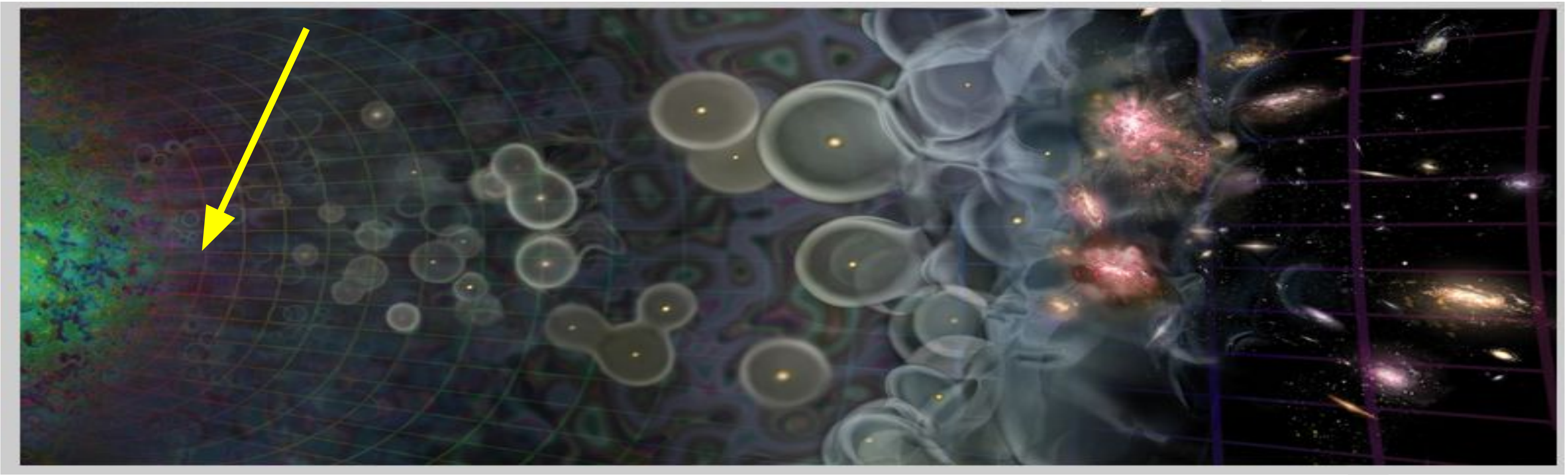
Cosmological recombination

Robert Kincaid



Signals From the Epoch of Cosmological Recombination (*Karl Schwarzschild Lecture*)

R.A. Sunyaev[1,2] and J. Chluba[3,1]

Using the cosmological recombination radiation to probe early dark energy and fundamental constant variations

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SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

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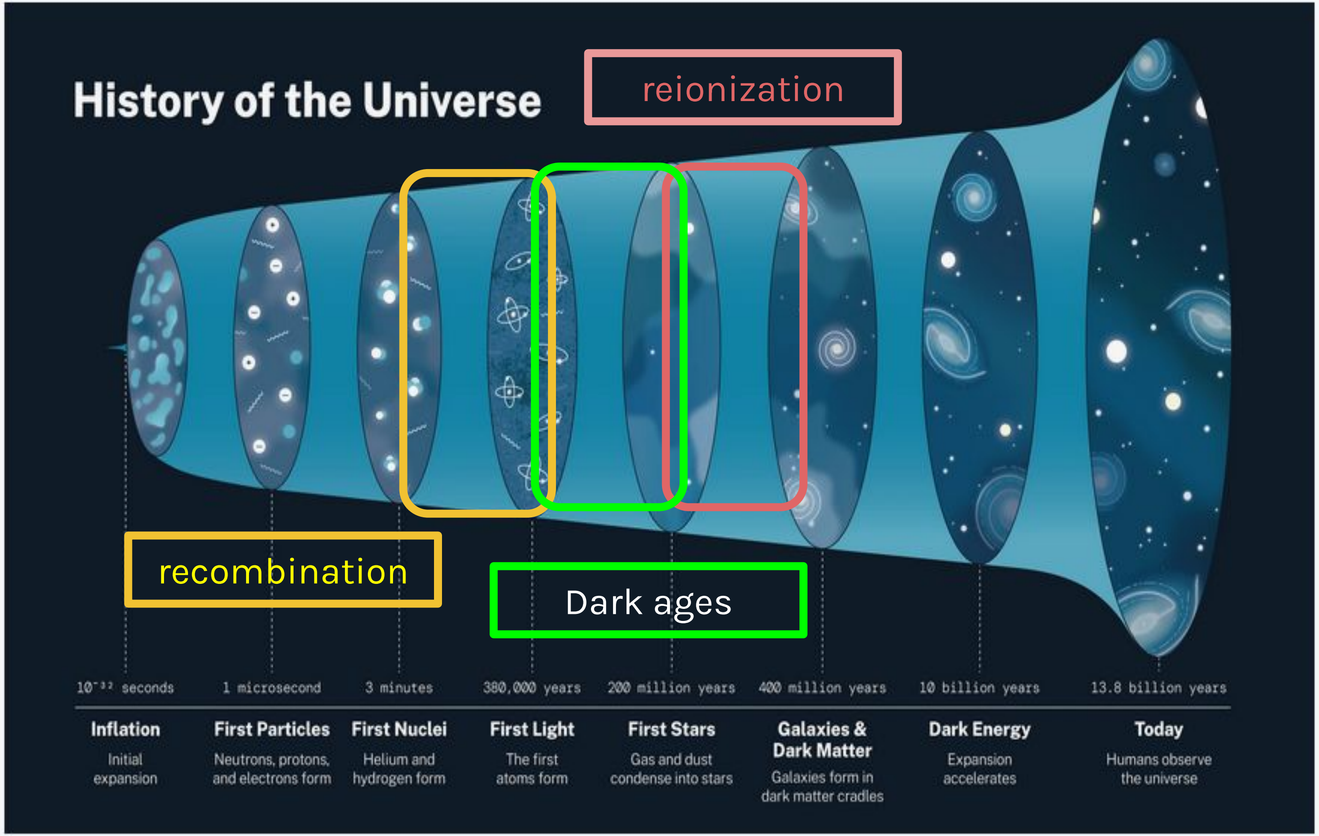
Robert Kincaid

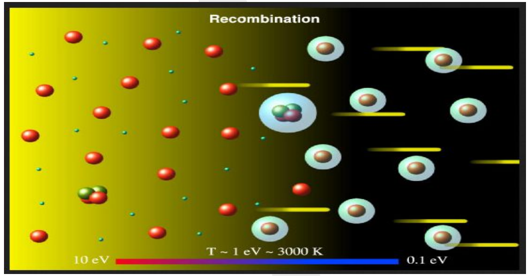
Recombination timeline and overview	Recombination simple process and its relation to other main epochs of cosmology
Hydrogen and Helium Recombination process	The channels in which recombination takes place. Using Saha and boltzmann equation to predict the relative photon baryon fractions over time. The significant of He recombination
Importance of Recombination on BAO	The time of recombination dictates the nature of the Baryonic Acoustic oscillations
Effect of recombination on the CMB	Release of photons during CMB leads to unique deviations in the CMB from a perfect blackbody which can be observable in the near future
Dependence of recombination of cosmological parameters	Observing the spectral distortions from epoch of hydrogen and helium recombination can provide an additional wy to determine key parameters of the universe.
Deviation from thermal equilibrium in early universe	Early universe in thermal equilibrium. If due to some process extra energy is added, the resultant and CMB recombination process will differ

Cosmological recombination overview



- Ambient path of photons and baryons exist
- Universe was opaque and thermal equilibrium
- Universe cools down while expanding allowing for the first binding of electrons to hydrogen
- Universe is now transparent allowing photons to permeate the universe (CMB)
- A sea of neutral H and He + trace heavy elements. The H absorbs this light and remains dark
- Gas is not uniform, regions clump getting hotter eventually allowing for fusion at the cores -> first stars

Cosmological recombination simple process



- Universe initially consisted of ionized plasma of baryons and photons in thermal equilibrium through thompson (elastic) scattering. H ~ 75% , He ~ 25%

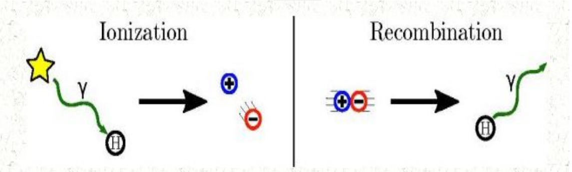
- Density of protons and electrons compared to photons - > Baryon asymmetry -> more photons than barons $N_e/N_\gamma \approx 10^{-8}$

- Plasma was opaque, mean free path of the photon was much smaller than the horizon size of universe

- As universe expands it cools and baryons of the plasma recombine to form neutral atoms. He combining first (higher charge to mass ratio) then hydrogen

- Columb attraction exists for ions of opposite charges. If favourable, ions combine to form neutral atom of lower energy than separated ions.

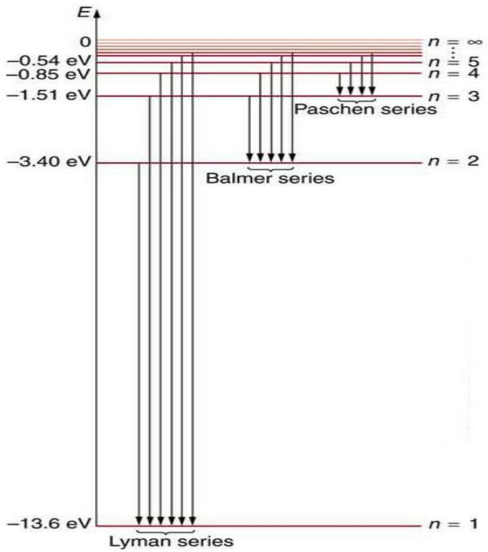
- Photon released is the energy difference of potential energy between ions and that of the neutral atom.



$$H(2s) \longrightarrow H(1s) + \gamma_1 + \gamma_2$$

$$p^+ + e^- \leftrightarrow \mathrm{H}(1s) + \gamma.$$

Both occur very slowly

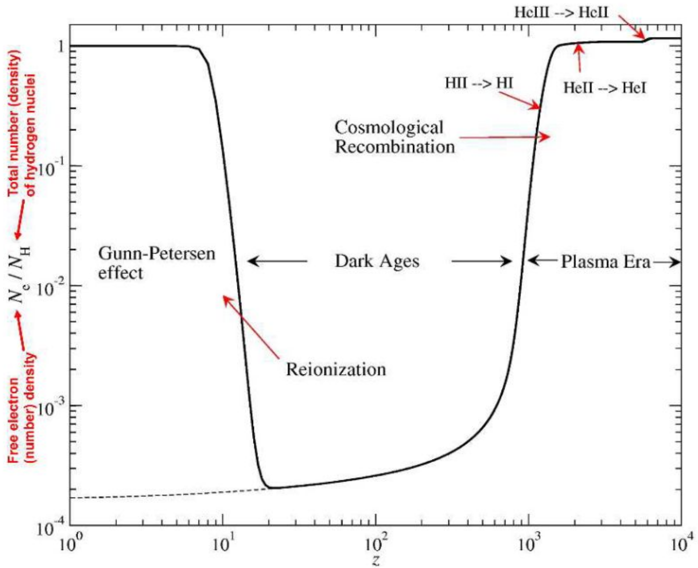


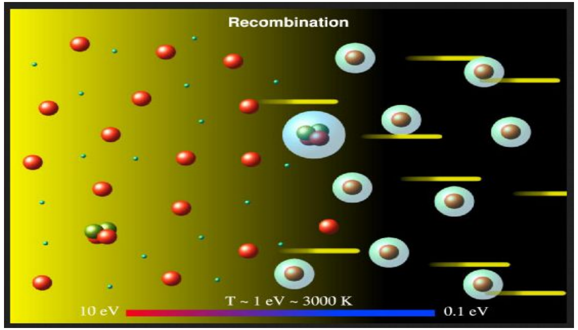
Cosmological recombination of H and HE

$N_\gamma \sim 1.1 \times 10^{12} \mathrm{cm}^{-3}$ $N_e \sim 500\,\mathrm{cm}^{-3}$,

$T_e = T_\gamma \sim 3815\,\mathrm{K}$

- Recombination for occured at about z ~ 1400 (H1), z ~ 2500 (HeI), z ~ 6000 (HeII)
- He has higher ionization energy than hydrogen (2 protons 2 neutrons)
- Radiative processes are therefore most important instead of collisional processes
- Normal recombination to ground state very inefficient. Since the emitted photon (13.6eV) has large cross-section and gets easily absorbed.
- Recombination has to occur through excited states 2s and 2p states - > non-equilibrium recombination needed to explain



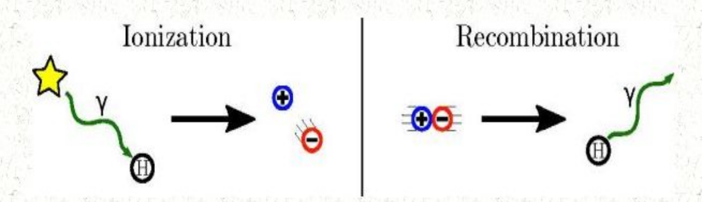


$$\mathrm{He}^{2+} + \mathrm{e}^- \longrightarrow \mathrm{He}^+ + \gamma$$

$$\mathrm{He}^+ + \mathrm{e}^- \longrightarrow \mathrm{He} + \gamma,$$

$$p^+ + e^- \leftrightarrow \mathrm{H}(1s) + \gamma.$$

$$H(2s) \longrightarrow H(1s) + \gamma_1 + \gamma_2$$



Cosmological recombination: Saha and boltzmann equation

- Direct recombination from ground state (13.6 eV photon) does not lead to net decrease of X_e due to large cross-section (easily absorbed).
- Recombination has to proceed through excited states n > 2 states where free electrons and photons exist in equilibrium.
- Electrons first combine to these n = 2 excited states then making their way down
- 2s-1s is forbidden (cannot occur via emission of single photon) since l=0 for both states. However, 2-photon emission can occur. (~ 10^8 slower than lyman-alpha)
- 2p-1s is another process that can occur which emits well-known lyman-alpha, however, same problem as 13.6 eV (easily absorbed).
- 2p-1s photon is therefore required to redshift out of the lyman alpha line to avoid capture -> scatters 10^8 times

$$\frac{X_e^2}{1-X_e} = \frac{1}{n_b}\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} e^{-\epsilon_0/k_B T}, \quad X_e = \frac{n_e}{n_b},$$

Early universe (Saha)

$$\frac{dX_e}{dt} = \langle\sigma_{\rm rec} v\rangle \left\{(1-X_e)\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-B_{\rm H}/T} - X_e^2 n_{\rm b}\right\}, \quad dt = \frac{da}{aH},$$

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$

photoionisation **recombination**

$$\frac{dX_e}{da} = \frac{\langle\sigma_{\rm rec} v\rangle n_{\rm b}}{aH}\left\{\frac{(1-X_e)}{n_{\rm b}}\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-B_{\rm H}/T} - X_e^2\right\}.$$

Recombination (boltzmann)

$$T \geq 0.4\ eV\ (z > 1300) \longrightarrow \frac{<\sigma_{rec} v> n_b}{aH} >> 0$$

Hubble rate less than recombination rate

$$T = T_{rec} \approx 0.3\ eV\ (z \approx 1300) \longrightarrow \frac{<\sigma_{rec} v> n_b}{aH} << 0$$

Hubble rate greater than recombination rate

Conclusion → **Hydrogen recombination is strongly delayed due to recombination from excited states**

Cosmological recombination: Saha and boltzmann equation

- Saha fromalism: Relation between degree of ionization and temperature using a statistical interpretation of a plasma in thermodynamic equilibrium
- We can use the Saha formalism to understand chemical evolution of early universe (z > 1300)
- Saha assumes chemical equilibrium and transitions occur from the ground state (ignores 2s and 2p excited states)
- Cannot be used for detailed evolution of Xe(T) since as soon as recombination starts, it goes out of equilibrium
- Recombination process therefore controlled by population of the first excited state and physical processes that populate and depopulate it.

$$\frac{X_e^2}{1-X_e} = \frac{1}{n_b}\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} e^{-\epsilon_0/k_B T}, \qquad X_e = \frac{n_e}{n_b},$$

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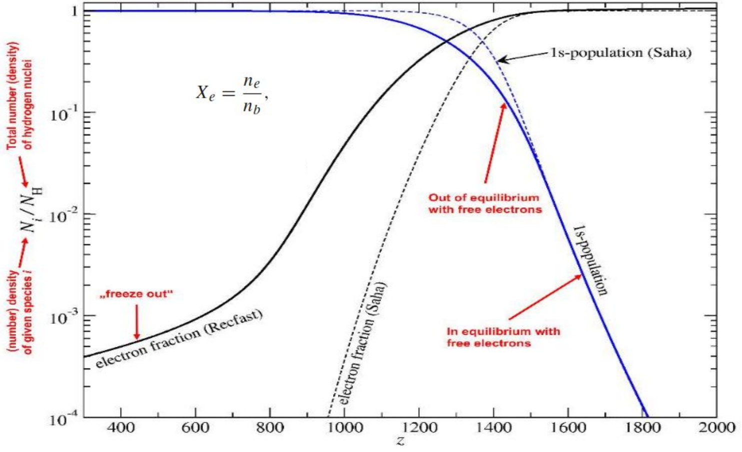
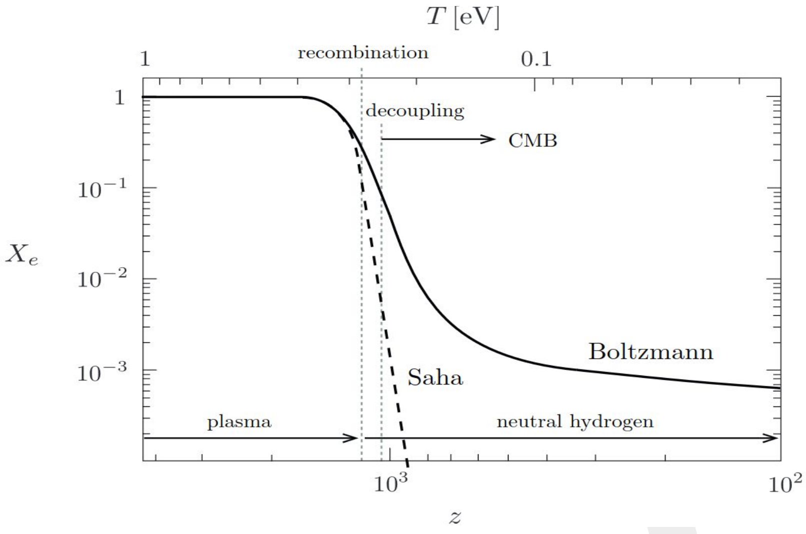
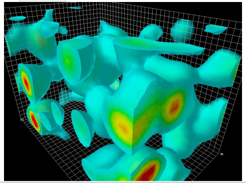
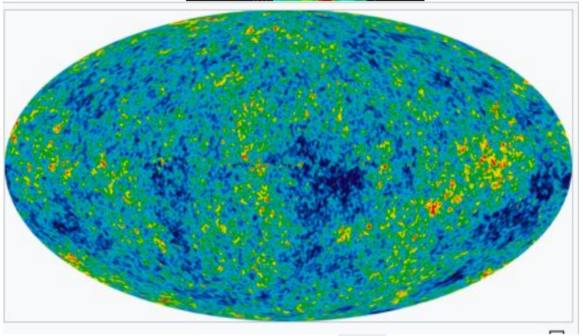


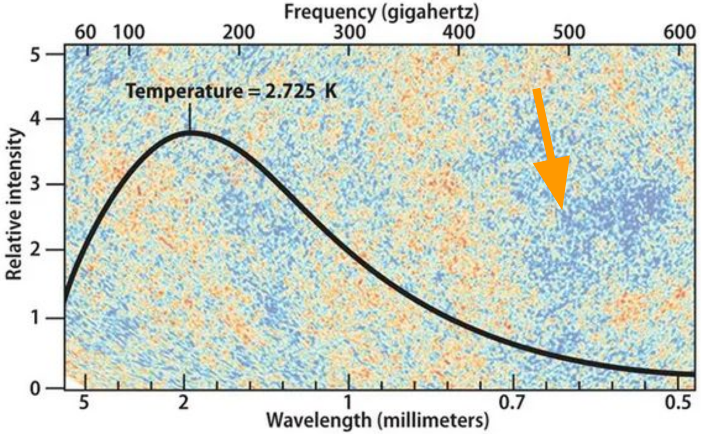


Cosmological recombination: effect on the CMB

- After recombination, photons decouple from baryons. Mean free path of photons rises to larger than Hubble distance
- Recombination controlled by the dynamics of transitions involving excited states that cascade down to ground states rather than direct ground state transitions.
- These are most visible in the Wien part of the CMB even though only few photons
- Temperature anisotropies in CMB are due to inhomogeneities in the distribution of matter.
- Ansistropies visible in the CMB were dictated at the time of recombination
- Recombination process imprints narrow features in the CMB spectrum providing and independent way to measure cosmological parameters
- Not to be confused with the Sunyaev-Zeldovich (SZ) effect. Compton scattering of CMB photons in galaxy clusters



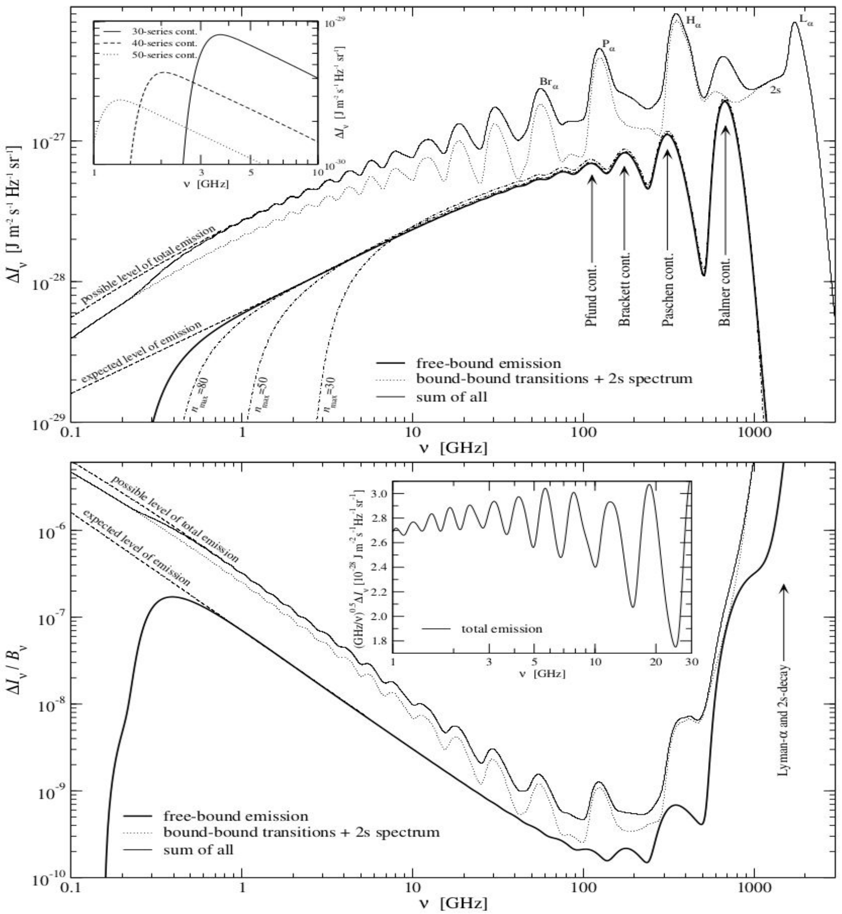




2s-two-photon and lyman a Spectral features in wien tail not detected

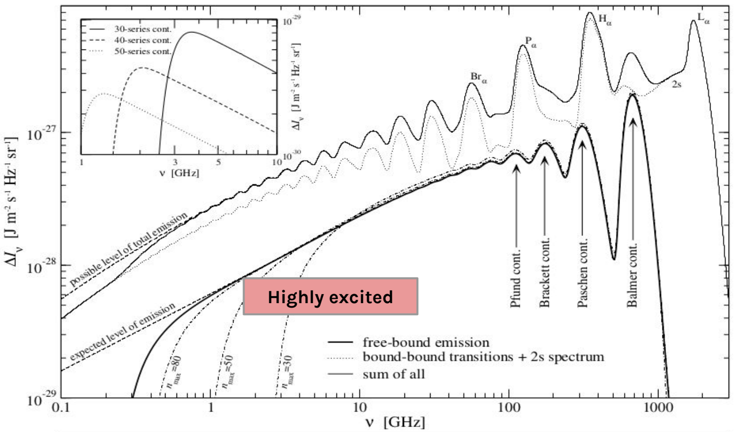
Cosmological recombination: effect on the CMB

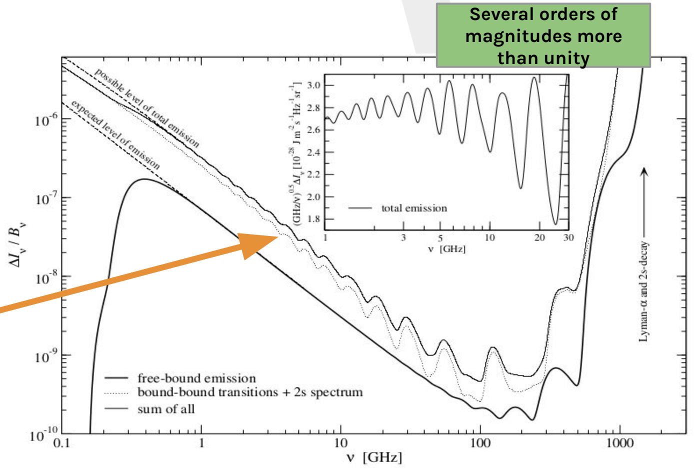
- Rate of recombination controlled by the 2p-1s and 2s-1s two-photon decay transitions which are both slow
- Lyman alpha scatter 10^8:1 times before escaping plasma permitting settling of 1s. At same time, 2s-1s 2 photon decay occurs at 1:10^8 -> control slowed recombination
- These 2 processes are the main cause of distortions seen in the CMB. Most noticeable in the Wien region.
- This region is naturally hard to probe due to foreground from interstellar dust
- The Rayleigh region distortions are much smaller as a result of the contributions from higher excited states that merge to form a continuum
- Overall, it modulates the CMB spectrum

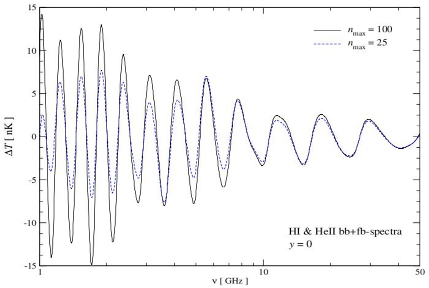


Cosmological recombination: effect on the CMB

- Photons that distort CMB emitted at z~ 1300-1400 and so are 10^3 redshifted
- Lower energy levels show sharp features while higher energy levels merge to form a continuum
- Large distortions in Wien region and much smaller in the rayleigh region (due to high specific entropy).
- At such high frequencies, cosmic infra-red background from dusty galaxies makes it impossible to measure
- Recombination spectrum 1- 10 Ghz on CMB for H and He contribution leads to a temperature difference of modulation behavior
- Behavior cannot be produced from noise or any astrophysical signals





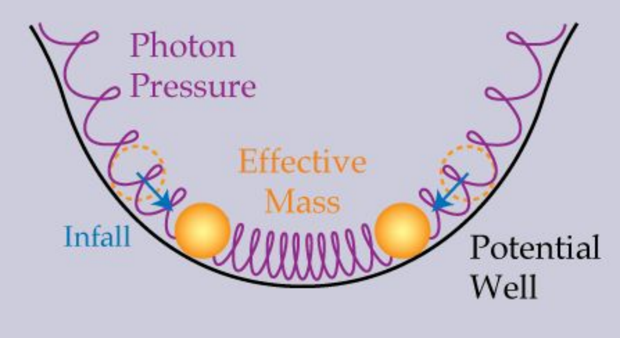


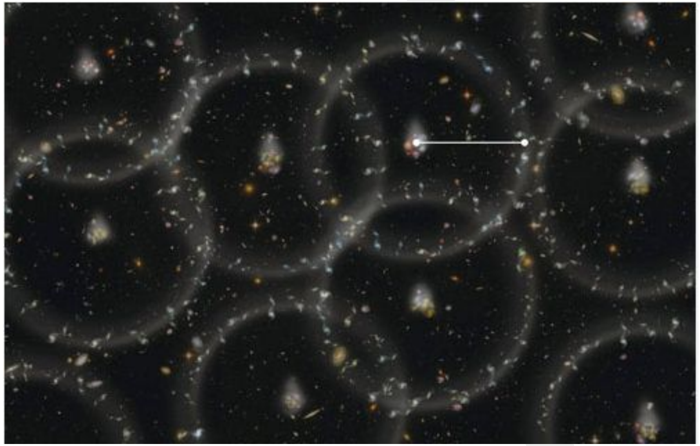
CMB - REC

$$\Delta T \sim \pm 5 - 15\,\mathrm{nK}$$

Cosmological recombination and its relation to Baryonic Acoustic Oscillations (BAO)

- Acoustic oscillations in the baryon/photon plasma
- Matter collapses due to gravity in regions of higher density.
- Baryons and photons in this primordial phase are still strongly coupled. Photons resist the collapse and push baryons outward
- The result is “ringing” or oscillatory modes of compression and rarefaction (adiabatic perturbations)
- Amplitude and position of peaks of BAO define by Universe key parameters and physical constants
- BAO can be measured from CMB and statistics of galaxy distributions.
- After recombination, photons decoupled and travelled freely and the oscillations that occurred were frozen
- BAO are a standard ruler and can be used to measure a length scale

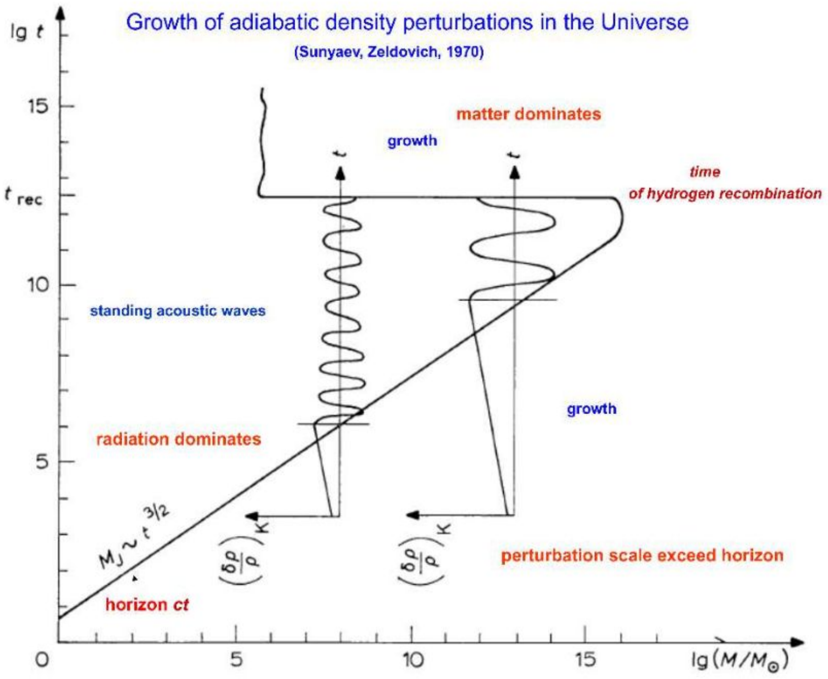




“Sound waves “ of the universe

Cosmological recombination: effect on the BAO

- Early Universe, any scale of astronomical significance was larger than horizon (ct),i.e. Mean free path of photons, jeans length of adiabatic density perturbations
- Adiabatic perturbations smaller than jeans-wavelength (~ct at early times) and so evolve as power law. Perturbations larger than jeans-mass-> unstable
- At later times, jeans-wavelengths ~ ct , perturbations smaller than jeans-wavelength should evolve as acoustic sounds waves
- 2 different regions of the universe had different densities and so expanded at different rates. Their corresponding density differences (perturbations) grow according to a power law
- Early universe jeans wavelength was close to ~ ct. According to jeans instability, Perturbations smaller than the jeans wavelength should evolve as sound (acoustic) waves
- Amplitude and position of peaks define by Universe key parameters and physical constants



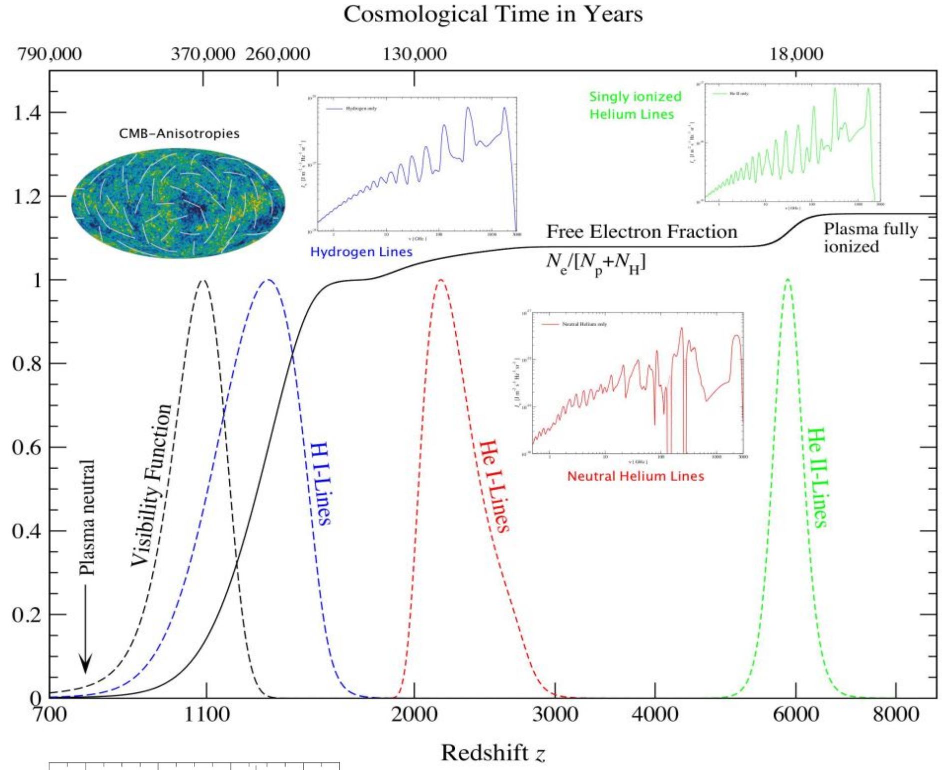
$$M_J = \frac{\pi \rho_m \lambda_J^3}{6} \sim \frac{\Omega^{-2}}{(1+(z/z_1\Omega))^3} M_\odot$$

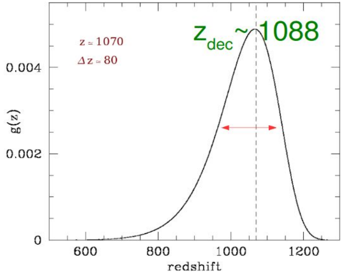
$$z_J = z_1 [(\frac{10^{16}\Omega^{-2}}{M})^{1/3} - 1]\Omega$$

$$\lambda_J \sim ct$$

Cosmological recombination: Last scattering surface

- Hydrogen recombination defines the last scattering surface
- Angular separation of acoustic peaks provides information about the distance to the last scattering surface
- The peak of the thompson visibility function defines the time in which CMB anisotropies were created
- The optical depth for thompson scattering by matter between proto objects (small density perturbation) is large and so fluctuations in CMB are smoothed
- Thompson visibility function - > exponential decay on both sides

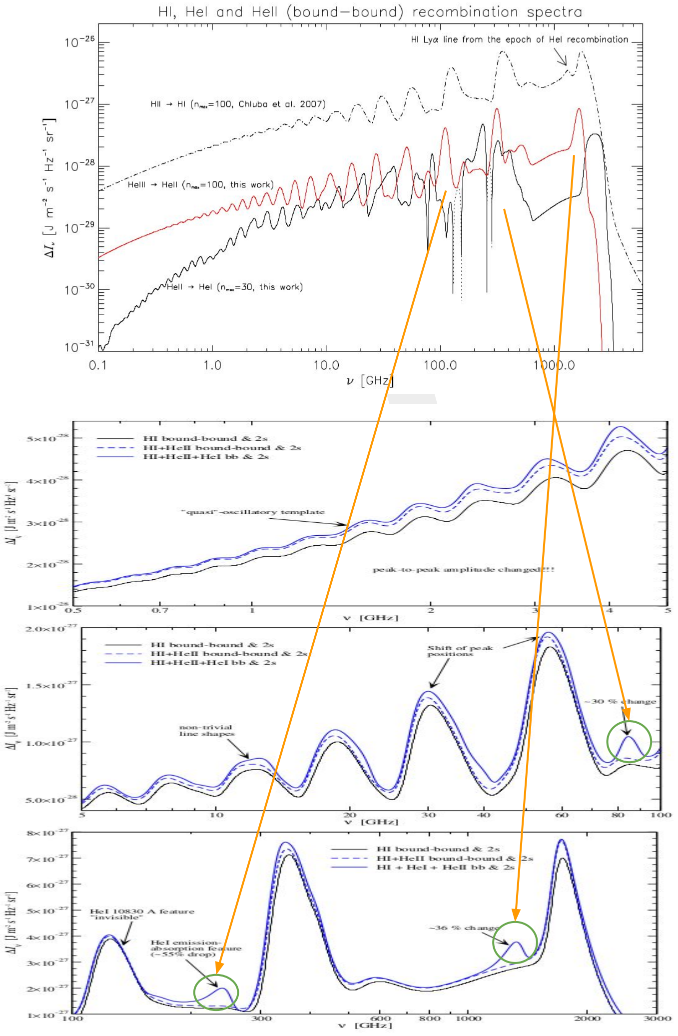




$$g(z) = e^{-\tau}\frac{d\tau}{dz},$$

Cosmological recombination: Important of Helium during recombination

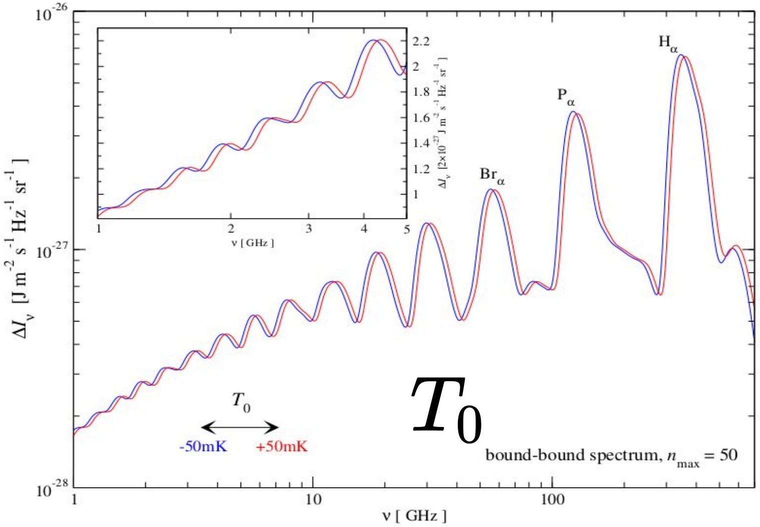
- Helium abundance very small, only constitutes ~ 8% of total nuclei. It still constitutes sizeable amount to full CMB
- Two epochs of helium recombination 1600 < z < 3500 HeII- HeI and 5000 < z < 8000 for HeIII - HeII
- Taking these 2 epochs into account ~ 16% contribution to recombination spectrum due to He in Universe
- HeIII - HeII occurs much faster than H following more closely the saha solution causing photons to be emitted in a narrower frequency range
- He has higher ionization potential (2 protons) and more effectively attracts
- Re-processing of He photons by hydrogen also lead to signatures in the spectrum
- Both these effects cause He emission lines to be more narrow and enhanced in some frequency bands
- Noticeable absorption peaks in the overall spectrum as compared to H

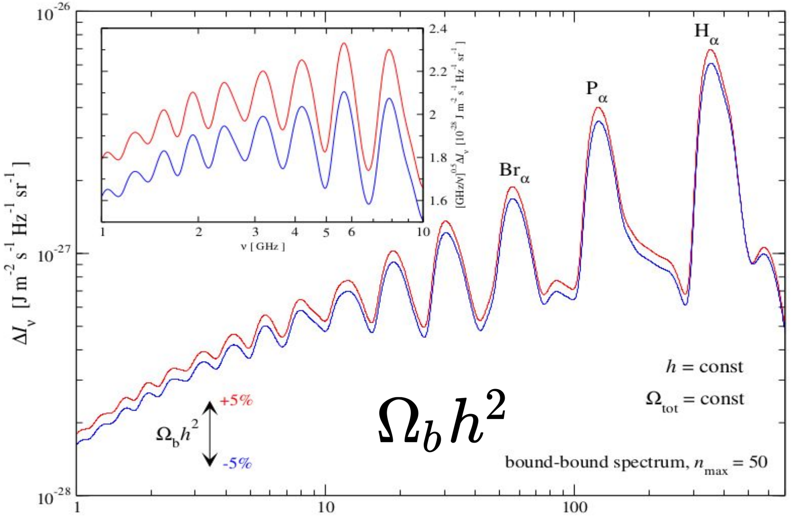


Recombination spectrum on cosmological parameters

- Measuring distortion of the CMB spectrum will provide a direct way to study recombination
- The CR photons from hydrogen and helium pre-date the last scattering process and as such allow probing physical phenomena in the pre-recombination era
- The CMB monopole temperature was varied and its impact on the recombination spectrum studied
- From CMB monopole temperature can obtain time of recombination. I.e when most of the emission in each transition occurs
- If recombination happened at a higher temperature then the line shifts to higher frequencies - > Frequency shift
- For v = 2GHz gives $\Delta\nu$~1 MHz which can be resolved by modern spectrometers
- Total number of photons released related to number of hydrogen atoms $N_b \propto \Omega_b h^2 \qquad \Delta\nu/\nu \sim \Delta T/T_0$
- Increasing baryons increases photons released therefore more energy per unit frequency bin - > amplitude increase

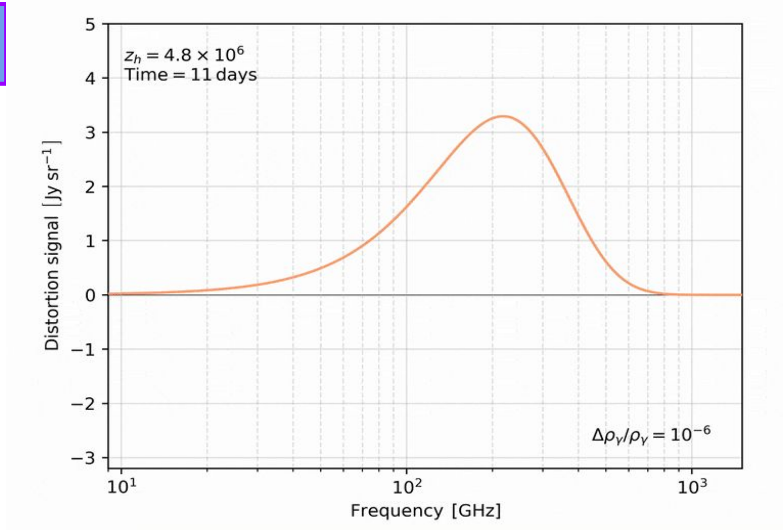
$$\Delta T \sim 1\ mK \longrightarrow \Delta\nu/\nu \sim 0.04\% \ \sim 1\,\text{MHz at } 2\,\text{GHz},$$

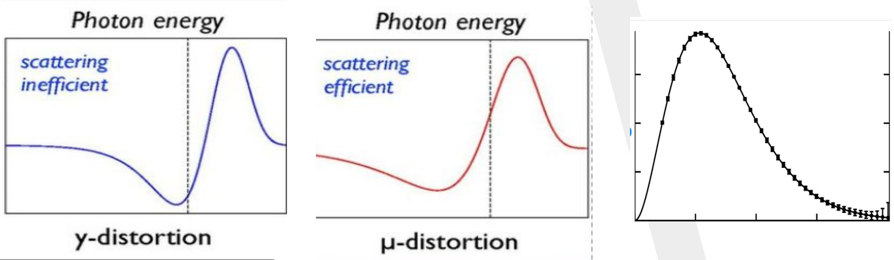




Deviation from thermal equilibrium of recombination on CMB

- The CMB is almost a perfect blackbody (at 2.7K) and distortions created during recombination are very small except for resonances in wien part
- This is because in early universe matter and radiation are in thermal equilibrium - > well before recombination Emission and absorption processes were in balance such that no net sigma is observed on CMB
- However, several standard and non-standard processes can cause departure from an ideal blackbody
- Energy release occurred at some point in the form of decay or annihilation of particles, primordial black hole evaporation, primordial magnetic fields, exotic particles (non-standard thermal history)
- Excess heat then transferred to the ambient CMB photon bath. Depending on when injected causes distortion
- 2 main types of distortions y and u type. Y and u are dimensionless and measure total energy injected
- Y-distortion is characterized as deficit of photons at low and excess at high frequencies





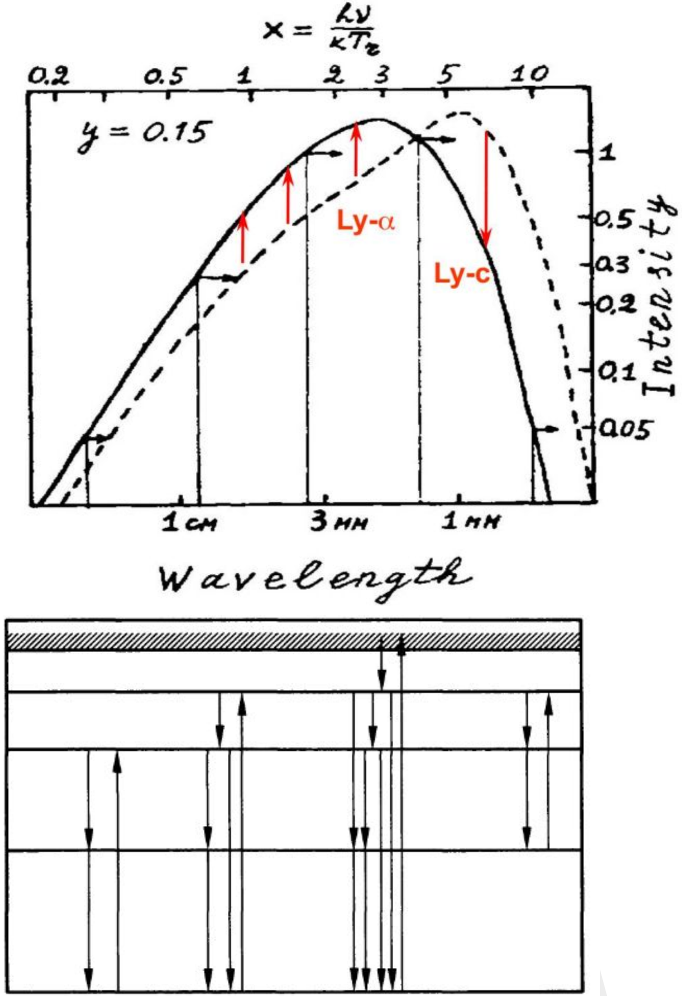
y era | U era | Thermal

$z < 5 \times 10^4$ | $2 \times 10^6 > z > 5 \times 10^4$ | $z > 2 \times 10^6$

Present

Deviations from thermal equilibrium effects on atomic transitions

- Small imbalance exists between atomic emission and absorption which leads to the development of closed loops
- Cyclic transitions results due to a non-equilibrium radiation field
- Excess of photons leads to excess photoionization of hydrogen in ground state.
- The deficit of photons in low frequency part will lead to excess of electrons captured to highly excited states
- It then release low energy photons as it cascades down to ground state
- Electrons make cyclic transitions absorbing photons in spectral region is high and emitting where low where
- Electron moves between same levels absorbing and emitting each time
- Overall effect is a net change in photons which alter the total radiation coming from atomic transitions



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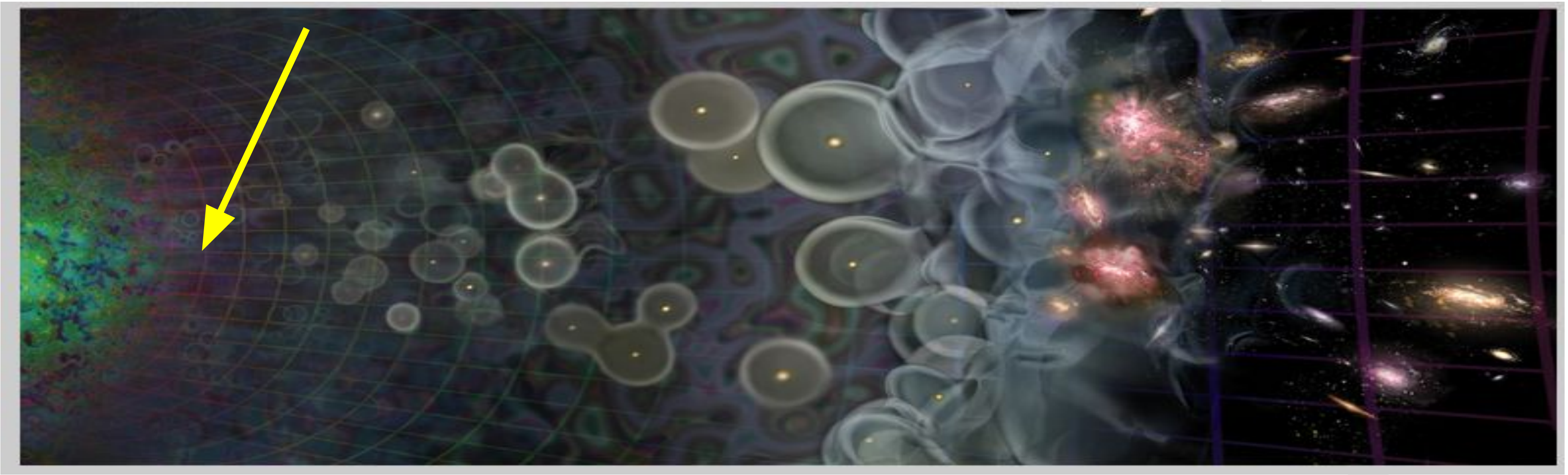

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