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KAIST Astrophysics (PH481) - Part 1

Week 4b

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Kwang-il Seon (선광일)

Korea Astronomy & Space Science Institute (KASI)

University of Science and Technology (UST)

What are the Lyα absorption systems?

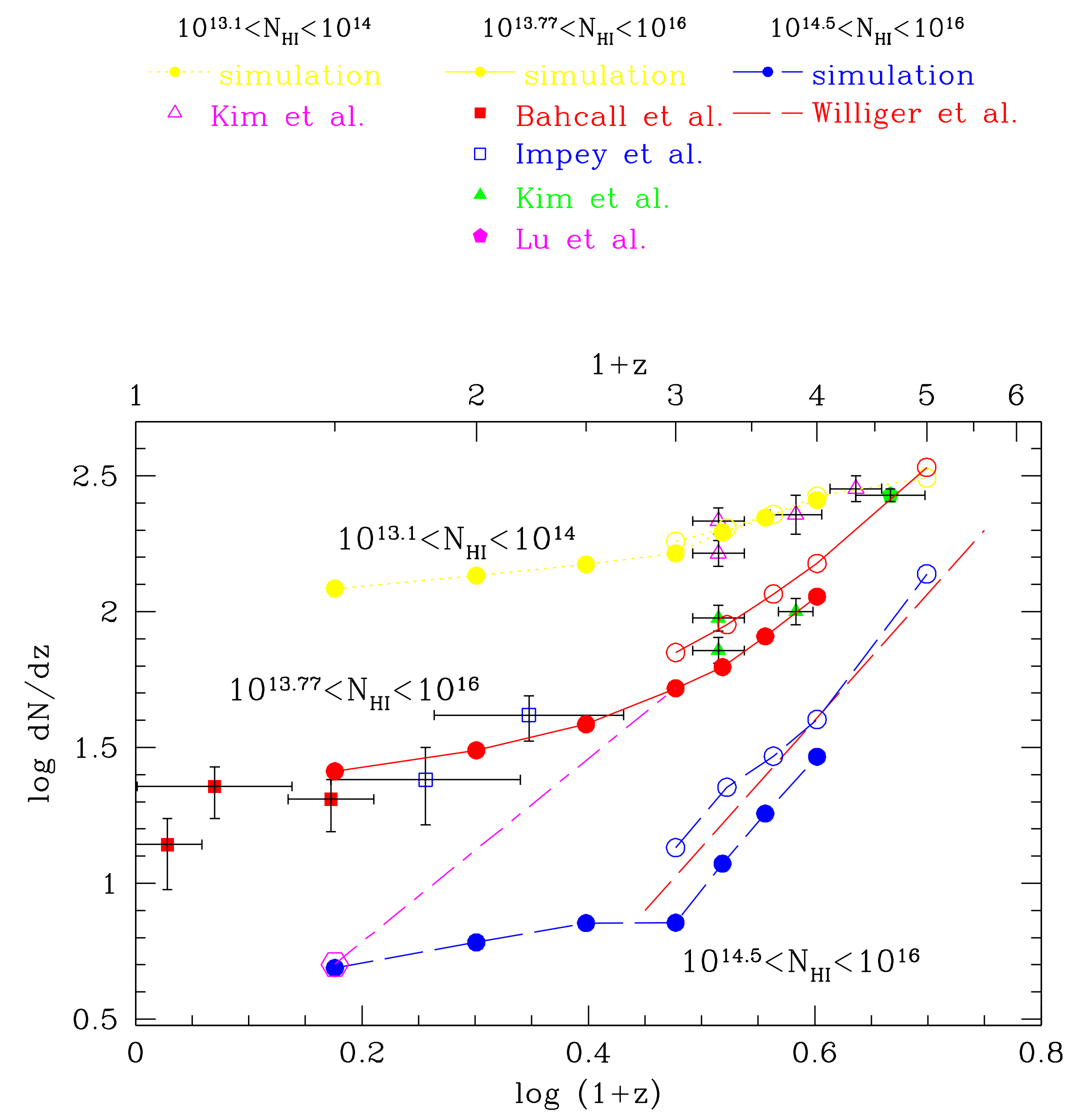
- They are probably intergalactic hydrogen clouds and galaxies.

- Astronomers have speculated that the Lyα forest clouds might be pregalactic gas fragments that later collapsed and coalesced to form galaxies.

- They are generally associated with galaxies, but not always.
  - For instance, 3C 273 lies behind the Virgo cluster of galaxies, and has a couple of absorbers in the cluster's redshift range, but they cannot be cleanly identified in position and redshift with specific neighboring galaxies.
  - At low redshift, many of the galaxies that are responsible for the Damped Lyman Alpha (DLA) absorption can be directly identified.
    - These galaxies are a heterogeneous population. They are not just the most luminous galaxies, but include dwarf and low surface brightness galaxies.
    - There are even cases where no galaxy has been identified to sensitivity limits.

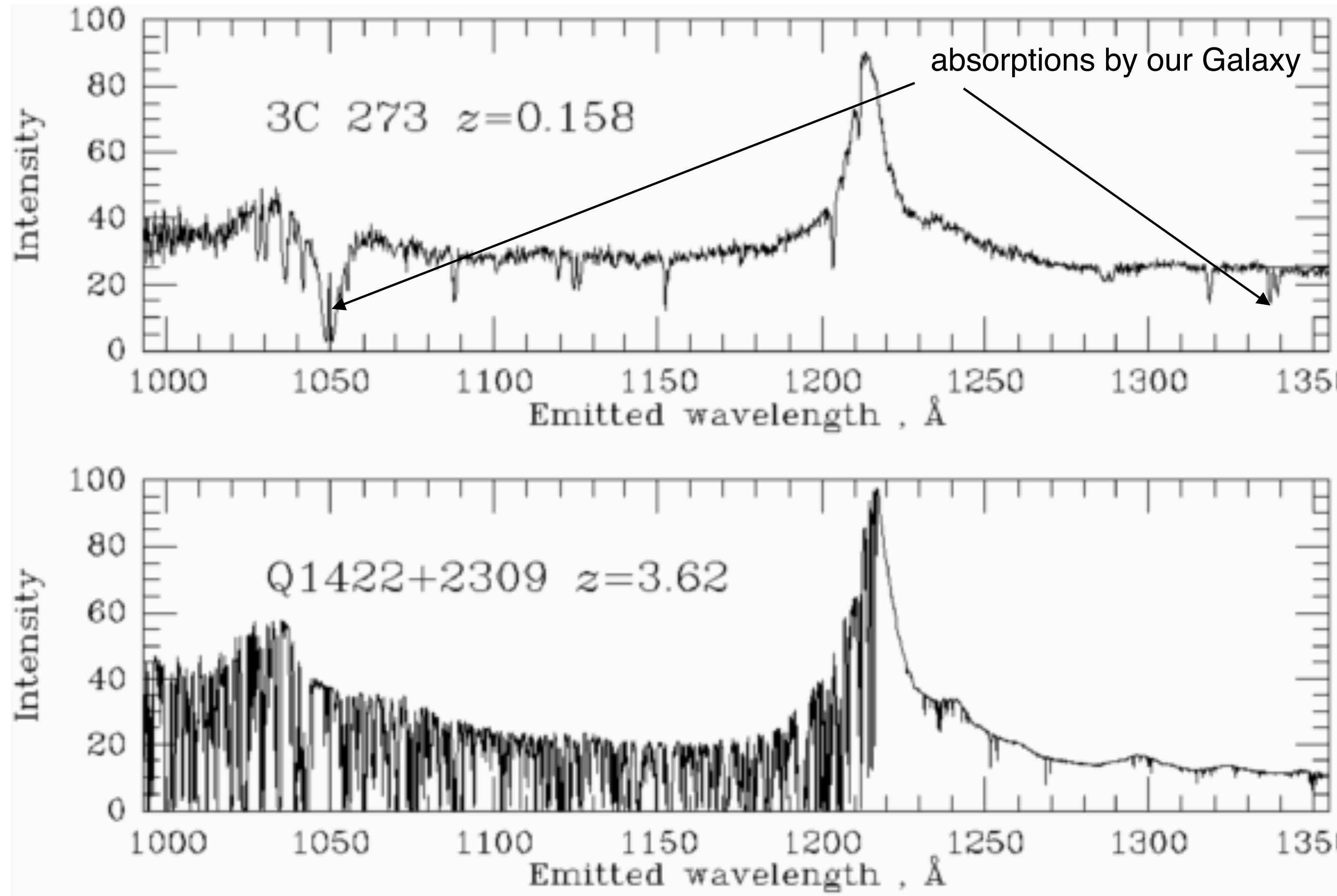
Evolution of Lyα Absorption Systems

- The Lyα absorption component evolves strongly with cosmic time.
  - We see dramatically ***more absorbers toward higher redshifts***.
  - However, they have not completely disappeared at low redshifts. When the launch of HST provided the first capability of measuring Lyα at low redshifts to the required accuracy, it was found that a few of these absorbers remain in the local Universe.
- The evolution of the Lyα forest may be intimately connected with the history of galaxy formation.
- This dramatic ***evolution in the number of forest clouds is mostly due to the expansion of the Universe, with a modest contribution from structure growth.***

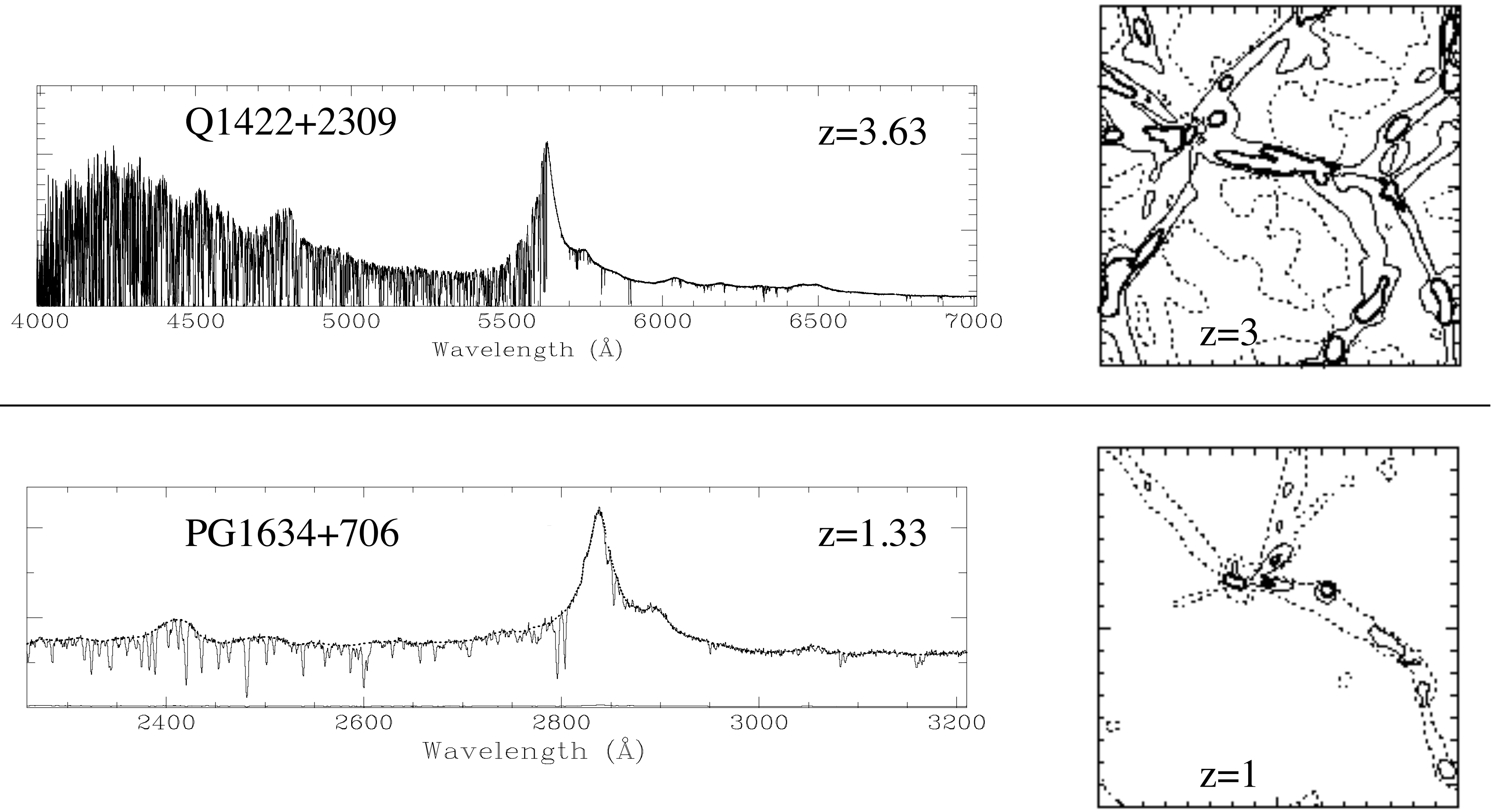


Evolution of the number of lines within a given range of column density obtained from numerical simulations and observations (Efstathiou et al.)

- This figure compares two quasars at very different redshifts, 3C 273 at z = 0.158 and 1422+2309 at z= 3.62.
- The spectra were shifted to a common scale in emitted wavelength.

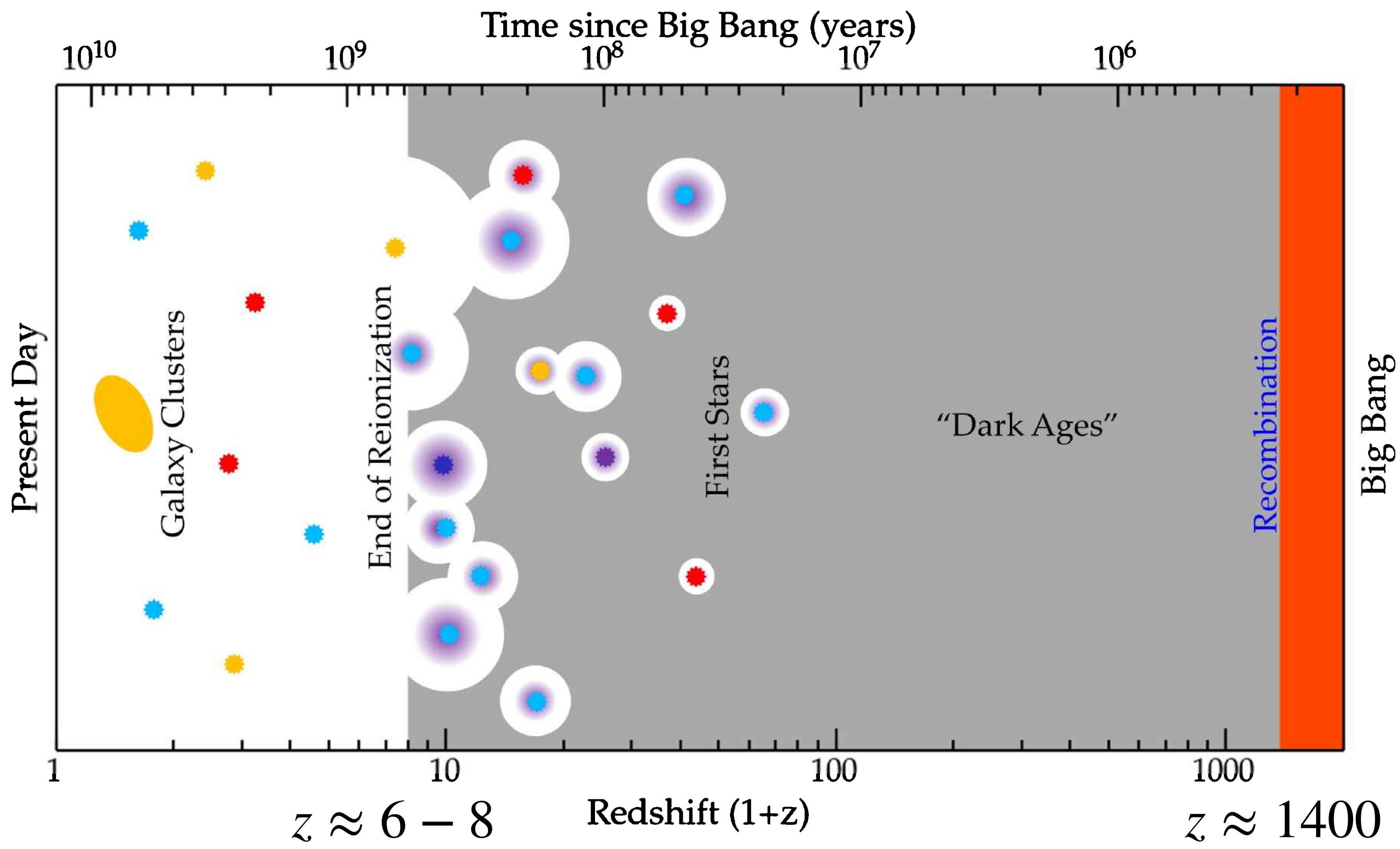


- At low redshift, 3C 273 shows only a handful Lyα absorbers, including the strong and broad absorption from its light intercepting the disk of a foreground spiral galaxy (ours). Our galaxy also produces absorption in the C IV lines around 1550 Å, which appear at 1337 Å in the quasar's emitted frame.
- Hundreds of lines can be identified in the spectrum of 1422+2309, with the densest concentration near the quasar redshift - ***this is a very general feature showing how the density of Lyα absorbers decreases with cosmic time.*** The strong and broad emission peak is Lyα, which is almost chopped in half by the onset of the Lyα forest in the high-redshift quasar.



- Illustration of structure evolution of intergalactic gas from high to low redshift.
  - Higher redshift quasars show a much thicker forest of Lyα lines.
- The right-hand panels show slices through N-body/hydrodynamic simulation results at two epochs z = 3 and z = 1.
  - Three contour levels are shown : 10^{11} cm^{-2} (dotted lines), 10^{12} cm^{-2} (solid lines) and 10^{13} cm^{-2} (thick solid lines).
  - Evolution proceeds so that the voids become more empty and even lower column density material is found in filamentary structures at low redshifts.

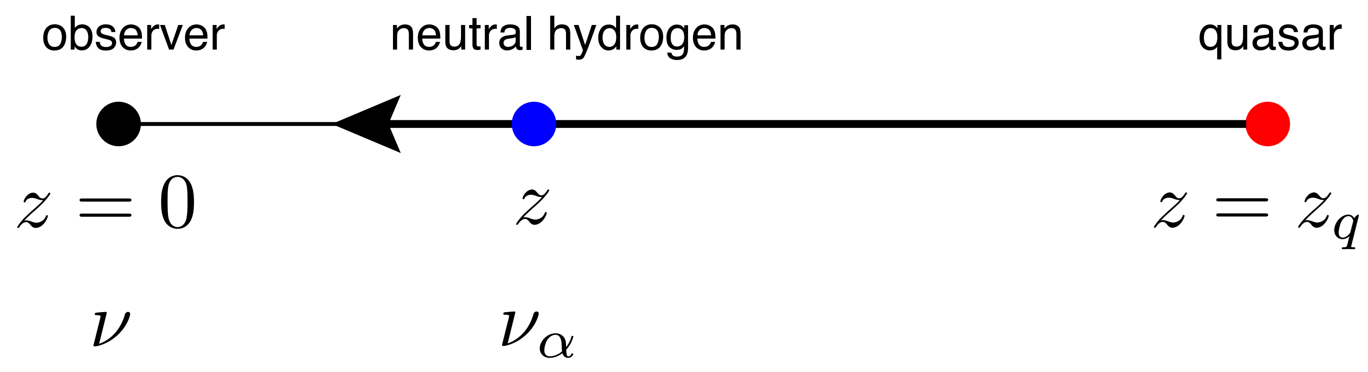
Dark Ages, Reionization Epoch



- In the early Universe, some hundred million years after the Big Bang, the temperature became low enough for electrons to combine with protons for the first time.
  - This is known as the epoch of recombination. This left the gas in the Universe in an overall neutral state.
- In today's Universe, however, nearly all of the gas between the galaxies is fully ionized.
  - ***There should have been a moment in the history of the Universe when it becomes ionized again.*** This period is known as the epoch of reionization.

- What caused the cosmic reionization?
  - How exactly this came to happens is still not fully understood, but one strong candidate for causing this to happen is the formation of ***the very first stars and galaxies***.
  - The other possible explanation would be strong high-energy radiation from quasars, and they do seem to have an effect, but the latest estimates indicate that they would contribute no more than ~ 10% to the total ionizing background radiation needed.
- When did the cosmic reionization happen?
  - One of the strongest pieces of evidence for the increasing fraction of neutral gas in the IGM is the Lyα forest and the so called ***Gunn-Peterson trough***.
  - The latter is named from the study of Gunn and Peterson (1965). The spectrum of a quasar, is intrinsically a bright continuum source with only a few very broad features. However, spectra of distant quasars show a large number of narrow absorption features, resembling the trunks of trees tightly packed together in a forest. This feature was therefore named the Lyα forest.
  - ***At higher redshifts, the absorption features appear closer together, until finally a completely absorbed trough is observed.*** This indicates that the universe was previously more filled with neutral gas, and ***at some point the IGM was completely neutral***.
  - The Gunn-Peterson trough is typically observed at $z \sim 6$, thus marks the end of the epoch of reionization.

Gunn-Peterson Effect



- In order to understand the Gunn-Peterson effect, let's consider radiation emitted at some frequency ν that lies blueward of Lyα by a quasar at redshift z_q. The emitted photons pass through the local Lyα resonance as they propagates towards us through a smoothly distributed sea of neutral hydrogen atoms, and are scattered off the line-of-sight with a cross-section of

$$\sigma_\nu = \frac{\pi e^2}{mc} f_\alpha \phi_\nu = \chi_0 \phi_\nu,$$

where ϕ_ν is the Voigt profile of the Lyα line, normalized so that $\int \phi_\nu d\nu = 1.$

- The total optical depth for resonant scattering at the observed frequency ν is given by the line integral of this cross-section times the neutral hydrogen density $n_{\rm HI}$,

$$\tau_\nu^{\rm GP} = \int_0^s \sigma_\nu n_{\rm HI} dl = \int_0^s \chi_0 \phi_\nu n_{\rm HI} dl.$$

- In an expanding Universe, the integral should be performed along the proper distance in the local comoving frame. We, therefore, want to use the redshift z instead of the proper length l travelled by light. Then, the optical depth becomes

$$\tau_\nu^{\mathrm{GP}} = \chi_0 \int_0^{z_q} \phi_\nu n_{\mathrm{HI}} \frac{dl}{dz} dz$$

- The expansion of the Universe is homogeneous and isotropic on large scale, and thus can be described by a simple scale factor $a(z)$, which is customarily normalized so that $a(t_0) = 1$ at the present time $t_0 = 13.80\ \mathrm{Gyr}$ after the Big Bang.
- The expansion of the Universe if frequently described in terms of the Hubble parameter, $H(t) \equiv \dot{a}/a$. The value of the Hubble parameter at the present time is the Hubble constant:

$$H_0 = H(t_0) = 67.74\ \mathrm{km\ s^{-1}\ Mpc^{-1}} = 2.195 \times 10^{-18}\ \mathrm{s^{-1}}$$

- The scale factor today, $a(t_0) = 1$, is greater that the scale factor at the redshift z, $a(z) = 1/(1+z)$. We obtain the proper length element in terms of the redshift.

$$dl = cdt = c\frac{da}{\dot{a}} = c\frac{da}{Ha} = c\frac{dz}{H(1+z)} \quad \rightarrow \quad \frac{dl}{dz} = \frac{c}{H(1+z)}$$

- Then, the Gunn-Peterson optical depth is given by $\tau_\nu^{\mathrm{GP}} = \chi_0 \int_0^{z_q} \phi_\nu n_{\mathrm{HI}} \frac{c}{H} \frac{dz}{1+z}$.

- The thermal and natural broadening ($\Delta v_{\rm thermal} \sim 13$ km s^{-1} for $T = 10^4 K$) is tiny compared to the "broadening" due to the Hubble expansion ($\Delta v = cz \sim 30{,}000$ km s^{-1} for $z = 0.1$). Thus, we can treat the Voigt function as being very strongly peaked at the Lyα frequency ν_α in the local comoving frame. This resonance will occur at the redshift of z such that $\nu = \nu_\alpha/(1+z)$, i.e., at $z = \nu_\alpha/\nu - 1$.

- Then, ***in the comoving frame at*** z, the frequency interval $d\nu$ can be expressed by $d\nu/\nu = dz/(1+z)$. Finally, we obtain

$$\tau_\nu^{\rm GP} = \chi_0 \int_0^{z_q} \phi_\nu n_{\rm HI} \frac{c}{H} \frac{d\nu}{\nu} \approx \frac{\chi_0 c}{\nu_\alpha} \frac{n_{\rm HI}(z)}{H(z)}.$$

- At low redshifts ($z \approx 0$), this becomes an optical depth $\tau_\nu^{\rm GP} = 15{,}200 \dfrac{n_{\rm HI}}{\langle n \rangle_{\rm b,0}}$,

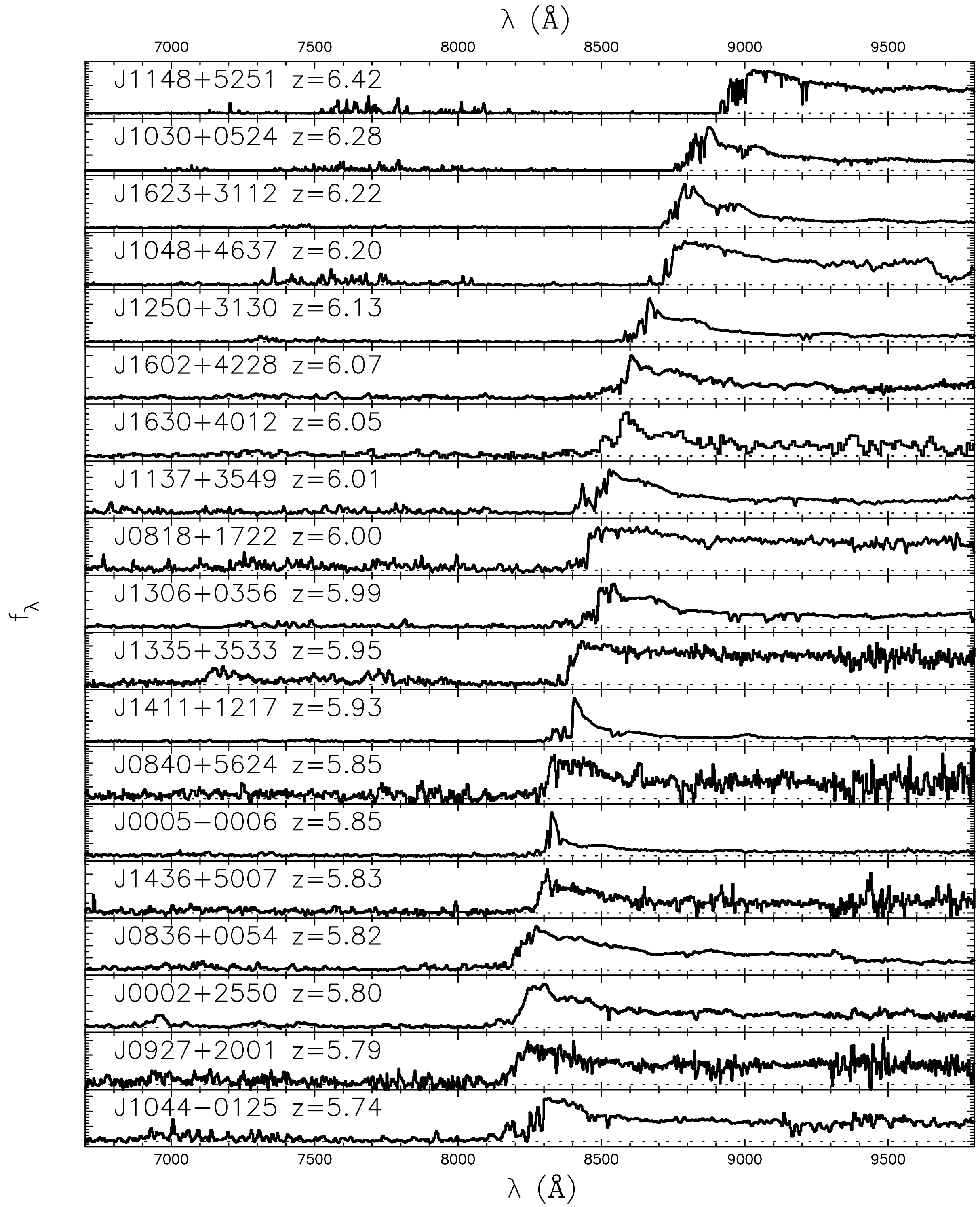
where the baryon number density at the present time is $\langle n \rangle_{\rm b,0} = 2.5 \times 10^{-7}$ cm^{-3}.

- Thus, ***even when the number density of neutral hydrogen atoms is one part in 10,000 of the baryon density, the optical depth is larger than one.***
- ***This result implies the spectrum of a low redshift quasar, for instance 3C 273 at*** $z = 0.158$***, should be black between*** $\lambda = 1216$Å ***and*** $1216 \times 1.158 = 1408$Å***. However, this is not the case.***

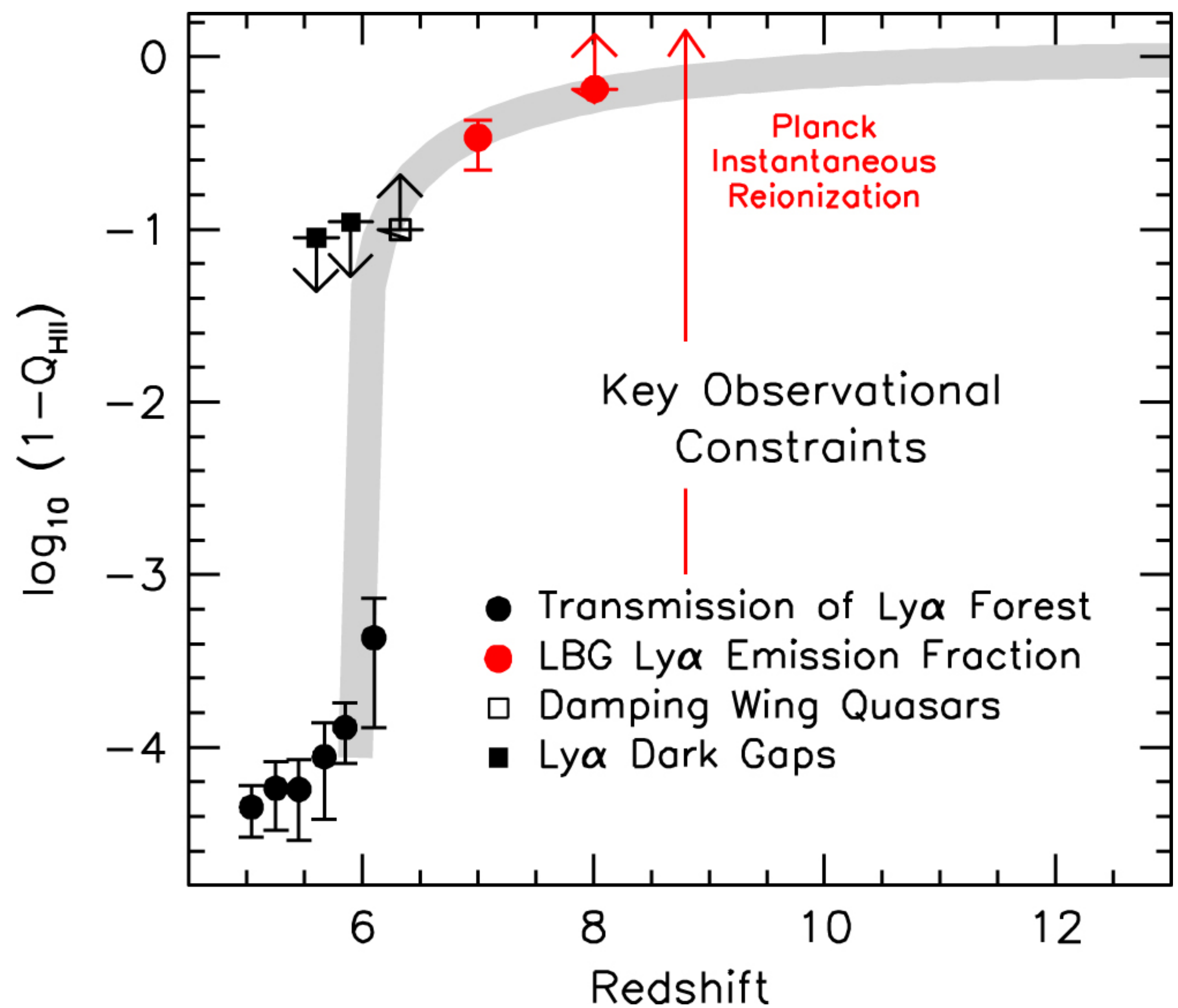
End of the cosmic reionization

- The result indicates that ***either [1] intergalactic medium has a density very much lower than the mean baryon density of the Universe (gas is somehow segregated efficiently into galaxies) or [2] intergalactic gas is very highly ionized.***

- The absence of a Gunn-Peterson trough at redshifts $z < 5$ is now regarded as evidence that the IGM at low redshifts is highly ionized, not that it is absent.
- The figure shows spectra for high-redshift quasars. Notice that the Gunn-Peterson trough bluewards of the QSO Lyα emission is clearly apparent in the highest redshift ones.
- This indicates that the Universe has become somewhat more neutral at these redshifts. A similar behavior is also seen bluewards of the QSO Lyβ regions of the same spectra.
- These spectra show that the reionization of the IGM has ended at $z \approx 6$.



- In the figure, the filling factor of ionized hydrogen is denoted $Q_{\rm HII}$.
- The latest results (Planck Collaboration et al., 2015) places reionization at $z \sim 8.8$, assuming a model in which the universe is instantly reionized.
  - Studies of the cosmic microwave background (CMB) tell us of the column density of ionized material in front of the last scattering surface.
  - Thomson scattering of CMB photons upon free electrons causes the signal to become partially linearly polarized, allowing us to calculate a Thomson optical depth which in turn can be used to estimate when reionization took place.
  - The red arrow shows the instantaneous reionization redshift from Planck Collaboration et al. (2015).
- The gray shaded region schematically follows the evolution in the filling factor.



Summary of constraints on the redshift at which reionization took place. (Bouwens et al. 2015).

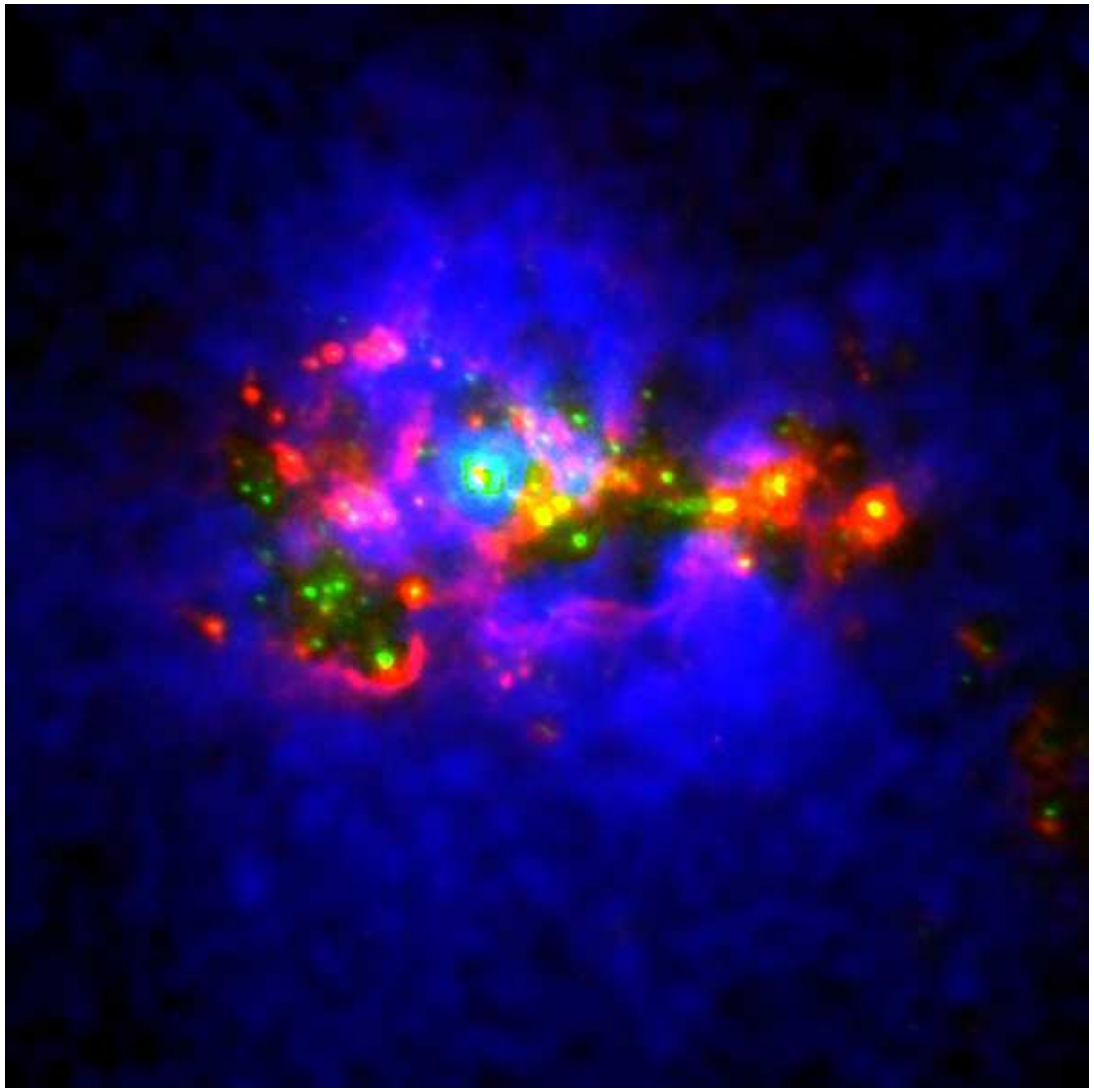
The points include Gunn-Peterson and Lyα dark gaps from Fan et al. (2006) and McGreer et al. (2015), quasar damping wings from Schroeder et al. (2013), and Lyα galaxies from Schenker et al. (2014).

Lyman-Alpha Emitters (LAEs)

- We have studied about the Lyα absorption features. How about the Lyα emission?
- A Lyman-alpha emitter (LAE) is a type of actively star-forming galaxy that emits Lyα radiation and (in general) low in mass.
  - The Lyα line in most LAEs is thought to be caused by recombination of interstellar hydrogen that is ionized by an ongoing burst of star-formation.
  - There are many methods available to find galaxies at high redshift. One method which is getting increasingly popular is that of targeting the Lyα emission of young, star-forming galaxies.
- History
  - It was first suggested by Patridge & Peebles (1967) that the Lyα emission line could be used to find distant galaxies, as it should be strong in star-forming systems.
  - It soon became clear that their assumptions were not realistic; for example, they assumed distant galaxies to have the same size as our Milky Way but with an average surface brightness equal to that of intense star formation. Even with more realistic assumptions taken into account, early surveys targeting the Lyα line ended up in failure (e.g., Pritchet 1994).
  - Meier & Terlevich (1981) found that only one metal-poor galaxy of the nearby, three galaxies showed any Lyα emission. The first detection of high-redshift Lyα emission was made in 1998 in Cowie & Hu (1998).
  - Now, thanks to new and improved technologies, the sample of known emitters at redshifts between z = 2-7 is growing rapidly.
  - ***What could be the causes of such difficulties in detecting Lyα emitting galaxies?***

- The Lyα photons are resonantly trapped.
  - The Lyα is a resonance line and thus becomes optically thick even at modest column densities.
  - Lyα photons are scattered ''endlessly'' in neutral hydrogen, which greatly increases the path length for these photons. This increases the chance of absorption by dust grains, so that even a small amount of dust can be enough to preferentially absorb the Lyα radiation.
  - However, the dust alone is not the decisive factor behind Lyα escape.
  - Lyα escape depends sensitively on the distribution and kinematics of neutral gas. Lyα scatters coherently in the rest frame of the H I atom, and at scattering events is shifted in frequency by the velocity of the scattering medium. Thus as Lyα may escape from galaxies because of frequency shifts, the kinetic structure of the atomic gas becomes imprinted onto the line.
  - ***Therefore, understanding the radiative transfer mechanism of Lyα is crucial.***
    - The sensitive dependence of Lyα transfer to the gas density distribution and kinematics complicates interpretations of Lyα observations.
    - On the other hand, the close interaction of the Lyα radiation field and gaseous flows in and around galaxies implies that the Lyα line contains information on the scattering medium, and may thus present an opportunity to learn more about atomic hydrogen in gaseous flows in and around galaxies.

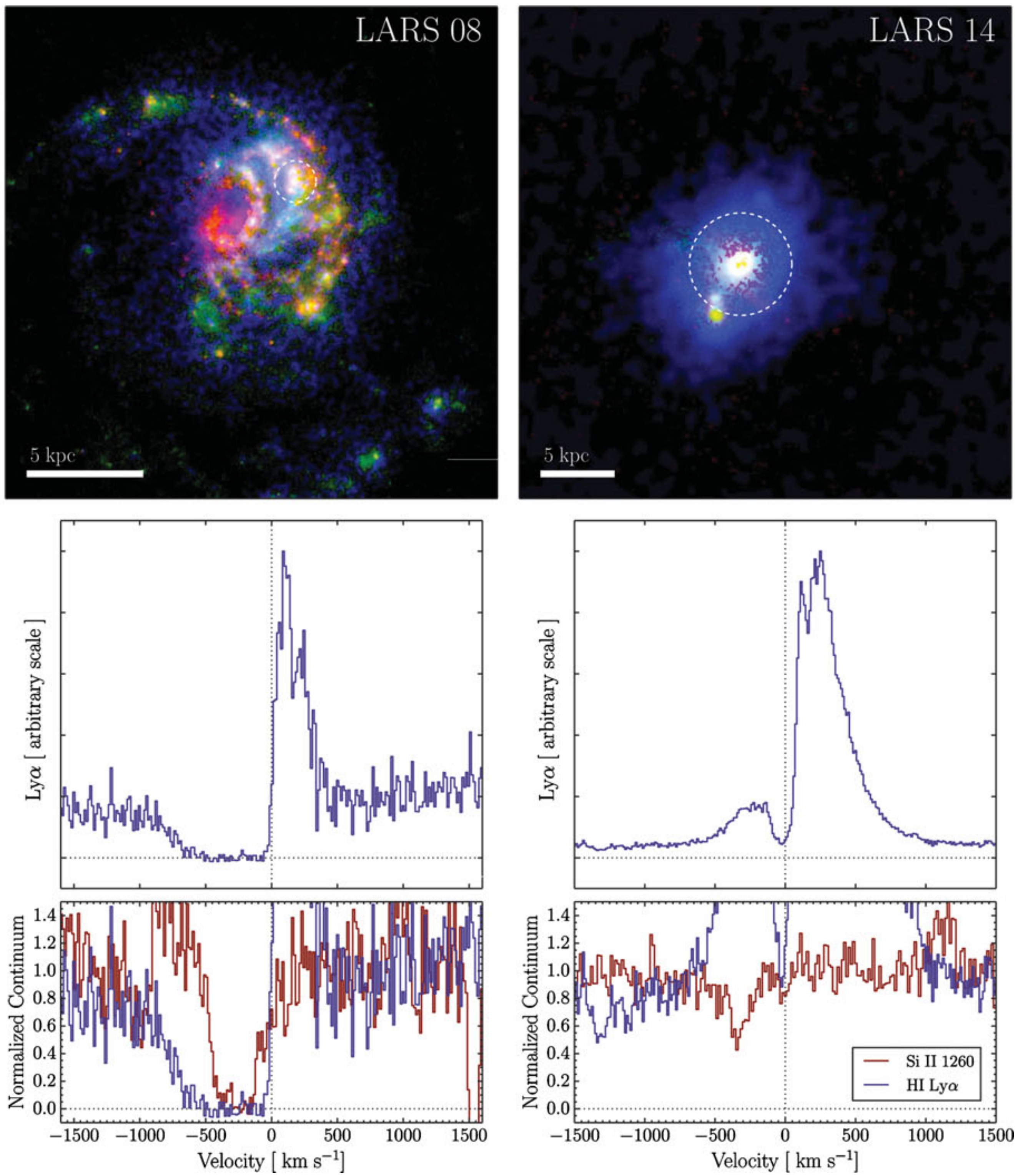
Nearby LAEs



- Lyman Alpha Reference Sample (LARS), a project in which 14 nearby galaxies and their Lyα emission are studied in detail using the Hubble Space Telescope.

- RGB composite of Hα (red), UV-continuum (green) and Lyα (blue) of the 38 Mpc distant, metal-poor, dwarf starburst galaxy ESO 338-04. The size of the image is 20x20 arcsec, or 3.5x3.5 kpc. ***Lyα emission is not dominated by the bright super star clusters that dominate the production of ionizing photons.***

- Towards most of them, Lyα is rather seen in absorption. ***Most of the escaping Lyα emission comes from a diffuse extended component*** where Lyα/Hα >> 10, that can only be produced by resonant scattering (Ostlin et al. 2009)



- Example images and Lyα spectra of local galaxies.
  - Upper panels show color composite images, encoding Hα in red, FUV continuum in green, and Lyα in blue.
  - Dotted white lines indicate the size and position of the HST/COS aperture.
  - Lower panels show the corresponding spectra around Lyα (dark blue) and SI II 1260Å (red).

Lyα Emission Mechanisms

- ***Collisional excitation***: The 'collision' between an electron and a hydrogen atom can leave the atoms in an excited state, at the expense of kinetic energy of the free electron. Then, the hydrogen atom emits Lyα and decays to the ground state. This process is also referred to as Lyα production via ***'cooling'*** radiation.

- ***Recombination***: Recombination of a free photon and electron can leave the electron in any quantum state (n, l). Radiative cascades to the ground state can then produce a Lyα photon.

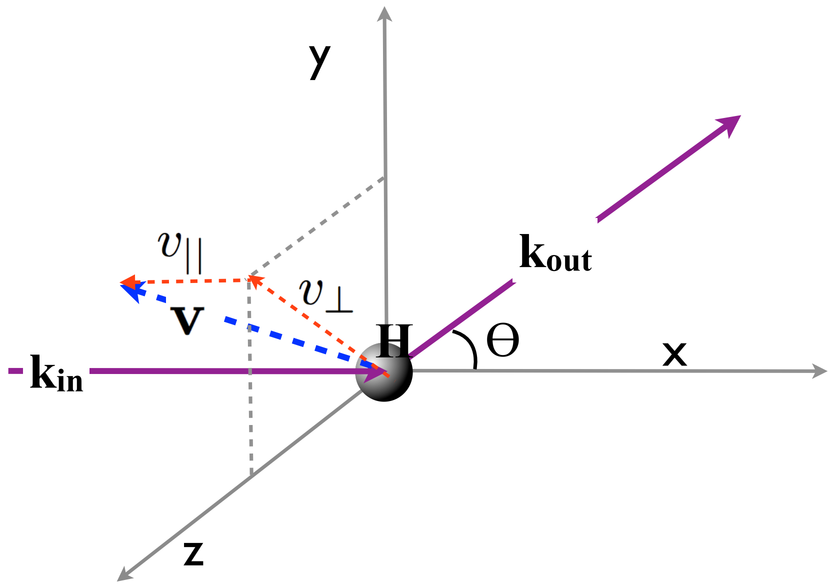
Astrophysical Lyα Sources

- ***Interstellar H II regions***
  - Interstellar H II regions are the most prominent sources of Lyα emission in the Universe. Hot, (mostly) massive and young stars produce ionizing photons (Lyman continuum; $E > 13.6$, $\lambda < 912\text{Å}$) in their atmospheres which are efficiently absorbed in the interstellar medium, and thus create ionized H II regions.
  - Recombining protons and electrons give rise to Lyα, Hα, etc lines. These lines are called 'nebular' lines.

- ***The Circumgalactic / Intergalactic Medium (CGM/IGM)***
  - Detailed analysis of the Lyα forest imply that the IGM is highly ionized. The CGM/IGM is photo ionized by the Universal "ionizing background" that permeates the entire Universe. The ionizing background is generated by adding the contribution from all ionizing sources.
  - Collisional excitation mechanism in the shock-heated warm ($T \sim 10^4$ K) or hot ($T \sim 10^6$ K) gas produces the cooling Lyα radiation.

Lyα scattering process

- Lyα scattering is coherent in the atom frame, but partially coherent in the lab (or gas) frame.
  - In most astrophysical conditions, the energy of the Lyα photon before and after scattering is identical in the frame of the absorbing atom. This is because the life-time of the atom in its $2p$ state is only $\Delta t = 1/A_\alpha \sim 10^{-9}$ s. In most astrophysical conditions, the hydrogen atom in this state in not 'perturbed' (by other particles) over this short time-interval, and energy conservation forces the energy of the photon to be identical before and after scattering.
  - Because of random thermal motions of the atom, energy conservation in the atom's frame translates to a change in the energy of the incoming and outgoing photon that depends on the velocity of the atom and the scattering direction. This type of scattering is known as ***'partially coherent' scattering***.



$$\nu_{\rm in}^{\rm atom} = \nu_{\rm in}^{\rm gas} - \frac{\nu_\alpha}{c}\mathbf{v}\cdot\mathbf{k}_{\rm in}$$

$$\nu_{\rm out}^{\rm gas} = \nu_{\rm out}^{\rm atom} + \frac{\nu_\alpha}{c}\mathbf{v}\cdot\mathbf{k}_{\rm out}$$

Here, $\nu_{\rm in}^{\rm atom} = \nu_{\rm out}^{\rm atom}$ if the atomic recoil is ignored. Then, we obtain

$$\nu_{\rm out}^{\rm gas} = \nu_{\rm in}^{\rm gas} - \frac{\nu_\alpha}{c}\mathbf{v}\cdot\mathbf{k}_{\rm in} + \frac{\nu_\alpha}{c}\mathbf{v}\cdot\mathbf{k}_{\rm out}$$

Basic Equations

Resonance-scattering cross-section

$$\sigma_\nu = \frac{\pi e^2}{m_e c} f_{12} \frac{\Gamma/4\pi^2}{(\nu-\nu_0)^2 + (\Gamma/4\pi)^2}$$

$$\begin{aligned}
\nu_0 &= 2.47\times10^{15}\ \mathrm{Hz,\ Ly}\alpha\ \mathrm{frequency}\\
f_{12} &= 0.4146,\ \mathrm{oscillator\ strength}\\
\Gamma &= 6.265\times10^{8}\ (=A_{21}),\\
&\quad \mathrm{damping\ constant\ (Einstein\ A\ coefficient)}\\
m_e &= \mathrm{electron\ mass}\\
e &= \mathrm{electron\ charge}\\
c &= \mathrm{speed\ of\ light}\\
v_z &= \mathrm{H\ atom's\ velocity\ along\ the\ photon\ direction}\\
v_{\rm th} &= \mathrm{thermal\ velocity\ of\ H\ atoms}
\end{aligned}$$

$$\begin{aligned}
u &\equiv v_z/v_{\rm th}\\
\Delta\nu_D &\equiv \nu_0 \frac{v_{\rm th}}{c}\\
x &\equiv \frac{\nu-\nu_0}{\Delta\nu_D}\\
a &\equiv \frac{\Gamma}{4\pi\Delta\nu_D}
\end{aligned}$$

optical depth

$$\tau = \sigma_0 N_{\rm HI} H(x,a)$$

$$\sigma_0 = 5.85\times10^{-14}\left(T/10^4\ \mathrm{K}\right)^{-1/2}\ \mathrm{cm}^2$$

Note that $H(x=0,\ a)\approx 1$ for $a \ll 1$.

Hjerting function: $H(x,a) = \frac{a}{\pi}\int_{-\infty}^{\infty} du \frac{e^{-u^2}}{(x-u)^2+a^2}$

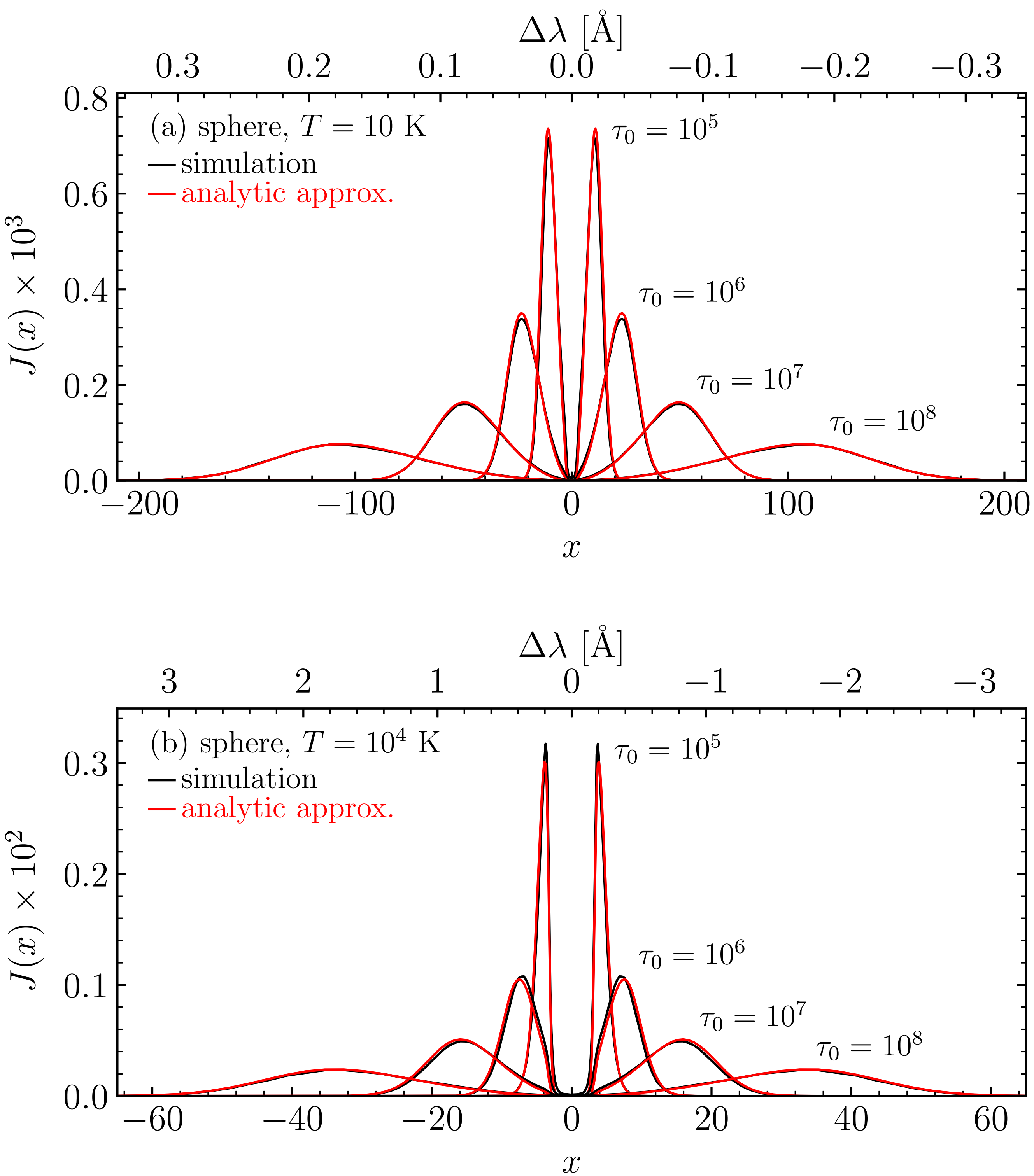
$$\sigma_{\nu_0} = \frac{1}{\sqrt{\pi}\Delta\nu_D}\frac{\pi e^2}{m_e c} f_{12}$$

In our Galaxy, a typical column density is $N_{\rm HI}\approx 10^{21}\ \mathrm{cm}^{-2}$.
Thus, the optical depth at the line center is

$$\boxed{\tau_0 = 5.9\times10^{7}\frac{N_{\rm HI}}{10^{21}\ \mathrm{cm}^{-2}}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1/2}}$$

The Lyα optical depth is really huge !!!

Emergent Lyα Spectra from a static medium



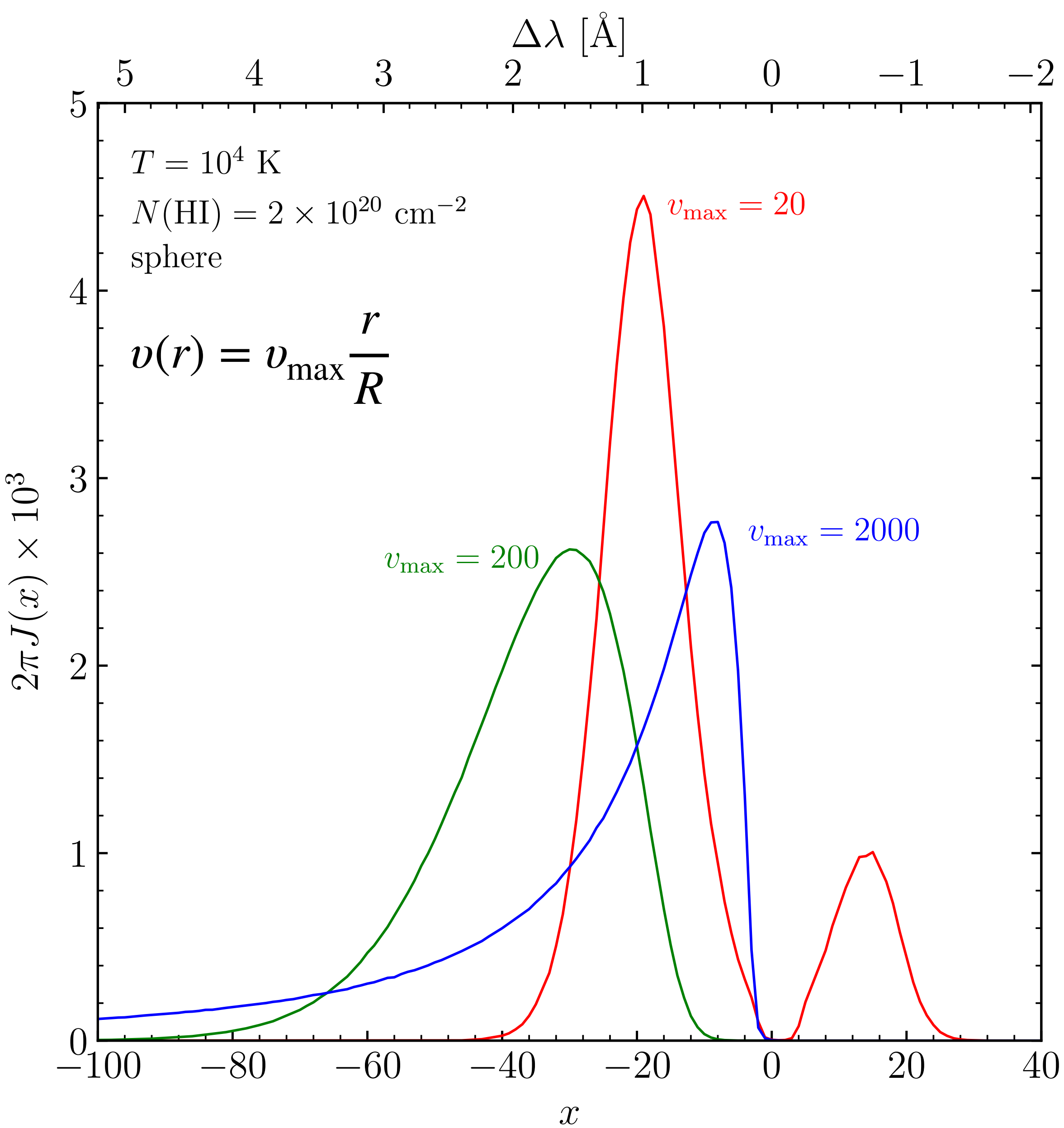
Seon & Kim (2019)

- Emergent Lyα spectra from a ***static***, homogeneous sphere at (a) $T = 10$ K and (b) $T = 10^4$ K, with various optical depths ($\tau_0 = 10^5, 10^6, 10^7, 10^8$).
- The emission-line profile has the characteristic double peak with a deep central trough.
  - The reason for this is the large cross-section at the line center. Thus, the Lyα photon cannot travel very far before it hits a hydrogen atom.
  - However, due to thermal motion of the gas atom, the photon picks up a small Doppler shift at each scattering, either to the blue or to the red. In this way the photons slowly diffuse not only in space but also in frequency. The move away from the line center makes the scattering cross-section decrease and thus it becomes easier to escape after having diffuse either to the red or the blue side of the line center.

Emergent Lyα spectra from an expanding medium

Emergent Lyα from an isotropically expanding spherical cloud.

In this simulation model, the expanding velocity profile is assumed to be $v(r) = v_{\rm max}\,(r/R)$, where R is the maximum radius of the spherical medium.

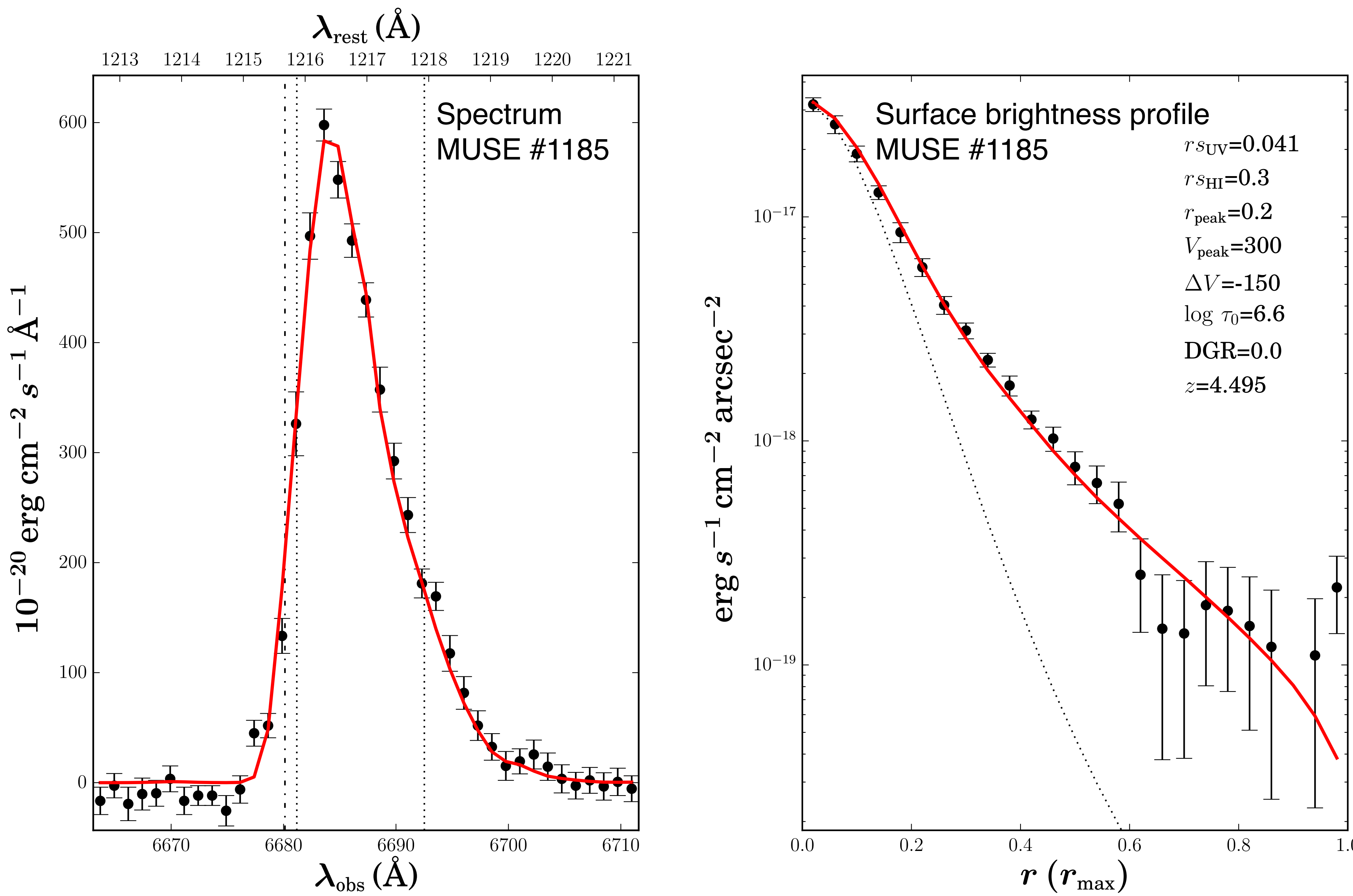


Seon & Kim (2019)

- If gas is outflowing, then in the reference frame of an outflowing shell of gas, the "blue" photons will be redshifted and thus be in the line center where the scattering cross-section is high. Hence they will scatter multiple times and be trapped in this gas, and once again diffuse in frequency.
- On the other hand, the "red" photons will be even redder in the reference frame of the outflowing gas, and pass through freely. The “blue” photons trapped in the shell can escape once they have diffused to the red side.
- Thus, outflows have the effect of erasing the blue peak, not by absorbing the photons, but rather by turning them into red photons.
- This is often the case in high-redshift galaxies due the enhanced star formation.

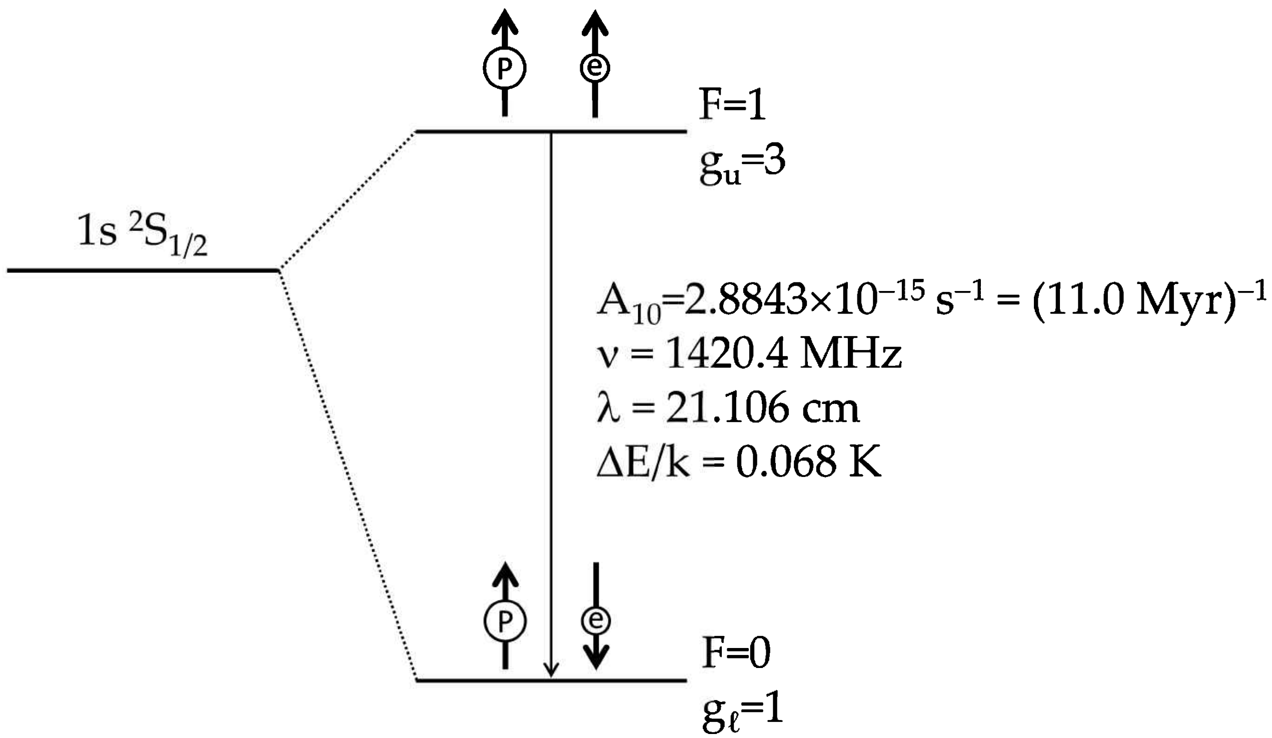
Lyα line profile and surface brightness profile

- In many cases, the Lyα line spectra from high-redshift galaxies show redshifted shapes, as shown in the following figure.
  - In this figure, the black symbols are observed data and the red lines are the best-fit models. We considered an outflow of the medium that represents a momentum-driven wind in a gravitational potential well. This result demonstrates that the outflowing halo model with Lyα scattering can successfully reproduce both the spectrum and the surface brightness profile of high-redshift galaxies at z =3–6.

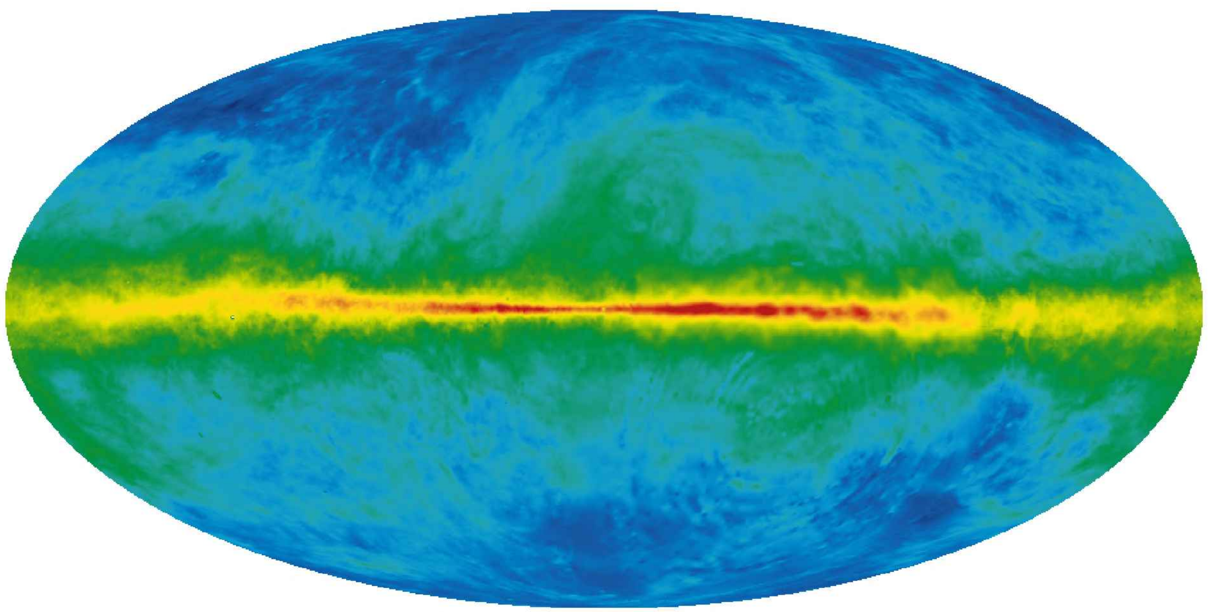


Song, Seon & Hwang (2019)

Hydrogen 21 cm Line



All-sky image of emission at 21 cm



- The 21 cm line is often called spin-flip transition in the ground state of the hydrogen atom
  - The higher energy state occurs when the proton and electron spins are parallel. The difference in energy between the spin-parallel state and the spin-antiparallel state is 5.87×10^{-6} eV, corresponding to a wavelength of 21 cm.
  - This energy difference is much lower than the kinetic temperature of the neutral ISM, as well as being lower than the temperature of the cosmic microwave background (CMB).
  - Therefore, the relative population between the two level will be readily controlled by collisions and the background radiation, such as CMB.

21 cm spin temperature

- The spin temperature of 21 cm line is defined by the relative population between two hyperfine levels.

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-h\nu_{21}/kT} = 3e^{-T_*/T} \quad (T_* = h\nu_{21\mathrm{cm}}/k = 0.068\ \mathrm{K})$$

- The spin temperature is determined by 3 mechanisms.
  - Direct Radiative Transitions by the background radiation field (Cosmic Microwave Background): $T_{\mathrm{CMB}} = 2.73\ \mathrm{K}$
  - Collisional Transitions (collision with hydrogen and electron): T_{gas}
  - Lyα pumping: Indirect Radiative Transitions involving intermediate levels by the scattering of Lyα photons:

The Lyα line profile is assumed to have a shape : $I(\nu) = I_0 \exp\left[-\frac{h(\nu-\nu_0)}{kT_\alpha}\right]$.

- Using the above definitions, the 21 cm spin temperature is determined by a combination of the three temperatures.

$$T_{\mathrm{spin}} = \frac{T_{\mathrm{CMB}} + y_{\mathrm{gas}} T_{\mathrm{gas}} + y_\alpha T_\alpha}{1 + y_{\mathrm{gas}} + y_\alpha},$$

where y_{gas} and y_α are weighting factors that depends on the particle density and the Lyα radiation intensity.

Spin temperature in a low density medium

- In a very low density medium, such as in the IGM, the collisional excitation and de-excitation are very weak ($y_{\rm gas} \ll 1$) and thus the direct radiative transition due to the CMB photons would predominantly control the relative population between the hyperfine structures (unless the Lyα pumping effect plays a role).
  - Then, the 21 cm spin temperature is equal to the CMB temperature: $T_{\rm spin} = T_{\rm CMB}$.
  - The radiative transfer equation in the Rayleigh-Jeans regime can be written in terms of temperature:

$$T(s) = T(0)e^{-\tau} + T_{\rm spin}\left(1 - e^{-\tau}\right)$$

  - If the spin temperature $T_{\rm spin}$ and the background temperature $T(0)$ are equal to the CMB temperature $T_{\rm CMB}$, then we have

$$T(s) = T_{\rm CMB}$$

  - This indicates that neither emission nor absorption feature from the hydrogen gas is detectable.

Wouthuysen-Field Effect

- Wouthuysen (1952, AJ, 57, 31)

Wouthuysen, S. A. On the excitation mechanism of the 21-cm (radio-frequency) interstellar hydrogen emission line.

The mechanism proposed here is a radiative one: as a consequence of absorption and re-emission of Lyman-α resonance radiation, a redistribution over the two hyperfine-structure components of the ground level will take place. Under the assumption—here certainly permitted—that induced emissions can be negelcted, it can easily be shown that the relative distribution of the two levels in question, under stationary conditions, will depend solely on the shape of the radiation spectrum in the Lα region, and not on the absolute intensity.

The shape of the spectrum of resonance radiation, quasi-imprisoned in a large gas cloud, could only be determined by a careful study of the "scattering" process (absorption and re-emission) in a cloud of definite shape and dimensions. The spectrum will turn out to depend upon the localization in the cloud.

Some features can be inferred from more general considerations. Take a gas in a large container, with perfectly reflecting walls. Let the gas be in equilibrium at temperature T, together with Planck radiation of that same temperature. The scattering processes will not affect the radiation spectrum. One can infer from this fact that the photons, after an infinite number of scattering processes on gas atoms with kinetic temperature T, will obtain a statistical distribution over the spectrum proportional to the Planck-radiation spectrum of temperature T. After a finite but large number of scattering processes the Planck shape will be produced in a region around the initial frequency.

Photons reaching a point far inside an interstellar gas cloud, with a frequency near the Lα resonance frequency, will have suffered on the average a tremendous number of collisions. Hence in that region, which is wider the larger the optical depth of the cloud is for the Lyman radiation, the Planck spectrum corresponding to the gas-kinetic temperature will be established as far as the shape is concerned. Because, however, the relative occupation of the two hyperfine-structure components of the ground state depends only upon the shape of the spectrum near the Lα frequency, this occupation will be the one corresponding to equilibrium at the gas temperature.

The conclusion is that the resonance radiation provides a long-range interaction between gas atoms, which forces the internal (spin-)degree of freedom into thermal equilibrium with the thermal motion of the atoms.

Institute for Theoretical Physics of the City University, Amsterdam.

Using a thermodynamic argument, Wouthuysen speculated the followings:

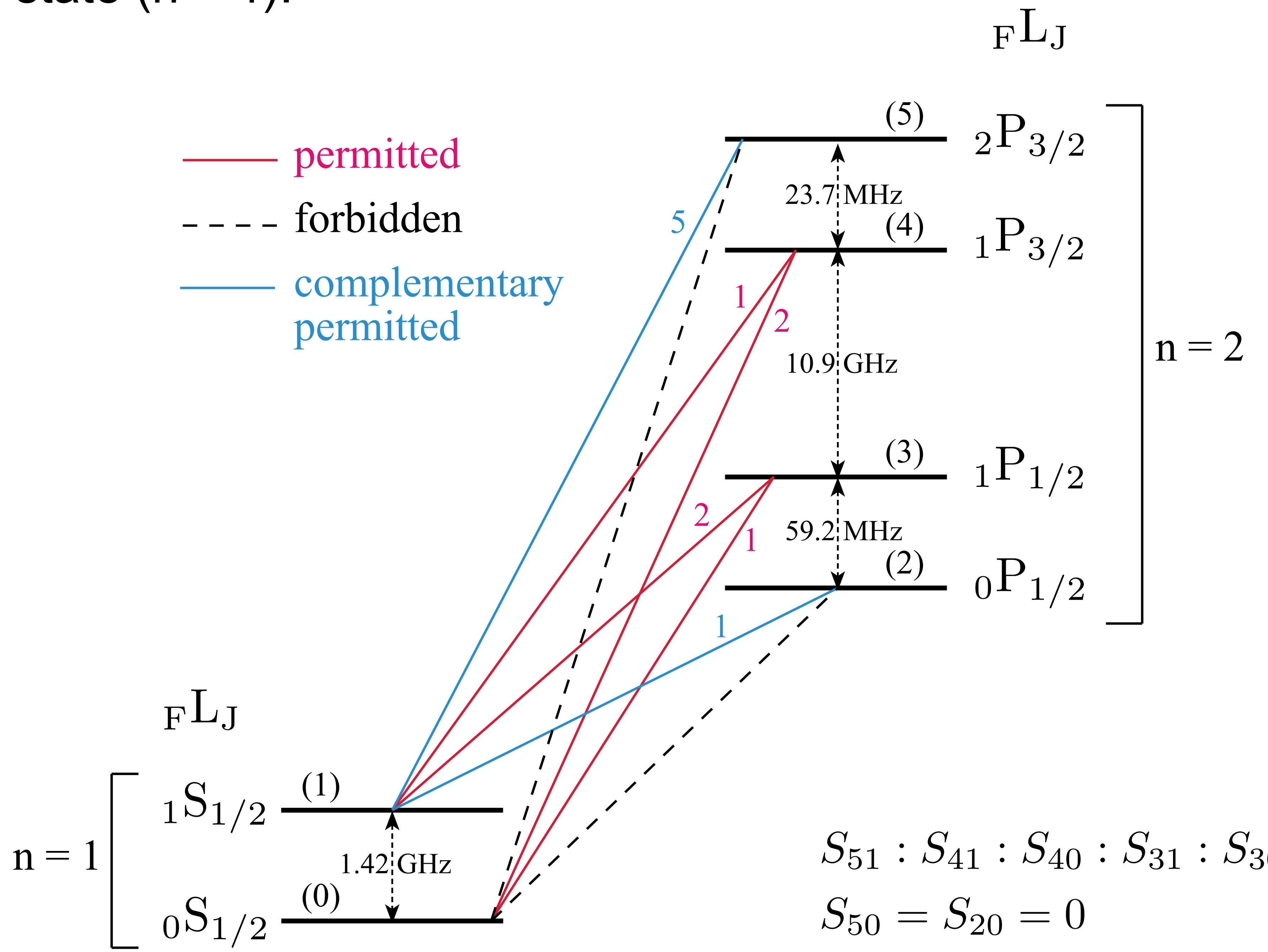
A tremendous number of scattering will establish the Planck-like spectrum, at the Lyα line center, corresponding to the gas-kinetic temperature.

Then, the Lyα spectrum is coupled with the hyperfine state of the hydrogen atom.

In the end, ***the 21cm spin temperature will become equal to the kinetic temperature of the hydrogen gas.***

Coupling between the Lyα and 21 cm population

- Lyα line is not caused by a single transition.
- While Lyα photons are absorbed and re-emitted, the transitions between the hyperfine levels of n = 2 and n = 1 will alter the hyperfine populations in the group state (n = 1).



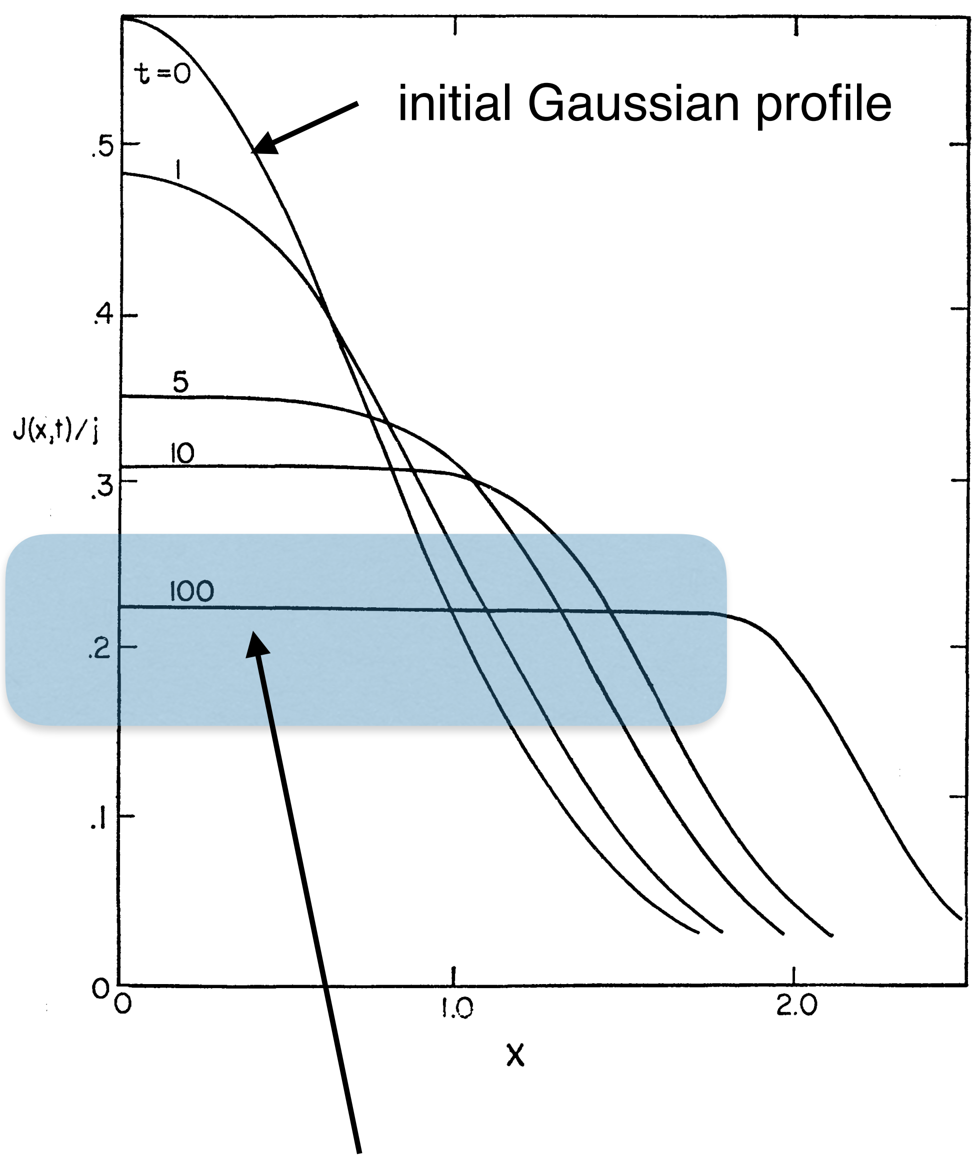
$$S_{51} : S_{41} : S_{40} : S_{31} : S_{30} : S_{21} = 5 : 1 : 2 : 2 : 1 : 1$$

$$S_{50} = S_{20} = 0$$

Relaxation of Lyα Profile

- Field (1958, PIRE, 46, 240; 1959, ApJ, 129, 551)

Recoil effect = momentum transfer between H atom and photon



spectral shape at the Lyα line center

Without recoil:

The spectral profile of Lyα, ***within the medium,*** becomes flat at the line center when the photons undergo a large number of resonance scatterings.

$$J(\nu,\, t \rightarrow \infty) = \mathrm{constant}$$

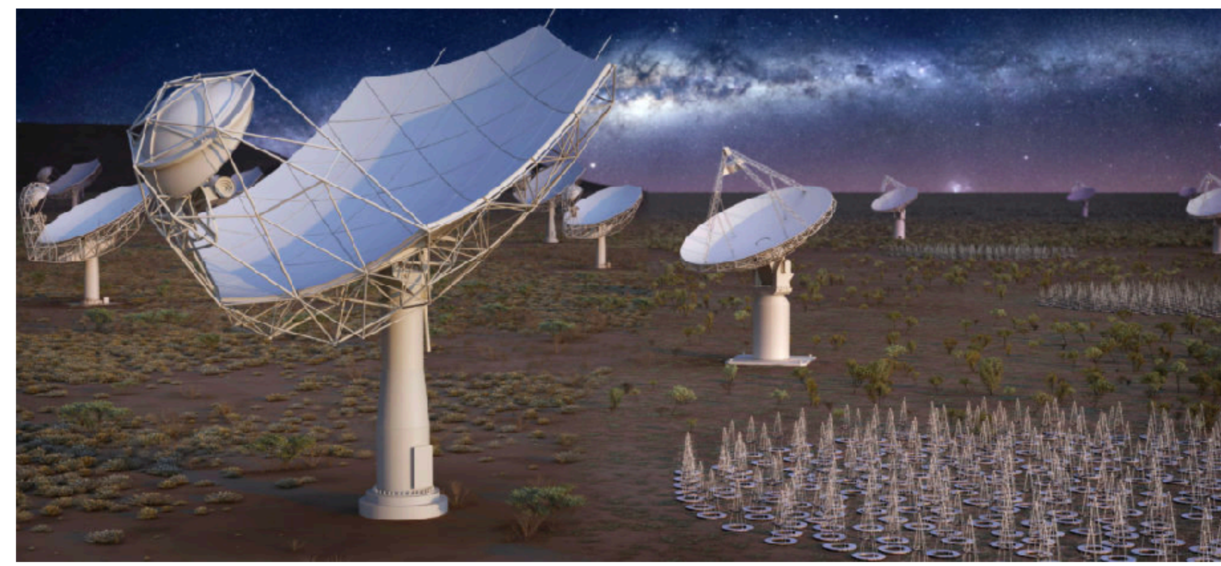
With recoil:

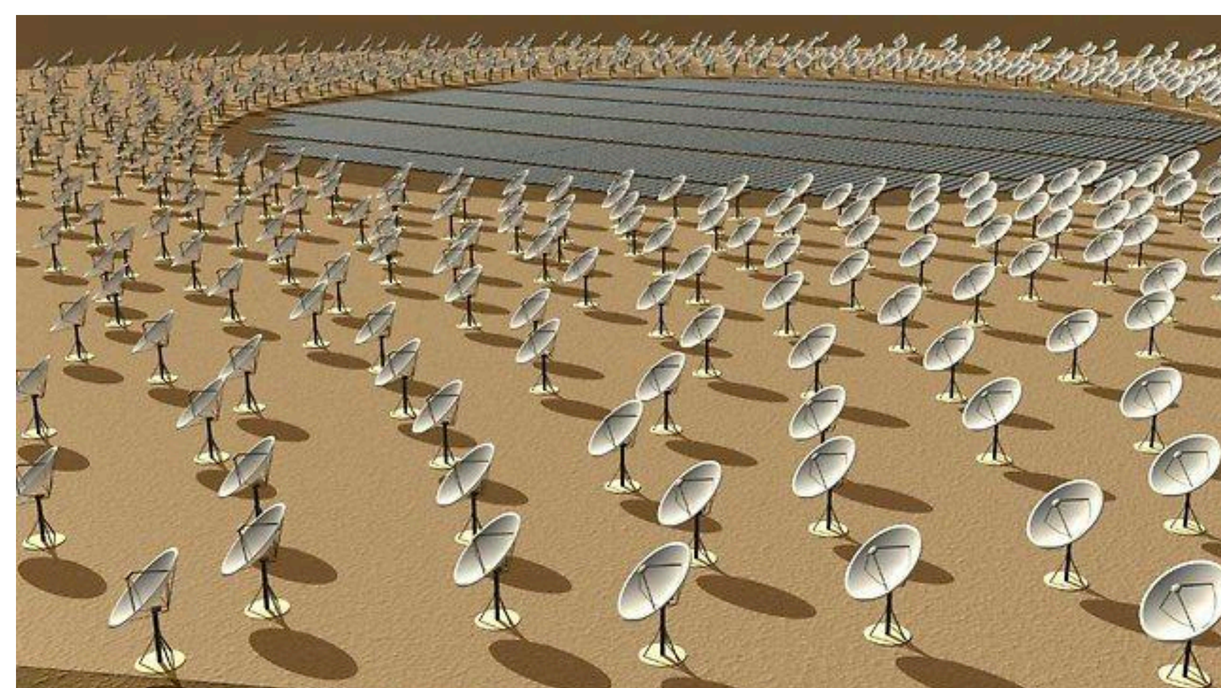
Recoil of the scattering atom changes the slope of the Lyα central profile ***"at the limit of an infinite number of scattering"*** and gives a Boltzmann like (exponential) functional shape:

$$J(\nu,\, t \rightarrow \infty) \propto e^{-\frac{h(\nu-\nu_\alpha)}{kT_{\rm gas}}}$$

SKA project

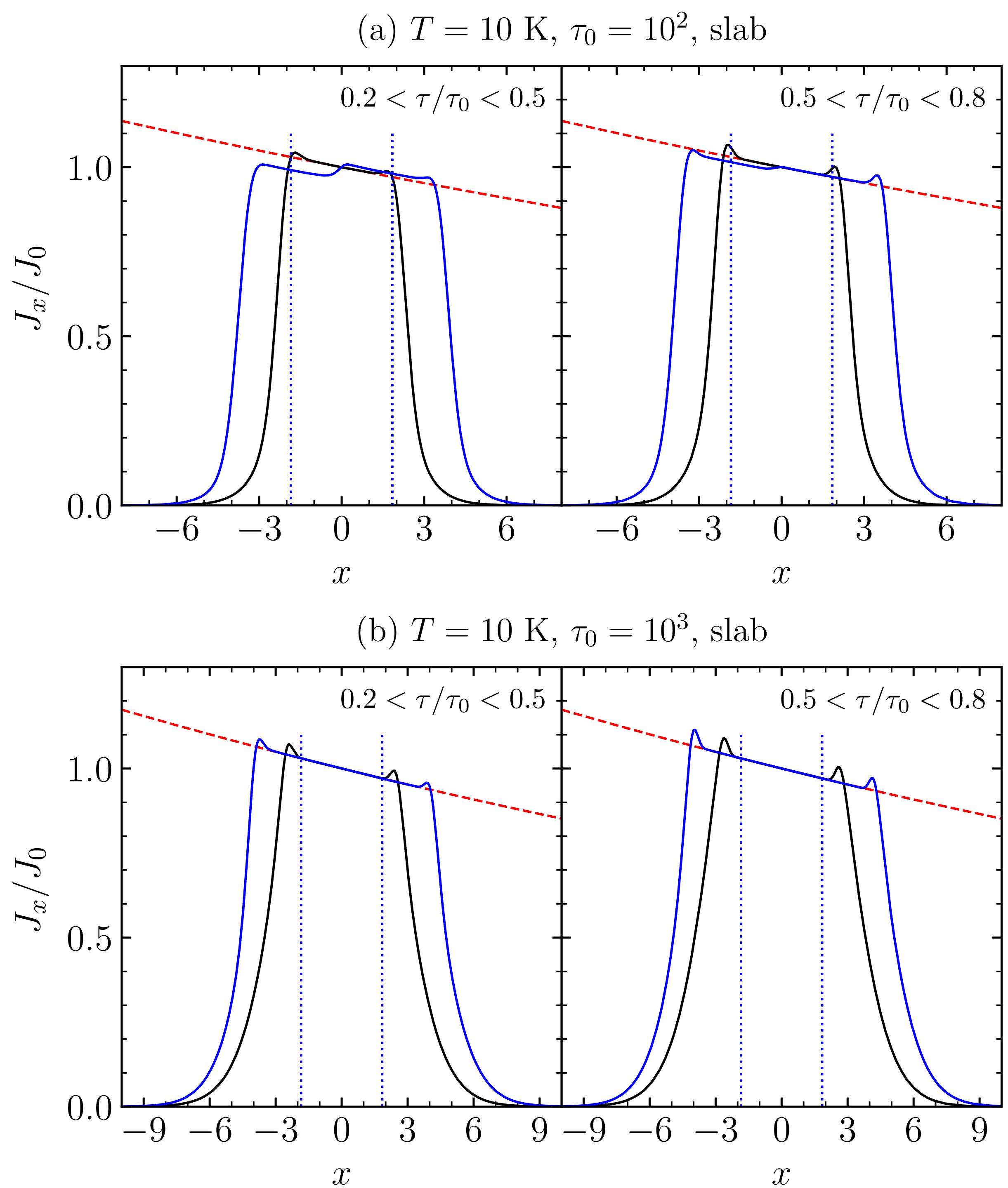
- The first stars and galaxies in the reionization epoch will produce a huge number of Lyα photons and these photons are expected to have coupled the H I spin temperature to the gas kinetic temperature via scattering in the Lyα resonance.
- By establishing an H I spin temperature different from the temperature of the CMB, ***the WF coupling should allow observations of H I during the reionization epoch using the redshifted 21 cm line.***
- This is one of the main objectives of the Square Kilometer Array (SKA).
    - The full SKA will include several hundreds of dishes (up to two thousand, though the exact number is not yet fully defined), each 15m in diameter. The majority of these dishes will be located in South Africa.
    - The SKA project in now in its final pre-construction phase (or detailed design phase) which consists of fine-tuning the design of the telescope. The SKA is to be constructed in two phases: Phase 1 (SKA1) and Phase 2 (SKA2). SKA1 is due to begin construction around the end of 2021.





The Lyα spectral profile inside the medium

- But, wait!!
  - How many scattering is enough for the WF effect?
  - No clear answer has been provided until now.
- The left-side figures show the Lyα spectra calculated using a Monte-Carlo method.
  - The red dashed lines represent the exponential function $e^{-h(\nu-\nu_0)/kT_{\rm gas}}$.
  - The blue and black lines are Lyα spectra predicted from the simulation.
- The Lyα spectra ***"inside"*** the medium clearly show a Boltzmann-like shape with the gas kinetic temperature $T_{\rm gas}$ even at an optical depth as low as $\tau_0 = 10^2$.
- ***Therefore, the WF effect would occur in most of astrophysical circumstances.***



Seon & Kim (2019)