The Epoch of Reionization & First Galaxies

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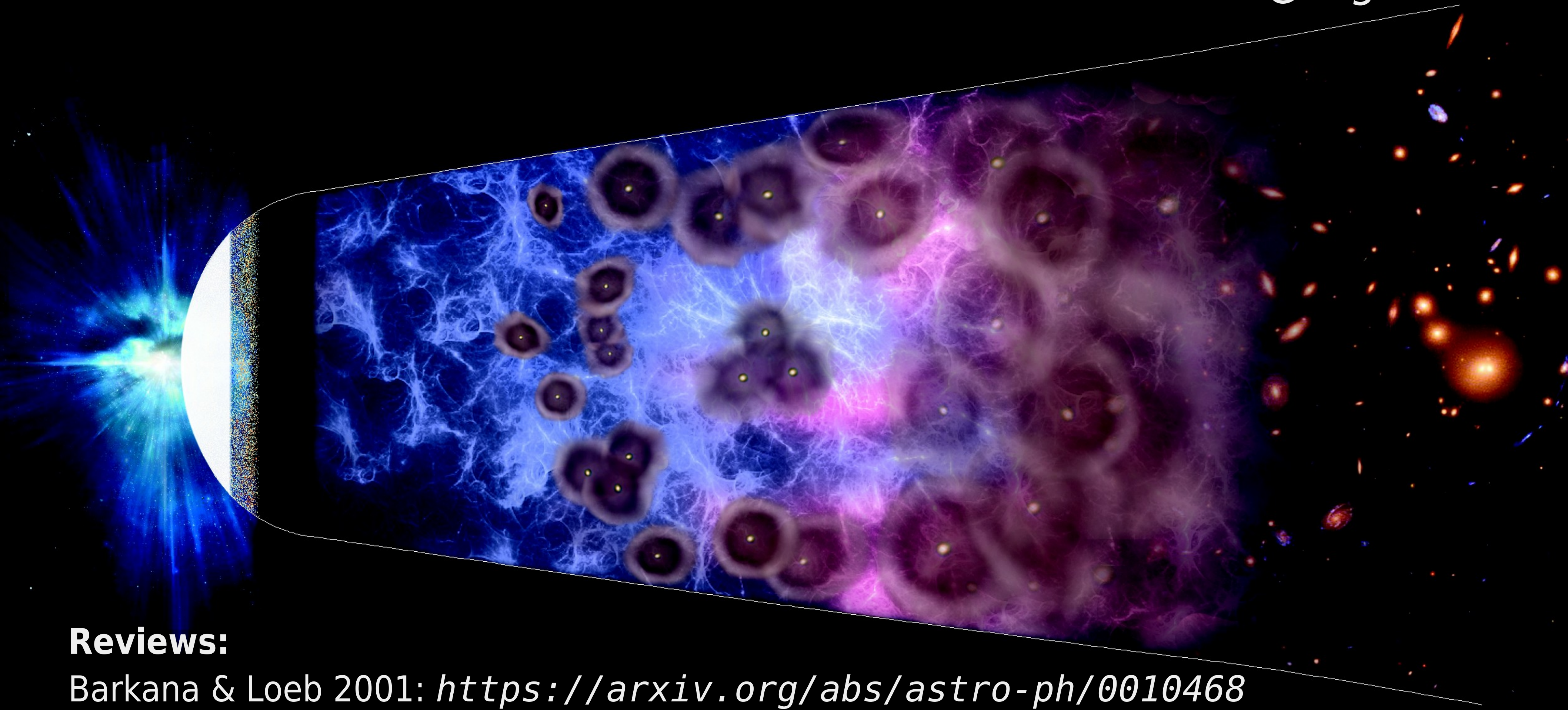
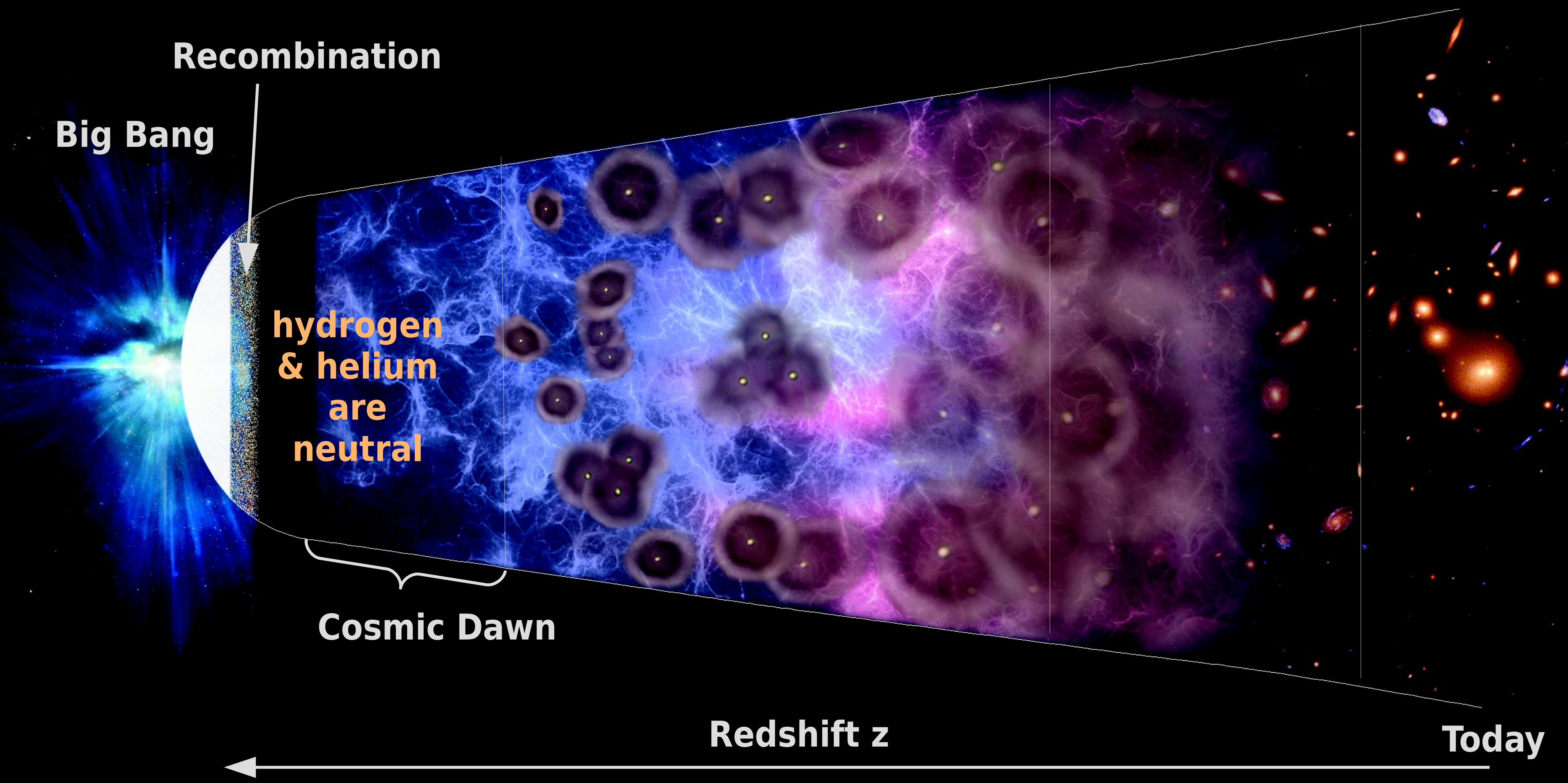


Reviews:

Barkana & Loeb 2001: *https://arxiv.org/abs/astro-ph/0010468*
Furlanetto, Oh & Briggs 2006: *https://arxiv.org/abs/astro-ph/0608032*

Credits: ERC and EU Research SPR19/P53

The evolution of the Universe



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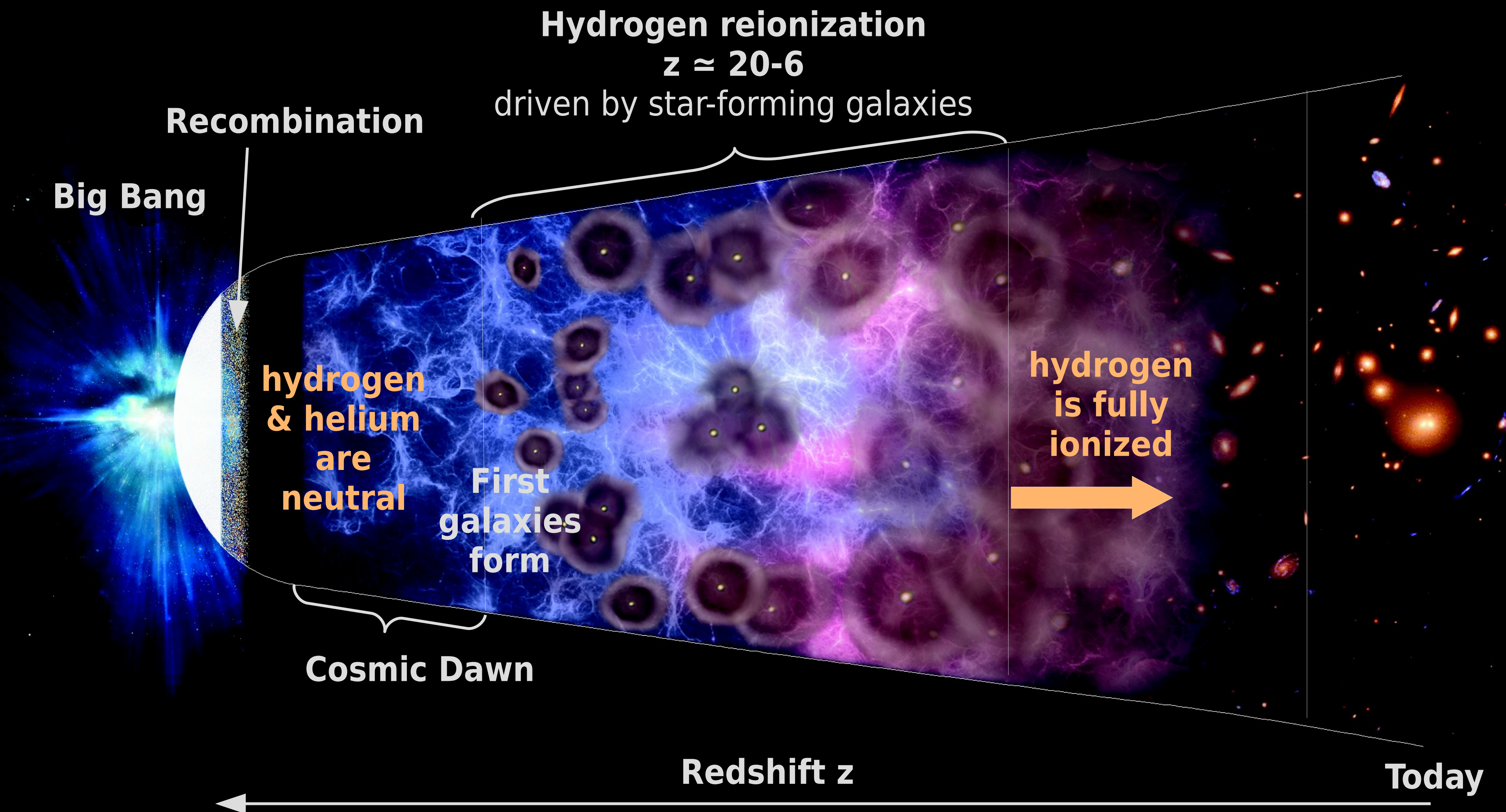

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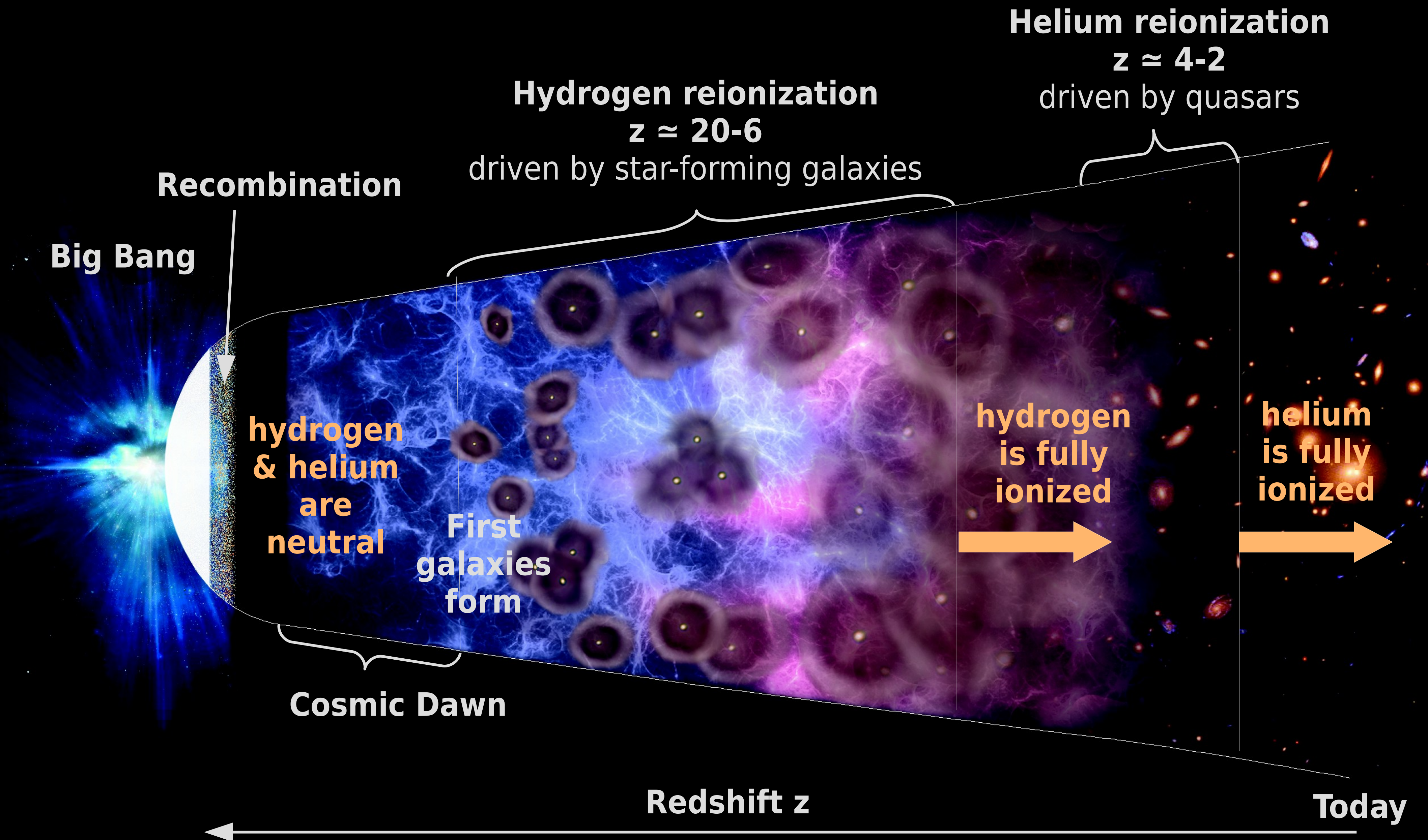

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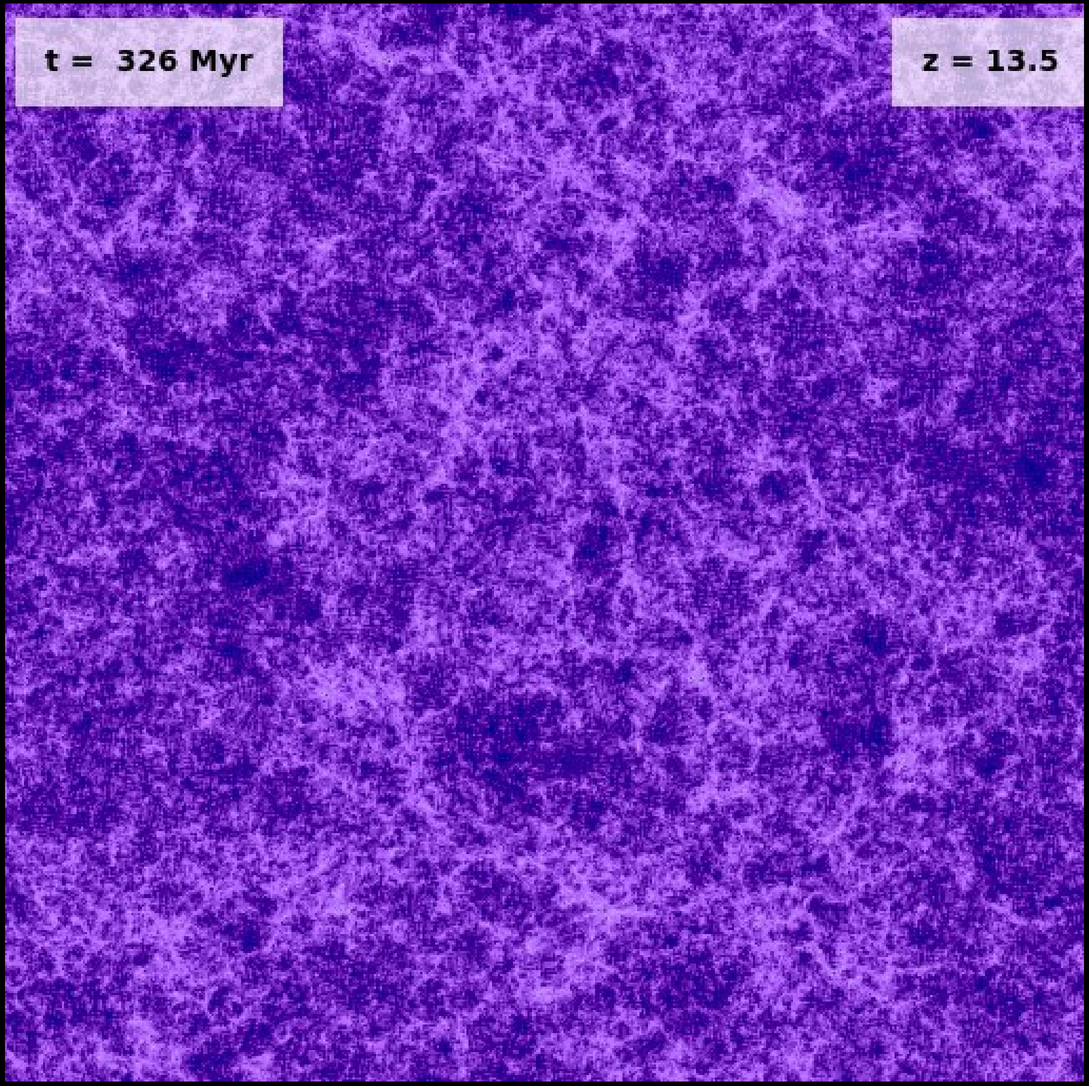
Hydrogen reionization



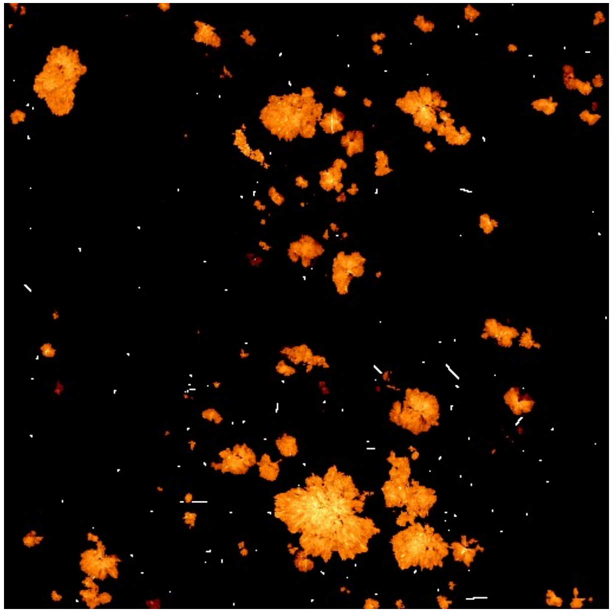
Hydrogen reionization

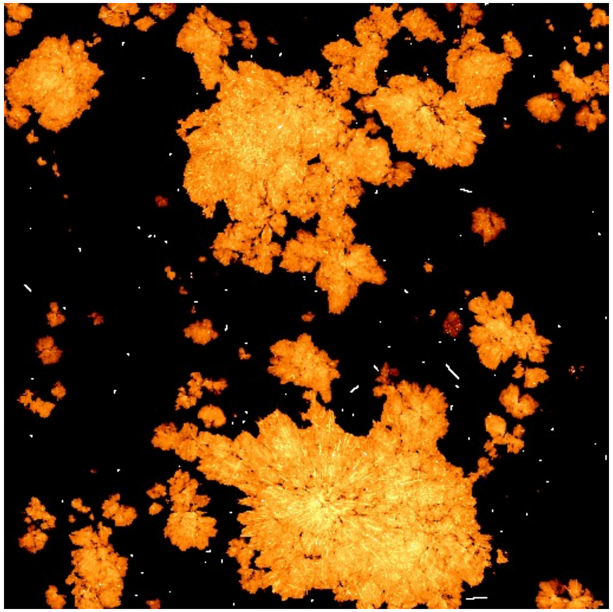
PRE OVERLAP PHASE
Each galaxy builds a region of ionized hydrogen around itself, the Strömgren sphere

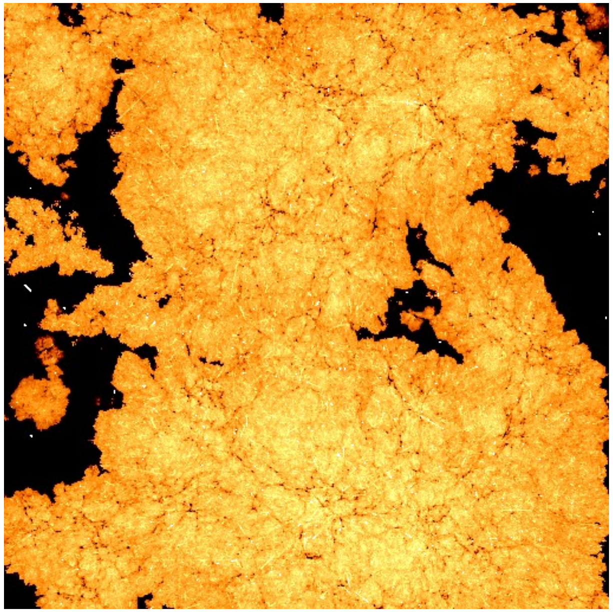
OVERLAP PHASE
Ionized spheres grow and start merging

POST OVERLAP PHASE
Large ionized regions start to merge and reionize the left-over neutral islands

START *Reionization continues* ***END***

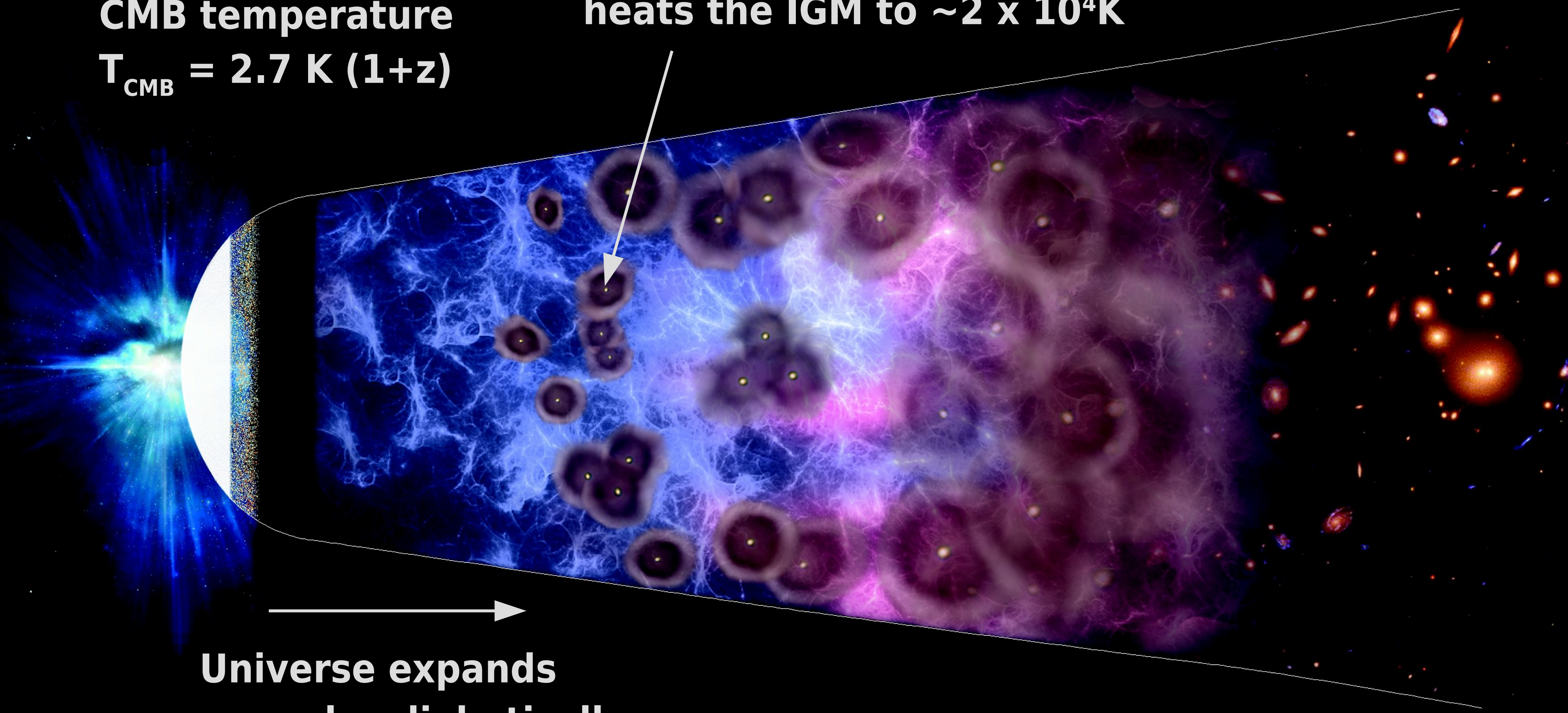






Reionization is inhomogeneous and extended.

Thermal evolution of the IGM



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The thermal evolution of the IGM

After recombination the Universe cools adiabatically.

→ $p V^{\gamma} = \text{const.}$

For an ideal gas we have: $p V = N k_B T$

→ $T V^{\gamma-1} = \text{const.}$

For monoatomic gas: $\gamma = 5/3$

→ $T V^{2/3} = \text{const.}$

→ $T \propto V^{-2/3}$

p = pressure

V = volume

T = temperature

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For monoatomic gas: $\gamma = 5/3$

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→ $T \propto V^{-2/3} \propto a^{-2}$

$T \propto (1+z)^2$

p = pressure

V = volume

T = temperature

Scalefactor $a = 1 / (1+z)$

Beginning: $a = 0, z = \infty$

Today: $a = 1, z = 0$

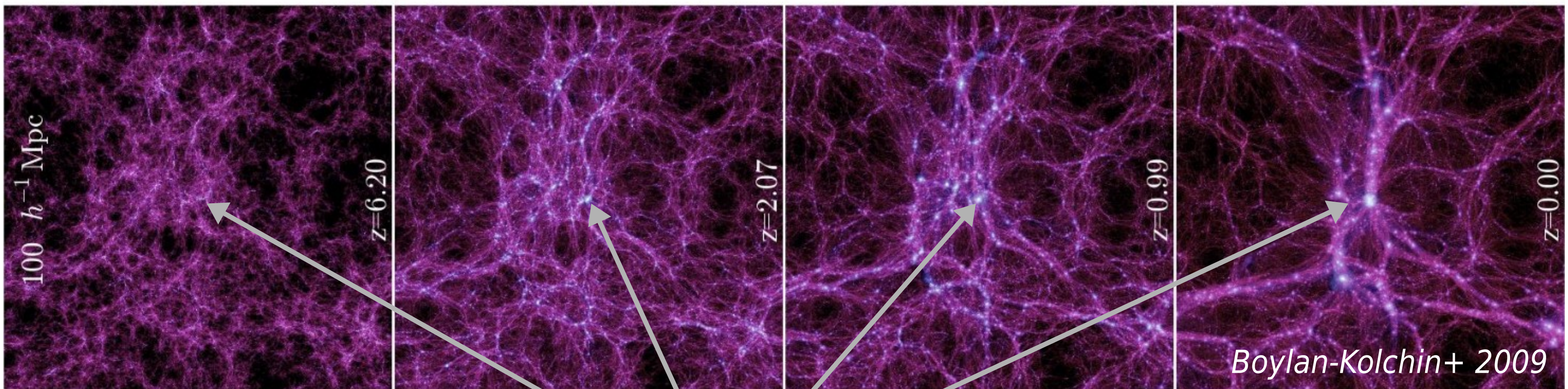
Length: $L(a) = L_0\, a$

Volume: $V(a) = L(a)^3 = L_0^3\, a^3$

$V \propto a^3$

Sources of reionization

earlier **time** later



most massive galaxies form earlier
& have more time to grow

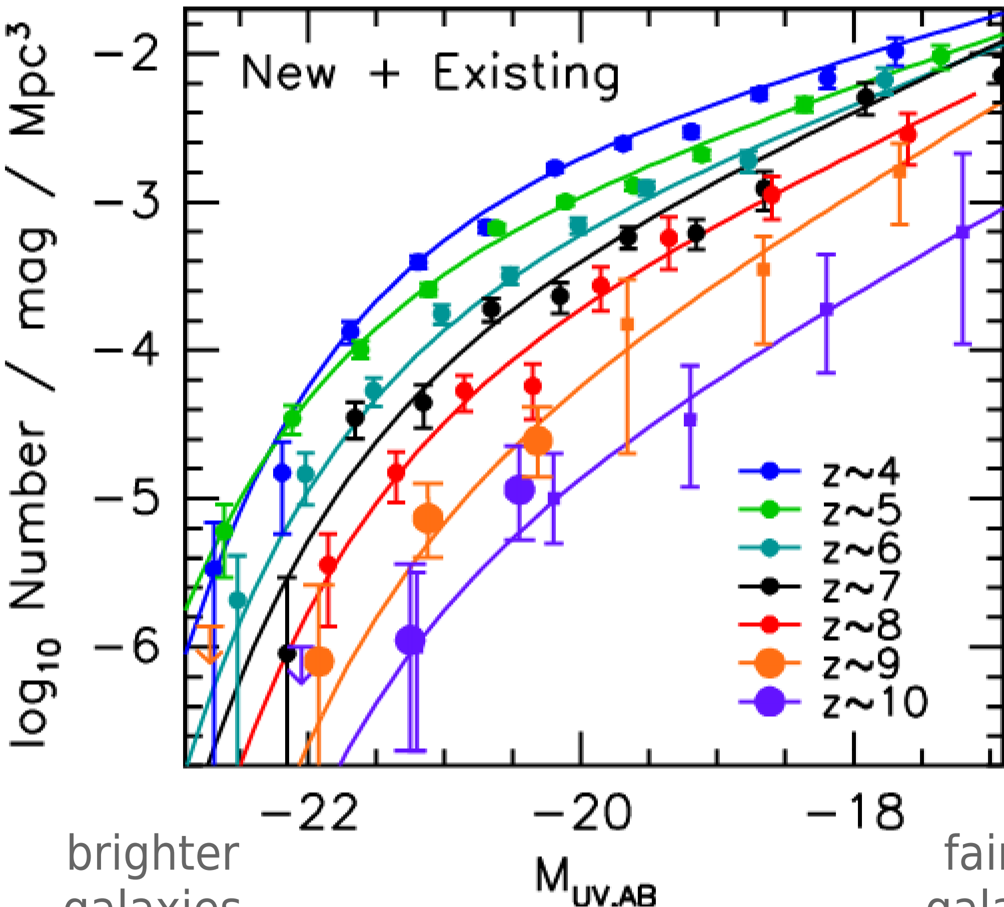
Gravity causes the initial fluctuations in the density field to grow over time, i.e. slightly over-dense regions increase their density and become more confined, while slightly under-dense regions become more under-dense.

Galaxies form in the density peaks. The most massive galaxies have formed in the very first density peaks, while less massive galaxies have formed later.

At each time there are far more low massive galaxies than very massive galaxies.

Sources of reionization

Bouwens+ 2019

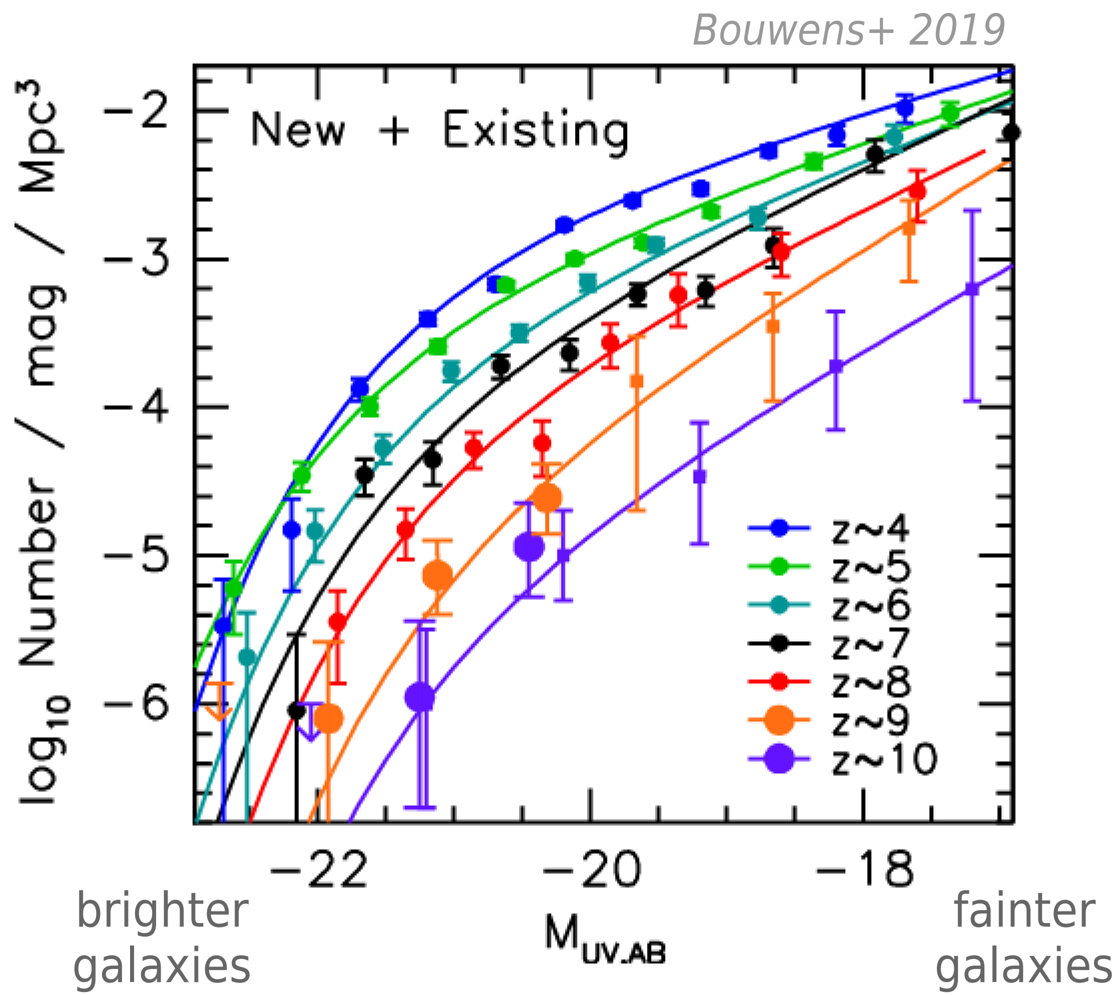


brighter galaxies

fainter galaxies

Observations of the luminosities of the first galaxies have confirmed:

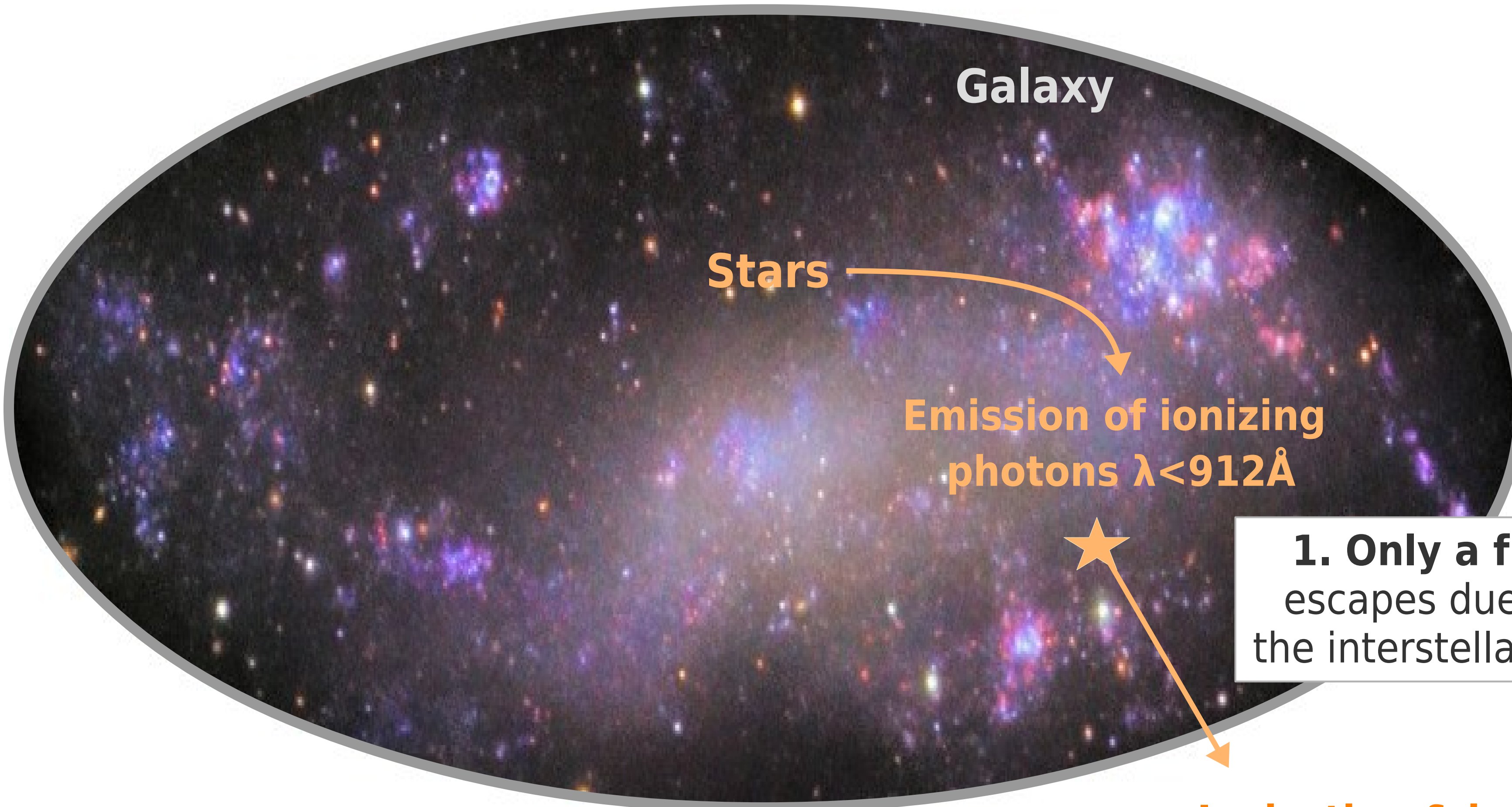
Sources of reionization



Observations of the luminosities of the first galaxies have confirmed:

- There are more fainter (low mass) than brighter (high mass) galaxies.
- The number of galaxies increases as the Universe evolves.

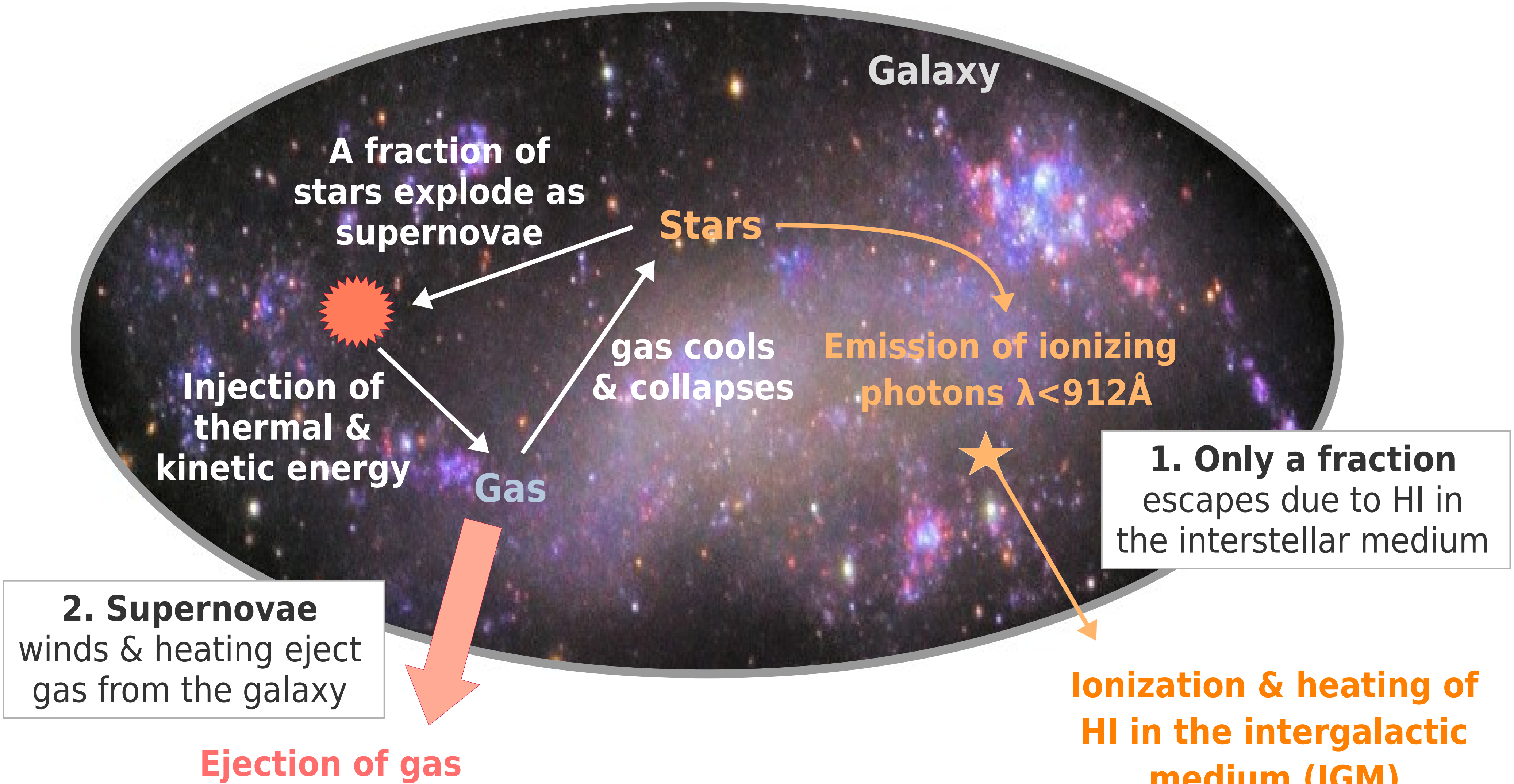
What physical processes affect the contribution of galaxies to reionization?



1. Only a fraction escapes due to HI in the interstellar medium

Ionization & heating of HI in the intergalactic medium (IGM)

What physical processes affect the contribution of galaxies to reionization?



Reionization feedback on galaxies

The virial temperature of a halo with virial mass M_{vir} at redshift z can be determined as

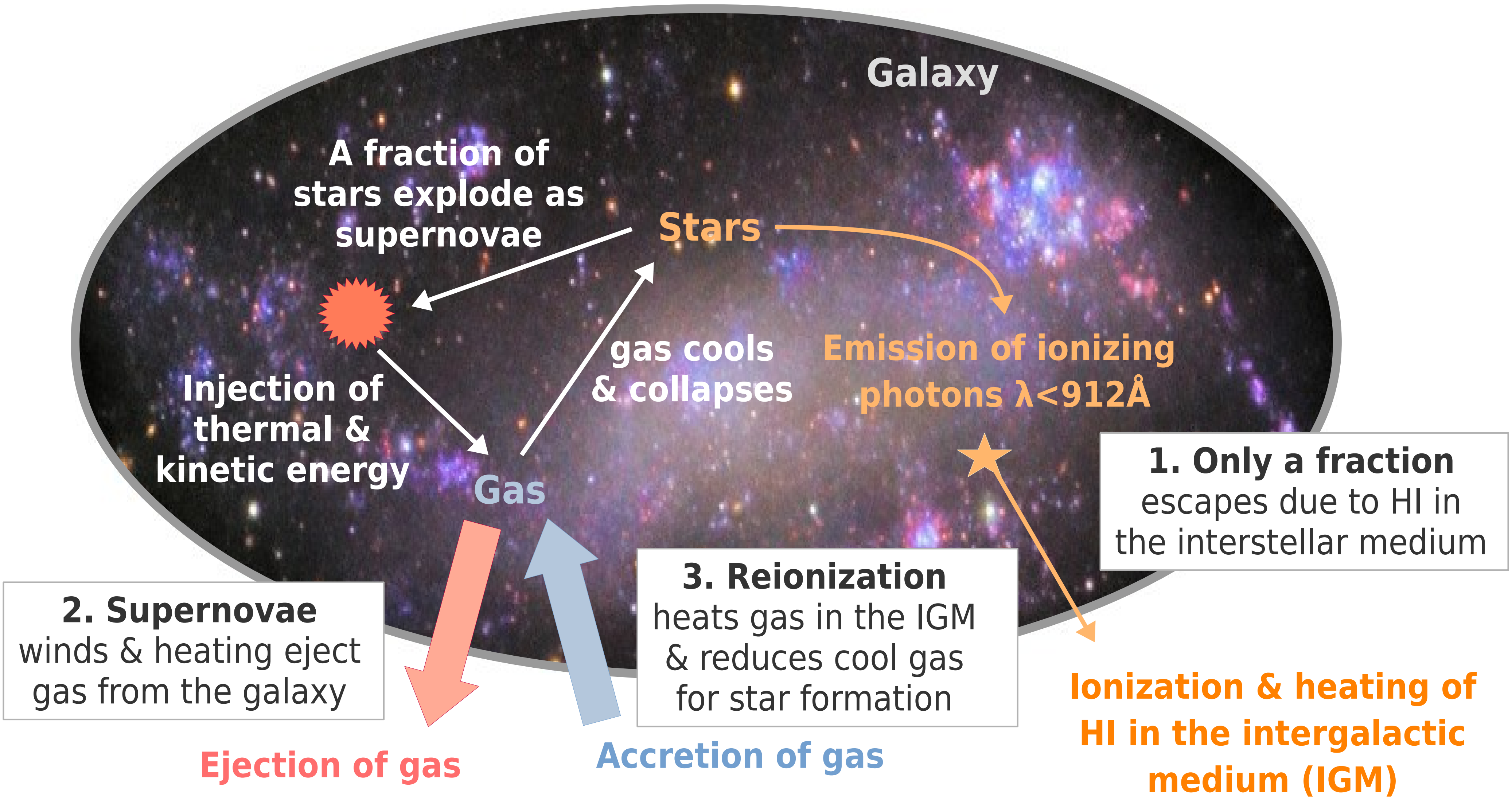
$$T_{vir} = 1.69 * 10^4 \left(\frac{\mu}{0.6}\right) \left(\frac{\Omega_m}{0.3}\right)^{1/3} \left(\frac{1+z}{10}\right) \left(\frac{M_{vir}}{10^8 h^{-1} M_{sun}}\right)^{2/3} K$$

where μ is the molecular mass and Ω_m the matter density parameter.

A halo of 10^8 M_{sun} has at z=9 has a virial temperature of T_{vir}~2×10^4K. Imagine a halo with a smaller mass embedded in an ionized region (T~2×10^4K). What happens to its gas?

Slide credit: P. Dayal

What physical processes affect the contribution of galaxies to reionization?



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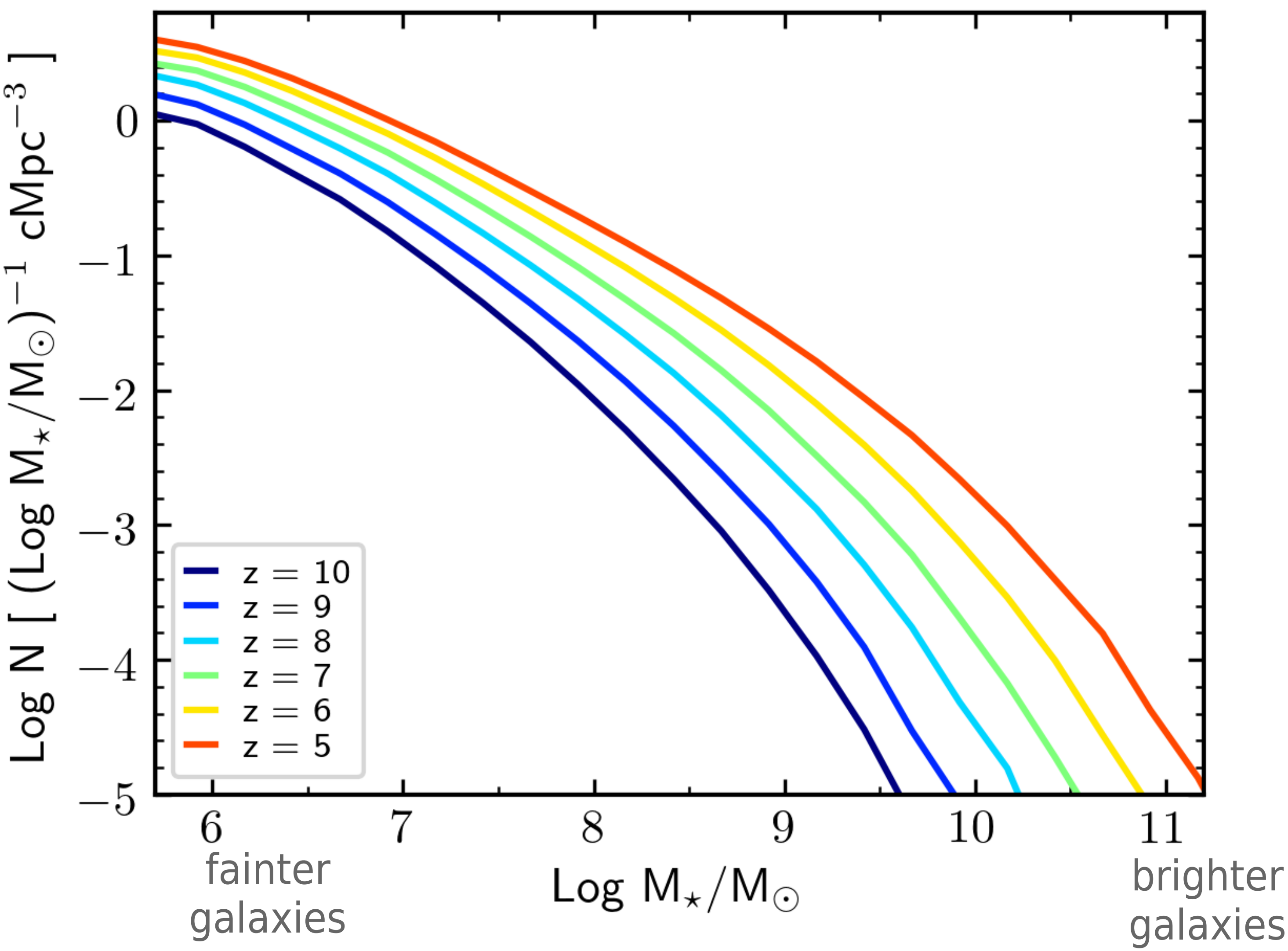

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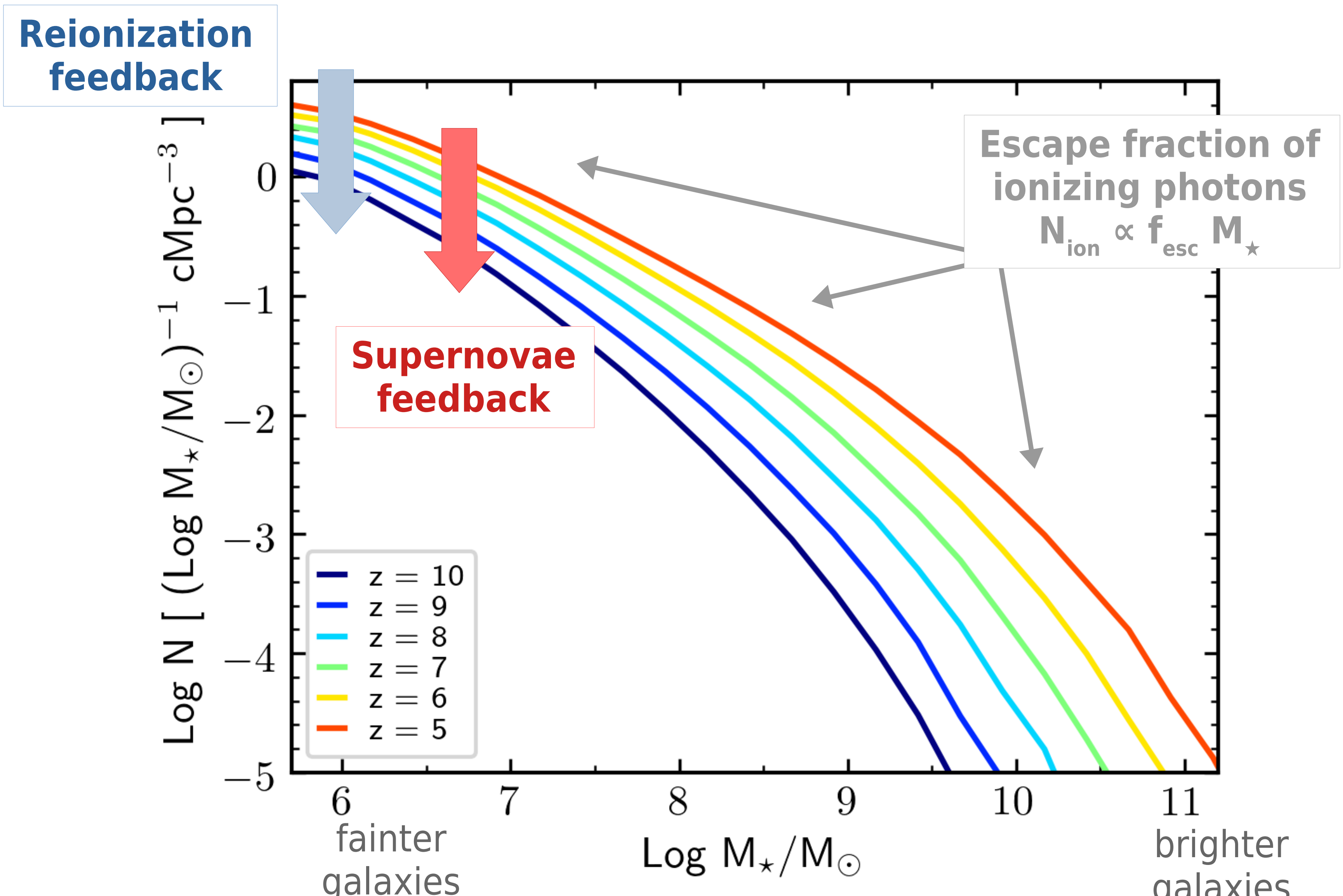
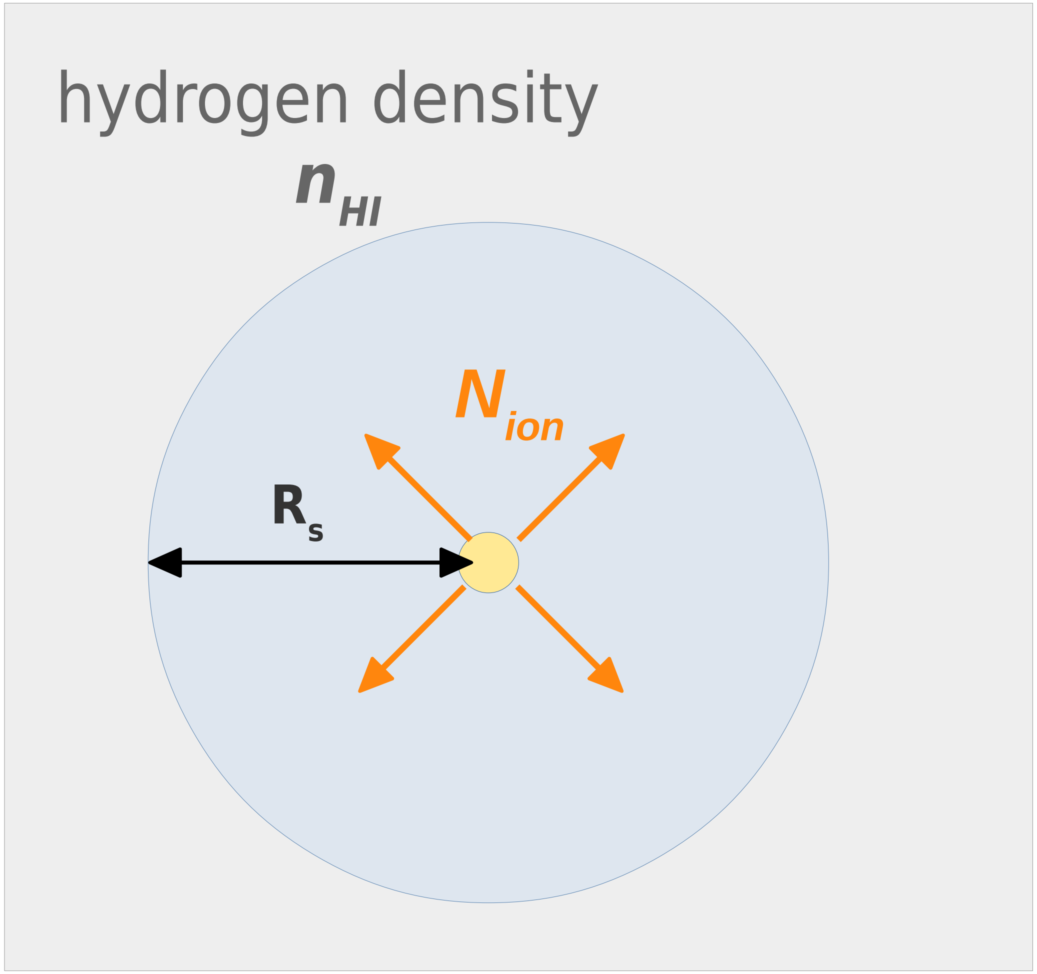


Strömgren sphere

Galaxy emits hydrogen ionizing photons ($\lambda < 912$Å) at a rate N_{ion} [number/sec]

The intergalactic medium around the galaxy has a number density n_{HI} [cm^{-3}]



What is the size of the ionized sphere around the galaxy?

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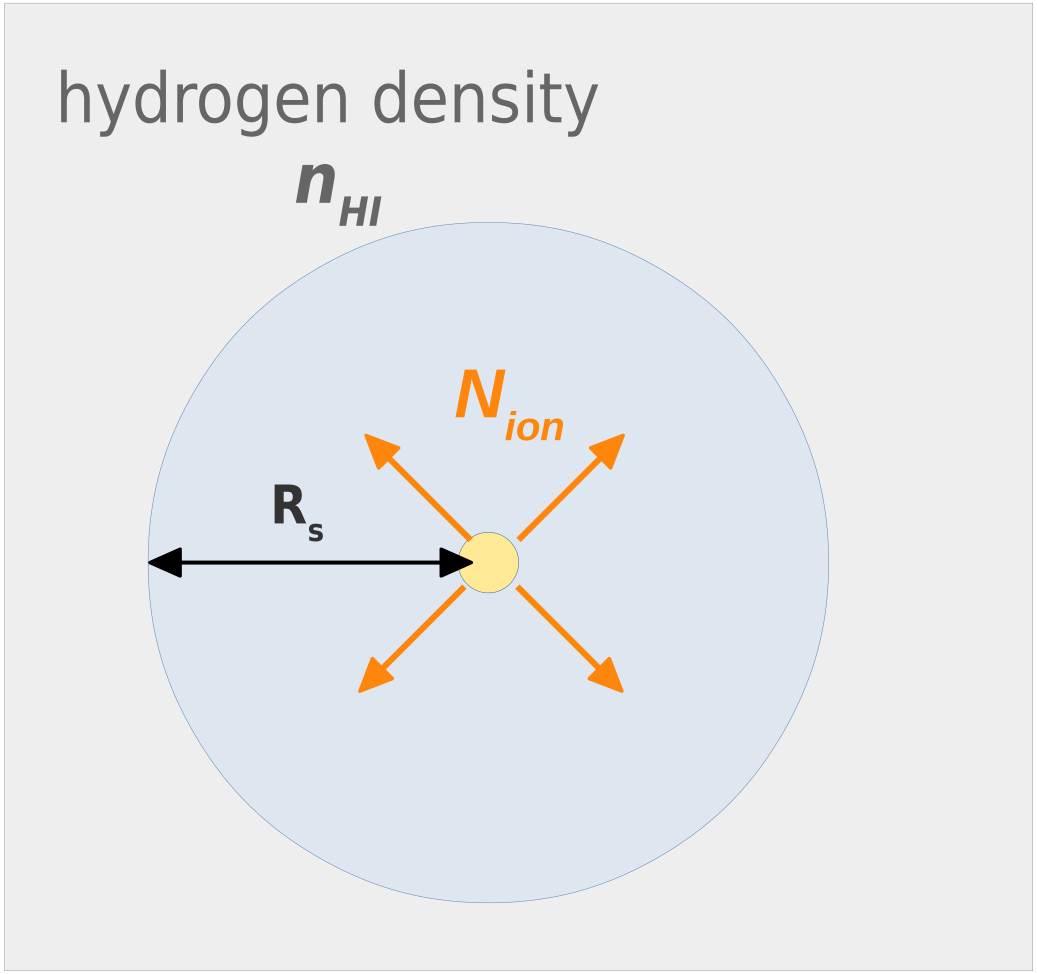

What is the size of the ionized sphere around the galaxy?

rate of ionizations = rate of recombinations

$$N_{ion} = \alpha\, n_e n_p\, V$$

$$V = 4\pi R_s^3 / 3$$

Radius of the Strömgren sphere:

$$R_s = (3N_{ion} / 4\pi\, \alpha\, n_e n_p)^{1/3}$$

Key physics - Reionization

The reionization history is expressed through the evolution of the ionization fraction Q_{HII} of hydrogen:

$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{\bar{t}_{rec}}$$

ionization rate   recombination rate

The “ionization rate” describes the growth of the ionized regions due to sources of ionizing photons, while the “recombination rate” describes the decrease in the ionized regions due to recombinations ($p + e \rightarrow H$). Sources of ionizing photons are stellar populations in galaxies; only a fraction (f_{esc}) of the ionizing photons produced in within the galaxy (n_{ion}^{ISM}) can escape into the intergalactic medium (IGM) and contribute to reionization.

$$\dot{n}_{ion} = f_{esc}\,\dot{n}_{ion}^{ISM}$$

The recombination time scale decreases as more ionized atoms and free electrons are present.

$$\bar{t}_{rec} = \left[\chi_e \bar{n}_H \alpha_B C\right]^{-1}$$

factor to account for excess in free electrons due to ionized helium

hydrogen density

Case-B recombination coefficient

clumping factor of the IGM

$$C = \frac{\langle n^2 \rangle}{\langle n \rangle^2}$$

Example: Deriving the reionization history

$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{\bar{t}_{rec}}$$

number of ionizing photons per hydrogen atom and time

number of recombinations per hydrogen atom and time

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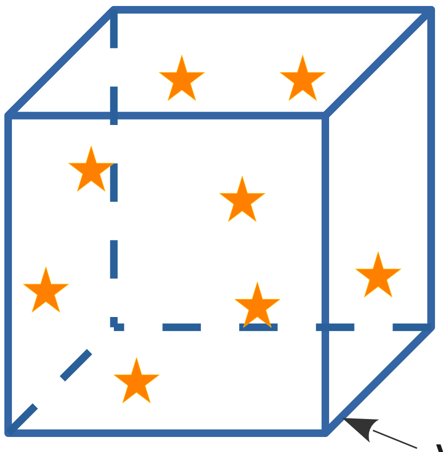


$$\dot{n}_{ion} = \frac{\sum_i^{N_{sources}} \dot{N}_{ion,i}}{V}$$

[# / sec]

[# / (cm³ sec)]

Volume V with $\bar{n}_H$

Example: Deriving the reionization history

$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{\bar{t}_{rec}} \qquad \bar{t}_{rec} = \left[\chi_e \bar{n}_H \alpha_B C\right]^{-1}$$

number of ionizing photons per hydrogen atom and time

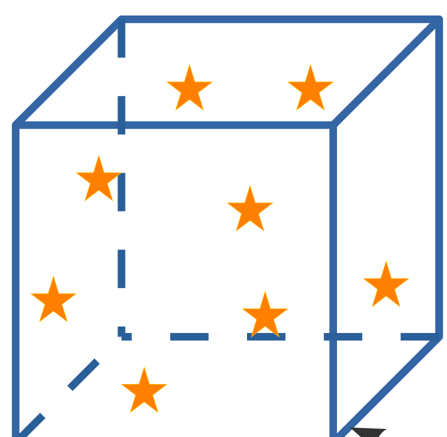
number of recombinations per hydrogen atom and time

Assumptions:

1) gas density is homogeneous: C = 1

2) ionizing emissivity is constant in time: $\dot{n}_{ion}(t) = \dot{n}_{ion}$

3) gas only consists of hydrogen: $\chi_e = 1$



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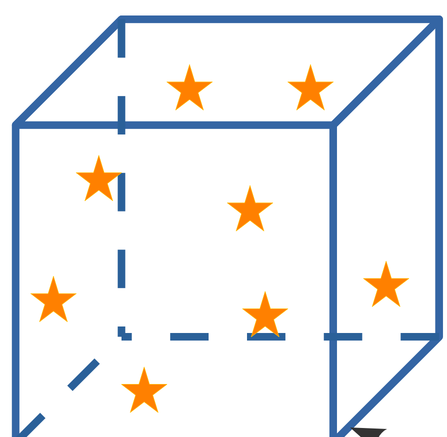

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Example: Deriving the reionization history

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$$-1/t_{rec} \ln\left(\dot{n}_{ion}/\bar{n}_H - Q_{HII}/t_{rec}\right) + 1/t_{rec} \ln\left(\dot{n}_{ion}/\bar{n}_H\right) = t$$

$$\ln\left(\dot{n}_{ion}/\bar{n}_H - Q_{HII}/t_{rec}\right) = t/t_{rec} + \ln\left(\dot{n}_{ion}/\bar{n}_H\right)$$

$$\dot{n}_{ion}/\bar{n}_H - Q_{HII}/t_{rec} = \dot{n}_{ion}/\bar{n}_H \exp\left(-t/t_{rec}\right)$$

$$\boxed{Q_{HII}(t) = \dot{n}_{ion}/\bar{n}_H \; t_{rec} \left[1 - \exp\left(-t/t_{rec}\right)\right]}$$

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Observational evidence for reionization

1. Cosmic Microwave Background

The CMB photons scatter with free electrons. The corresponding electron scattering optical depth is

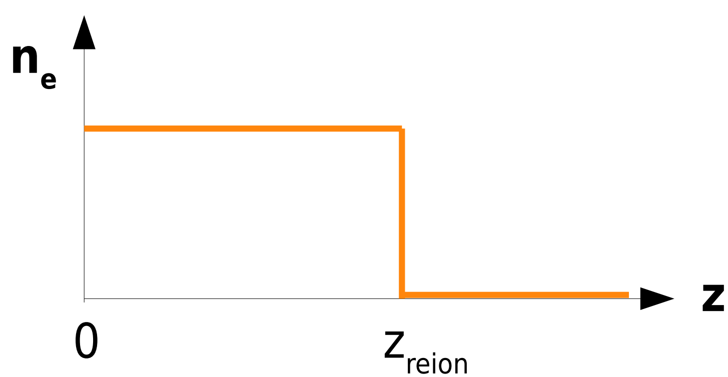
$$\tau_e = \int_0^{z_{reion}} \sigma_T n_e \frac{dl}{dz} dz$$

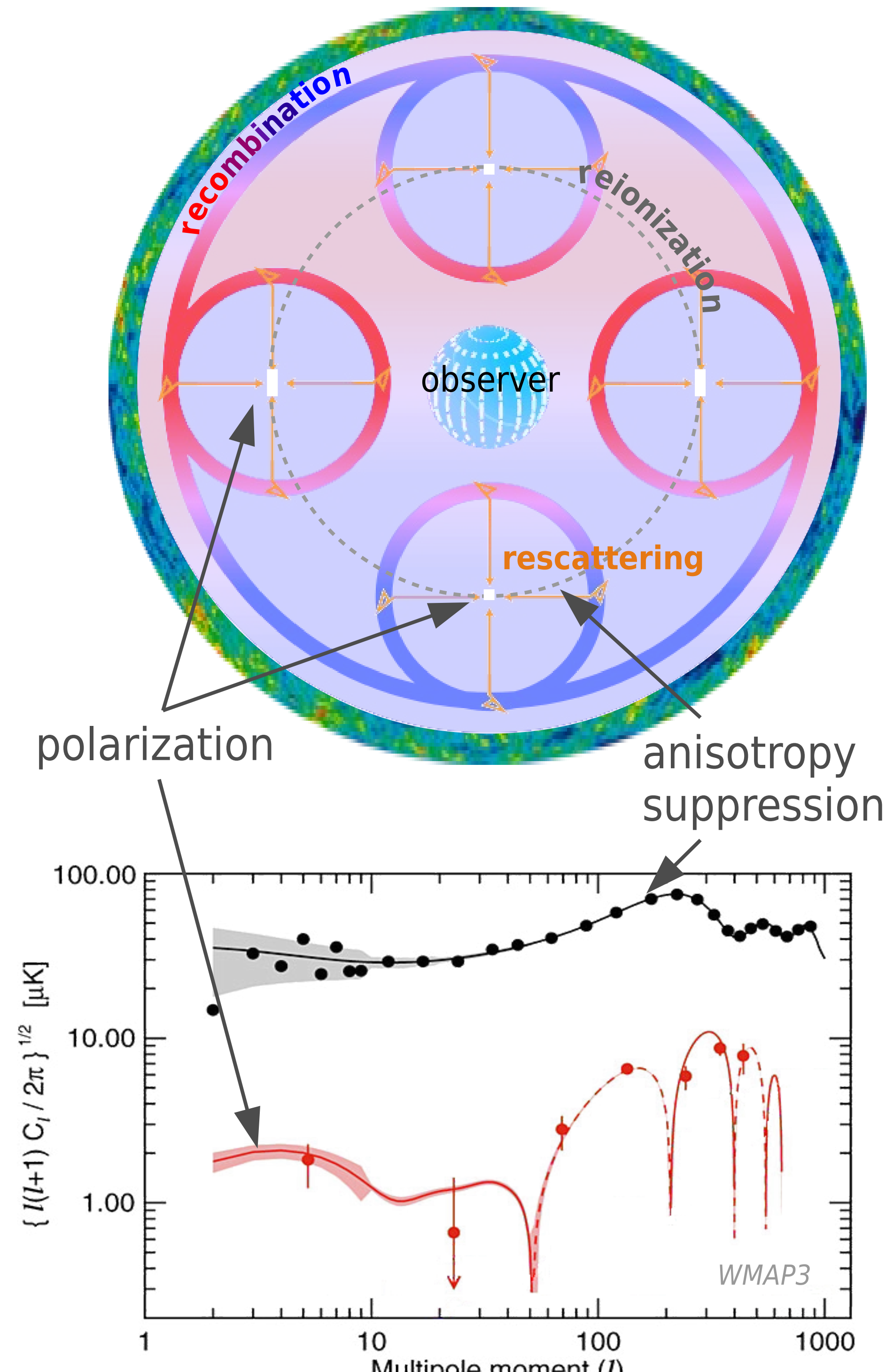
n_e = comoving electron number density

σ_T = Thomson scattering cross section

$\tau_e = 0.055 \pm 0.009$

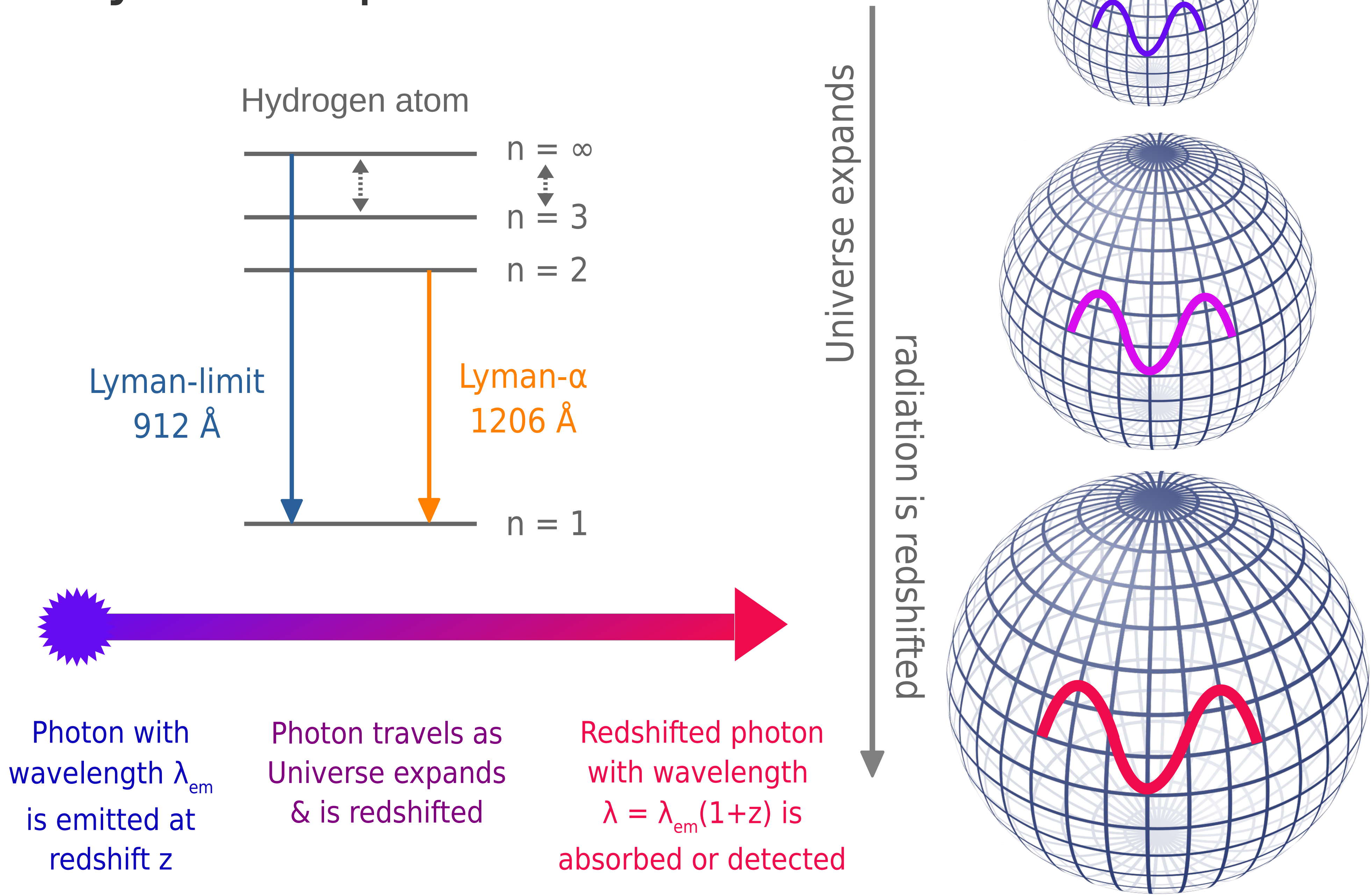
From the CMB optical depth we can infer an instantaneous reionization redshift.



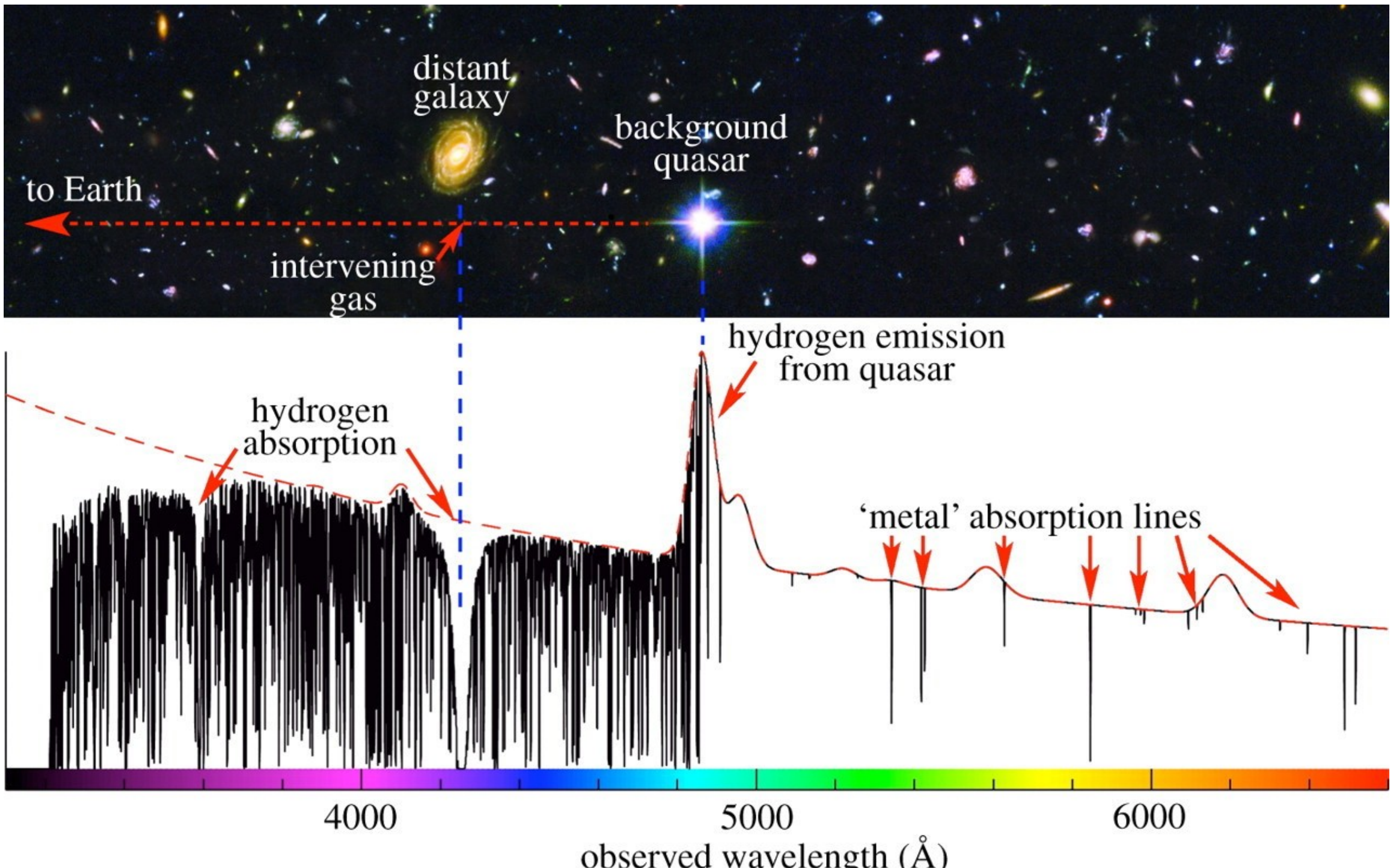


CMB tutorial: http://background.uchicago.edu/~whu/intermediate/intermediate.html Page et al. 2007

Lyman-α photons



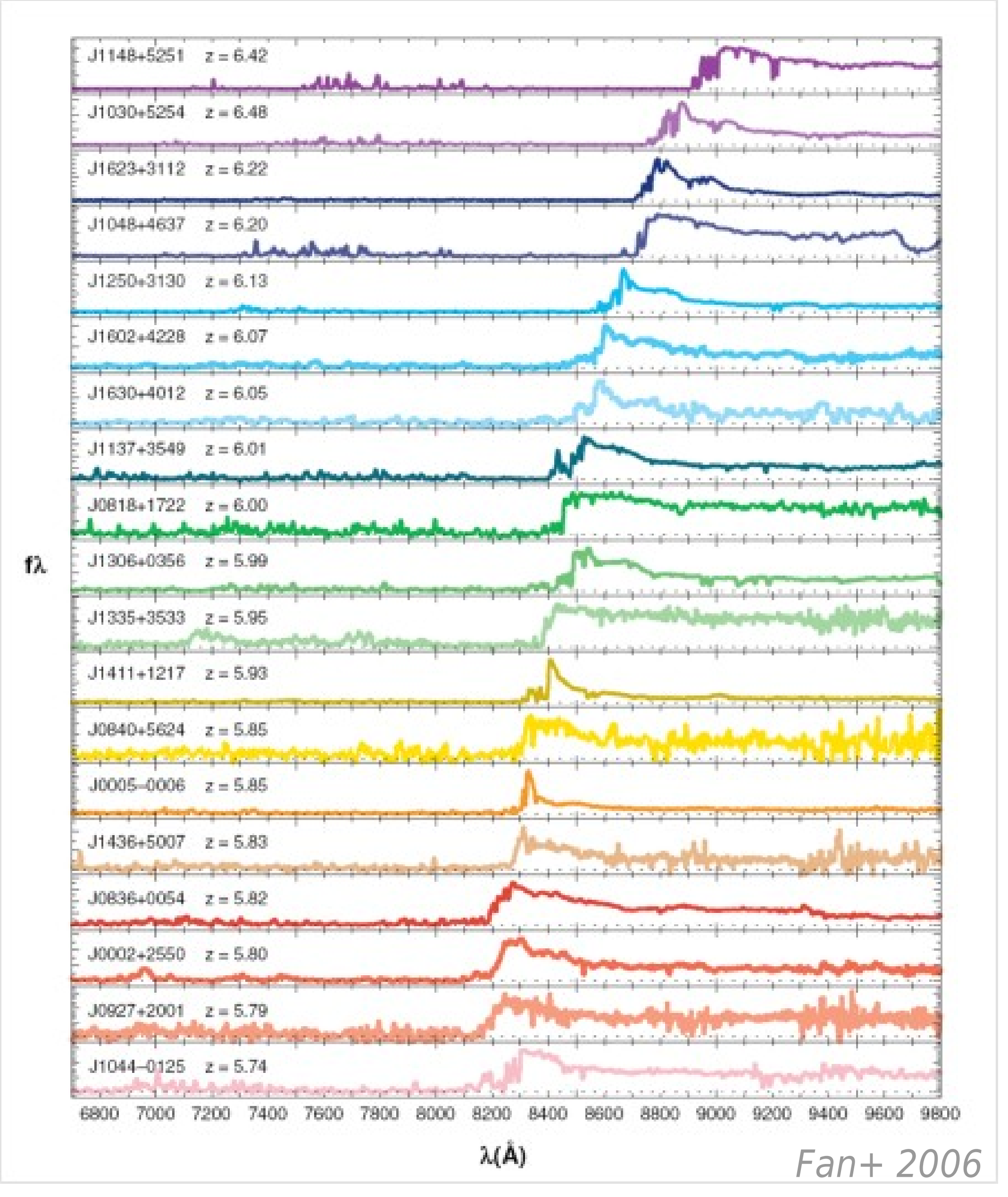
2. Gunn-Peterson trough



Pettini 2011

Quasar emits radiation → Radiation travels as Universe expands & is redshifted → Neutral hydrogen in the IGM absorbs Lyman-α always at 1206Å → Quasar spectra shows absorption at wavelengths shorter than 1206Å

2. Gunn-Peterson trough



Fan+ 2006

If the photons of the quasar spectra passes the neutral gas in the IGM during reionization, they are nearly completely absorbed at wavelengths shorter than 1206Å (in the rest frame of the quasar!)

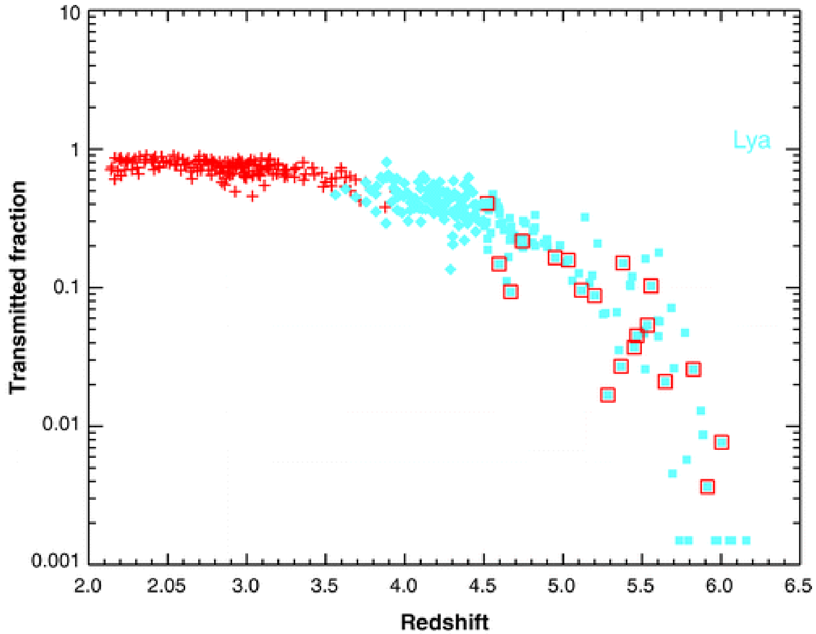
$$\tau_{GP}(z) = \tau_0 \frac{n_{HI}}{\bar{n}_{HI}}$$

$$\tau_0(z) \equiv \frac{\pi e^2 f \lambda_\alpha}{m_e c H(z)}$$

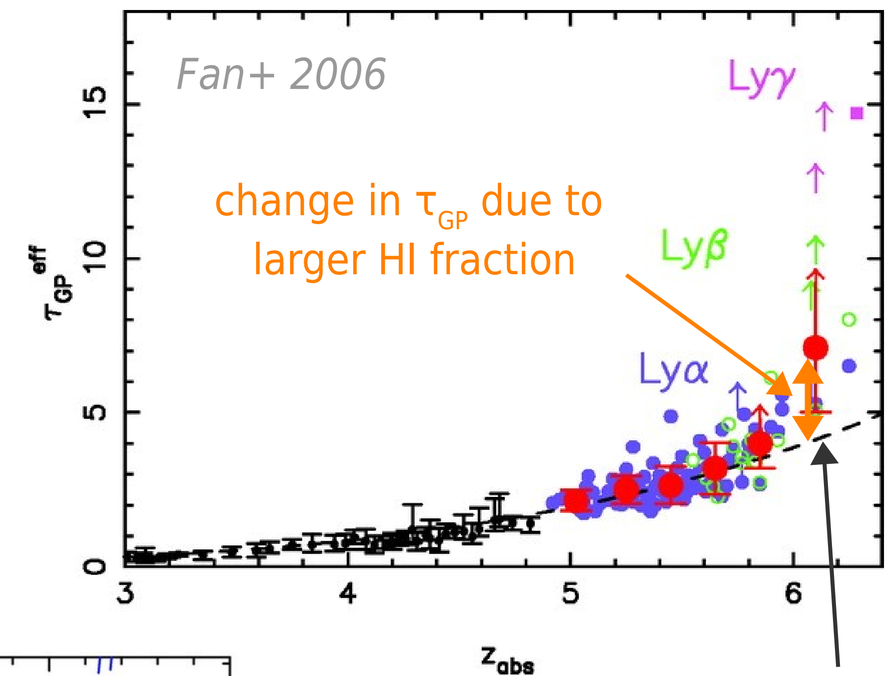
$$\simeq 1.5 * 10^{-5} h^{-1} \Omega_m^{-1/2} \frac{\Omega_b h^2}{0.019} \left(\frac{1+z}{8}\right)^{3/2}$$

One neutral hydrogen atom out of 10^5 can cause complete absorption blue-ward of Lyman-α

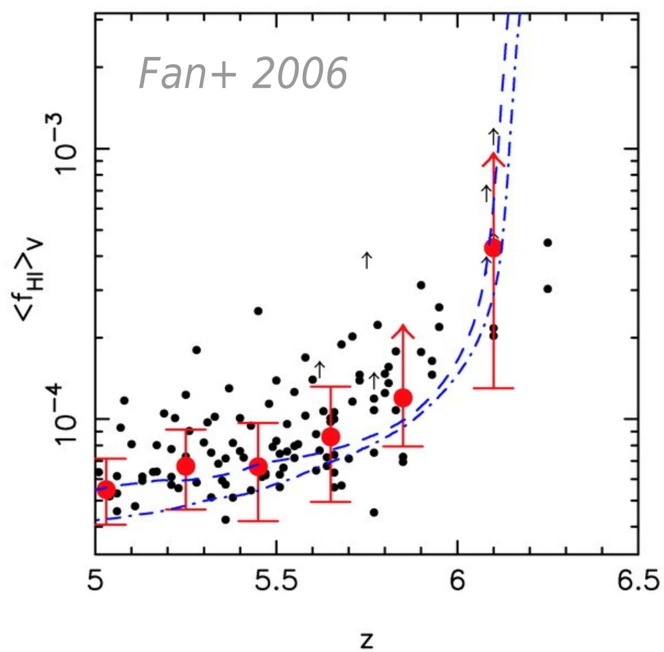
Inferring reionization state from Gunn-Peterson trough



Fan X, et al. 2006.
Annu. Rev. Astron. Astrophys. 44:415–62



change in τ_{GP} due to density evolution



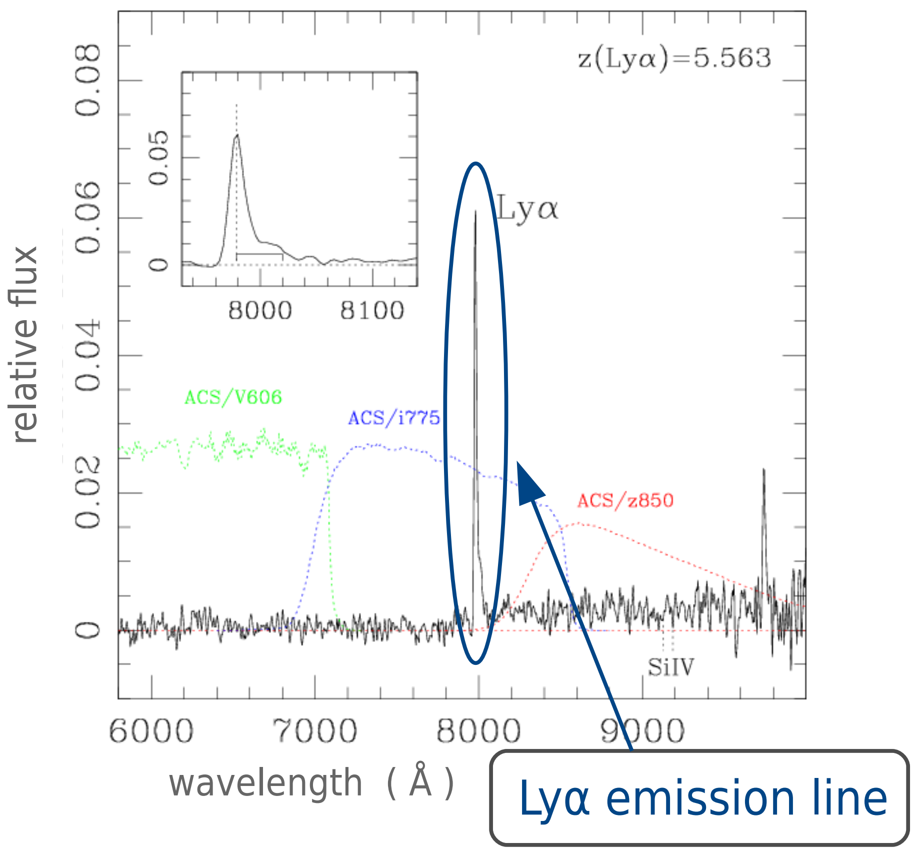
Lyman-α transmission drops at $z \gtrsim 5$ to 6 & τ_{GP} rises

z ≃6 marks end of reionization

Inferred evolution of the HI fraction, which begins to rise at z>6

Observing high-redshift galaxies

Vanzella et al. 2010



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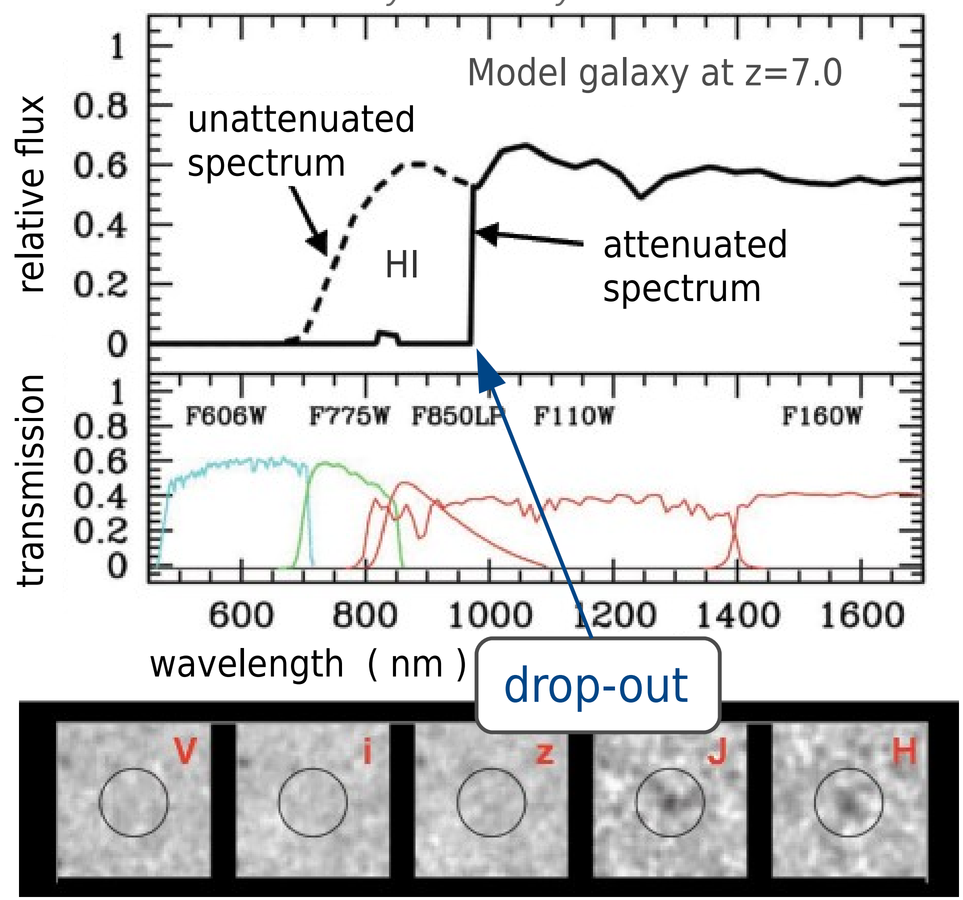
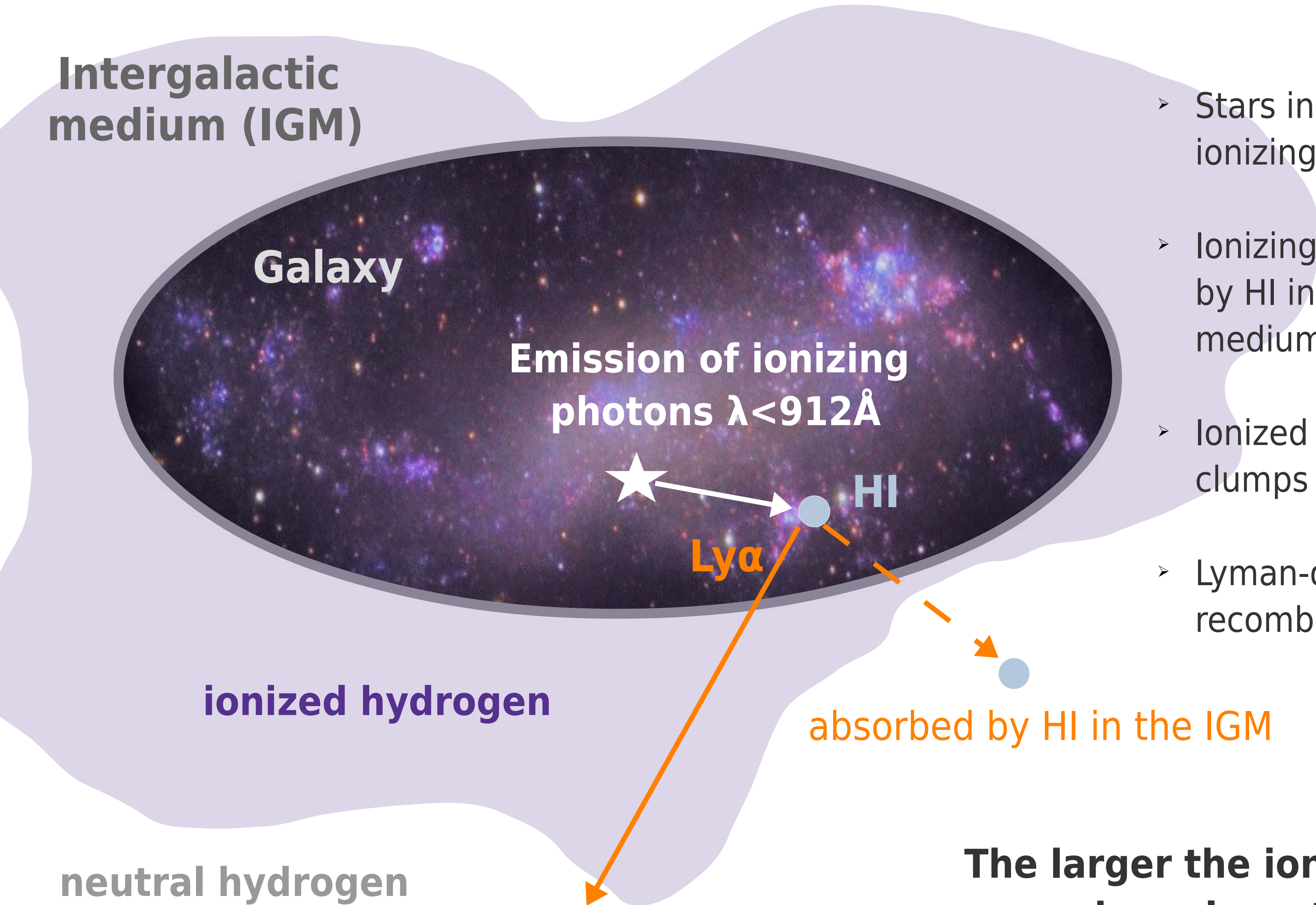


Lyman-α emitters (LAEs)
are detected by means of their Lyman-α emission line.

Lyman Break Galaxies (LBGs)
are detected by means of the absorption of their spectrum bluewards the Lyman limit.

3. Lyman-alpha emitters



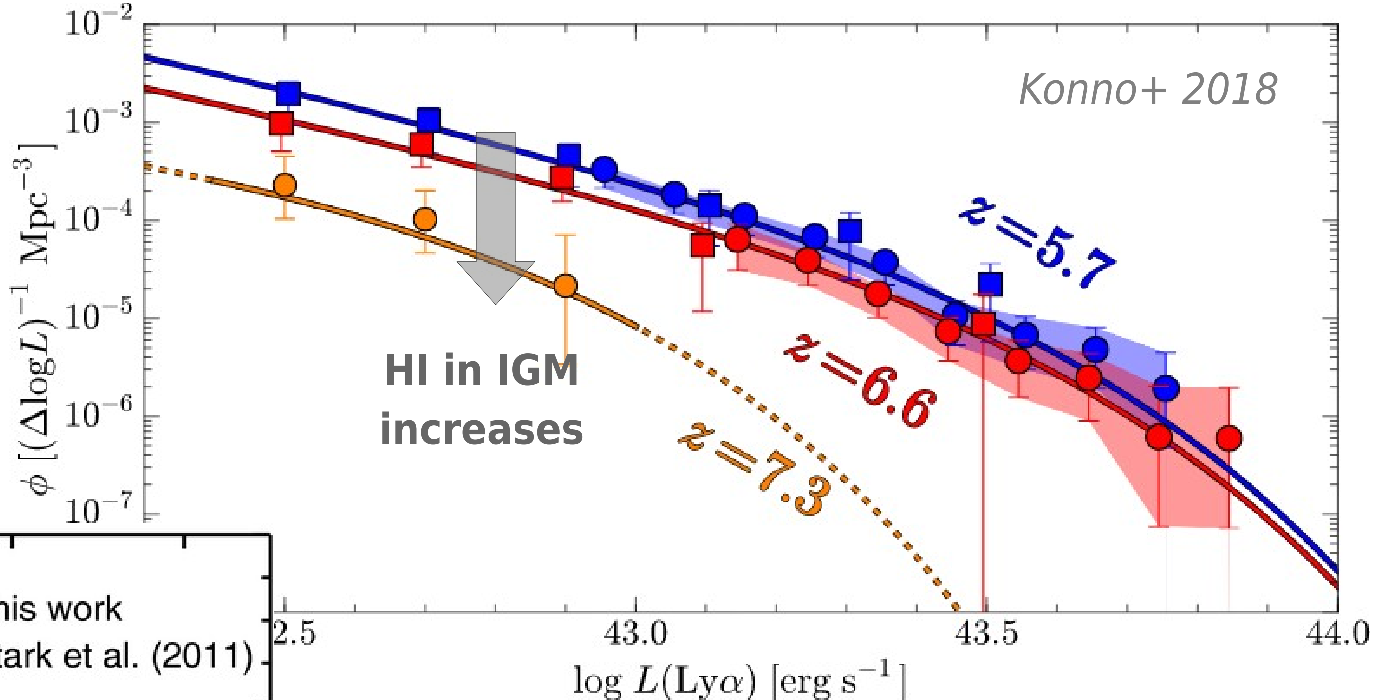
- Stars in the galaxy emit HI ionizing photons
- Ionizing photons are absorbed by HI in the interstellar medium (ISM)
- Ionized hydrogen in dense clumps recombines quickly
- Lyman-α is emitted as part of recombination radiation

Lyα line has been redshifted out of HI absorption. It is transmitted through the IGM.

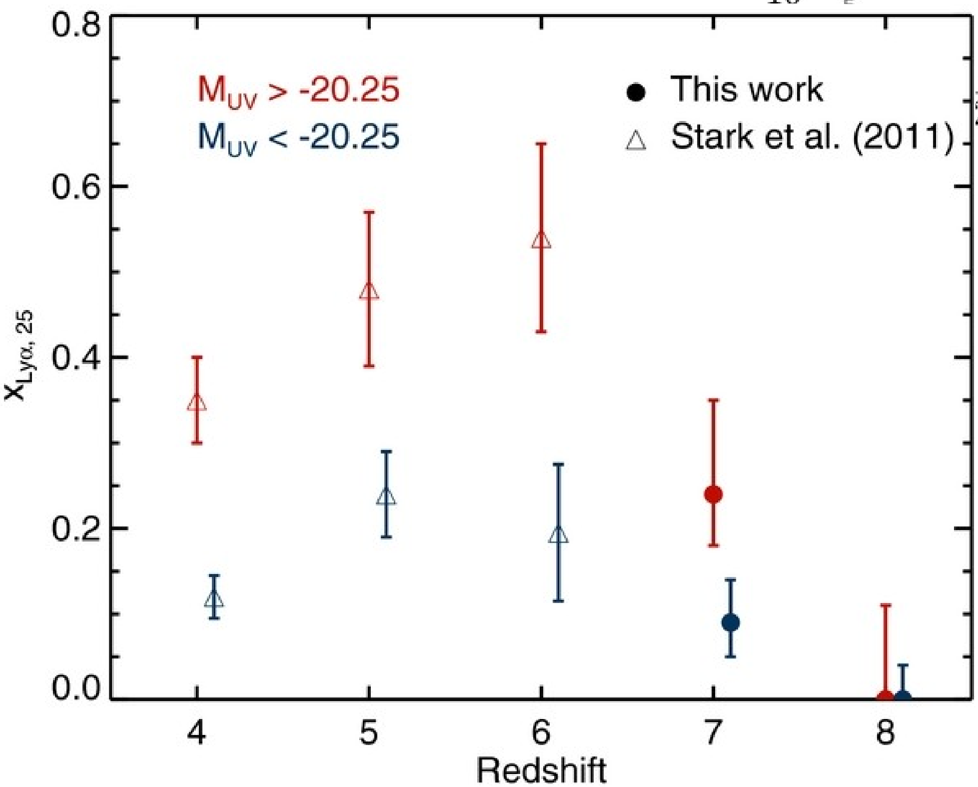
The larger the ionized regions around a galaxy, the higher is its fraction of Lyα radiation that is transmitted through the IGM.

3. Lyman-alpha emitters

The decrease of galaxies with a detected Lyα line could be due to a higher HI fraction.

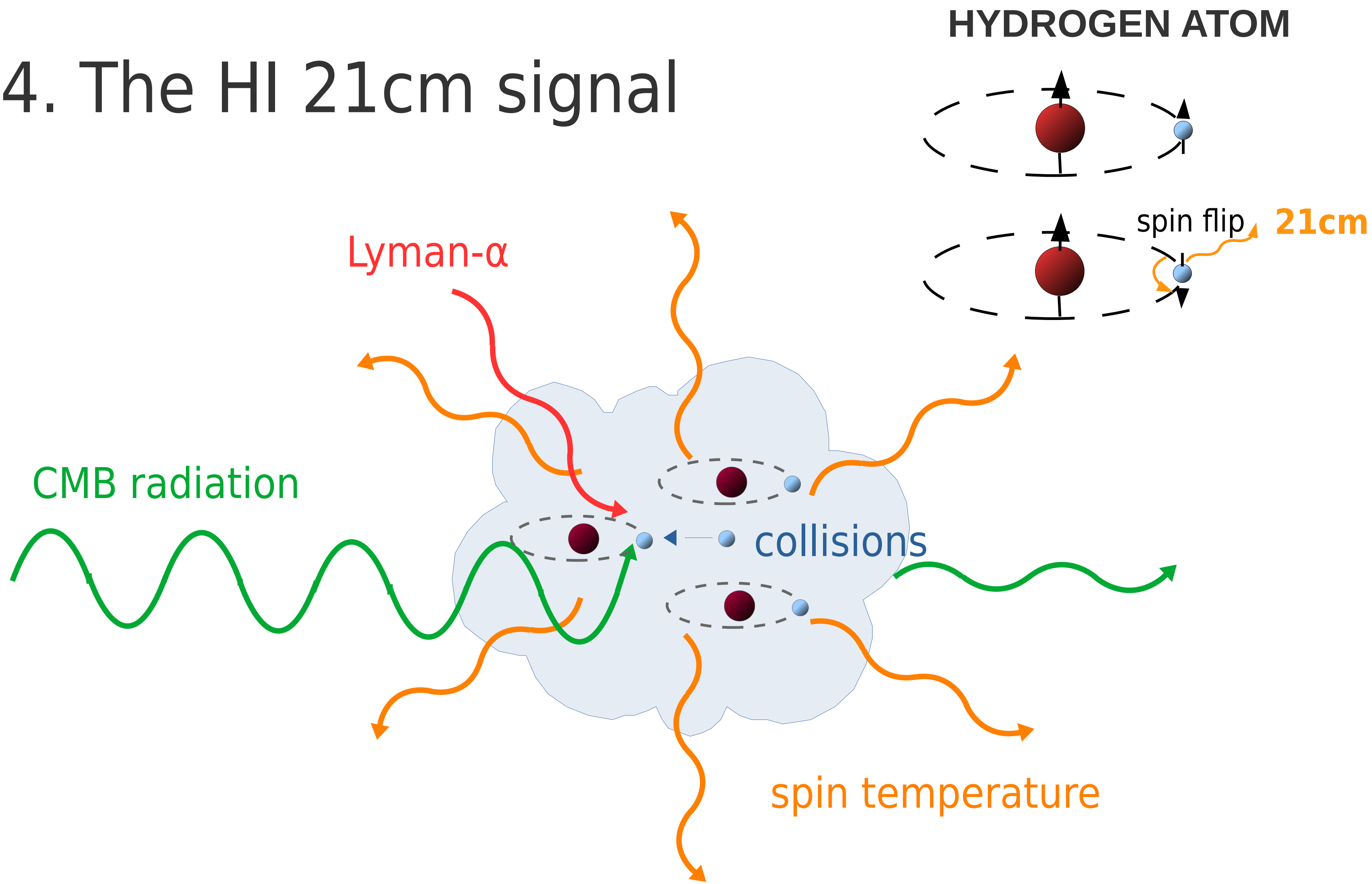


Schenker+ 2014



The fraction of galaxies showing a Lyα line decreases rapidly at z>6. Effects of reionization kick in between z~6 and 7, and reionization is over by z~6.

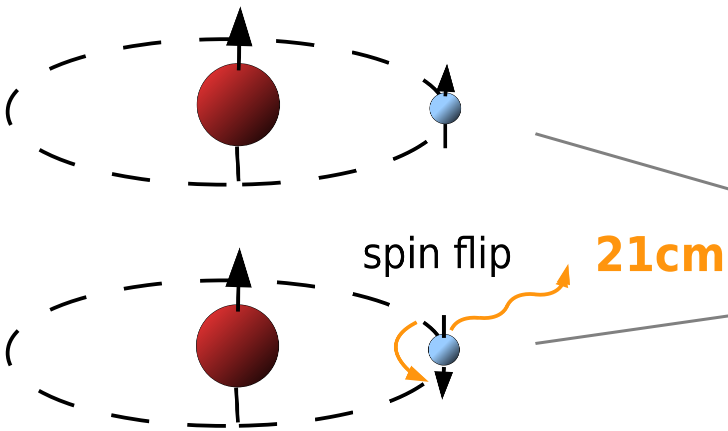
4. The HI 21cm signal

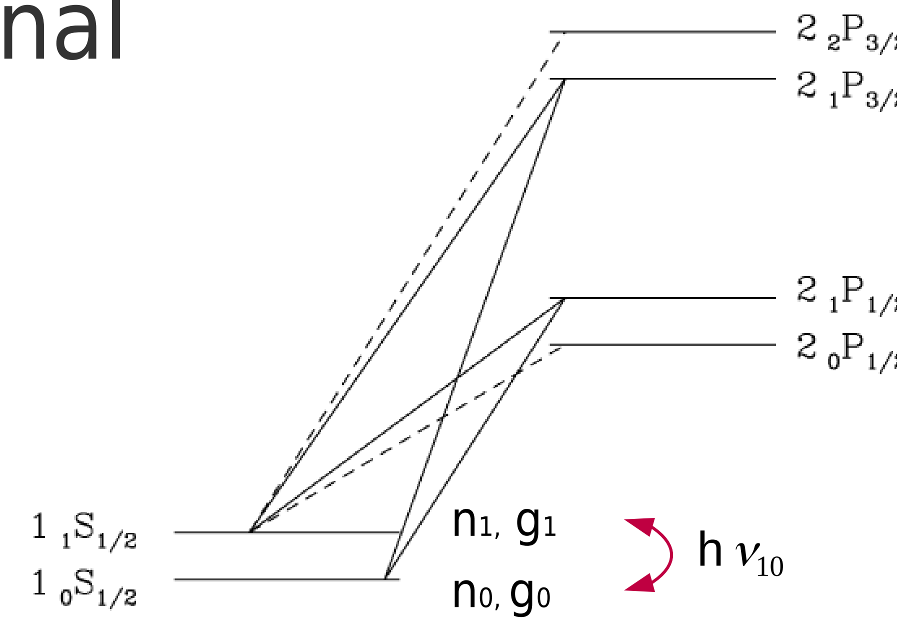


δT is determined by the amount of HI present in the gas and determines the strength of emission or absorption of the 21cm line

4. The HI 21cm signal

HYDROGEN ATOM





Wouthuysen-Field effect: Distribution of levels 0 and 1 reflects the intensity profile of the background radiation near Lyman α

Spin temperature T_s

determines the fraction in the triplet and the singlet state.

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(\frac{-h\,\nu_{10}}{kT_S}\right)$$

kinetic temperature

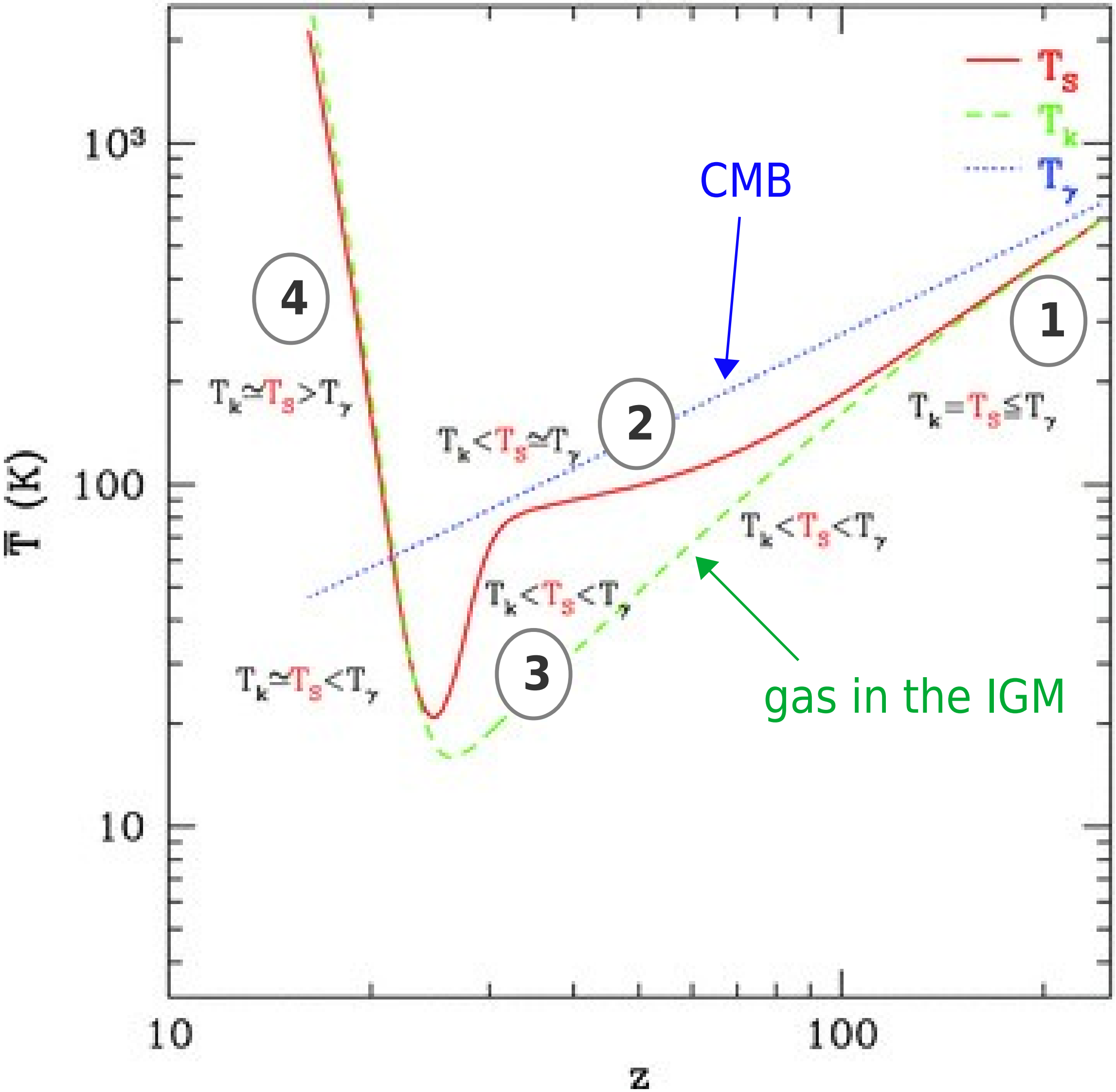
brightness temperature of the 21 cm radiation

color temperature

$$T_S = \frac{T_\gamma + y_c T_c + y_L T_L}{1 + y_c + y_L}$$

4. The HI 21cm signal

Mesinger+ 2011



1. High gas density couples T_S to T_k with gas cooling adiabatically

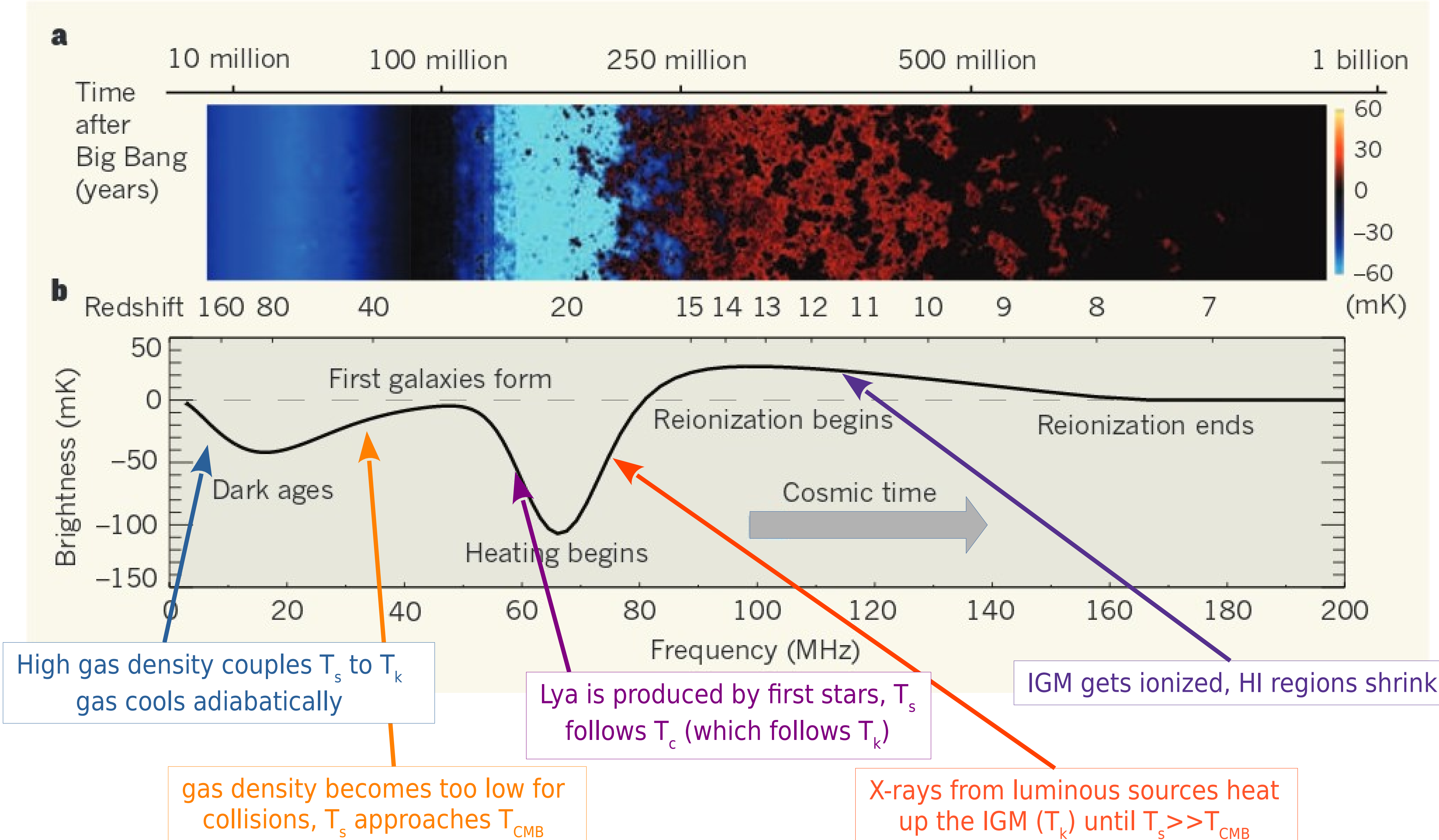
2. gas density becomes too low for collisions, T_S approaches T_γ

3. Ly-α is produced by first stars, T_S follows $T_c \simeq T_k$

4. X-rays from luminous sources heat the IGM until $T_S >> T_\gamma$

4. The HI 21cm signal

Pritchard & Loeb 2010



Outstanding questions in reionization

1. Sources of reionization: Main contribution probably from star-forming galaxies but how much do quasars contribute?

2. Ionizing escape fraction from galaxies f_{esc}: What are the f_{esc} values? And how does f_{esc} depend on the physical processes in the galaxies?

3. How many small mass galaxies are there during reionization? What is the “minimum galaxy mass”?

4. How strong is the feedback of reionization on galaxies? How strongly is subsequent star formation suppressed?