The Physics of Baryons

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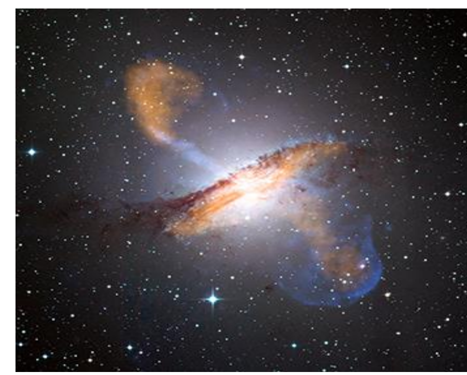


Outline of the talk

- ***Appearance of the baryons in the Universe – the quark-hadron phase transition***
- ***Primordial nucleosynthesis***
- ***Decoupling from radiation***
- ***Recombination***
- ***Distribution of baryons in the Universe***

The appearance of baryons in the Universe – the quark-hadron phase transition

The transition occurs when the chemical potential of both phases are equal: $\mu_q(P) = \mu_h(P)$

The pressure of quark+ gluons ⟶ $$P_{q-g} = \frac{\pi^2}{90} g_{eff} \frac{(kT)^4}{(\hbar c)^3} - B - AkT$$

with g_{eff} = 47.5, B = 58 MeVfm^{-3} and A = 3.53 fm^{-3} (Brown et al. 1988 ; Bacileri et al. 1988)

The pressure of pions ⟶ $P_\pi = \frac{g_\pi}{2\pi^2} \frac{(kT)^4}{(\hbar c)^3} I(y)$ ***with g_π = 3*** $I(y) = -\int_y^\infty x\sqrt{x^2 - y^2}\, \lg(1 - e^{-x}) dx$

and $y = m_\pi c^2/kT$ The mass of all pions was taken to be equal to 140 MeV/c^2

Solution of $P_{q-g} = P_\pi$ ⟶ y = 0.77048 ⟶ T = 182 MeV ⟶ t_{qh} = 61.2 μs

Variation of the total energy ⟶ $\frac{d\varepsilon}{dt} + 3H(P + \varepsilon) = 0$ ***with ⟶*** $H^2 = \frac{8\pi G}{3c^2}\varepsilon$

Total pressure: $P_{q-g} + P_\gamma + P_l$ remains constant during the transition but the total energy

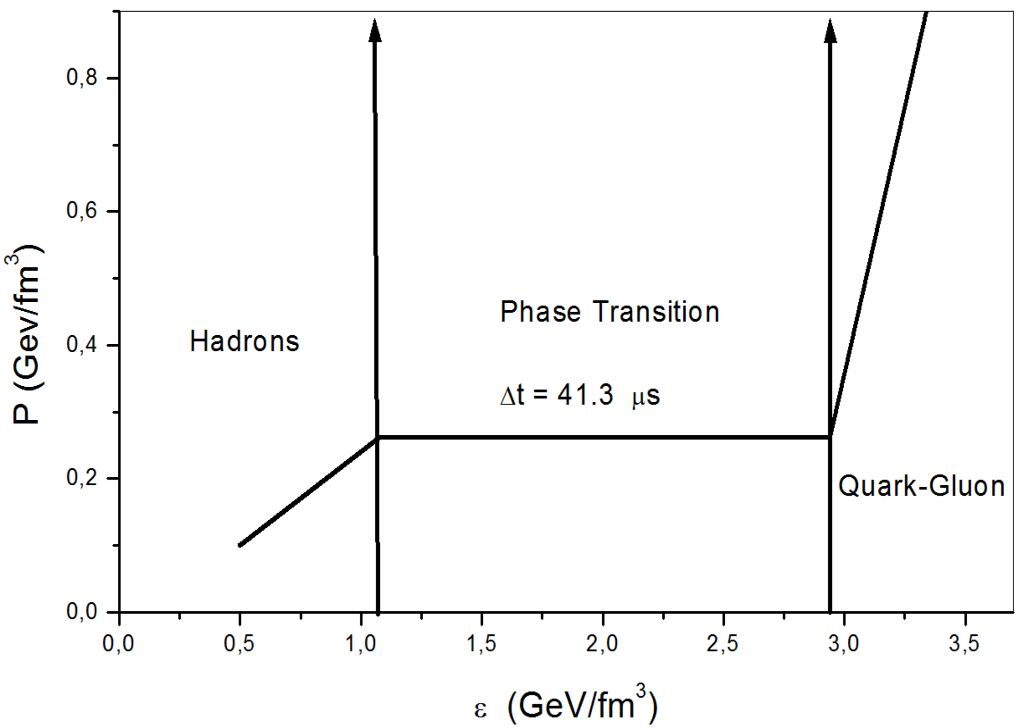
varies ⟶ $\varepsilon = x\varepsilon_1 + (1-x)\varepsilon_2$ ***x = fraction of matter in the quark phase***

$$\varepsilon_1 = 2941\, MeVfm^{-3} \quad \varepsilon_2 = 1075\, MeVfm^{-3} \quad P_t = 262\, MeVfm^{-3}$$

Energy variation: $$\frac{dx}{dt} = -\frac{\sqrt{24\pi G}}{(\varepsilon_1 - \varepsilon_2)c}\left[P_t + \varepsilon_2 + x(\varepsilon_1 - \varepsilon_2)\right]\sqrt{\varepsilon_2 + x(\varepsilon_1 - \varepsilon_2)}$$

Integration $0 \leq x \leq 1 \longrightarrow (t_2 - t_1)$ ***= duration of the phase transition = 41.3*** μs

$$(t_2 - t_1) = \frac{2c}{\sqrt{24\pi G P_t}}\left[arctg\left(\sqrt{\frac{\varepsilon_1}{P_t}}\right) - arctg\left(\sqrt{\frac{\varepsilon_2}{P_t}}\right)\right]$$



Entropy conservation:

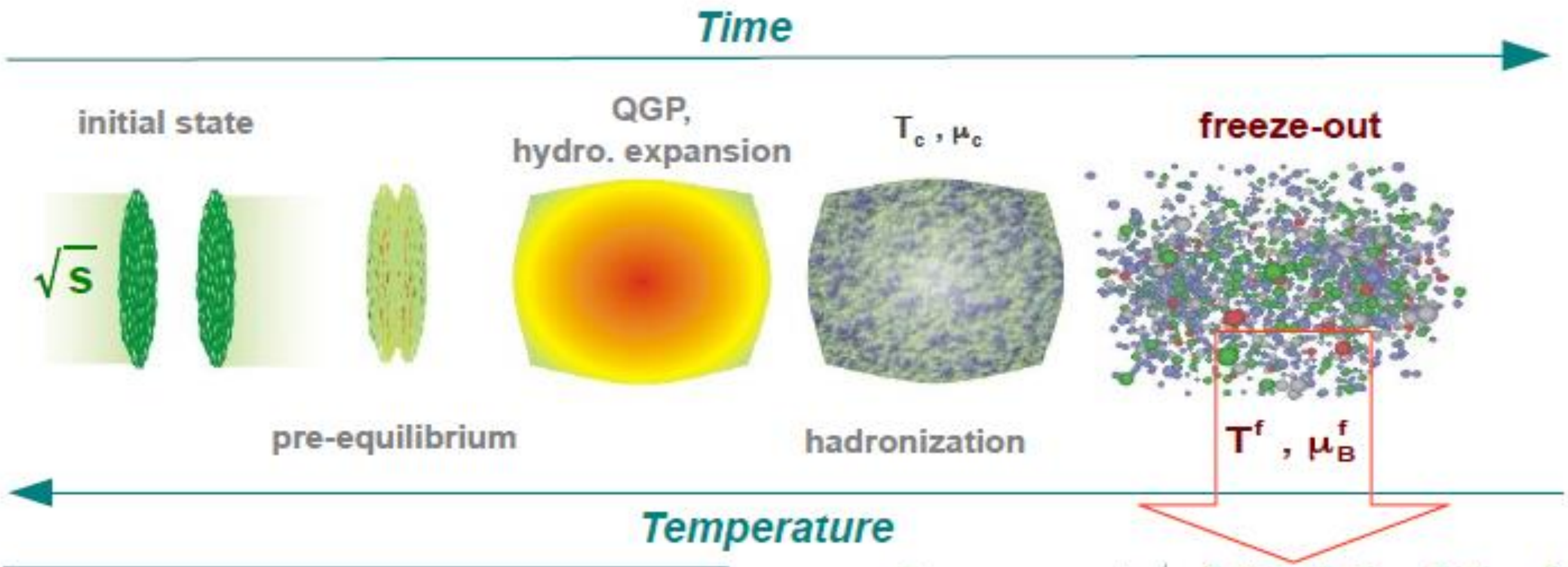
$$\frac{a_2}{a_1} = \frac{\left(P_t + \varepsilon_1\right)^{1/3}}{\left(P_t + \varepsilon_2\right)^{1/3}} = 1.557$$

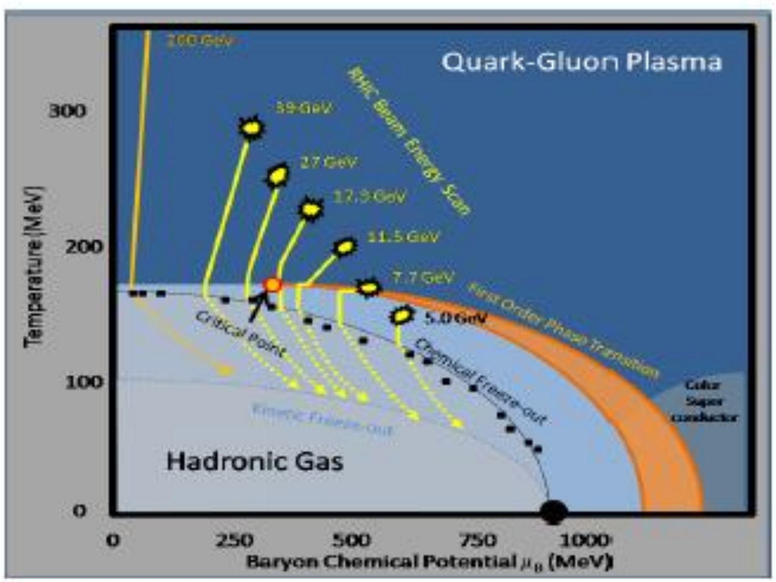
Friedman expansion:

$$\frac{a_2}{a_1} = \frac{\left(t_i + \Delta t\right)^{1/2}}{t_i^{1/2}} = 1.294$$

"Mini-inflation" – after the phase transition the universe is 20% bigger – energy provided by the latent heat of the transition

Deconfinement with heavy ions collisions





freeze-out: $\left(T^{f,ch}, \mu_B^{f,ch}, \mu_Q^{f,ch}, \mu_S^{f,ch}\right)$

Deconfinement Temperature

150-180 MeV

Energy Density

1-2 GeV.fm $^{-3}$

After the phase transition – the ratio between protons and neutrons is the equilibrium value

$$\frac{n}{p} = \exp\left(-\frac{\Delta mc^2}{kT}\right) \quad with \ \ \Delta mc^2 = 1.294\,MeV$$

Thus, just after the transition ⟶ n/p = 0.9933

Equilibrium is maintained by the reactions

$$\begin{cases} n \rightleftarrows p + e^- + \bar{\nu}_e \\ e^+ + n \rightleftarrows p + \bar{\nu}_e \\ n + \nu_e \rightleftarrows p + e^- \end{cases}$$

Equilibrium is broken when ⟶ $n_b \langle \sigma_\nu v \rangle \approx H \ \Rightarrow T \approx 0.93\,MeV \equiv t \approx 2.34\,s$

At decoupling ⟶ n/p = 0.248

After decoupling , neutrons decay and interact with protons to produce deuterium

$$n + p \rightleftarrows D^2 + \gamma$$

In this period the density of neutrons vary as $\longrightarrow$ $\frac{dn_n}{dt} + 3Hn_n = -\frac{n_n}{\tau_n} - n_n n_p \langle \sigma v \rangle_D + n_n \psi_n$

or, in terms of the particle concentration $\longrightarrow$ $X_n = n_n / n_b \, , X_p = n_p / n_b$ *and* $X_D = n_D / n_b$

$$\left.\begin{aligned} \frac{dX_n}{dt} &= -\frac{X_n}{\tau_n} - X_n X_p n_b \langle \sigma v \rangle_D + X_D \psi_n \\ \frac{dX_p}{dt} &= \frac{X_n}{\tau_n} - X_n X_p n_b \langle \sigma v \rangle_D + X_D \psi_n \end{aligned}\right\}$$

equations of evolution

If deuterium is produced in quasi-equilibrium $\longrightarrow$ $\frac{X_n X_p}{X_D} = \frac{\psi_n}{\langle \sigma v \rangle_D} = \frac{2}{3}\left(\frac{mkT}{4\pi\hbar^2}\right)^{3/2} \frac{e^{-B/kT}}{n_b}$

with B = 2.225 MeV and $n_b = \frac{3H_0^2}{8\pi G}\frac{\Omega_b}{m_N}\frac{g_{eff}(T)}{g_{eff}(T_0)}\frac{T^3}{T_0^3} = 3.9 \times 10^{24}\Omega_b h^2 T_{MeV}^3 \; cm^{-3}$

When the deuterium concentration reaches a critical value $\longrightarrow$ $X_n X_p / X_D \approx 1$

New reactions take place leading to He synthesis

$$\begin{cases} D^2 + D^2 \to He^3 + n \rightleftarrows H^3 + p \\ H^3 + D^2 \to He^4 + n \end{cases}$$

From the precedent equations $\longrightarrow$

$$\frac{X_n X_p}{X_D} = \exp\left[23.387 - \frac{3}{2}\lg T_{MeV} - \lg \Omega_b h^2 - \frac{2.225}{T_{MeV}}\right] \approx 1$$

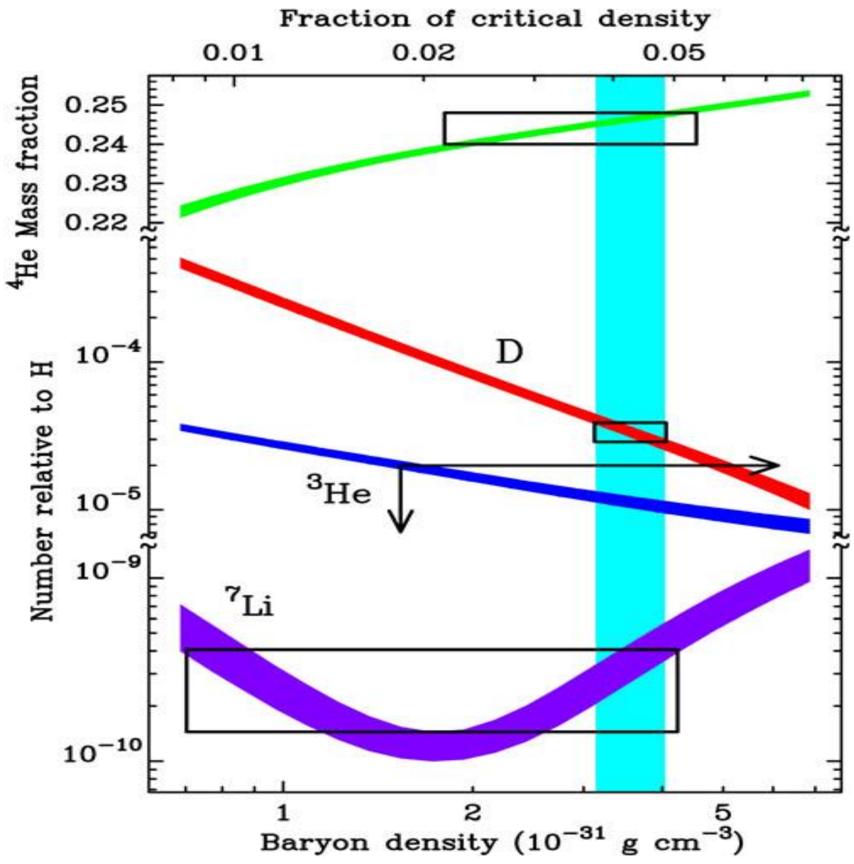
For $\Omega_b h^2 = 0.022$ $\longrightarrow$ $T_c = 0.0714$ MeV , $t_c = 396.6$ s

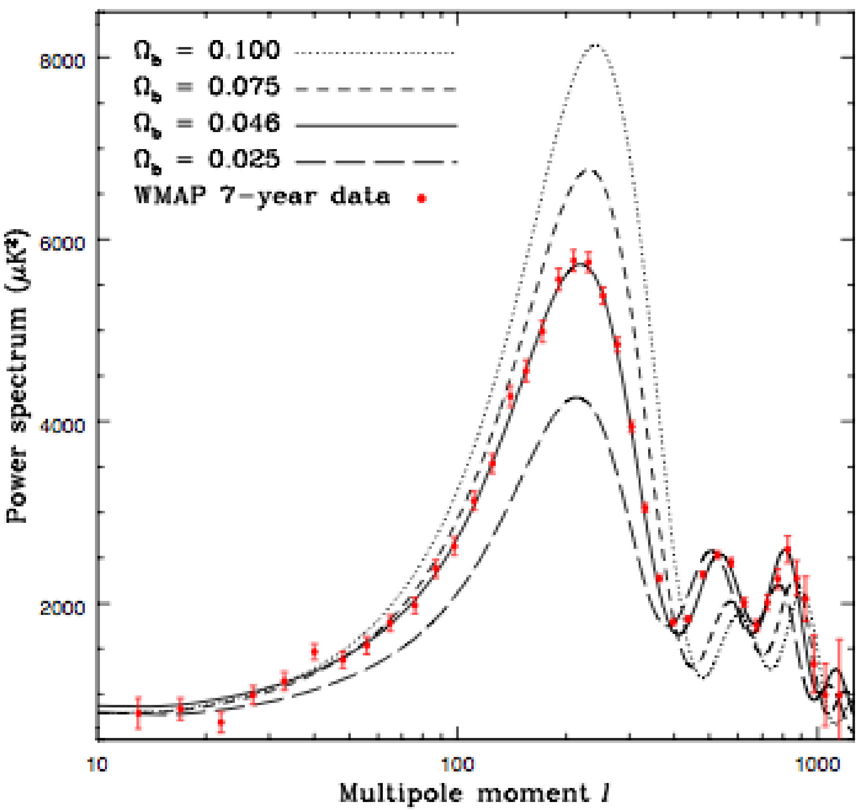
and the neutron fraction $\longrightarrow$ $X_n = X_n^0 \exp\left(-\frac{t_c - t_0}{\tau_n}\right)$ ***or $X_n \approx 0.127$***

The abundance of helium is approximately $Y(He) \approx 2\, X_n = 0.254$

Nucleosynthesis of He^4 , He^3 , D^2 , Li^7 can be used to fix the baryon content in the universe

Determination of the baryon fraction





Extragalactic HII Regions (Izotov & Thuan 2010):
Y(He) = 0.2565±0.0010 *$\Omega_b h^2 = 0.0248 \pm 0.0020$*

Quasars (Pettini et al. 2008) : D/H = 2.8 x 10 $^{-5}$
$\Omega_b h^2 = 0.0213 \pm 0.0010$

Vacca et al. (2011) $0.019 < \Omega_b h^2 < 0.021$ (including ^{7}Li)

Fit of the acoustic peaks

WMAP – 7 years (Larson et al. 2010)
$\Omega_b h^2 = 0.0226 \pm 0.0057$
Planck (2013)
$\Omega_b h^2 = 0.02207 \pm 0.00033$

After the nucleosynthesis era, the expansion of the universe is still radiation dominated

until the matter energy density becomes dominant – $\frac{\pi^2}{30} g_{eff} \frac{(kT_0)^4}{(\hbar c)^3} (1+z)^4 = \frac{3H_0^2 c^2 \Omega_m}{8\pi G} (1+z)^3$

Using $\Omega_m h^2 = 0.143$ ***(Planck)*** $\longrightarrow$ $(1+z_{eq}) = 3340$ ***or*** $T_{eq} = 9100\ K$

Photons & baryons are still coupled - since the photon mean free path is less than c/H

Decoupling condition $\longrightarrow$ $\frac{1}{n_e \sigma_T} = \frac{c}{H}$

under ionization equilibrium $\longrightarrow$ $\frac{X_H^2}{1-X_H} = \frac{F(T)}{n}$ ***with*** $X_H = \frac{n_e}{(n_p + n_H)} = \frac{n_p}{n}$

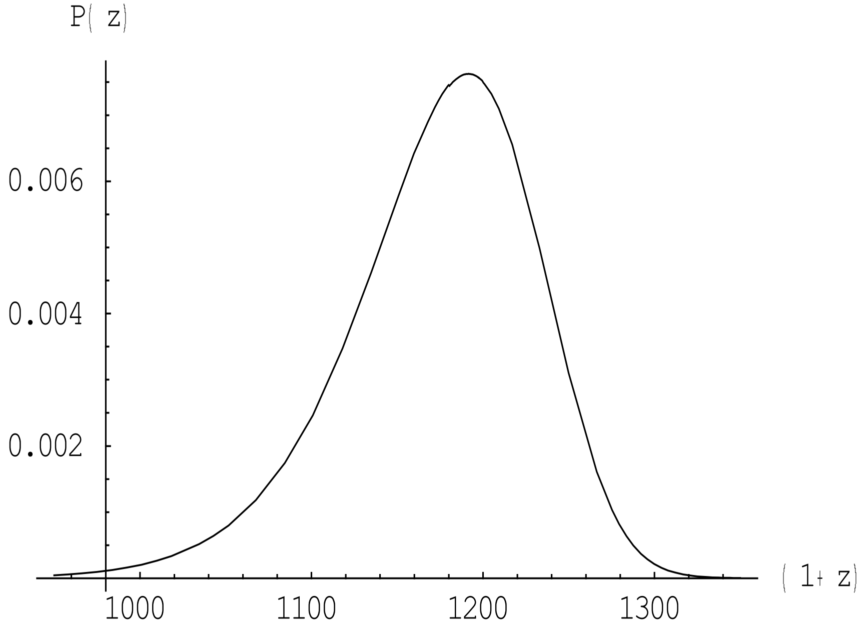
and $\begin{cases} F(T) = \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} e^{-I/kT} \\ n = 8.502 \times 10^{-6} \Omega_b h^2 (1+z)^3 \end{cases}$ ***numerical solution*** $\begin{cases} 1+z_{dec} = 1057 \\ T_{dec} = 2880\, K \\ residual\ ionization \approx 0.0092 \end{cases}$

The thickness of last scattering surface

The Thomson optical depth :

$$\tau_s(z) = \int_0^z \sigma_T c n X_H \left|\frac{dt}{dz'}\right| dz' = \frac{3\sigma_T c H_0 \Omega_b}{8\pi G} \int_0^z X_H(z') \frac{(1+z')^2 dz'}{\sqrt{\Omega_V + \Omega_m (1+z')^3}}$$

The probability for a photon be "last" scattered in the interval z, z+dz is $P(z) = e^{-\tau_s(z)} \left|\frac{d\tau_s(z)}{dz}\right|$



Maximum escape probability at

1+z = 1192

thickness at half-maximum

Δ z ≈ 118

Since $t_{rec} = 1/\alpha(T)n_e < H^{-1}$ ***the ionization decreases until "freezing" occurs, i.e.,***

$$\frac{dX_H}{dz} = \alpha_B(T(z))n(z)\frac{X_H^2}{H_0(1+z)\sqrt{\Omega_V + \Omega_m(1+z)^3}}$$

Freezing occurs at (1+z) ≈ 497 when $X_{H,res} \approx 0.00051$

Residual electrons interact with CMB photons, suffering a drag that keeps the matter temperature near the radiation temperature. Matter temperature varies as

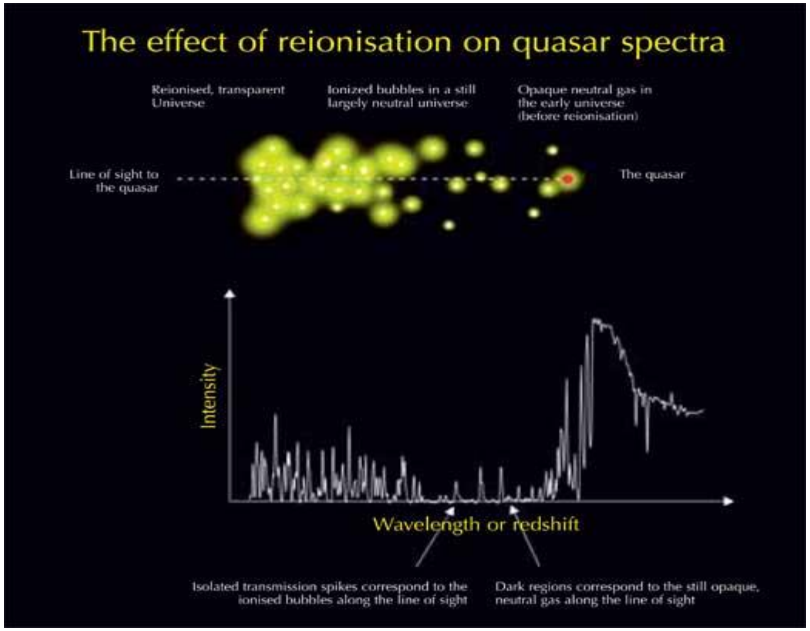
$$\frac{dT_m}{dt} = \frac{8\sigma_T a_r T_r^4}{3m_e c}\frac{X_H}{(1+X_H)}\left(T_r - T_m\right)$$

Define the Compton cooling timescale by ⟶ $t_c = \frac{T_m}{|dT_m/dt|} = \frac{3.69\times10^{19}}{(1+z)^4 X_{H,res}}\left(\frac{T_m}{T_m - T_r}\right)$

Thermal coupling is maintained as long as $t_c < H^{-1}$ ***or*** ⟶ $(1+z)^{5/2} \approx 2.34\times10^5\sqrt{\Omega_m h^2}$

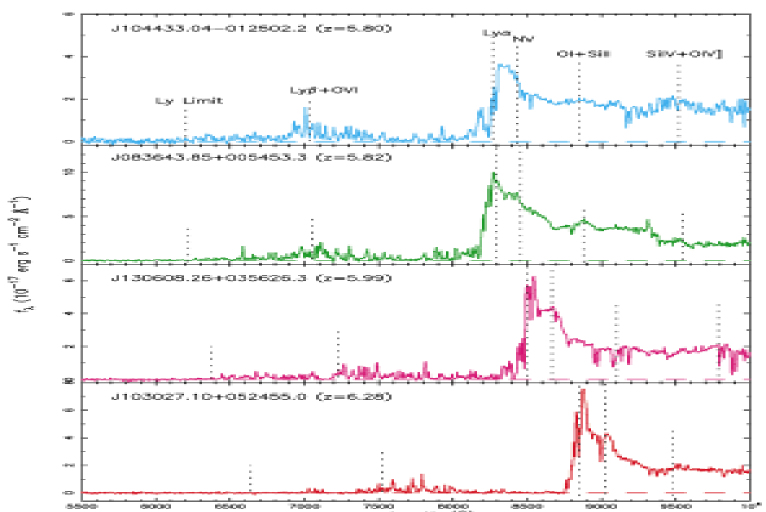
Thermal coupling ends at (1+z) ≈ 95 – after, adiabatic losses ⟶ $T_m \approx 250\left[\frac{(1+z)}{95}\right]^2 K$

The Gunn-Peterson trough

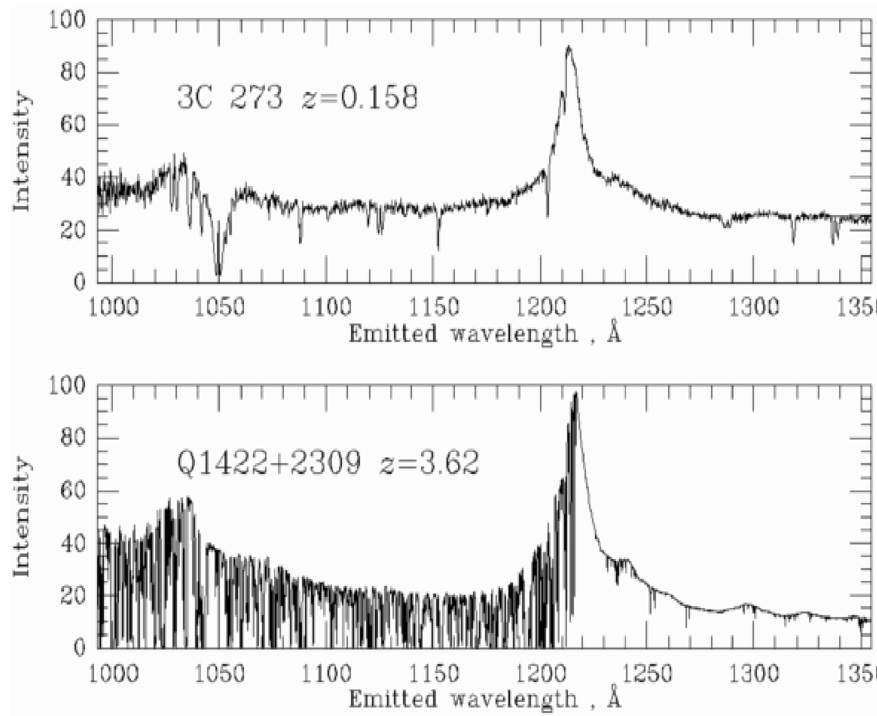


Radiation shortward Lyman-α is completely absorbed for QSOs with z > 6

The Universe is reionized at lower redshift since the transmitted flux at Lyman-α is not zero.



The Lyman-α forest



Formation of intergalactic HII regions around massive halos

Ionization balance $\longrightarrow$ $$\frac{d(n_{ion}V_p)}{dt} = \frac{dN_{uv}}{dt} - \alpha_B(T) n_{ion}^2 V_p$$

In terms of the comoving volume ($V = a^{-3}V_p$) and using the particle conservation

$$\frac{dV}{dt} = \frac{1}{n_0}\frac{dN_{uv}}{dt} - \alpha_B(T) C \frac{n_0 V}{a^3}$$

where $\longrightarrow$ $$n_0 = \frac{3H_0^2\Omega_b}{8\pi G\bar{\mu}m_p} \quad C = \frac{\langle n_{ion}^2 \rangle}{\langle n_{ion} \rangle^2} \quad n_{ion}a^3 = n_0$$

Maximum possible volume $\longrightarrow$ $$V_{\max} = \frac{N_{uv}}{n_0} = \frac{Q_{uv}}{n_0} M \left(\frac{\Omega_b}{\Omega_m}\right) f_* f_{esc}$$

with $\longrightarrow$ $$Q_{uv} = 6.62\times10^{60}\ ph/M_\odot \quad f_* = 0.3 \quad f_{esc} = 0.22$$

$$r_{\max} \approx 1.42\left(\frac{M}{M_\odot}\right)^{1/3} kpc \quad for\ \ M = 10^8 M_\odot \rightarrow r_{\max} \approx 660\, kpc$$

Define the filling factor F = ionized fraction of the causal volume of the universe

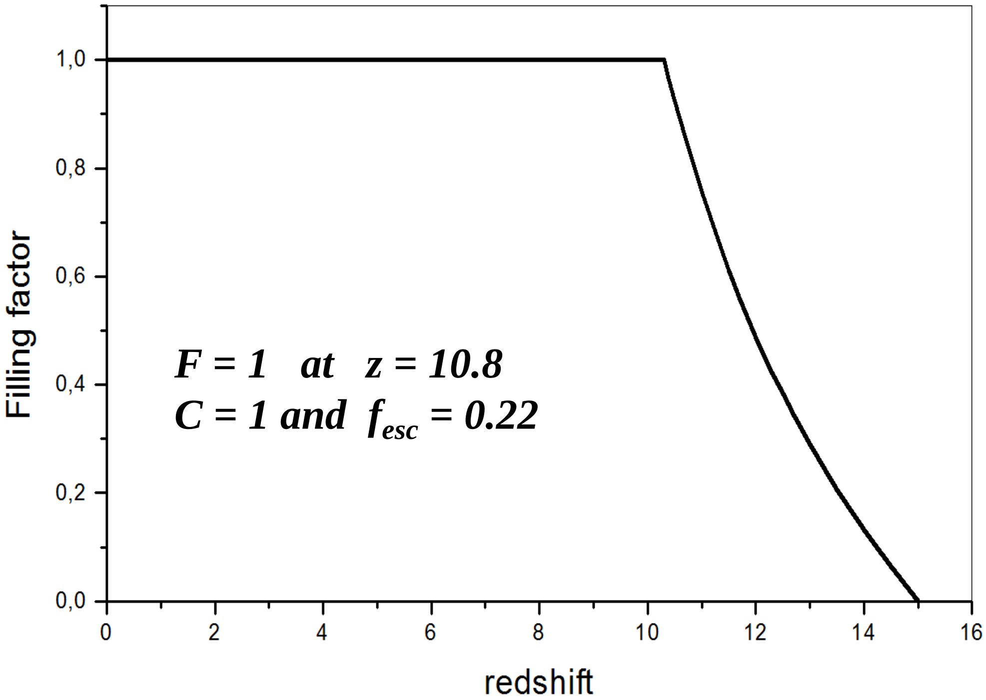
$$\frac{d}{dt}\sum_{ion}\frac{V_{ion}}{V_c} = \frac{1}{n_0 V_c}\sum_{ion}\frac{dN_{uv}}{dt} - \alpha_B(T)C\,\frac{n_0}{a^3}\sum_{ion}\frac{V_{ion}}{V_c}$$

Working the different terms

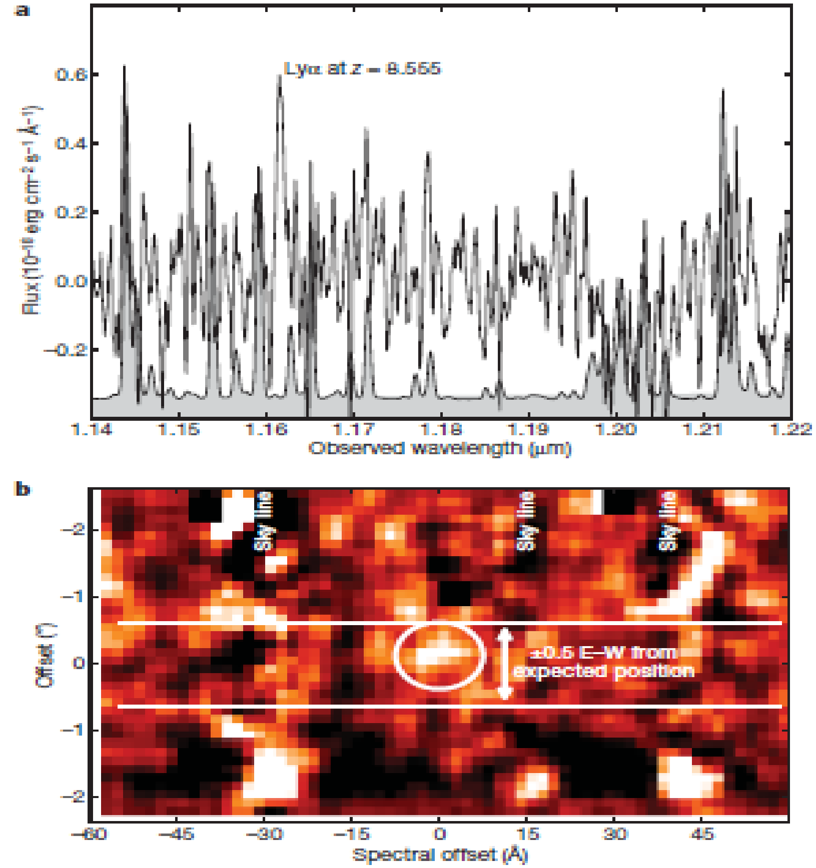
$$\begin{cases} \dfrac{d}{dt}\sum_{ion}\dfrac{V_{ion}}{V_c} = \dfrac{dF}{dt} \\ \dfrac{1}{n_0}\sum_{ion}\dfrac{1}{V_c}\dfrac{dN_{uv}}{dt} \approx \dfrac{1}{n_0}\sum_{ion}\dfrac{Q_{uv}}{\tau_*}\dfrac{M_*}{V_c}\, f_{esc} \approx \dfrac{Q_{uv}R_*}{n_0}\, f_{esc} \\ \alpha_B(T)C\,\dfrac{n_0}{a^3}\sum_{ion}\dfrac{V_{ion}}{V_c} = \alpha_B(T)C\,\dfrac{n_0}{a^3}F \end{cases}$$

Evolution of the filling factor $\longrightarrow$

$$\frac{dF}{dz} = \frac{\alpha_B C n_0}{H(z)}(1+z)^2 F - \frac{Q_{uv}R_* f_{esc}}{n_0(1+z)H(z)}$$



Evolution of the ionization filling factor



UDFy – 38135539
Ly-α galaxy at z = 8.555
(Lehnert et al. 2010 – Nature)

$$\tau_s = \int_0^{20} n_e(z)\sigma_T c F(z) \frac{dz}{(1+z)H(z)} = 0.090 \quad Planck = 0.0925$$

Thomson optical depth

The mean ionizing photon intensity & the Lyman-α absorption

Ionization produced by young formed stars $\longrightarrow$

$$j_\nu(z) = \frac{Q_{uv} R_*(z) f_{esc} h\nu_L}{4\pi} \delta(\nu - \nu_L)$$

Photon production rate – Salpeter weighted IMF $\longrightarrow$

$$Q_{uv} = 6.62 \times 10^{60}\ ph \cdot M_\odot^{-1}$$

Cosmic Star Formation Rate $\longrightarrow$

$$R_*(z) = \frac{(0.0103 + 0.12z)}{\left[1 + (z/4.0)^{2.8}\right]} M_\odot Mpc^{-3} yr^{-1}$$

Solution of the transfer equation $\longrightarrow$

$$I_\nu(z) = (1+z)^3 \int_z^{z_{\max}} \frac{c j_\nu(z')}{(1+z')^4 H(z')} dz' = \frac{Q_{uv} hc}{4\pi} \frac{f_{esc} R_*(z)}{H(z)}$$

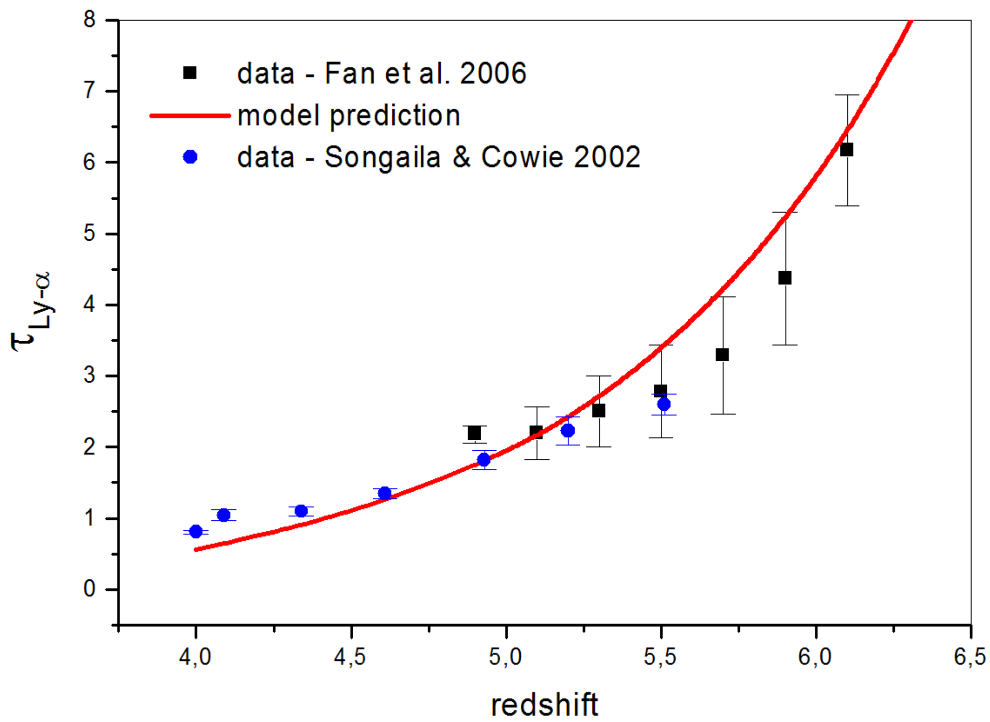
Ionization rate $\longrightarrow$

$$\Gamma = 4\pi \int_{\nu_L}^{\infty} \frac{I_\nu}{h\nu_L} \sigma_\nu d\nu = \frac{Q_{uv} c \sigma_0}{2H_0} \frac{f_{esc} R_*(z)}{\sqrt{\Omega_V + \Omega_m (1+z)^3}}$$

Ionization rate from Ly-α data

Ionization equilibrium is assumed

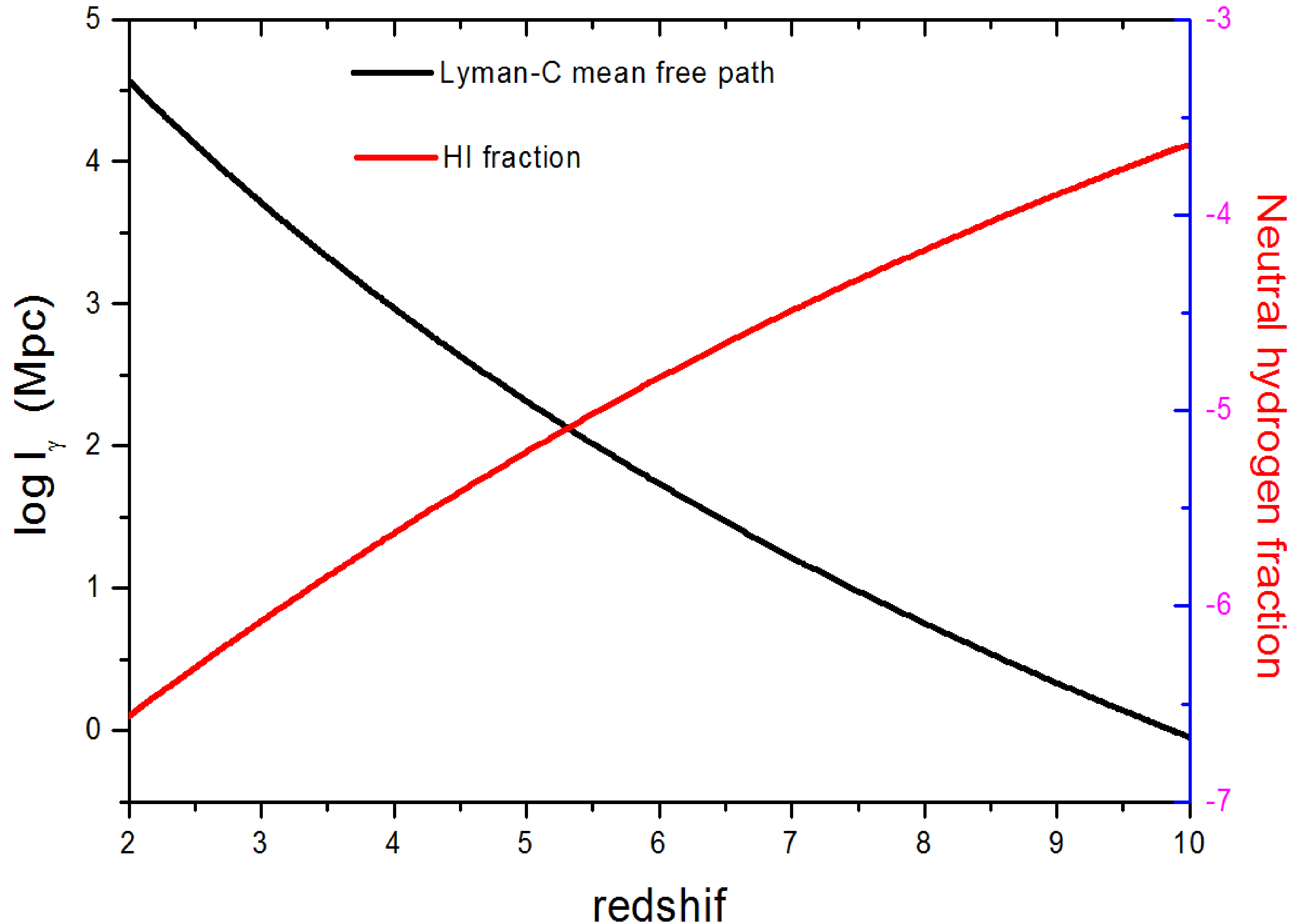
$$\begin{cases} \tau_{Ly-\alpha} = \dfrac{\pi e^2}{m_e c} f_{12}\lambda_{12} \dfrac{n_{HI}(z)}{H(z)} \\ n_{HI}\Gamma = \alpha_B n_e n_p \\ \tau_{Ly-\alpha} = 1.2\times 10^{-12} \dfrac{\left(\Omega_b h^2\right)^2}{\Gamma} \dfrac{(1+z)^6 \Delta}{\sqrt{\Omega_V + \Omega_m (1+z)^3}} \end{cases}$$



<u>Model parameters</u>

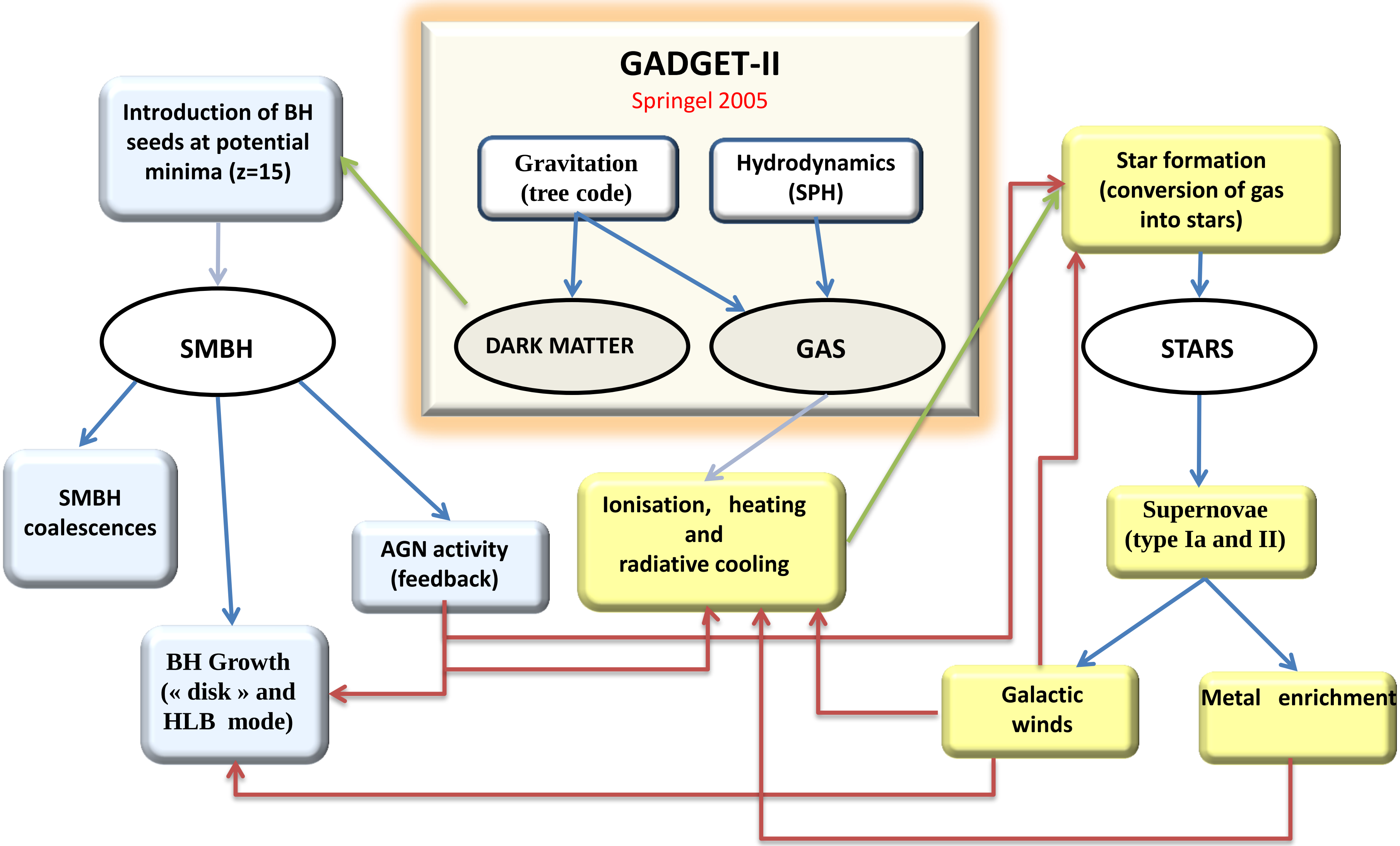
f_{esc} = 0.22 Δ = 1.0 (homogeneous)

Stars from young galaxies are able to reionize the intergalactic medium



Lyman-C mean free path
HI fraction
log l_γ (Mpc)
Neutral hydrogen fraction
redshif
5
4
3
2
1
0
-3
-4
-5
-6
-7
2
3
4
5
6
7
8
9
10

The Nice Code



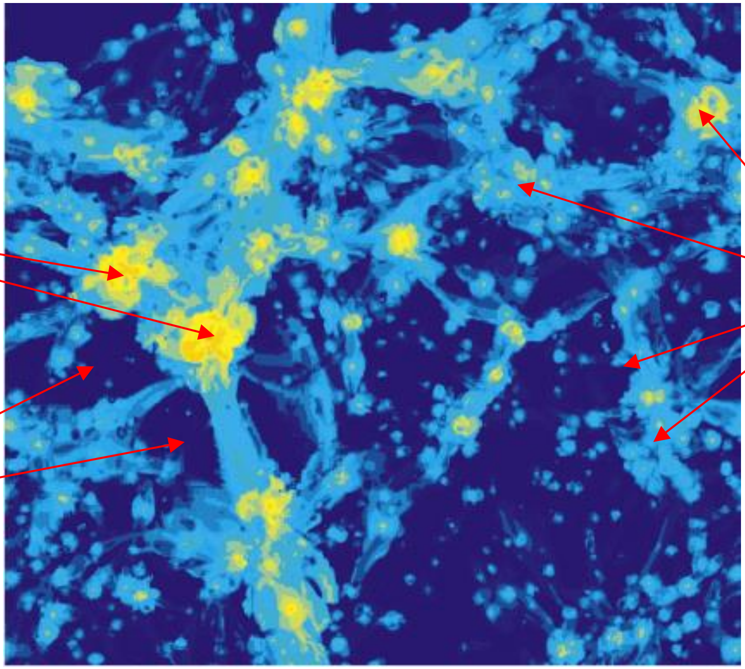
The Nice Code

- ***Return of mass to the ISM – stellar winds & envelope ejection (PNe, SNe)***
- ***Turbulent diffusion process of metals for chemical enrichment***
- ***Local ionization of the gas by young massive stars***
- ***Atomic infrared lines (besides H_2) – cooling of neutral gas***
- ***Supernovae – mechanical energy injected in a cavity of radius $R(t)=V(t-t_0)$ – (V=3000 km/s) – weighted by $w_i \sim 1/r_i^n$***
- ***Time delay due to the lifetime of stars is taken into account either for SNII and SNIa***
- ***AGNs***

$$
\begin{cases}
\dfrac{dE}{dt} = 0.1 L_d \\[2ex]
\dfrac{dE}{dt} = \dfrac{\pi}{2}\left(\dfrac{c}{V_A}\right) S^2 H^2 c r_H^2 = 4.0\times10^{28}\left(\dfrac{H}{10^4 G}\right)^2\left(\dfrac{M_{BH}}{M_\odot}\right)^2 erg/s
\end{cases}
$$

Distribution of baryons

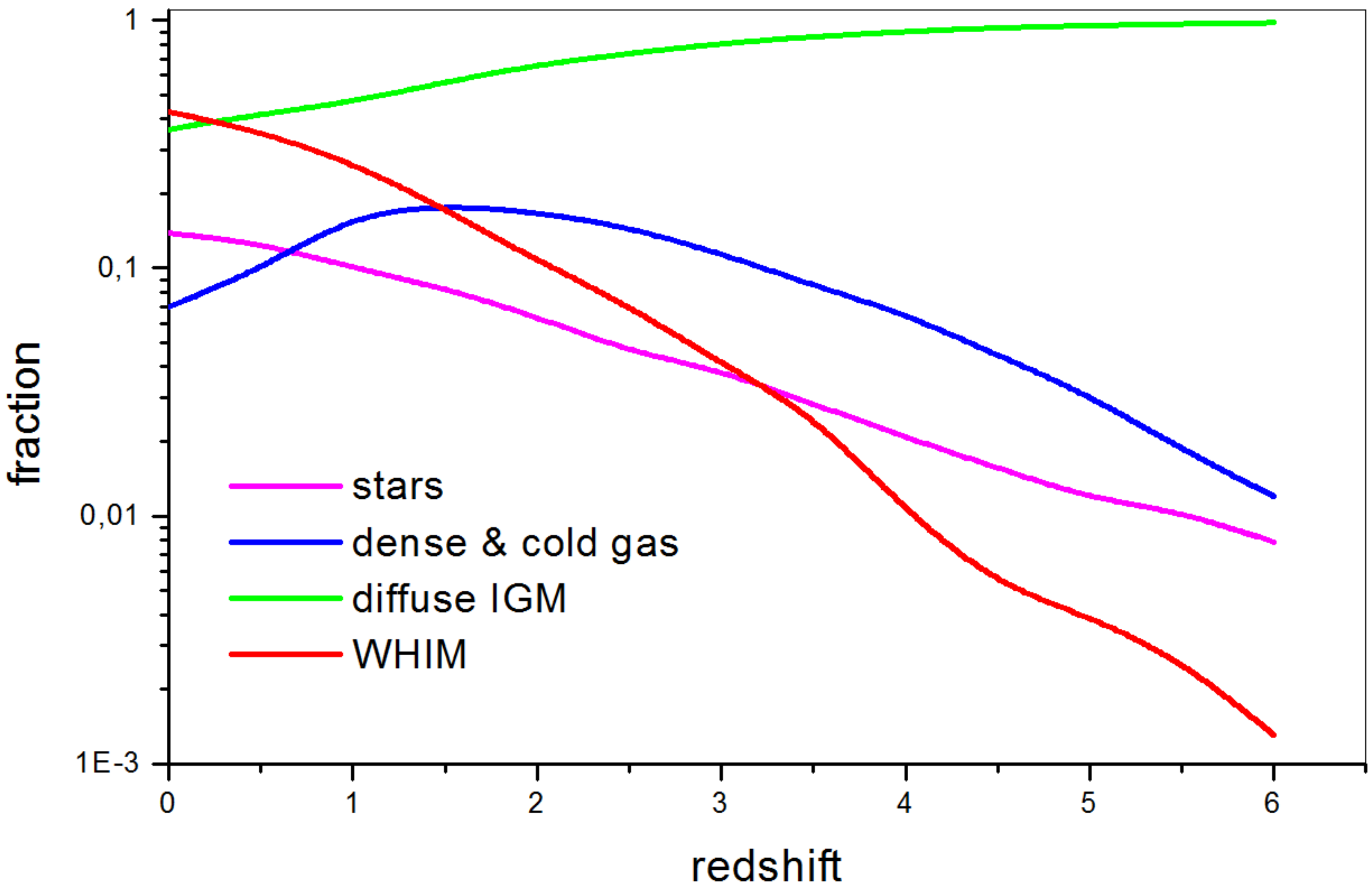
Stars = galaxies
dense cold gas
DLA features



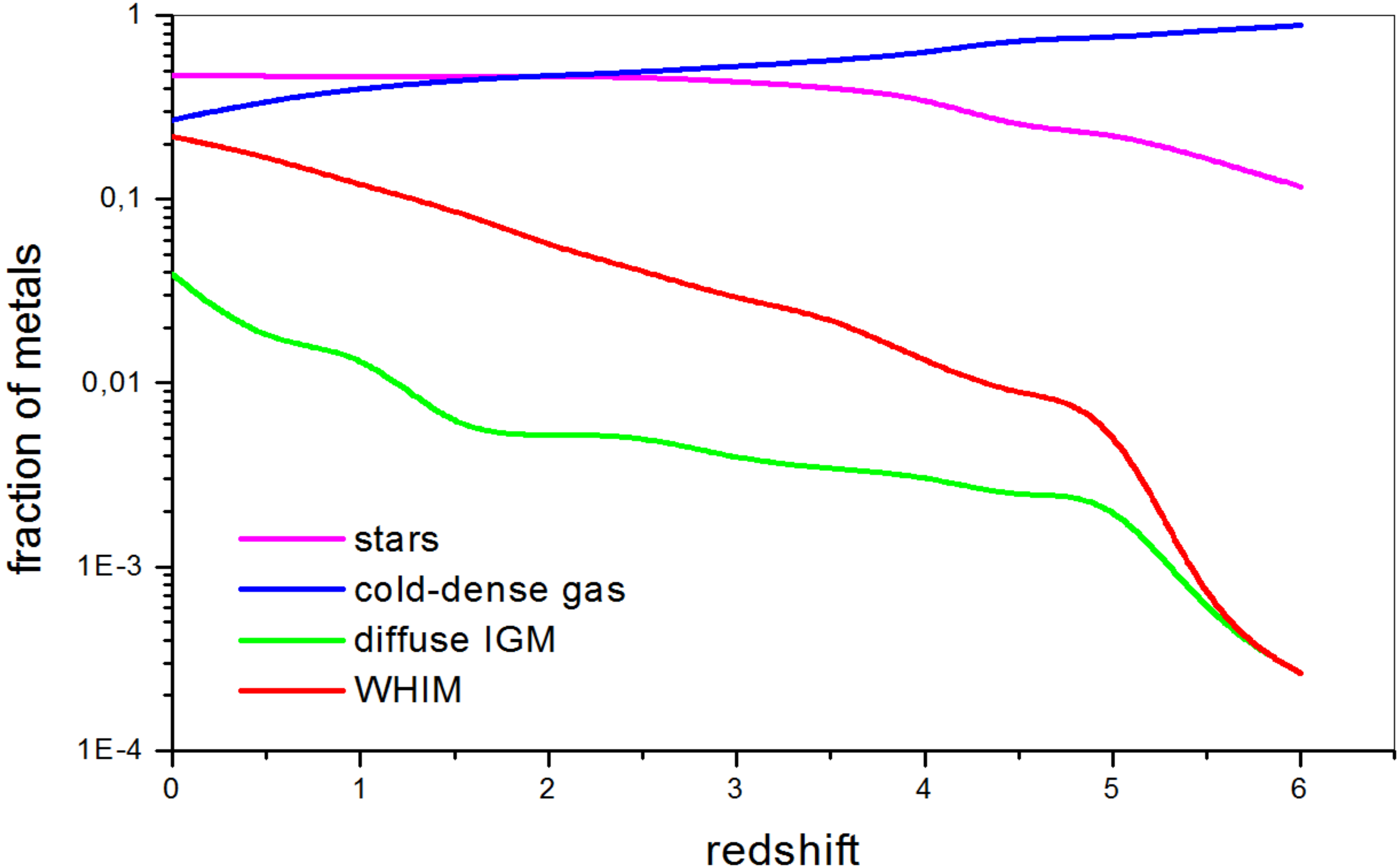
WHIM
Filaments & ICM
BLA + OVI features

Diffuse medium
photoionized gas
NLA - features

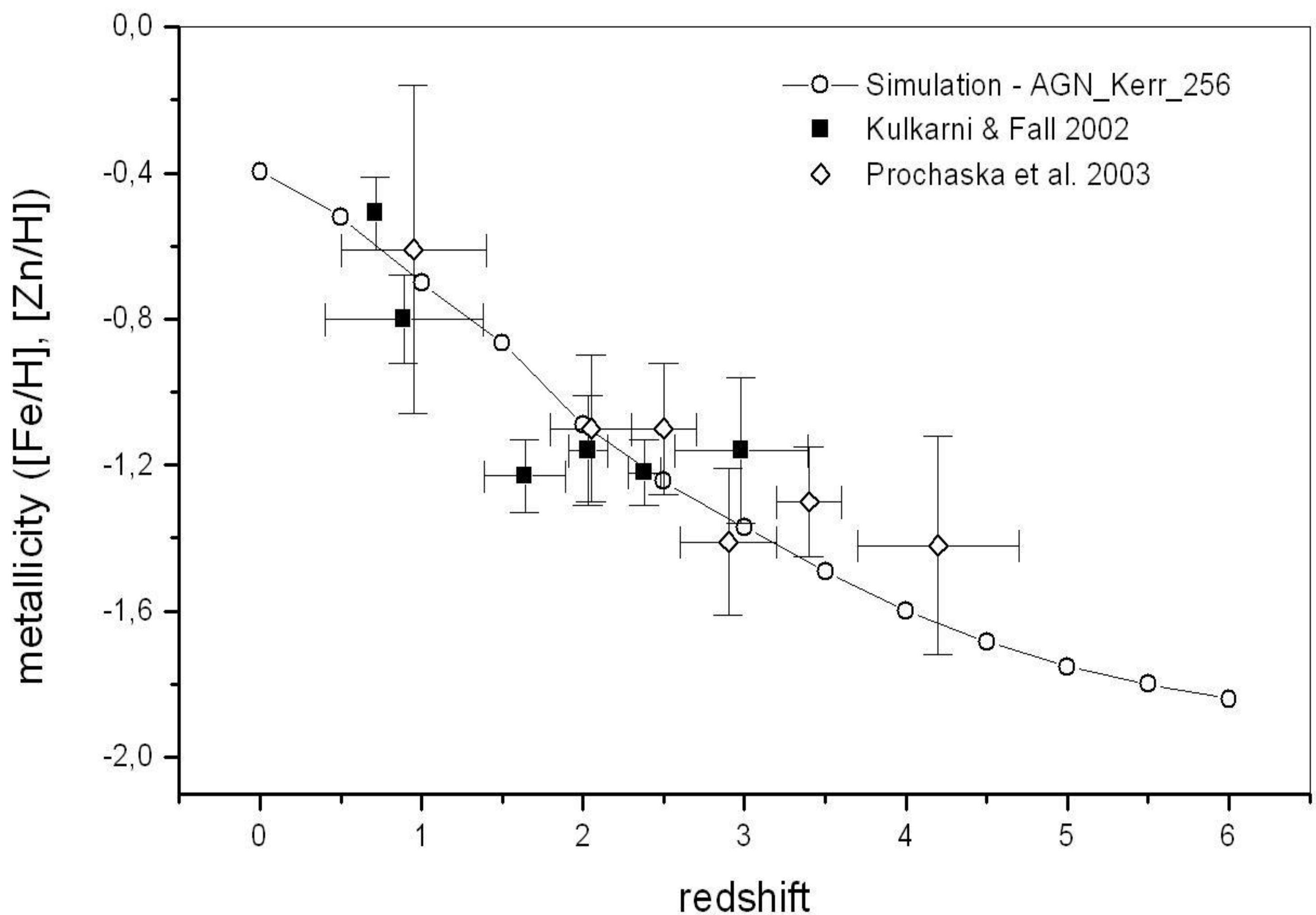
Evolution of the gas in different phases



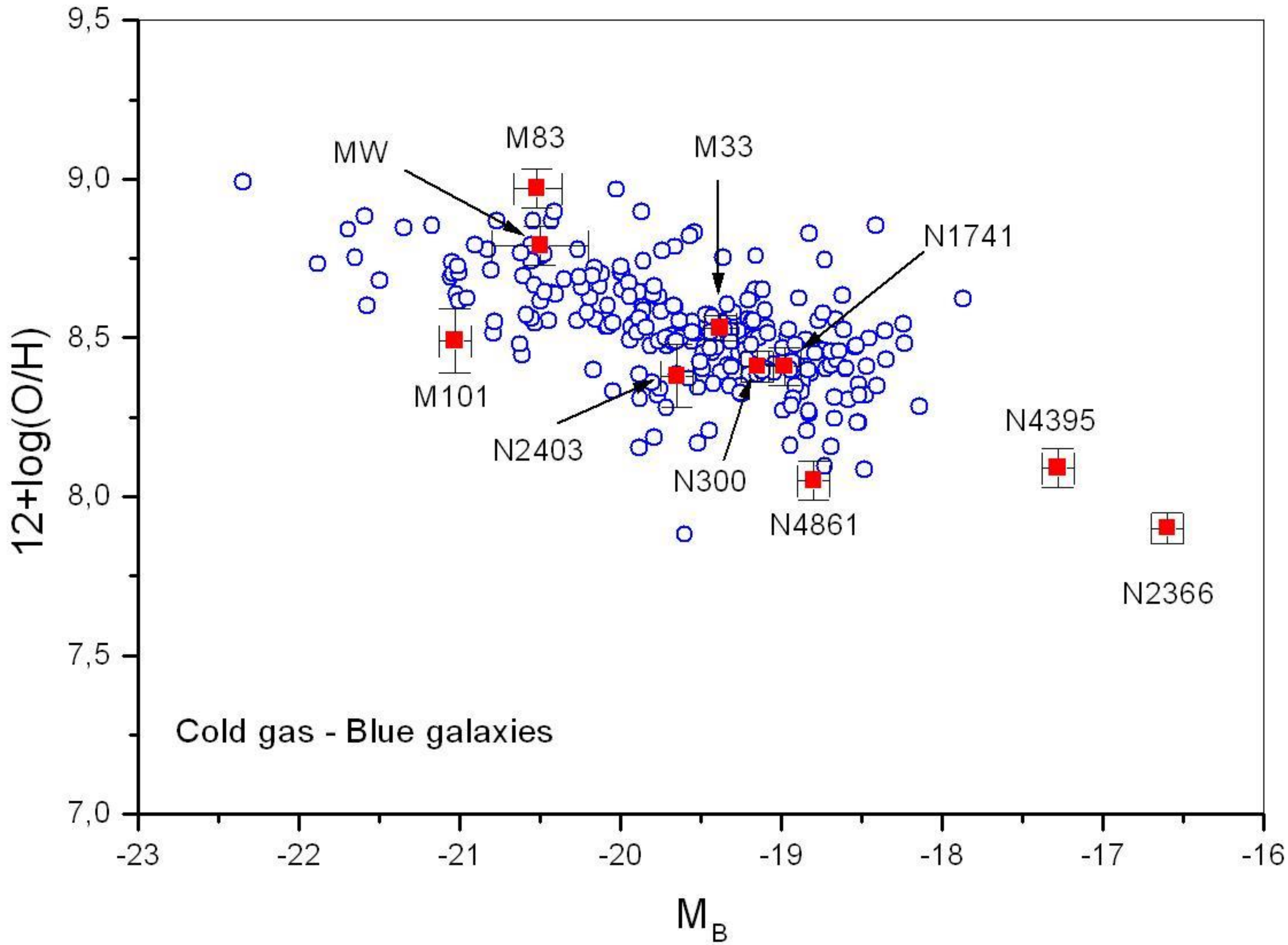
Evolution of the metal content in different phases



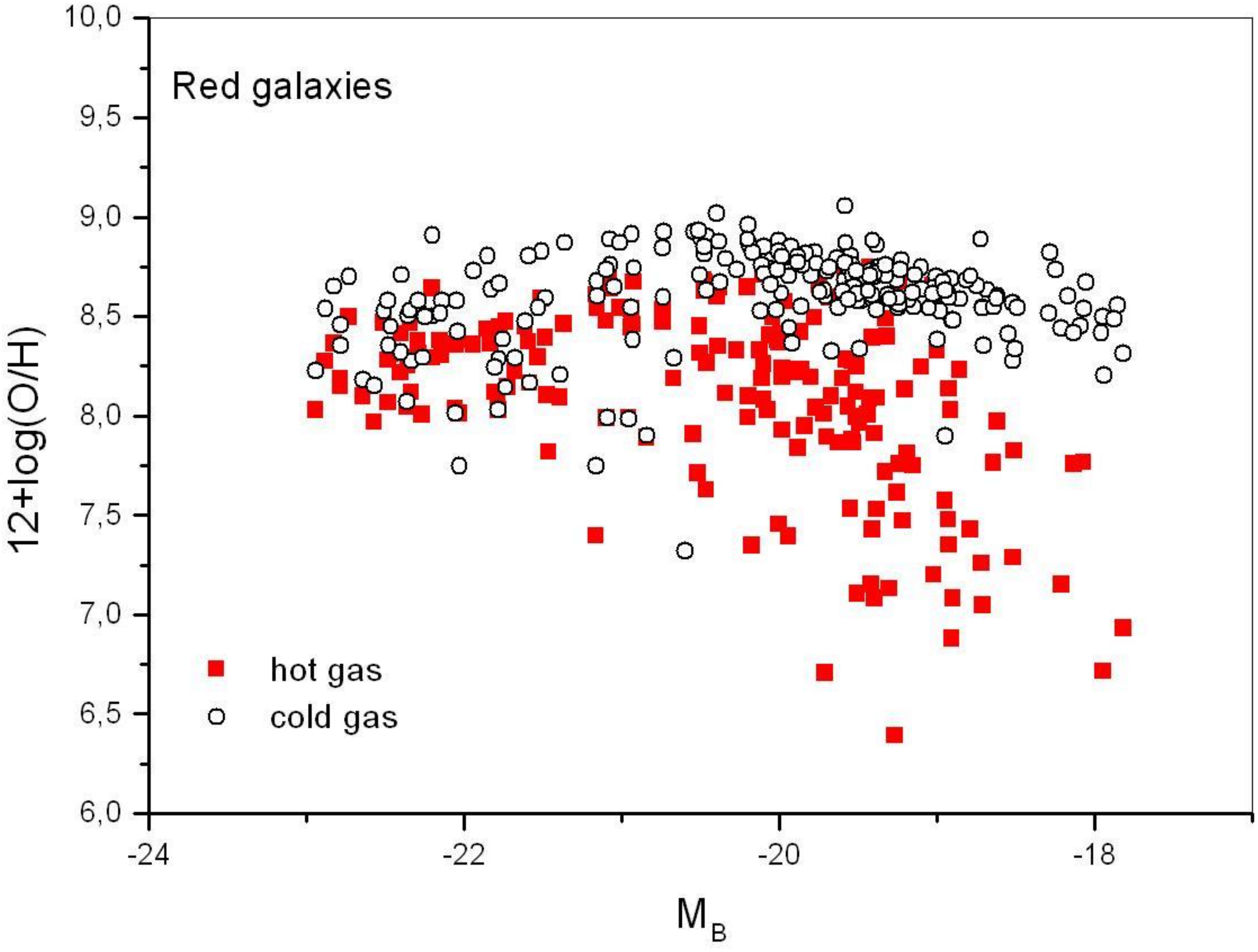
Metallicities – Cold gas vs DLA



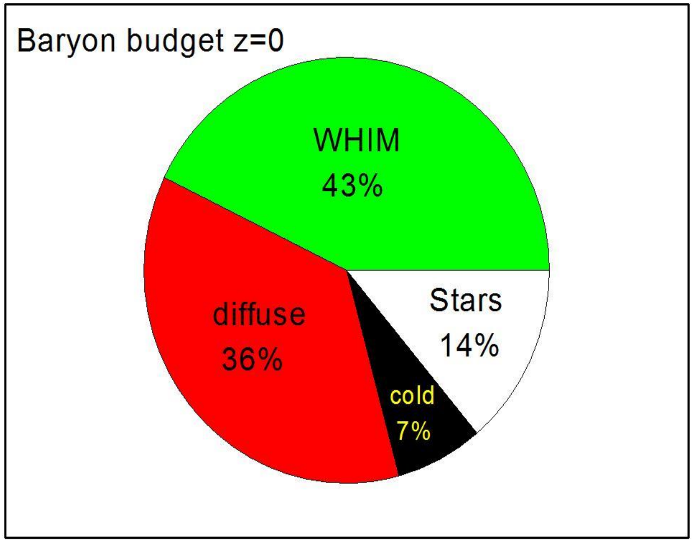
Oxygen abundances – cold gas phase
blue galaxies – local universe

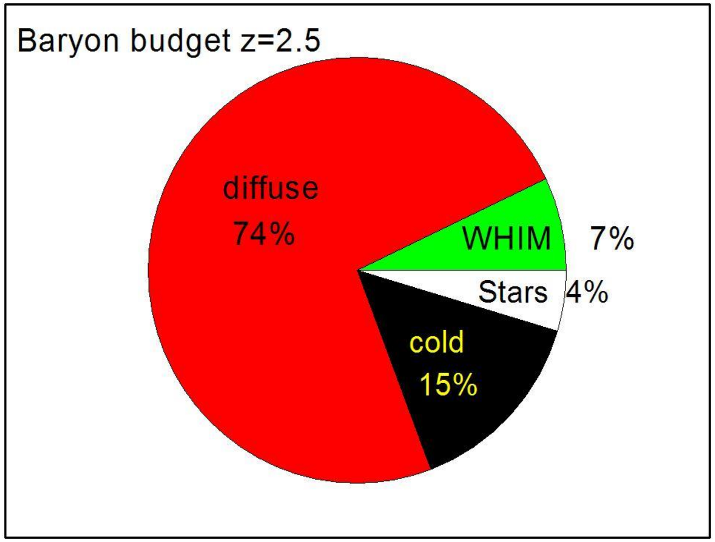


Cold & Hot Gas in Red Galaxies



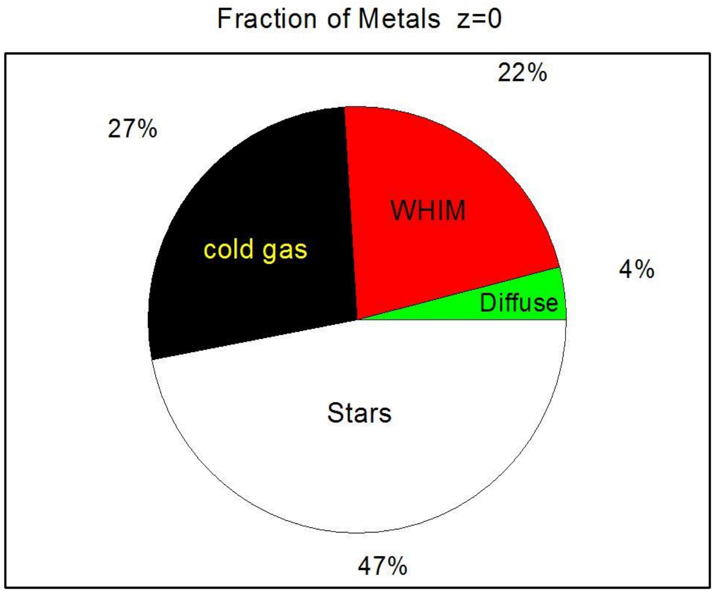
Baryon Budget

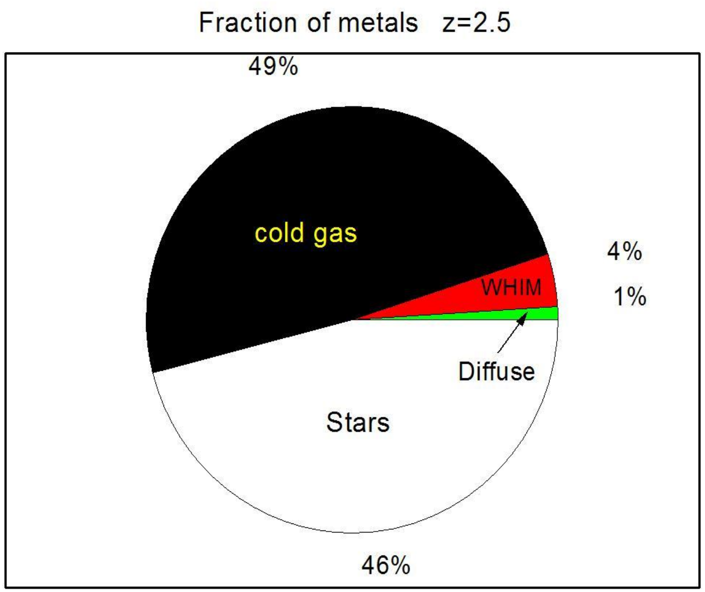




For comparison
Rasera & Teyssier (2005): at z = 0
Stars = 12.0%   cold gas = 1.2%   WHIM = 29.0% diffuse = 57.8%

Fraction of metals





Summary

- ***Baryons appear quite early, when the universe was about 61μs old, as a consequence of a first order phase transition. A "mini inflation" occurs, driven by the latent heat of the transition and nearly equal number of neutrons and protons are formed***

- ***When neutrinos decouple (T ~ 0.93 MeV) the neutron-to-proton ratio is 0.248 and then nuclear reaction produce ^{2}H, ^{3}He, ^{4}He and small amounts of ^{7}Li***

- ***Decoupling from photons occurs at z~1100 (or at T~2900 K)***

- ***Freezing of the ionization fraction at z~500 with $X_H \sim 5\mathrm{x}10^{-4}$ - thermal coupling between baryons and photons ends at z~95***

- ***Reionization around z~10-11 due to star forming galaxies***

- ***Baryons today are distributed in different phases: stars (14%), cold &dense gas (7%), WHIM (43%) and diffuse ionized medium (36%)***