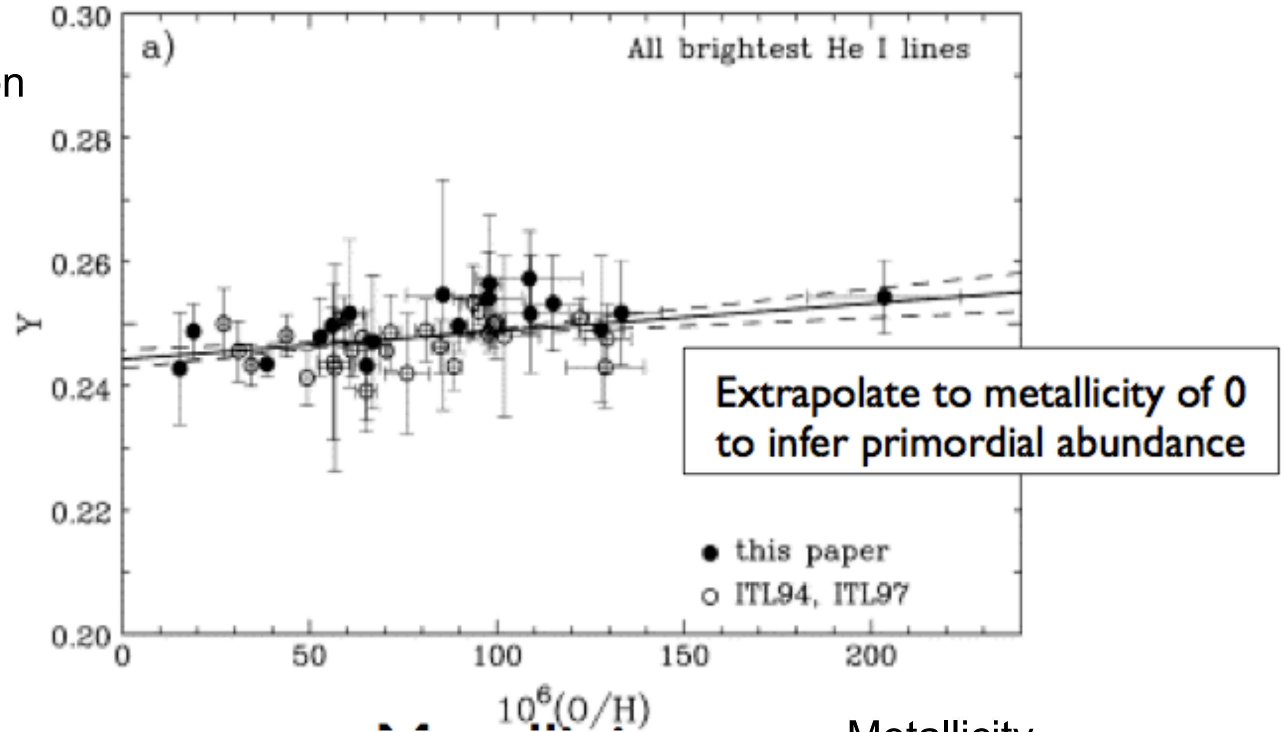
Result: [D/H] ~3 x 10^{-5}

Helium 4

Observe recombination lines from HII regions in low metallicity galaxies (oldest galaxies)

Measure abundance ratios of many elements He, O, N, H (metallicity)

Mass fraction of baryons in He 4

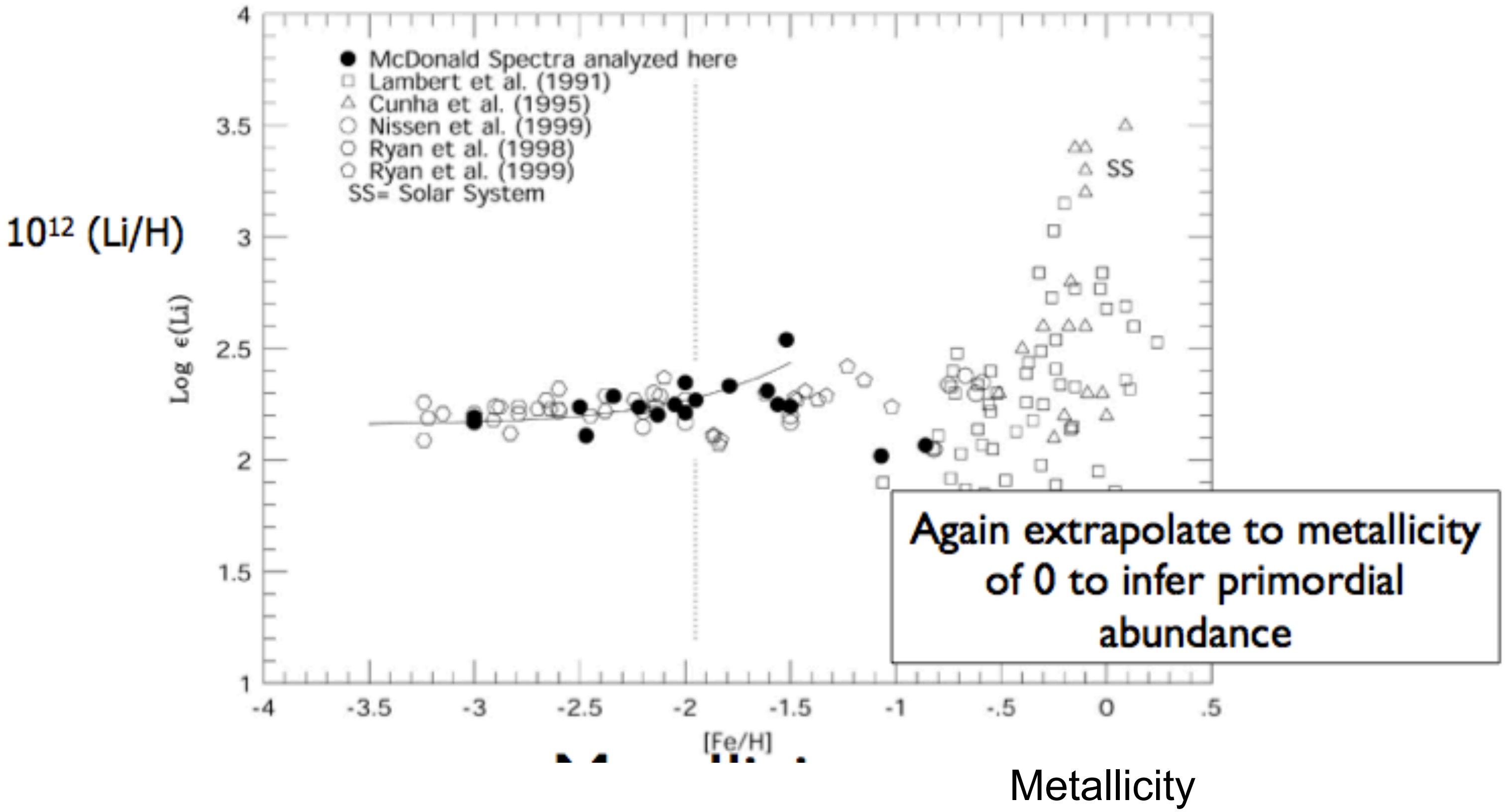


Metallicity

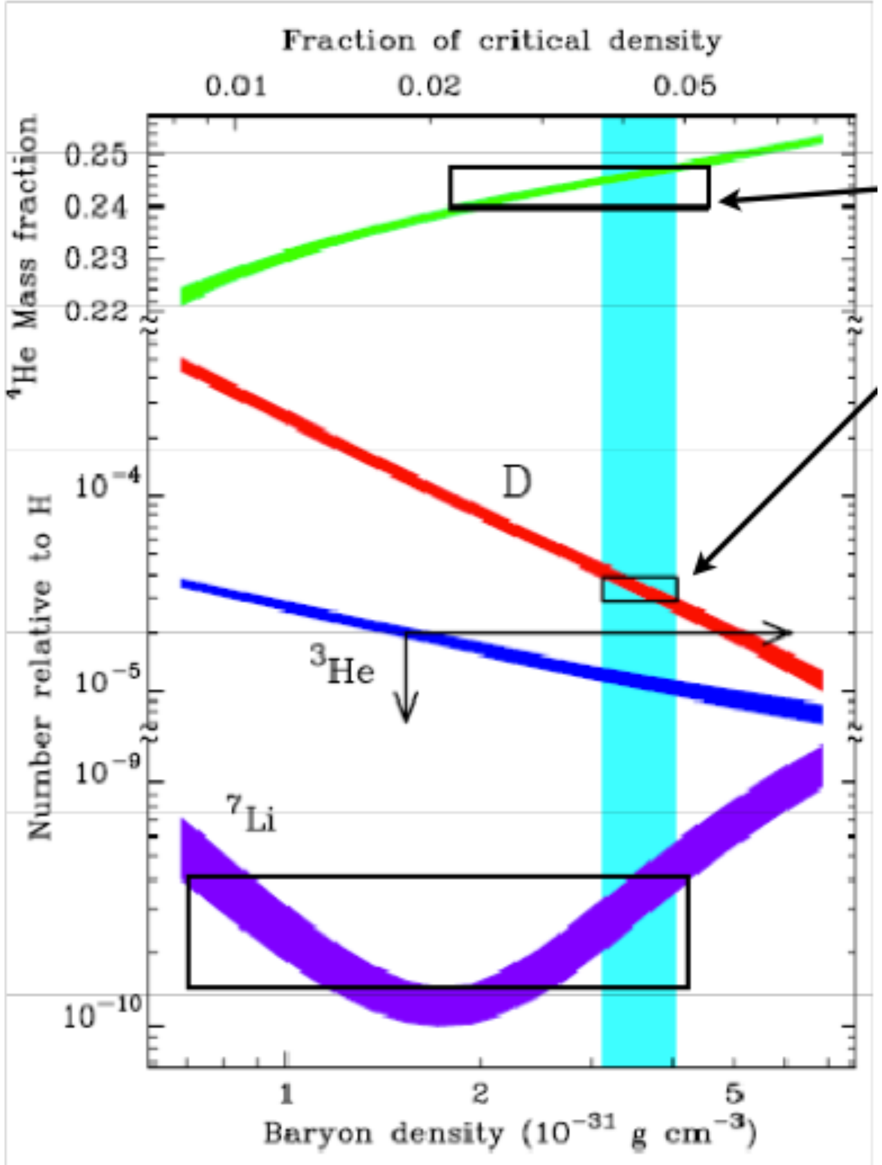
Lithium 7

Observe absorption in the atmospheres of cool, metal poor population II halo stars

Need to model the atmosphere of stars



Results



(the most useful result comes from Deuterium measurements)

Best Fit Baryon Density

$$\Omega_B h^2 = 0.019 \pm 0.0024$$

$$\Omega_B = 0.037 \pm 0.009$$

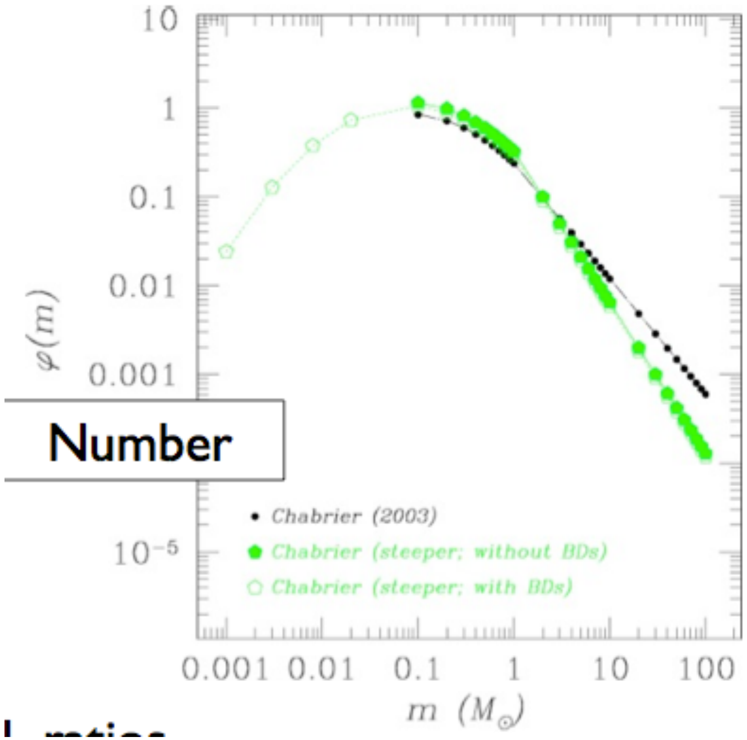
$\Omega_b \sim 0.04$

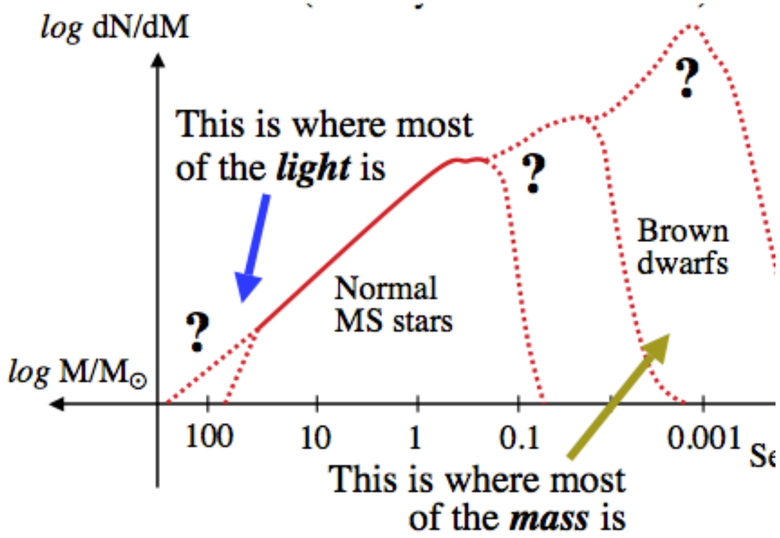
Cosmic baryon budget

We found out that $\Omega_b \sim 0.04$.

It would be interesting to “count all the baryons” and try to find out where is the baryonic matter → the cosmic baryon budget

Baryonic mass density in stars
(in galaxies)





Estimate mass from light

$L \sim M^3$
$M/L \sim M^{-2}$

low mass stars → high M/L ratios
high mass stars → low M/L ratios

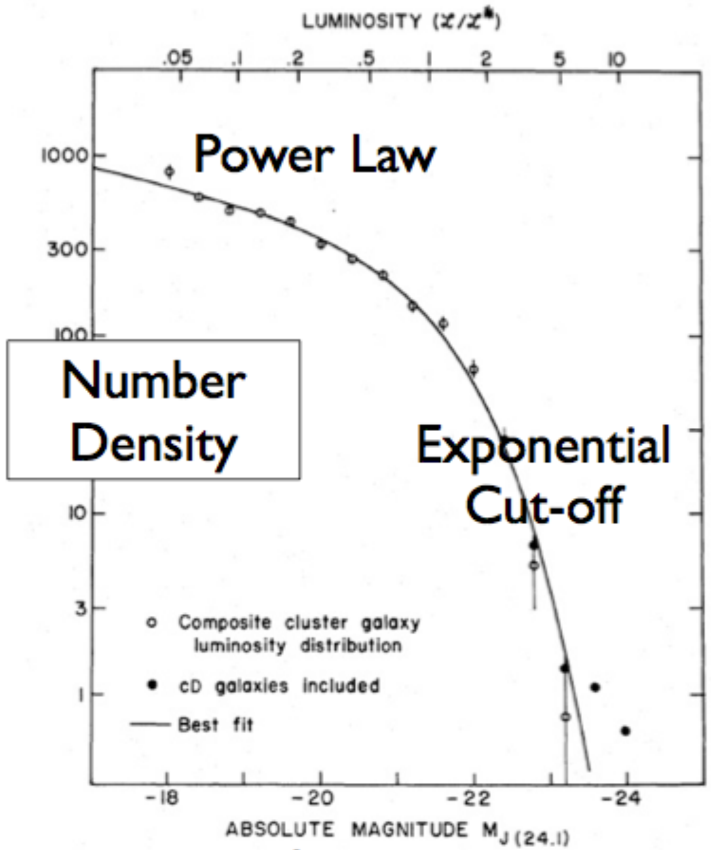
Integrating over the Initial Mass Function, we can compute an average M/L ratio.

complication: the M/L ratio of a population of stars (eg. stars from the same galaxy) depends also on the age

but age can be estimated from color: $\log_{10} M/L \sim -0.4 + 1.1\ (g-r)$

red galaxies → old
blue galaxies → young

Need to sum all luminosities (which are proxies for mass) and using the corrected mass functions, over the various populations (i.e., over many galaxies), using the luminosity function



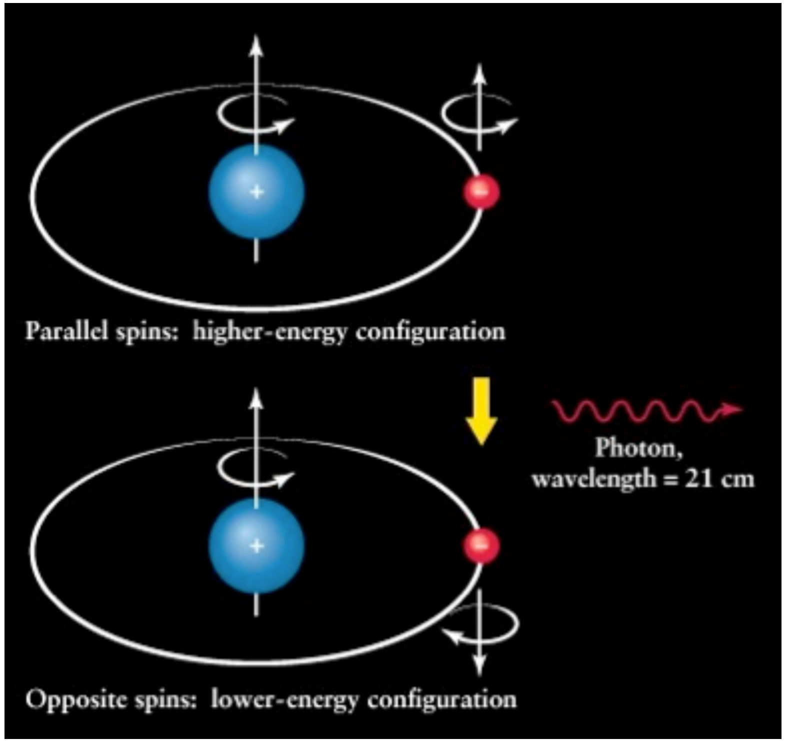
Results:

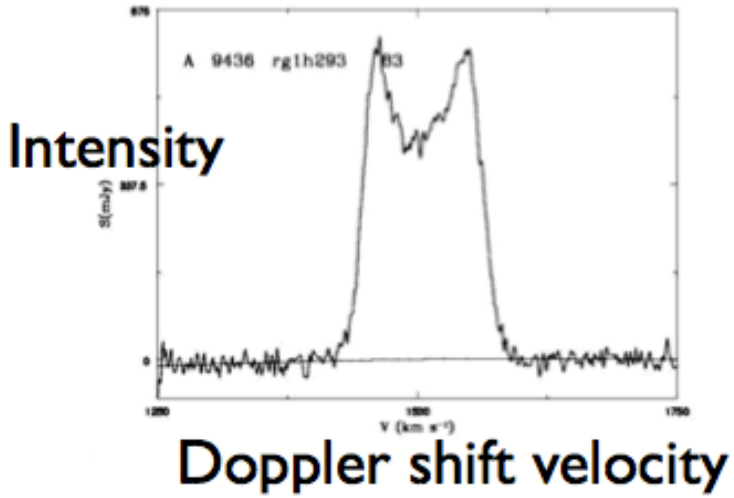
$$M_{stars} = 3 \times 10^8\ M_{sol}/Mpc^3$$

$$\Omega_{stars} = 0.002$$

Baryonic mass density in neutral atomic hydrogen
HI (in galaxies)

Hyperfine structure 21 cm





Spectra of a spiral galaxy at 21cm

Results: $\Omega_{HI\ gas} = 0.0003$

Baryonic mass density in molecular hydrogen H2
(in galaxies)

Difficult to search for H2 since it has no observable transitions

Assume CO emission is a good tracer of H2 (CO emission caused by H2 molecules colliding with CO)

Examine ratio of atomic hydrogen to molecular hydrogen in galaxies and then use this to convert from atomic hydrogen mass density

Results: $\Omega_{H2} = 0.0003$

So the total from galaxies is (very low, only 6.5% of the total baryonic density):

$$\Omega_{stars+gas} = 0.0026$$

Baryonic mass density in galaxy clusters (intra-cluster medium ICM)

Measured from X-ray photons coming from bremstrahlung radiation →

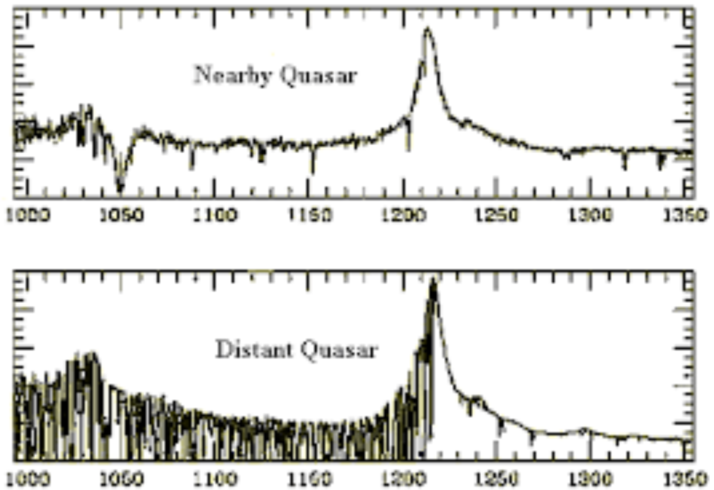
proportional to ρ_gas^2 x T_gas^(1/2)

Measuring T and light → mass (isothermal)

Results: Ω_ICM ~ 0.001

Baryonic mass density in between galaxies (inter-galactic medium IGM)

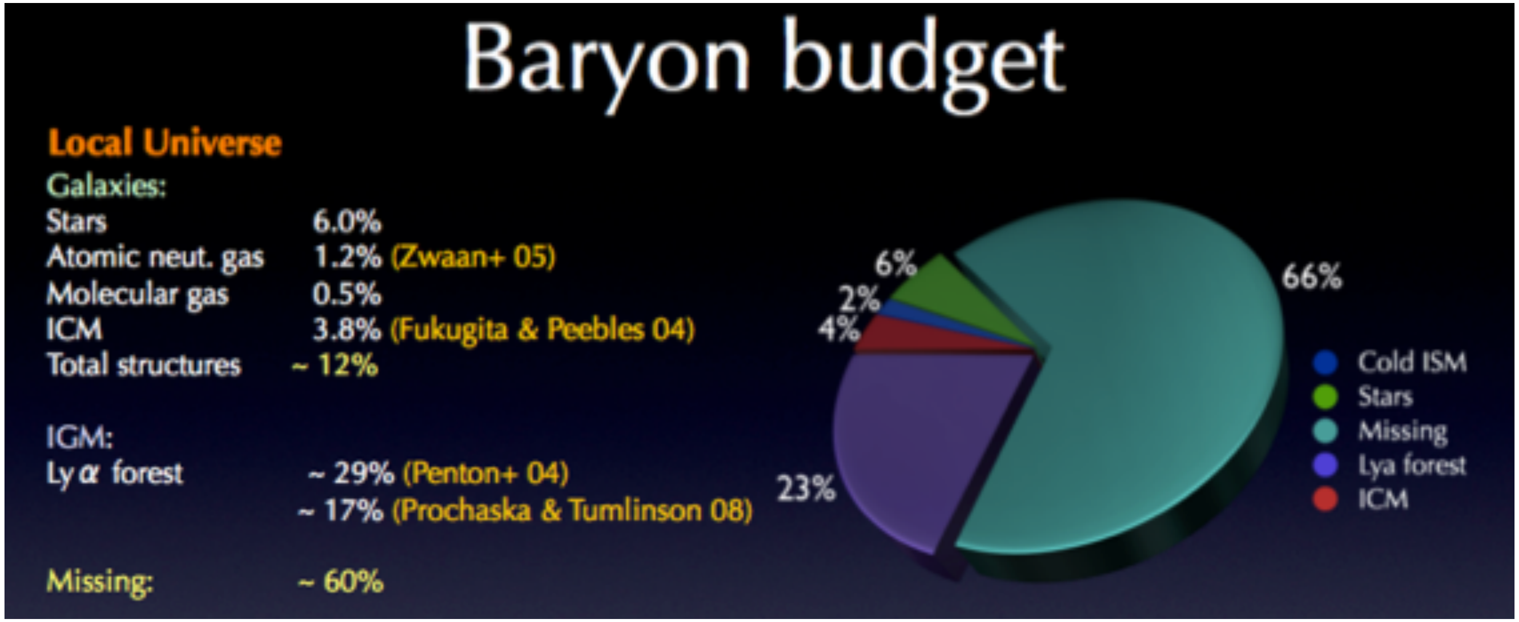
Measurements of Lyman_α forest
(absorption by IGM clouds of photons emitted by background quasars)



Results: Ω_IGM ~ 0.008

Putting all the results together, we get

Ω_b from galaxies+IGM+clusters ~ 0.014

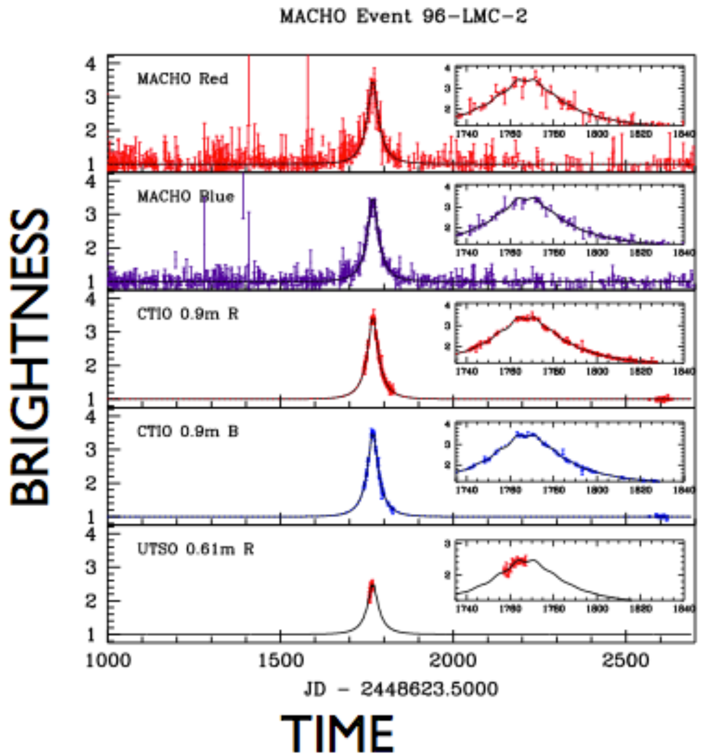


This is known as the problem of the missing baryons

Missing baryons

Baryonic mass density in MACHOs

First it was thought the solution might be a large amount of low-brightness objects: the Massive Compact Halo Objects,
i.e., a large amount of black holes, white dwarfs, neutron stars, large planets

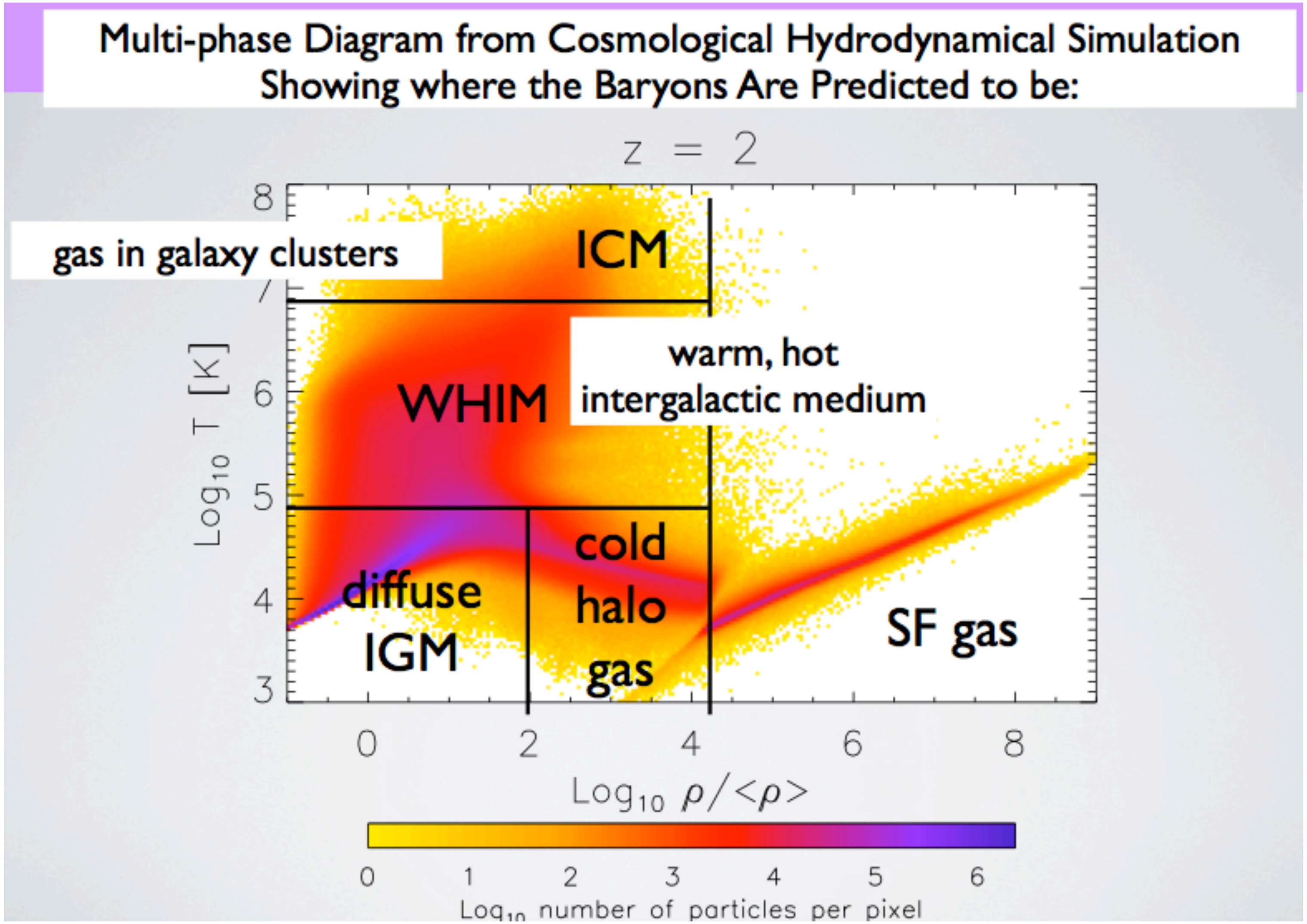


In the 1990s:

Extensive search for microlensing events

Results: Ω_MACHOs ~ negligible

Baryonic mass density in the cosmic web between clusters or field galaxies (warm/hot intergalactic medium WHIM)



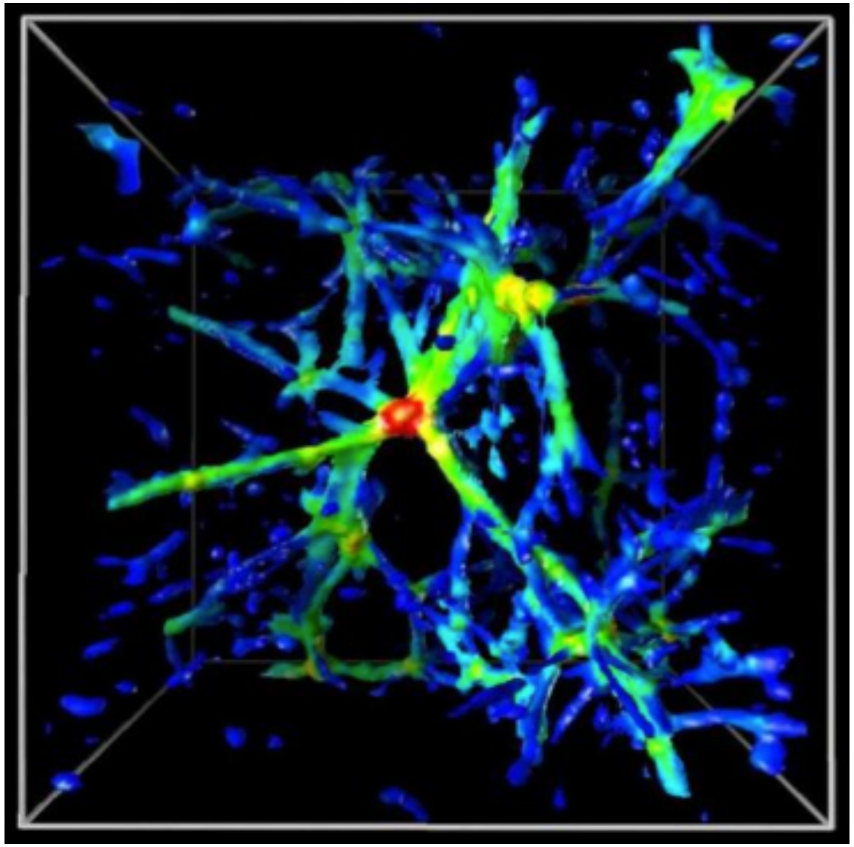
ICM intracluster medium : hot gas inside clusters

IGM intergalactic medium: diffuse gas between galaxies (Ly alpha forest)

WHIM warm/hot IGM: cosmic web between clusters

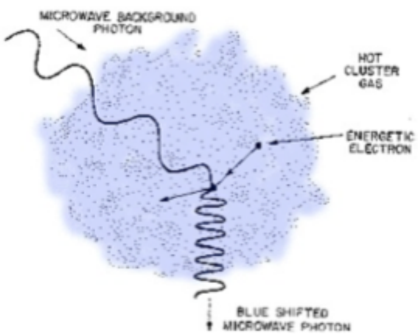
In the 2010s:

Detecting the WHIM



Thermal Sunyaev-Zeldovich effect

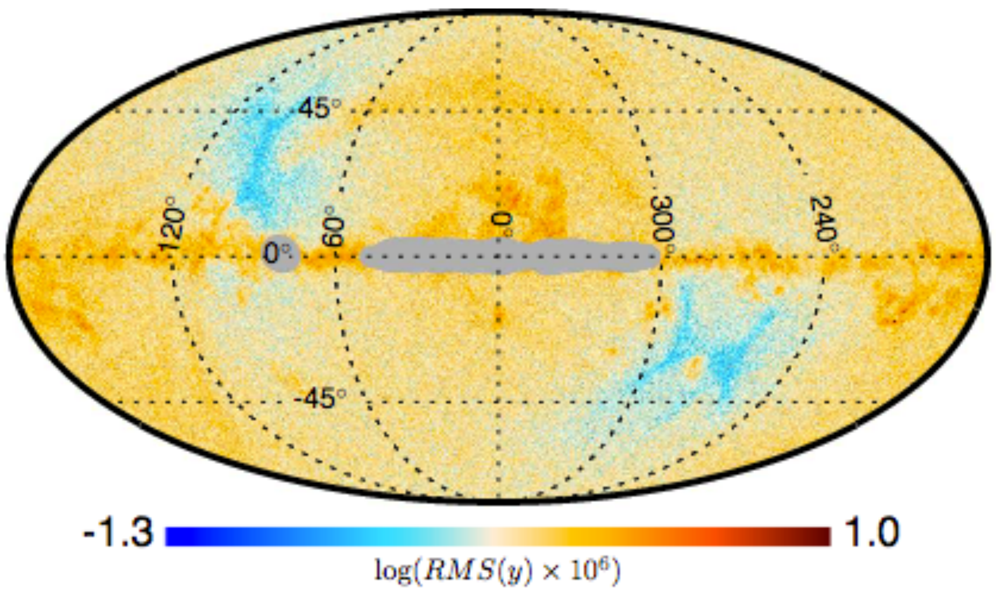
When CMB photons pass by hot ionized gas (like in a cluster), the photons can gain energy by scattering off of the hot electrons → T_CMB increases in the direction of a cluster

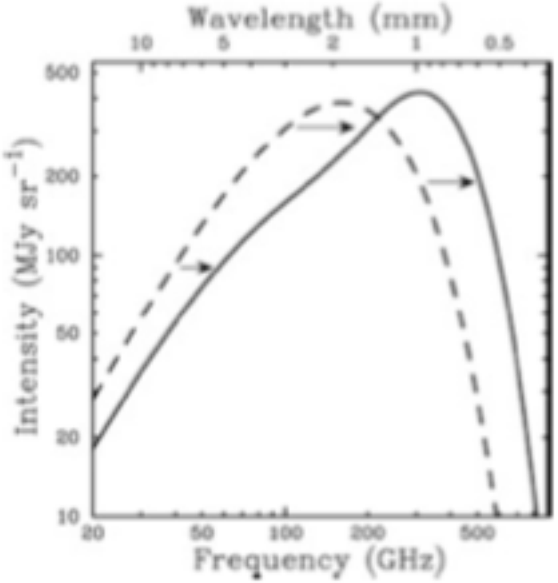


The amplitude of the effect (y) depends on the density of hot electrons → SZ is a measurement of the baryonic density

$$y = \frac{k_B \sigma_T}{m_e c^2} \frac{1}{A} \int n_e T_e dV = \frac{k_B \sigma_T}{m_e c^2} \frac{1}{A} \frac{0.88 f_B}{m_p} \sum_i M_i T_i$$

for clusters → y ~10^-6





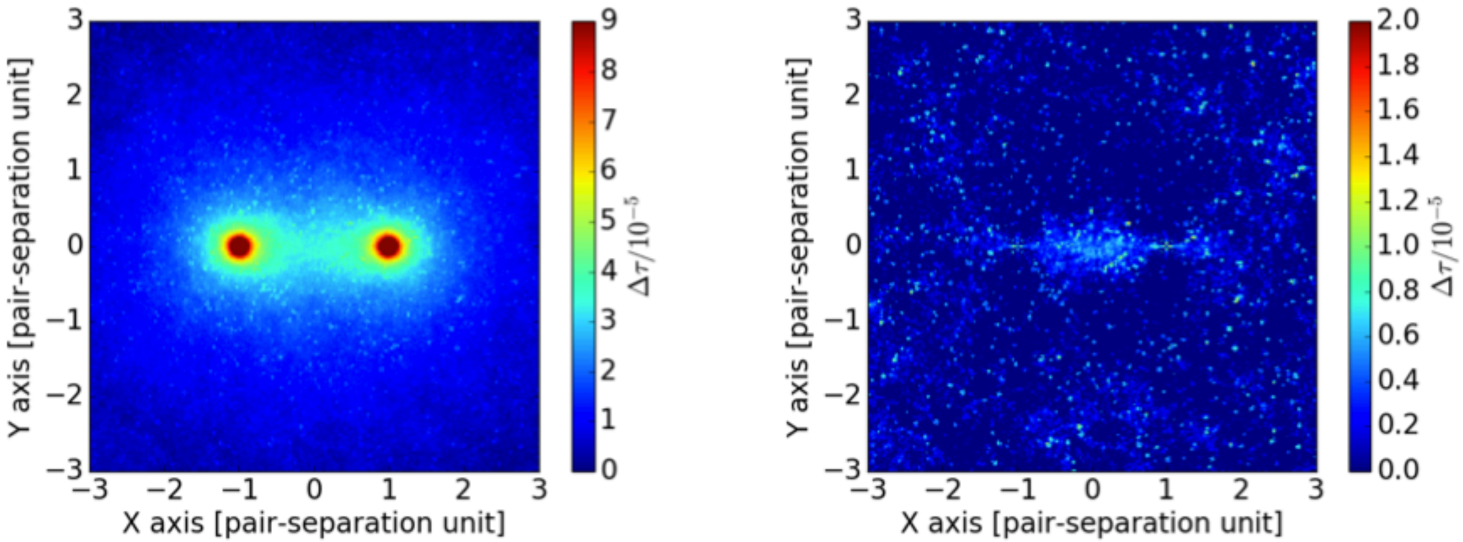
"A Search for Warm/Hot Gas Filaments Between Pairs of SDSS Luminous Red Galaxies", H. Tanimura, G. Hinshaw, I. McCarthy et al, MNRAS 483, 1, Feb. 2019 (arXiv:1709.05024)

Used the tSZ map from Planck 2015 and the luminous red galaxies LRG catalog from SDSS-DR12 (luminous galaxies at cluster centers) → found **260 000 LRG** pairs.

Stacking the signal from all pairs in one image (to increase SNR) and subtracting the cluster tSZ signal (with a model for cluster amplitude y), they found the residual signal coming from WHIM:

$$y = (1.31 \pm 0.25) \times 10^{-8}$$

Stacked pairs: before and after subtracting the cluster signal



First direct detection of a LSS filament

It has **δ ~ 5** → filaments are the largest and weakest-clustered structures

Absorption lines

The ionized WHIM should emit thermal bremstrahlung radiation.

But compared with the ICM, the WHIM gas has much lower temperature and density → impossible to detect its X-ray emission.

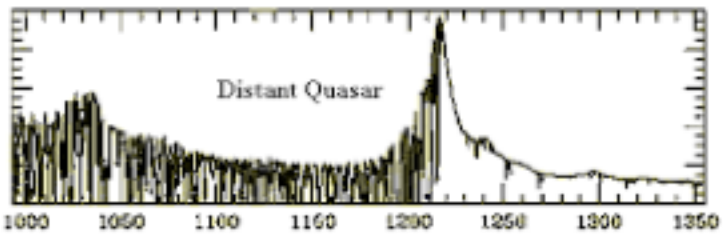
Use absorption techniques from its effect on background bright X-ray sources.

In the distant Universe, sources appear so faint that it is usually easier to detect them through absorption that through direct emission.

But still it may be needed a burst, like from a blazar (AGN with radio jet pointed toward us), to have enough signal for detection.

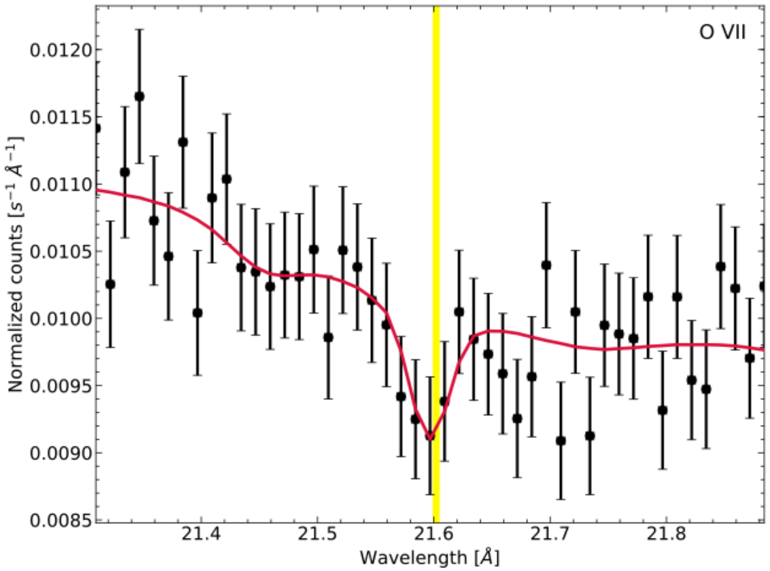
Unless some way of increasing the signal is found.
Again, through **stacking**:

Using all the absorptions at different redshifts of a single quasar → blueshift and stack them to increase SNR



“Detection of the Missing Baryons toward the sightline of H 1821-643”, O. Kovacs, A. Bogdan, R. Smith et al, ApJ 872, 1, Feb. 2019 (arXiv:1812.04625)

Adding 17 OVII absorption lines, the absorption from WHIM was seen in the spectra.



$$\Omega_b(\mathrm{O\,VII}) = \frac{\mu m_p H_0}{\rho_c c}\left[\left(\frac{\mathrm{O}}{\mathrm{H}}\right) f_{\mathrm{O\,VII}}\, Z/Z_\odot\right]^{-1} \cdot \frac{\sum_i N_i(\mathrm{O\,VII})}{\Delta X}$$

Results: Ω_WHIM = 0.017 (+/- 0.005)

It seems that the baryons on large-scales dominate the baryonic content of the Universe.

The current count is thus: Ω_b = 0.014 + 0.017

Mystery solved?

Dark matter

Ω_{dm}

The value of Ω_{dm} can be determined in various ways:

- direct mass measurements
- probes of structure formation: CMB anisotropies, weak lensing, galaxy clustering
- probes of geometry: Supernovas, BAO

There are 2 general types of dark matter:

- Cold dark matter (CDM): heavy particles (eg. WIMPs - weakly interacting massive particles)
- Hot dark matter (HDM): low mass particles (eg. neutrinos) - can erase small-scale perturbations

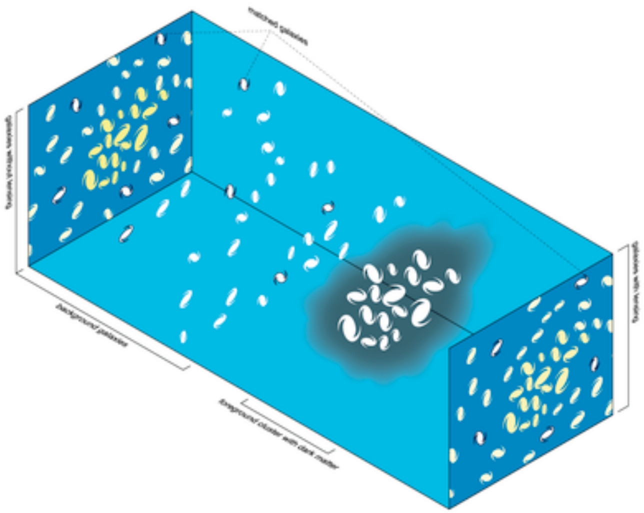
Evidence for dark matter

There is evidence for the existence of dark matter on various scales

Large-scale structure (LSS)

- From the small amplitude of CMB anisotropies → not enough time for baryonic matter to form the observed collapsed structures

- From the detection of correlations between galaxy ellipticities → well explained by the coherent deflection induced by “invisible” gravitational potentials



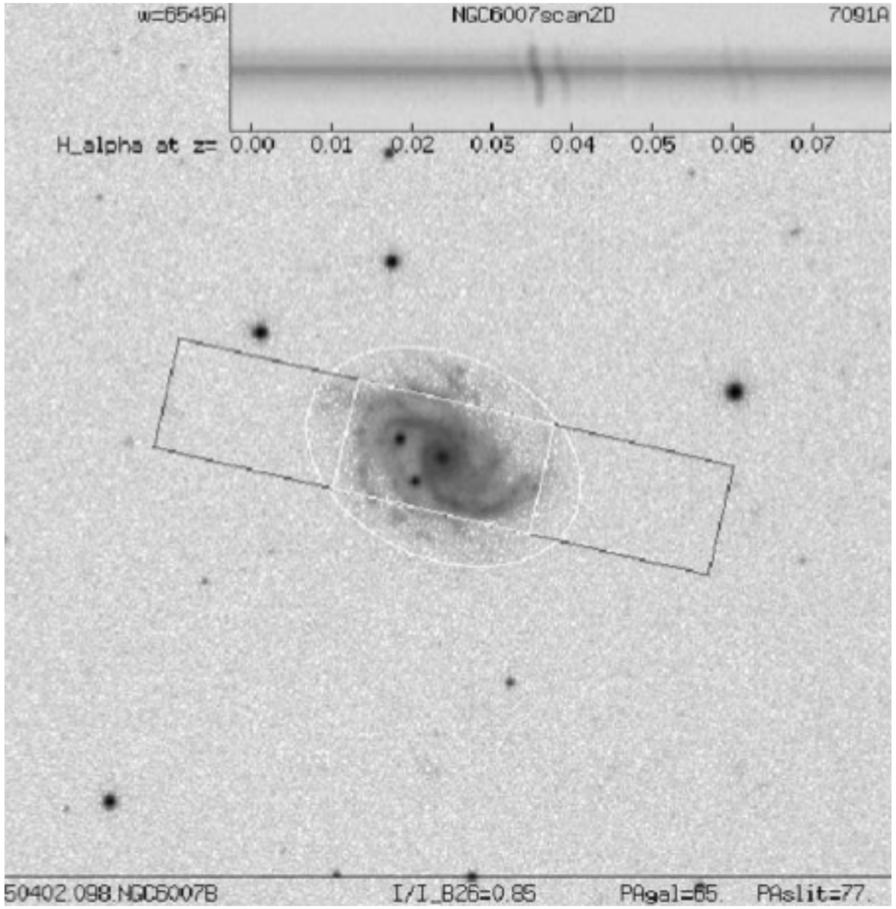
Clusters

- From their dynamics → need more mass

Galaxies

- From their rotation curves → need more mass

Dark matter in Galaxies (rotation curves)



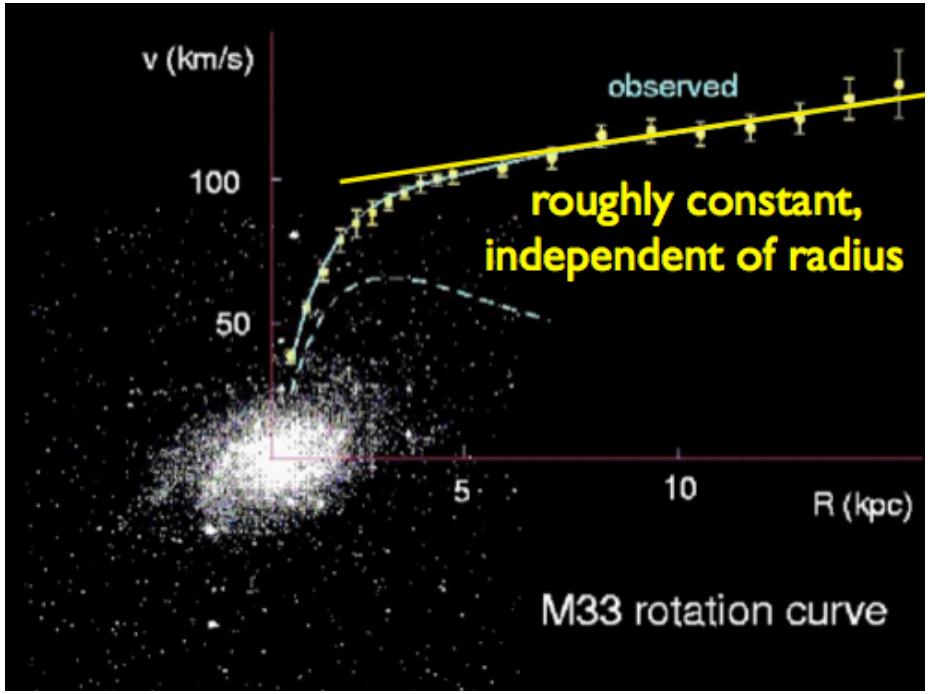
The rotation rate of a spiral galaxy can be measured by letting light pass through a slit along the axis of the galaxy and taking a spectrum

If the galaxy is not edge-on, we need to apply an inclination angle correction

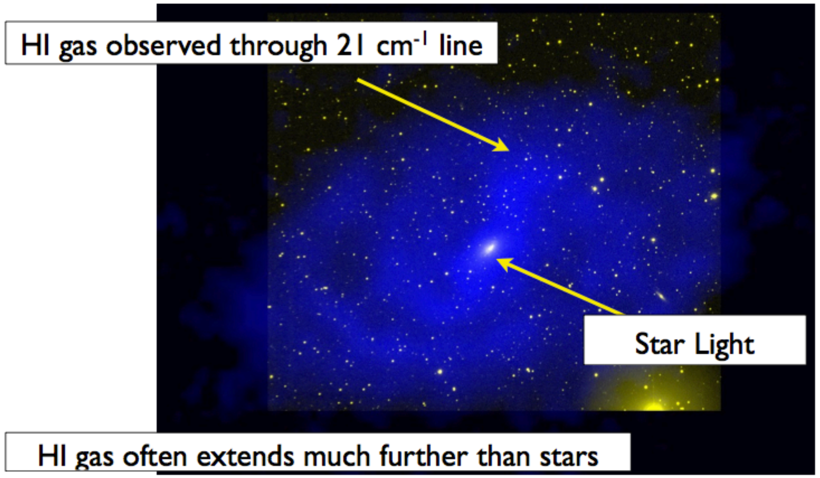
If the mass of the galaxy is mostly at the inner part → v_rot decreases with distance to the center (r)

$$\frac{GM(\leq r)}{r^2} = \frac{v_{\rm rot}^2(r)}{r}$$

force per unit mass — acceleration



However, the observed **v_rot is approximately constant** (beyond a certain radius) and it continues flat to very large distances



if v_rot flat → M increases with r

$$M(\leq r) = \frac{v_{\rm rot}^2 r}{G}$$

In principle, this does not need to be a problem, the distribution of mass in the galaxy could naturally be such that it increased with radius (no need to be concentrated in the center).

But the problem is that the **light in a galaxy decreases exponentially with radius** → for large radius, the total light inside the radius tends to a constant

$$I(r) = I_0 \exp(-r/h)$$

$$I_0 \int_0^{r_0} 2\pi r \exp(-r/h)\, dr$$
$$\propto h^2 - h(r+h)\exp(-r/h)$$

This means that the light is restricted to the inner part, up to a typical scale r = h

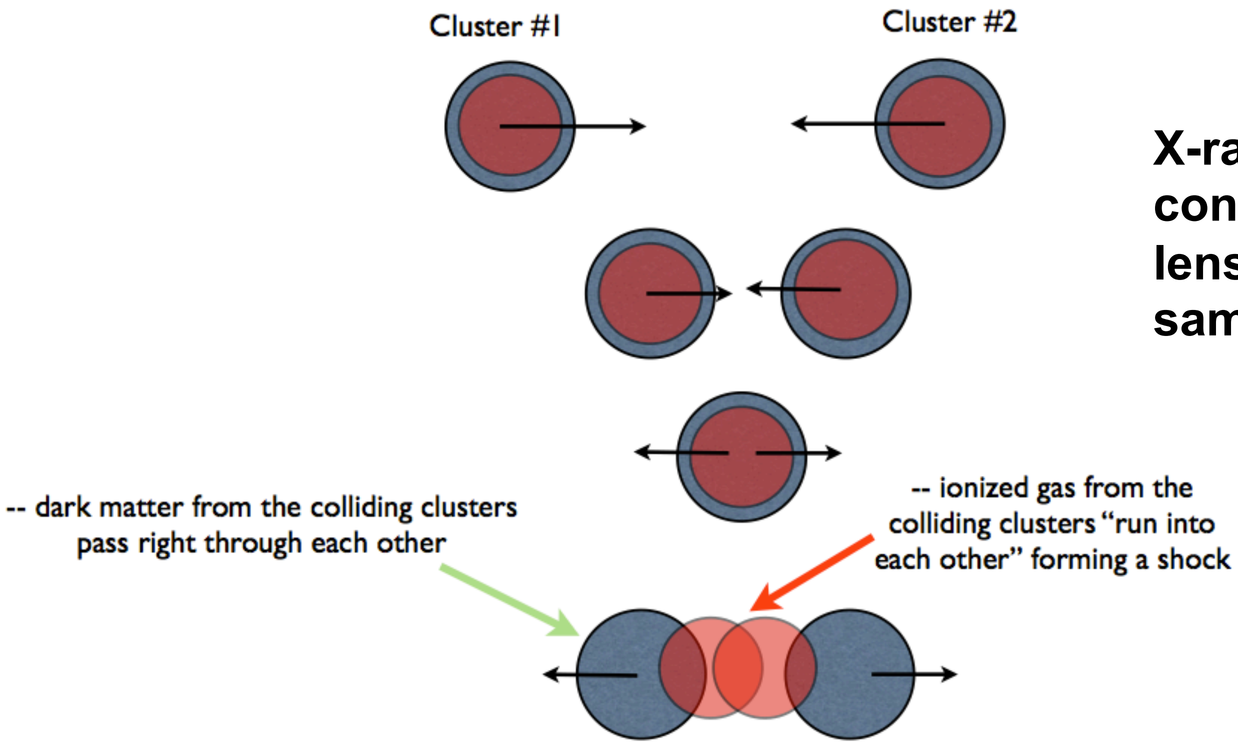
→ matter emitting light (baryonic matter) is also mostly in that part → the mass that increases with r cannot be luminous → **dark matter is needed**

This had been first suggested by Jan Oort in 1932, from observations of the motion of stars in the Milky Way.

Dark matter in Clusters (clusters collisions)

The observation that the velocities of individual galaxies in clusters could only be explained if total mass of the cluster was much greater than that seen in galaxies had been first suggested by Fritz Zwicky in 1933, based on observations of the nearby Coma cluster.

The observations of the colliding Bullet Cluster (2006) are well understood if there is dark matter in clusters.



X-ray emission and mass concentration (from weak lensing) are not at the same position

ICM (X-ray emission) and mass concentration (from weak lensing) are not at the same position → ICM gas is not the dominant mass contribution.

This is dark matter.

Notice that the galaxies of the clusters also passed right through.

“Direct” measurement of Ω_{dm}

A useful way to quantify the amount of dark matter in a structure is the mass-to-light ratio (M/L). It compares the total mass with the mass expected based on the luminosity.

The stars set the scale : (M/L)_stars ~1

Since stars have almost no dark matter and we saw that in stars $\Omega_b \sim 0.002$
→ M/L =1 means $\Omega_m = 0.002$ (and $\Omega_{dm} \sim 0$)

Dark matter density in galaxies

Total mass measured from rotation curves: $$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

is (M/L)_gal = 20 → Ω_m_gal = 0.04 → Ω_dm_gal ~0.04

Dark matter density in clusters

The total mass of a cluster can be determined in 3 different ways.

Each method makes some assumptions about the state of equilibrium of the cluster

1. Dynamics of the cluster galaxies → virial theorem
2. X-rays emission → hydrostatic equilibrium
3. Gravitational lensing → cluster symmetries

Galaxy motions

For systems that have collapsed gravitationally and are relaxed, the virial theorem is

E_kin = -1/2 E_pot

Galaxy are observed in spectroscopy → Doppler shifts are measured along the line-of-sight → the measured dispersion in the average velocity along the l-o-s is $\left\langle v_{\parallel}^{2} \right\rangle$

dispersion of the average velocity $\left\langle v^{2} \right\rangle = \left\langle v_{x}^{2} \right\rangle + \left\langle v_{y}^{2} \right\rangle + \left\langle v_{z}^{2} \right\rangle = 3 \left\langle v_{\parallel}^{2} \right\rangle$

$$E_{\text{kin}} = \frac{1}{2} \sum_i m_i \mathbf{v}_i^2 = \frac{3}{2} M \left\langle v_{\parallel}^{2} \right\rangle$$

$$E_{\text{pot}} = \frac{GM^2}{R_{\text{cl}}} \quad \rightarrow \quad M = \frac{3}{G} \left\langle v_{\parallel}^{2} \right\rangle R_{\text{cl}}$$

Typical values: $v \sim 1000$ Km/s; $R_{cluster} \sim 1$ Mpc → **$M \sim 10^{15} M_{Sun}$**

Knowing that the total mass of the galaxies in a cluster is $\sim 10^{13} M_{Sun}$

→ **M/L = 160**

→ Ω_m_cl = 160 x 0.002 = 0.32 → **Ω_dm_cl ~0.28**

The other 2 methods give similar results:

X-ray profiles

Ionized gas in clusters - assumed to be in hydrostatic equilibrium

$$\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{GM(r)}{r^2},$$

+ ideal gas p = nKT (n= ρ /m_p)

$$\rightarrow \quad M(r) = -\frac{rkT}{Gm_\mathrm{p}}\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}$$

This is the total mass needed to keep the hot gas (with pressure p, temperature T and density ρ) in equilibrium.

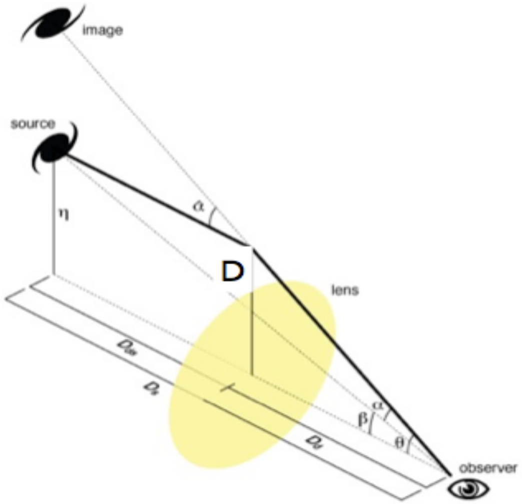
Also need to assume a density profile for the cluster (to be able compute dρ /dr), i.e., assume a model:

$$n(x) = \frac{n_0}{(1+x^2)^{3\beta/2}}, \quad x \equiv \frac{r}{r_\mathrm{c}}$$

$$\rightarrow \quad \frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} = \frac{\mathrm{d}\ln n}{\mathrm{d}\ln r} = -3\beta\frac{r^2}{1+r^2} \quad \rightarrow \quad M(r) = \frac{3\beta rkT}{Gm_\mathrm{p}}\frac{r^2}{1+r^2}$$

Typical values: kT ~10 KeV; r ~1 Mpc; β = 2/3 → **$M \sim 10^{15} M_{Sun}$**

Gravitational lensing



Measuring the positions of multiple images and giant arcs, we can constrain the mass distribution of the lens.

Need to model the lens. Also need to know the distance to the lens and to the source

Simple approximation: modeling the cluster as a sphere of mass M concentrated in the center, it produces a deflection of α for a light ray passing at a distance D from the center →

$$\tilde{\alpha} = \frac{4GM}{Dc^2}$$

$D = D_d D_{ds} / D_s$

Measure the deflection α, measure the distances → get the mass **$M \sim 10^{15}\ M_{Sun}$**

So, from the direct measurements of the densities in the Universe (with reliable results available from the 1980s-1990s), it was found that Ω_dm_clusters ~ 0.28

and also that **dark matter is increasingly important as we go to larger scales**

Sun: M/L = 1

$(M/L)_{galaxy} \sim$ 10-20 M_{solar}/L_{solar}

$(M/L)_{cluster} \sim$ 100-200 M_{solar}/L_{solar}

Universe: $M/L = 1400\Omega_M h^2$

$\sim 200\ (\Omega_M/0.3)(h/0.7)^2$

Note that the value Ω_{dm} ~ 0.28 is a good representation of the dark matter density in the Universe because clusters are very large quasi-linear structures that represent well the average densities of the whole Universe.

This value is confirmed by modern cosmological Ω_{dm} measurements with various cosmological probes (i.e., by model-dependent "indirect measurements"), including the well-known supernovae observations and CMB.

Also notice that the ratio between dark matter and baryonic matter is

$$\Omega_{dm} / \Omega_b = 7$$

much lower than the M/L ratio of 160, which is the ratio between dark mater and luminous matter

→ this confirms that most of baryonic matter is not in the form of stars/galaxies that contribute to the luminous matter of galaxies and clusters but as we saw, it is in the form of hot ionized gas - in clusters and in the cosmic web -

Dark energy

Ω_x

So, since the 1980-90s, much before the modern SN and CMB probes, cluster observations already gave a hint that the total matter density in the Universe was less than 1 : Ω_{dm} + Ω_b + Ω_v ~0.3 → this implies there is something else missing to reach the needed total of Ω = 1 (from Friedmann eq.), and moreover it is the dominant contribution!

$$\Omega = \Omega_m + \Omega_x = \Omega_{dm} + \Omega_b + \Omega_v \text{ (non-relativistic)} + \Omega_x = 1$$

It was first thought that it could be a hint for an **open Universe, oCDM**.
Indeed, curvature can be moved to the right-side of Einstein equation and be considered as a contribution to the densities, Ω_K

Is it curvature? → the Universe would need to have negative curvature (which would also imply it is open) in order to have $\mathbf{\Omega_K > 0}$ (the sign of Ω_K is opposite to the sign of K).
But no, later on CMB measurements found that most likely $\mathbf{\Omega_k = 0}$ → flat Universe (even though some recent data also point to $\mathbf{\Omega_K} < 0$ → this is part of the debate of the cosmological tensions)

It has been a long story of missing components → missing baryons, missing matter, and now the missing 70% of the Universe

Following the discovery of the dimming of distant supernovae, there was evidence that the expansion of the Universe started accelerating in recent times. The driver for this acceleration had to be the missing density: an additional component that only became dominant recently and that has the property of accelerating the expansion.

Since we do not know what is this new source of energy, it was decided to call it **Dark Energy**, $\Omega_x = \Omega_{DE}$

Today there are many theoretical and phenomenological models of dark energy. The simplest one capable of producing the acceleration is the **the famous Einstein's cosmological constant, Lambda Λ .**

The direct measurements are in agreement with modern results: **Planck final results (2018)**

$\mathbf{\Omega_{cdm} = 0.268 +/- 0.8\%}$

$\mathbf{\Omega_b = 0.049 +/- 0.4\%}$

→ $\Omega_m = 0.317$ $\Omega_\Lambda = 1 - \Omega_m = 0.683$