Reionised bubbles around primordial galaxies

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DAWN

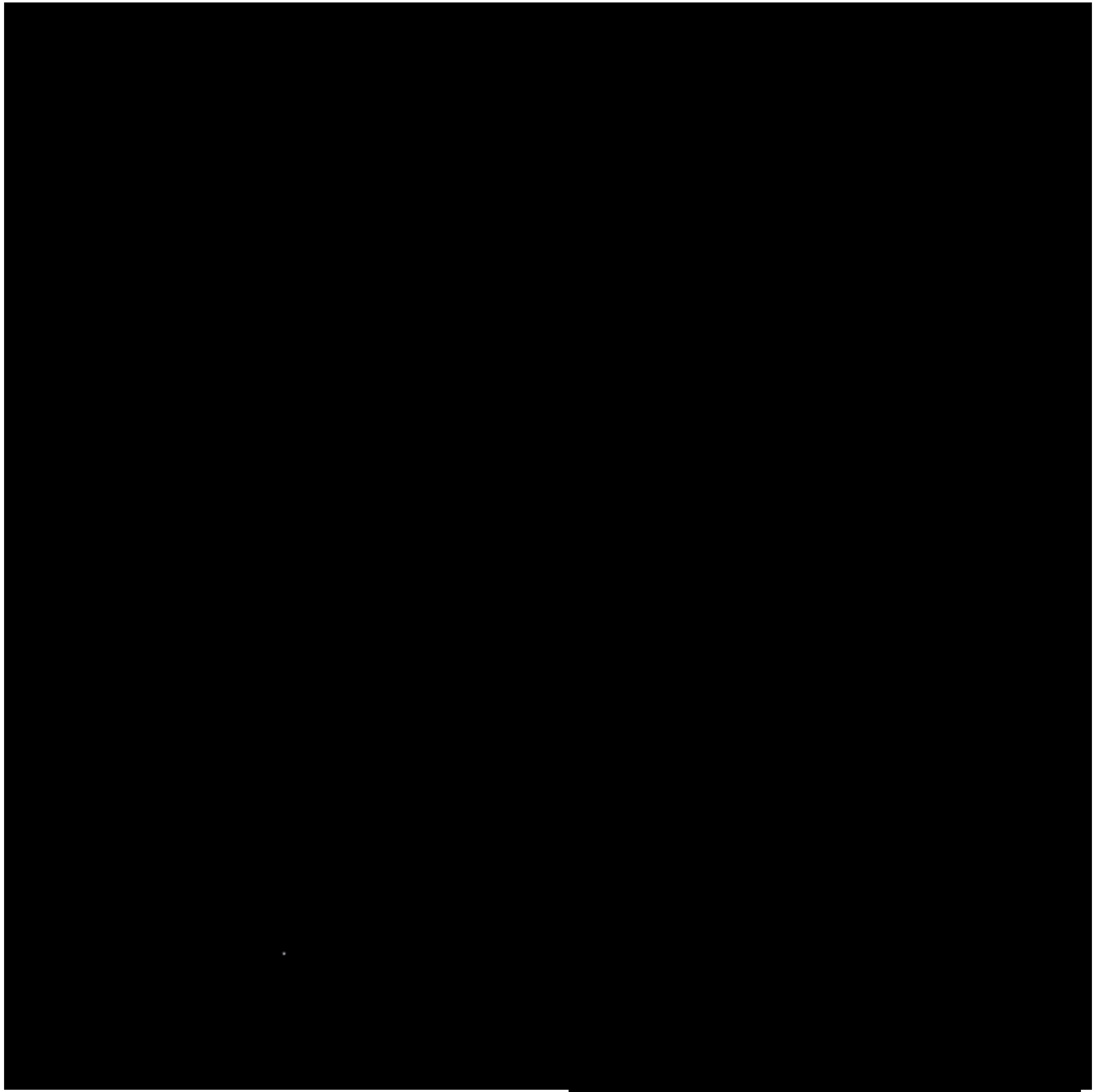
JADES JWST ADVANCED DEEP EXTRAGALACTIC SURVEY

DARK and DAWN

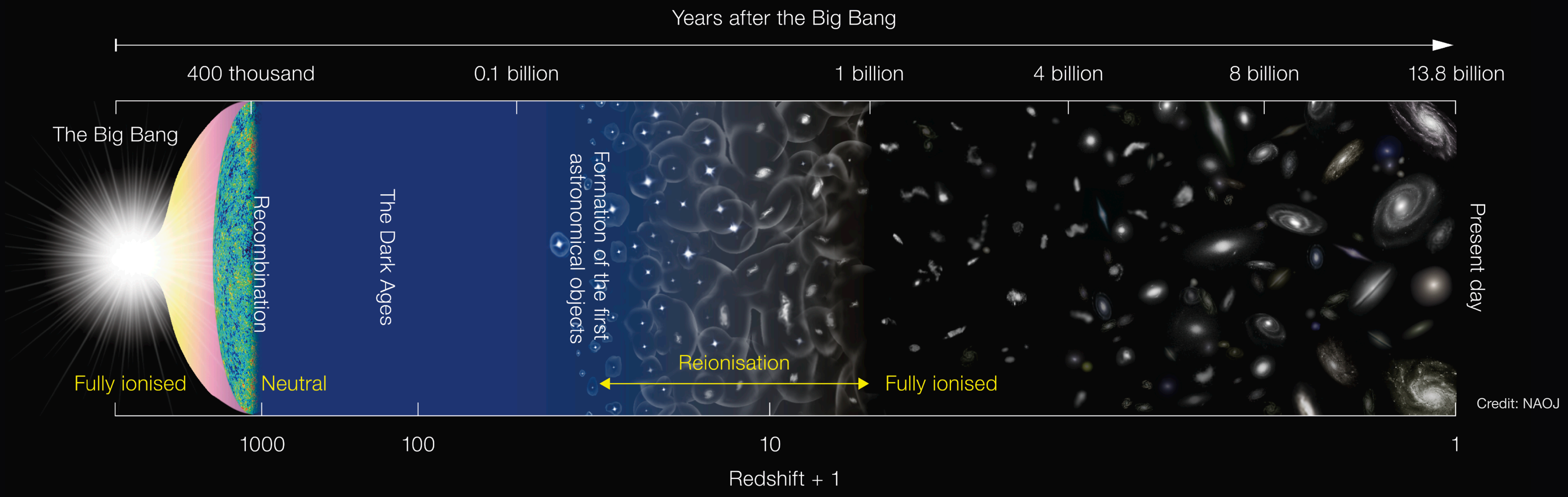
In the beginning, the Universe was dark…

… until the appearance of the first stars.

The formation of these first objects would have a lasting impact on the rest of the Universe's history.



An overview of galaxy evolution



Years after the Big Bang
400 thousand
0.1 billion
1 billion
he Big Bang
ΛCDM cosmology: early growth of DM halos allows gas to collapse into the first objects (week 6, Anne Hutter)
Recombination
The Dark Ages
Formation of the first astronomical objects
First galaxies quickly begin to emit ionising photons, which carves out ‘ionised bubbles’ around them
Reionisation
Fully ionised
Neutral
Fully ionised
1000
100
10
Redshift + 1


Years after the Big Bang
0.1 billion
1 billion
4 billion
The Dark Ages
Formation of the first astronomical objects
Within a few hundred million years, bubbles start to grow bigger, overlap, and at $z \approx 6$ the entire Universe had been reionised!
Reionisation
Fully ionised
100
10
Redshift + 1

How do we know galaxies drive reionisation?

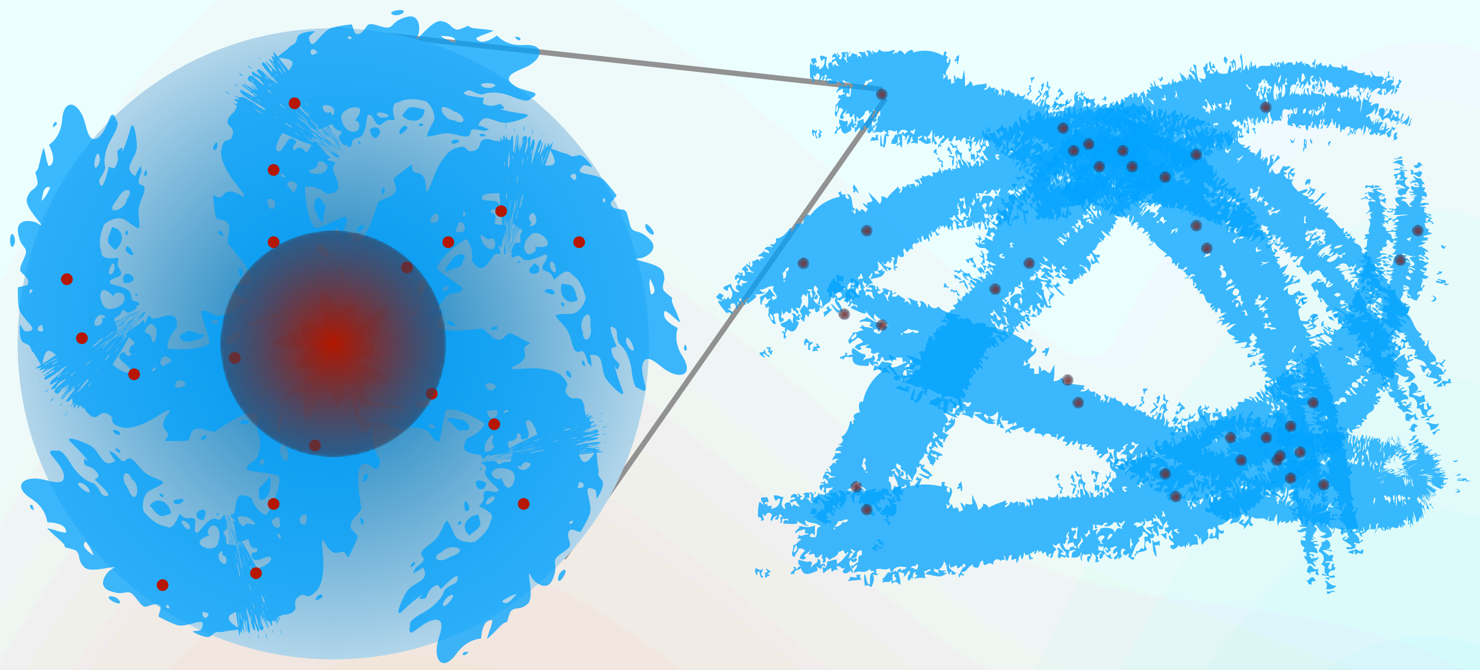
Work out the cosmic density of ionising photons, $\dot{n}_{\rm ion}$ (Mpc^{-3}), produced* by galaxies. Ingredients:

- Observed volume density of non-ionising, monochromatic ultraviolet (UV; wavelength of 1500 Å) luminosity output by galaxies, $\rho_{\rm UV}$ (erg s^{-1} Hz^{-1} Mpc^{-3})
- Conversion factor from observed non-ionising UV flux density to ionising photon rate, $\xi_{\rm ion}$ (Hz erg^{-1})
- Effective fraction of ionising photons that escapes galaxies, $f_{\rm esc}$

Combined: $\dot{n}_{\rm ion} = \rho_{\rm UV}\, \xi_{\rm ion}\, f_{\rm esc}$

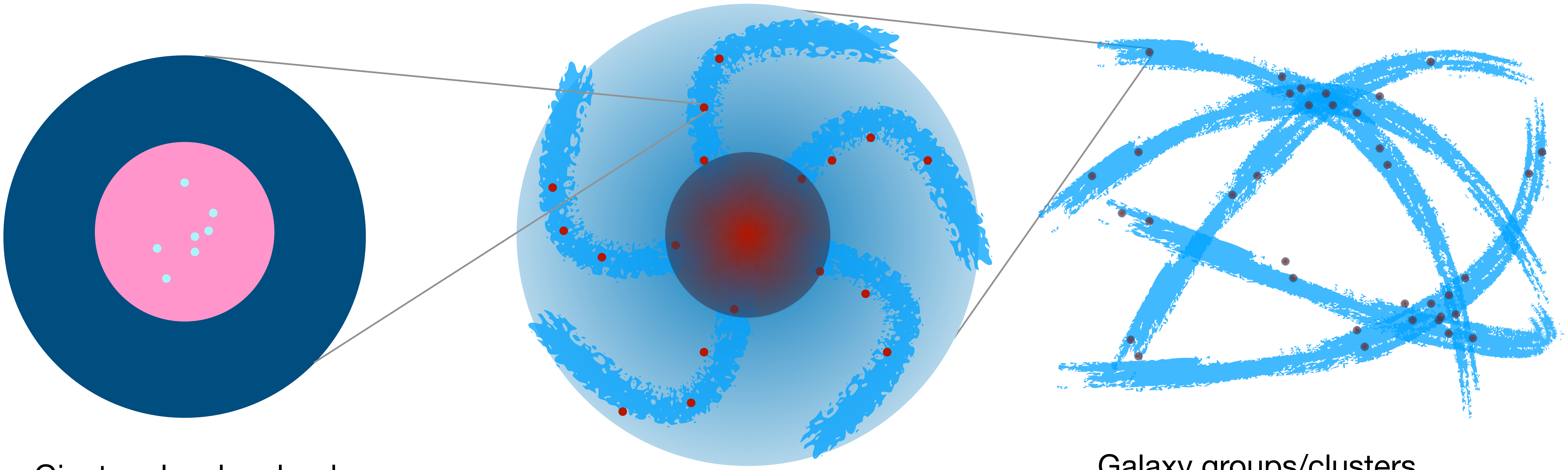
Given statistical properties of the observed galaxy population and under reasonable assumptions, galaxies can provide sufficient ionising photons to complete reionisation by redshift $z \approx 6$
(Robertson et al. 2013, 2015; Finkelstein et al. 2019)

* Agnostic to the actual sources of ionising photons: stars, accreting supermassive black holes?



Outside in: galaxy evolution in a cosmological setting

Physical scales in galaxy evolution



Giant molecular cloud (GMC), star clusters:

- 1-10 parsec (pc)
- 1-10 Megayear (Myr)
- 1-10 km/s

Galaxy:

- 1-10 kiloparsec (kpc)
- 100 Megayear (Myr)
- 10-100 km/s (stellar)

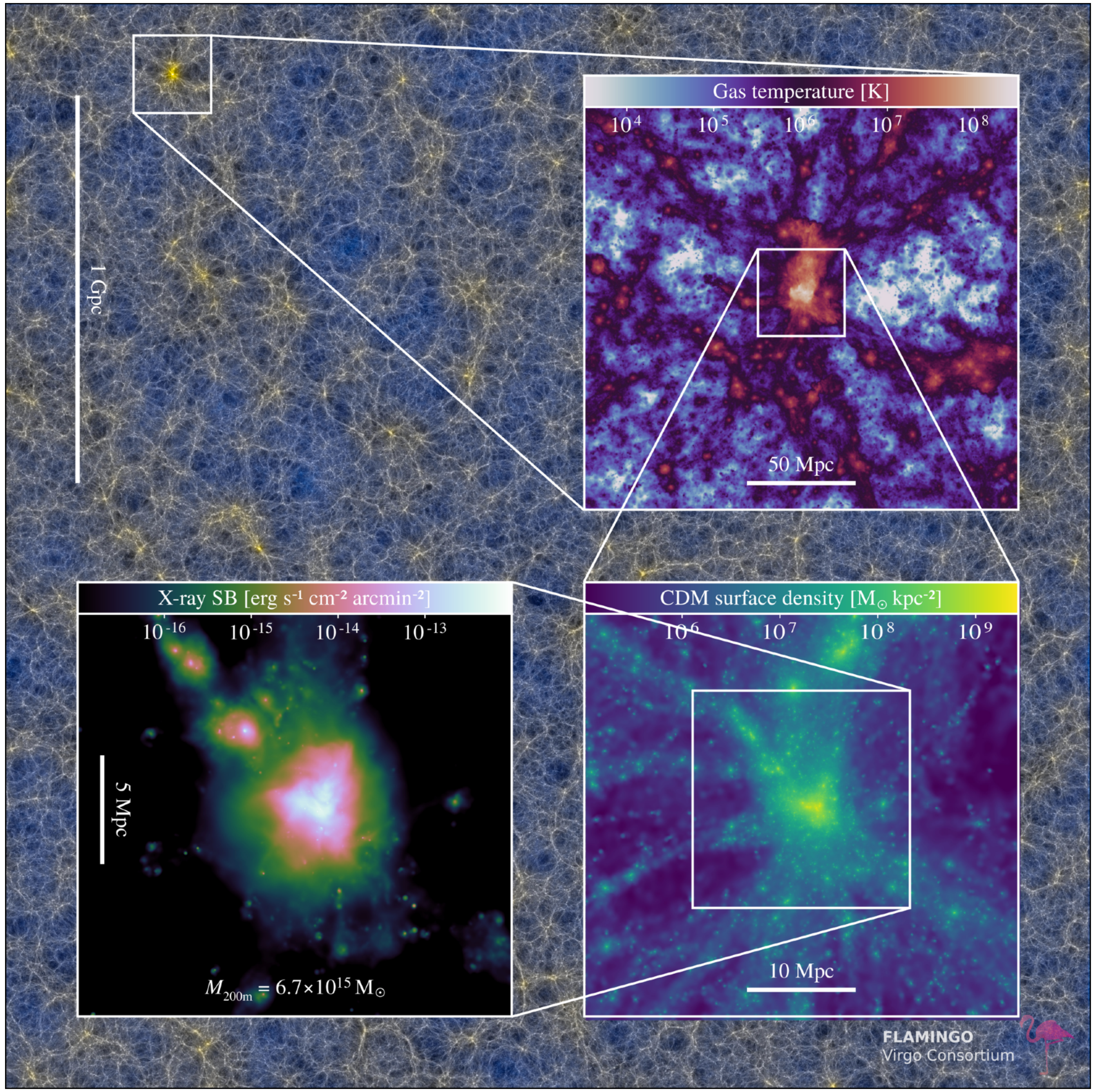
Galaxy groups/clusters, intergalactic medium (IGM):

- Megaparsec (Mpc)
- Gigayear (Gyr)
- >1000 km/s (apparent)

Galaxies in the cosmic web

FLAMINGO simulations (Schaye et al. 2023)

- Reionisation requires us to consider galaxies as embedded in structures on (much) larger scales
- Hydrodynamical simulations required to capture complex interplay between galaxies and their environments
- Star formation and gas accretion by black holes taking place on (sub-)parsec scales influences galaxy as a whole, and beyond (IGM)



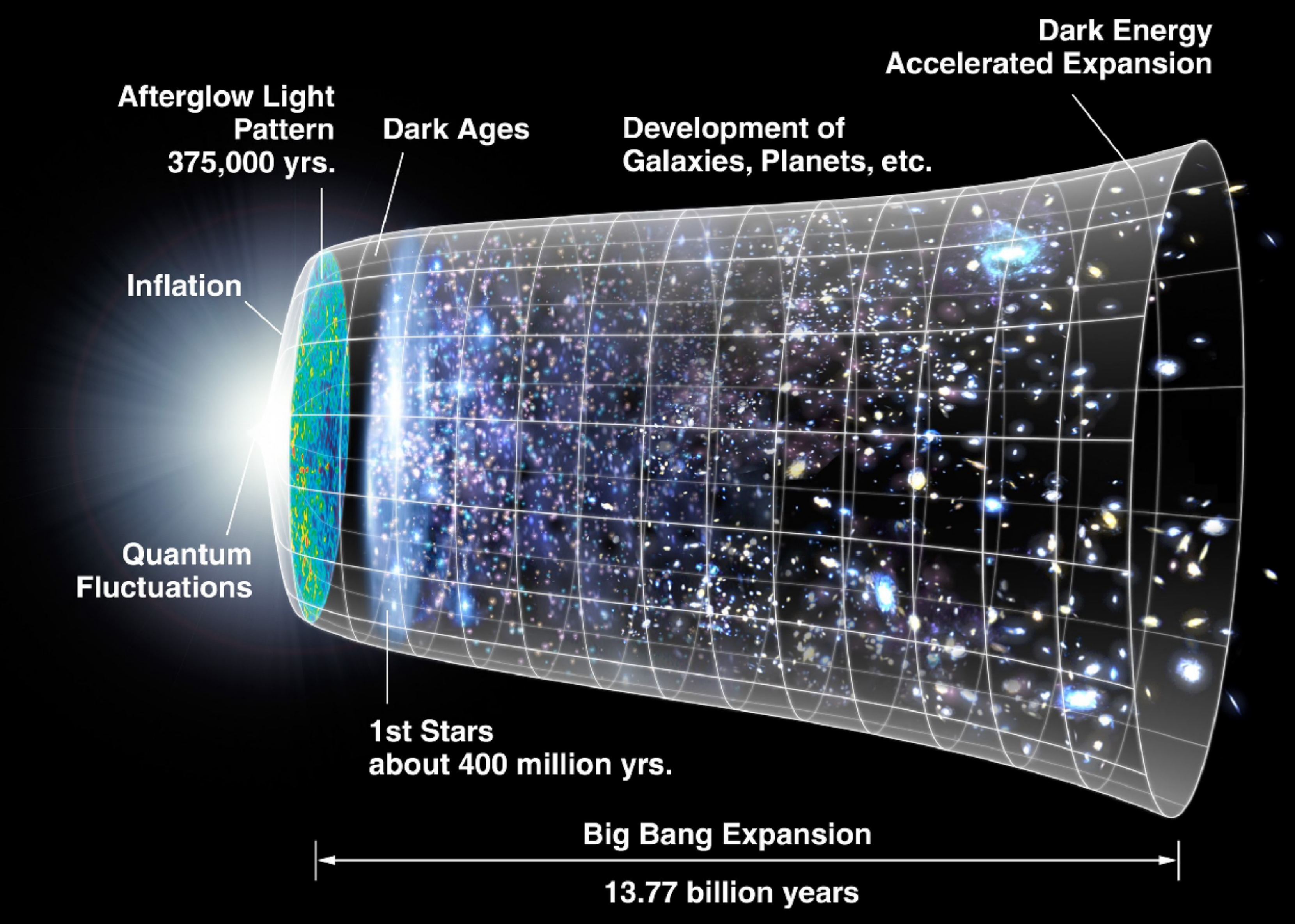
GR metric in an expanding universe

Cosmological Principle (homogeneous and isotropic universe) results in a metric with all spatial time dependence capture in the scale factor $a(t)$:

$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dr^2}{1 - Kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right] .$$

Under a coordinate transformation to comoving coordinates, $d\chi = dr/\sqrt{1 - Kr^2}$, a light ray following a null geodesic ($ds^2 = 0$) travelling on a radial trajectory ($d\theta = d\phi = 0$) obeys

$$\frac{d\chi}{dt} = \pm\frac{c}{a(t)}$$



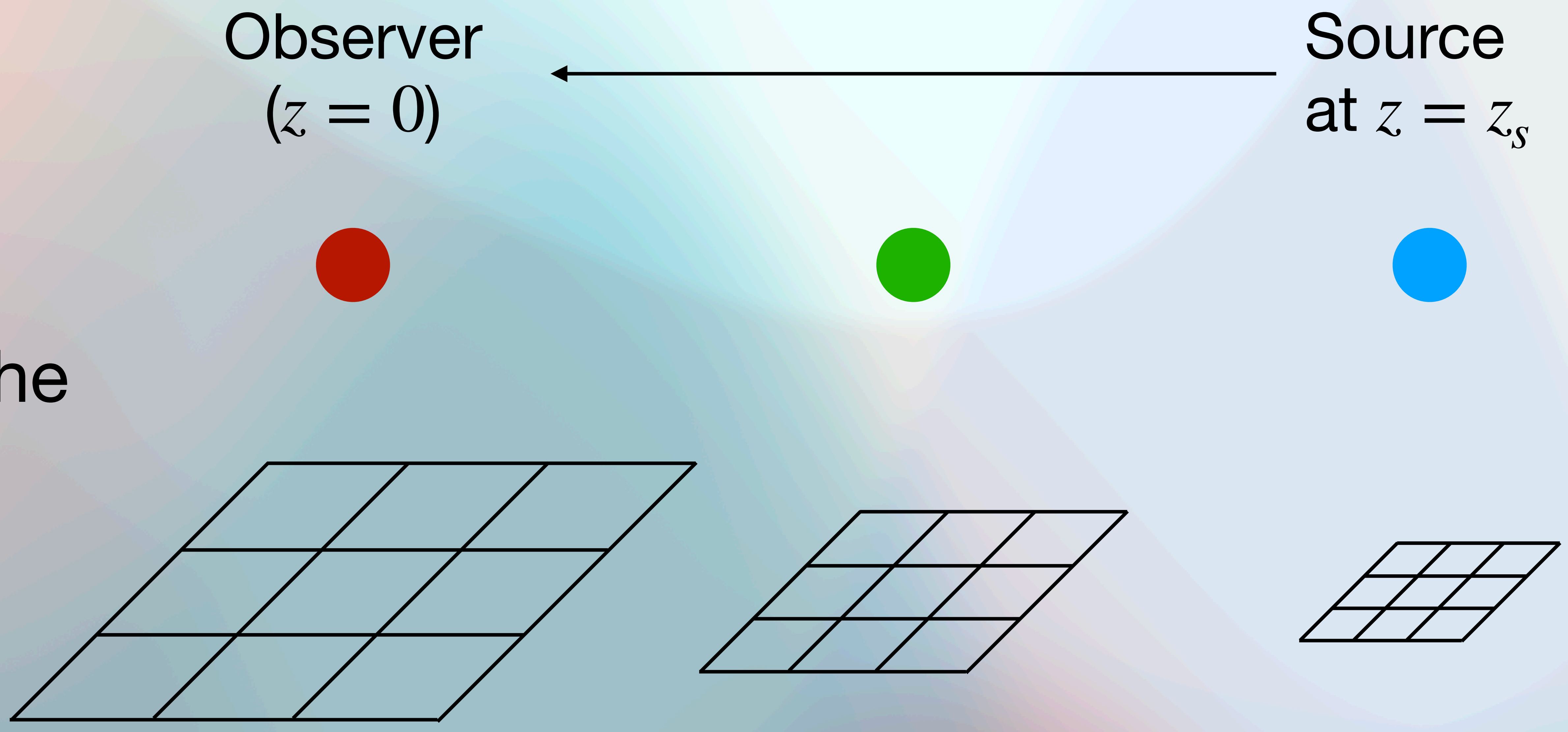
Observing distant galaxies in an expanding universe

While light travels from a source at cosmological distance, the Universe around it expands, causing the wavelength of the photon to redshift by a factor

$$\frac{\lambda_{\mathrm{obs}}}{\lambda_{\mathrm{emit}}} = \frac{a_0}{a(t)} = 1 + z$$

where typically the present-day scale factor is set to $a_0 = 1$. The rate of expansion is measured by the Hubble parameter $H(z) = \dot{a}/a$, which at $z = 0$ (today) represents the Hubble constant:

$$H_0 = \dot{a}/a\Big|_{z=0} \approx 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



Measuring distances in an expanding universe

For the photon trajectory with a minus sign (for an inward radial trajectory),

$$\frac{d\chi}{dz} = -\frac{c}{a(t)}\frac{dt}{dz} = -\frac{c}{a}\frac{dt}{da}\frac{da}{dz} = \frac{c}{\dot{a}a}\frac{1}{(1+z)^2} = \frac{c}{H(z)}\,.$$

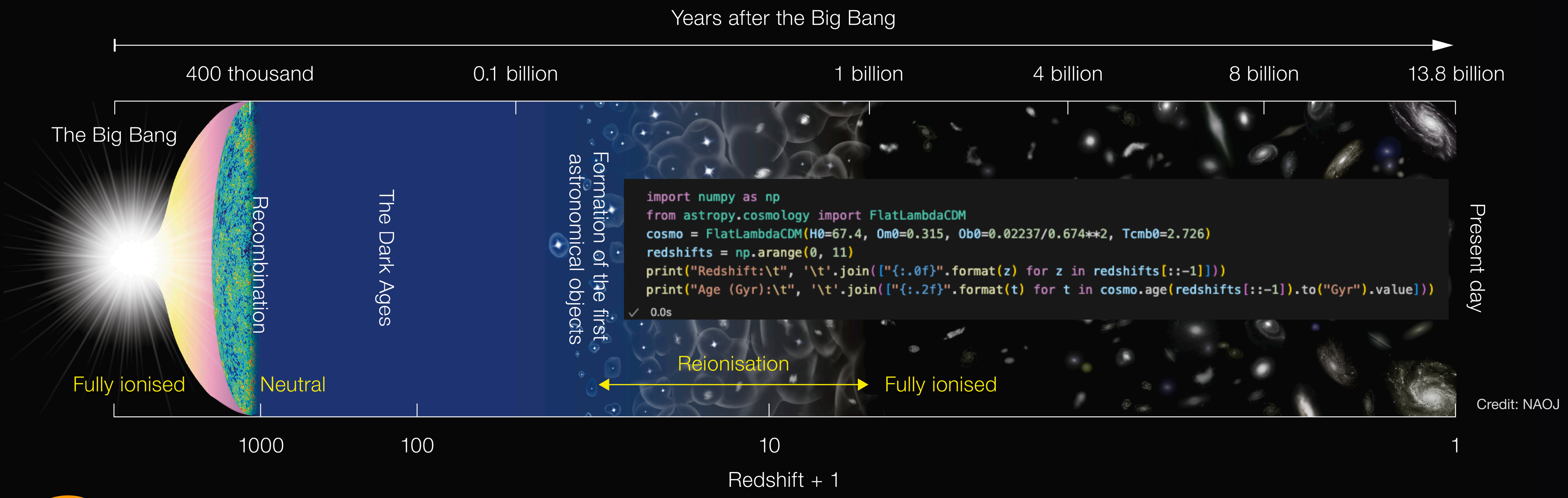
We can always get the (comoving) geodesic distance to a source at redshift z via

$$\chi(z) = \int_0^{\chi} d\chi' = \int_0^{z} dz'\,\frac{d\chi}{dz'} = \int_0^{z} dz'\,\frac{c}{H(z')}\,,$$

but practically, we simply express cosmological distances in terms of redshift

Redshift and lookback time

Scale monotonically (but highly nonlinearly!)



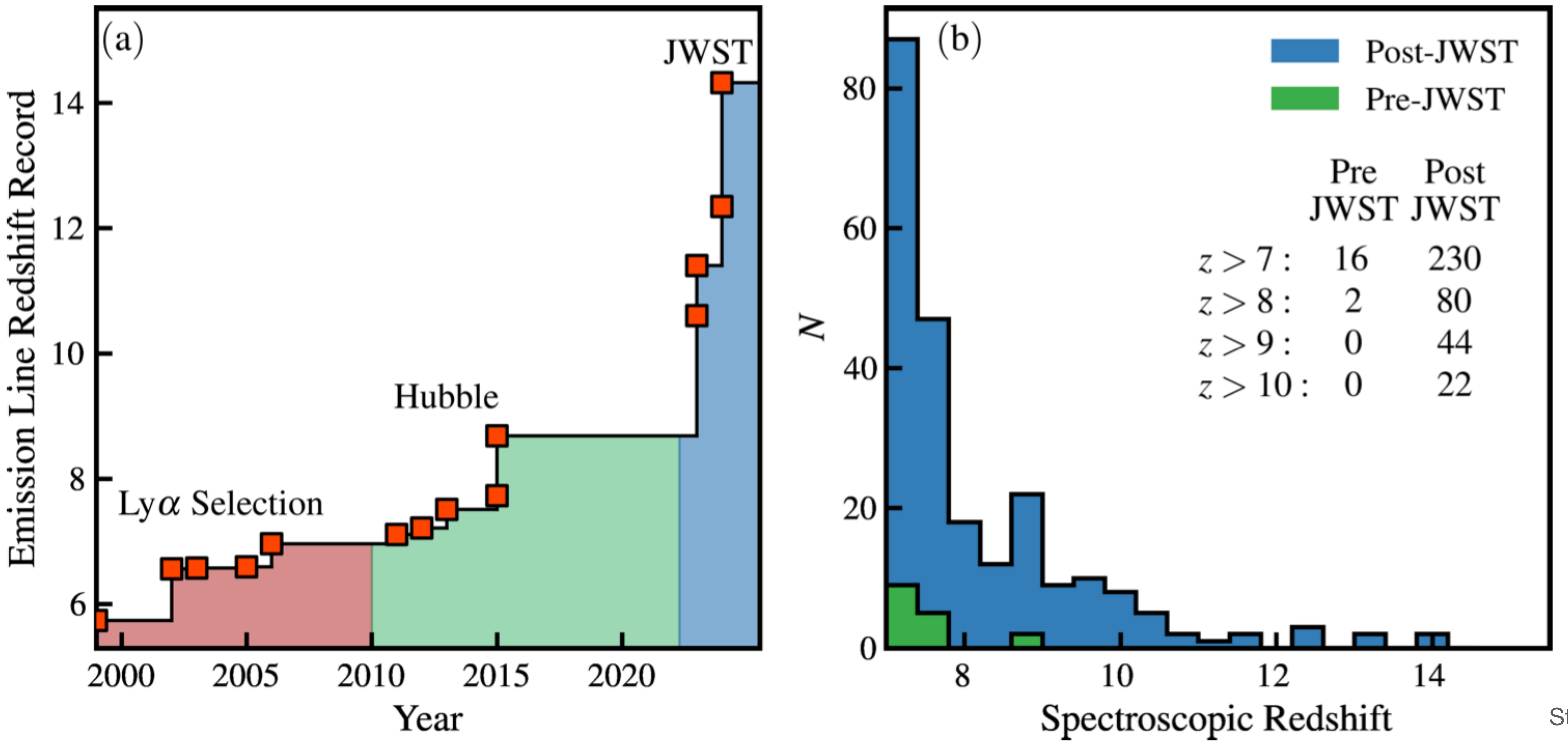

```python
import numpy as np
from astropy.cosmology import FlatLambdaCDM
cosmo = FlatLambdaCDM(H0=67.4, Om0=0.315, Ob0=0.02237/0.674**2, Tcmb0=2.726)
redshifts = np.arange(0, 11)
print("Redshift:\t", '\t'.join(["{:.0f}".format(z) for z in redshifts[::-1]]))
print("Age (Gyr):\t", '\t'.join(["{:.2f}".format(t) for t in cosmo.age(redshifts[::-1]).to("Gyr").value]))
```

✓ 0.0s

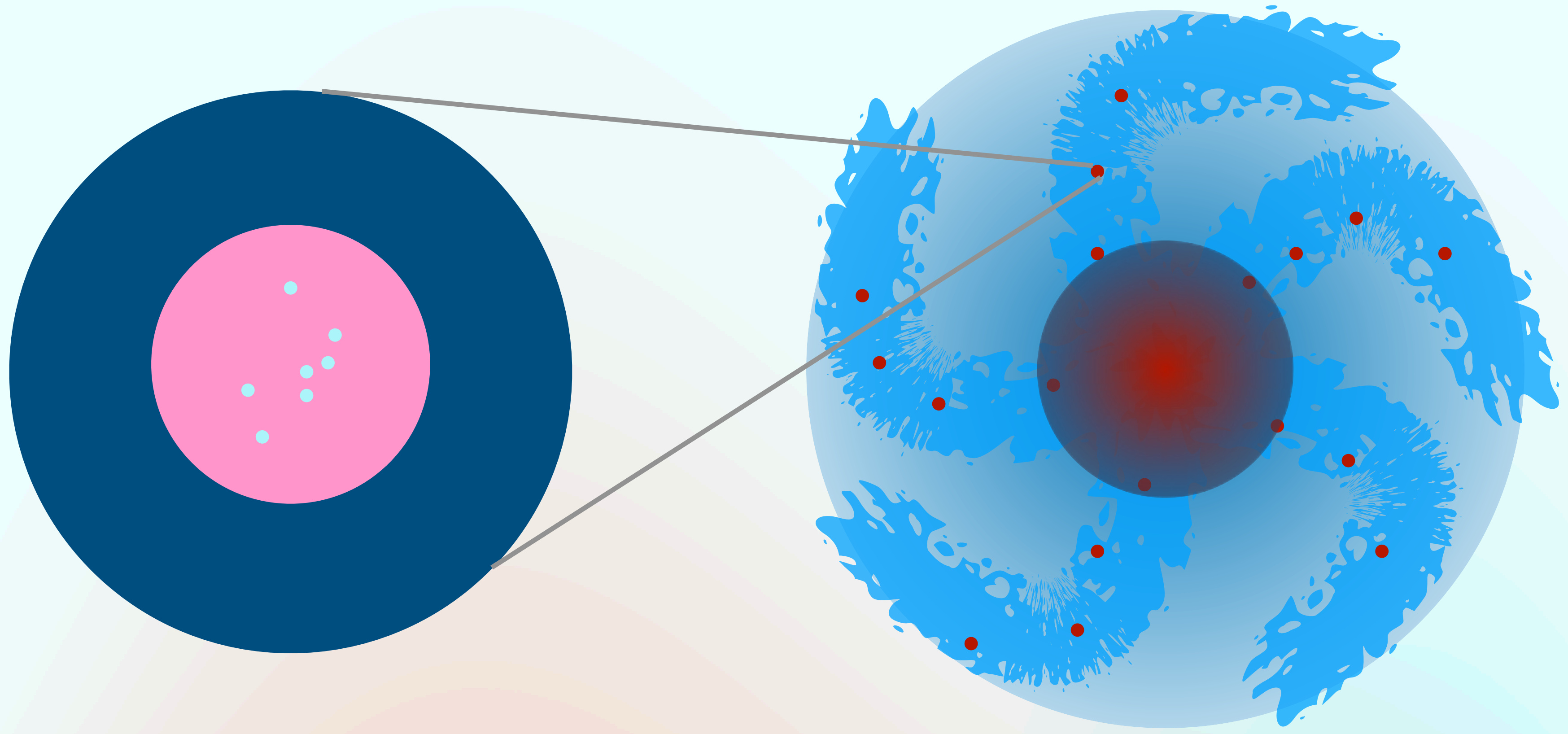
astropy-powered
astropy.org

Redshift:	10	9	8	7	6	5	4	3	2	1	0
Age (Gyr):	0.47	0.54	0.64	0.76	0.93	1.17	1.53	2.14	3.27	5.84	13.79

Redshift confirmation: historical perspective

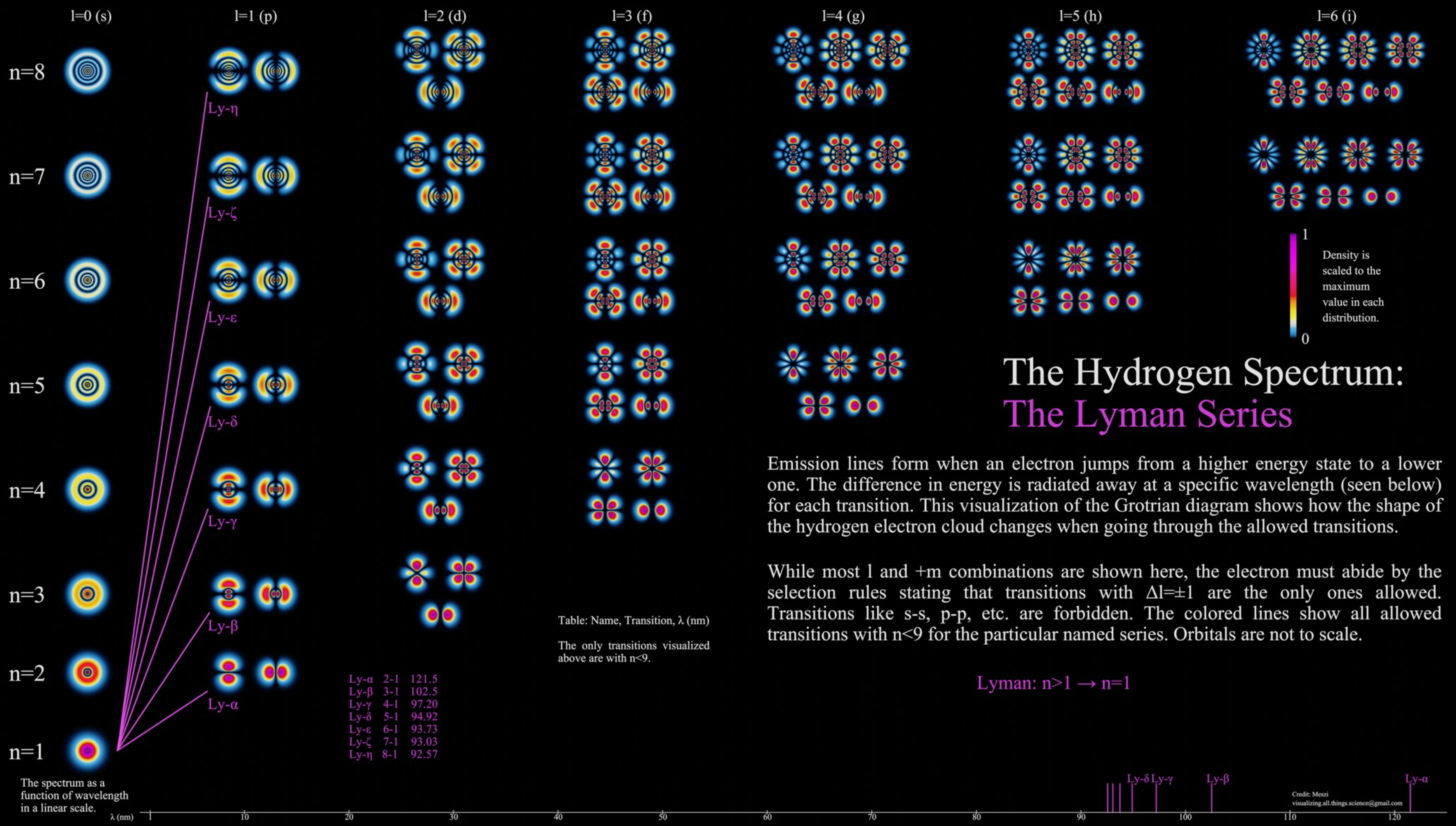


Stark et al. (2025)

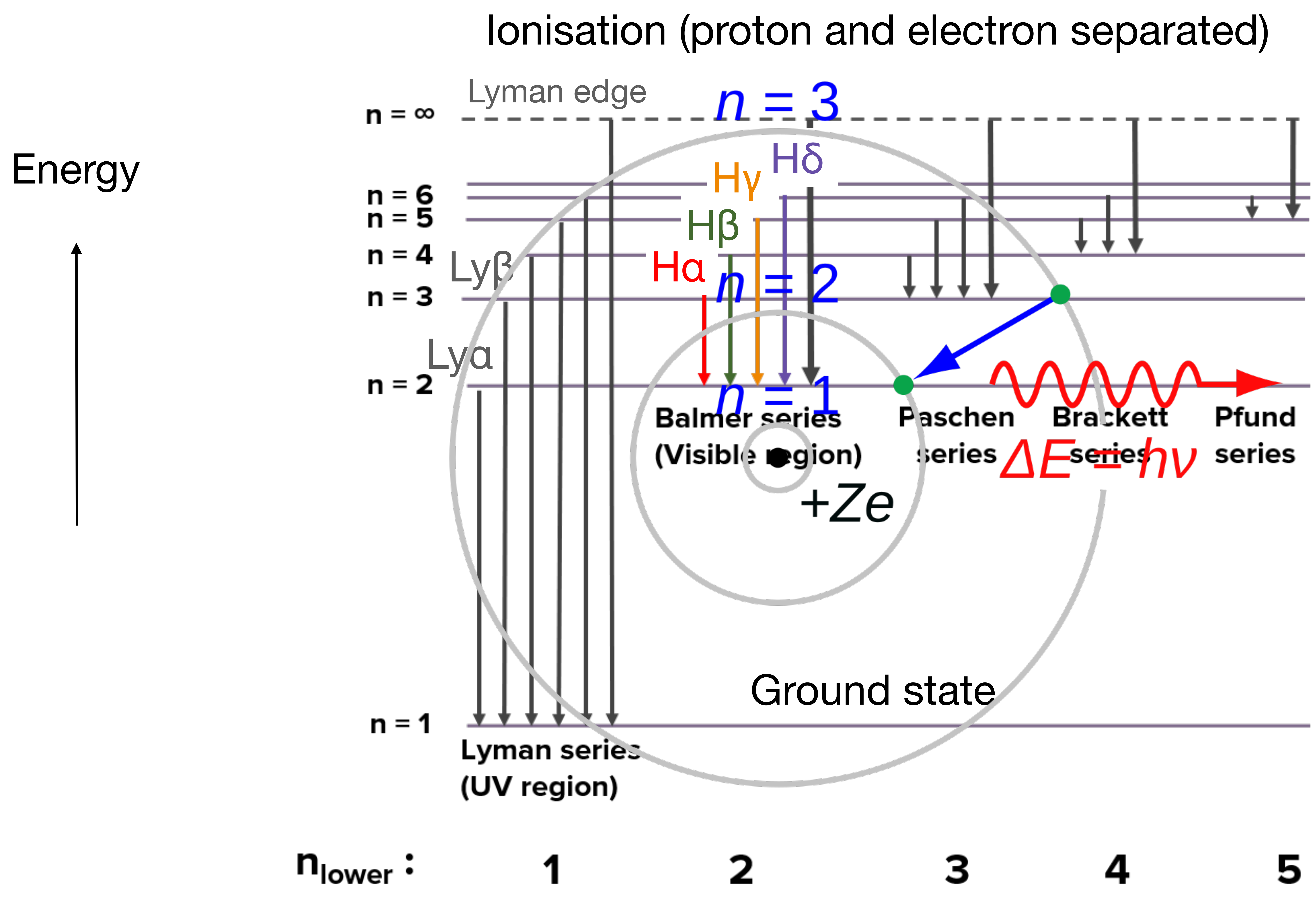


Inside out: how quantum physics manifests on galaxy scales

Hydrogen atom (HI)



Hydrogen electronic transitions in Bohr model



Wavelengths ($E = hc/\lambda$)

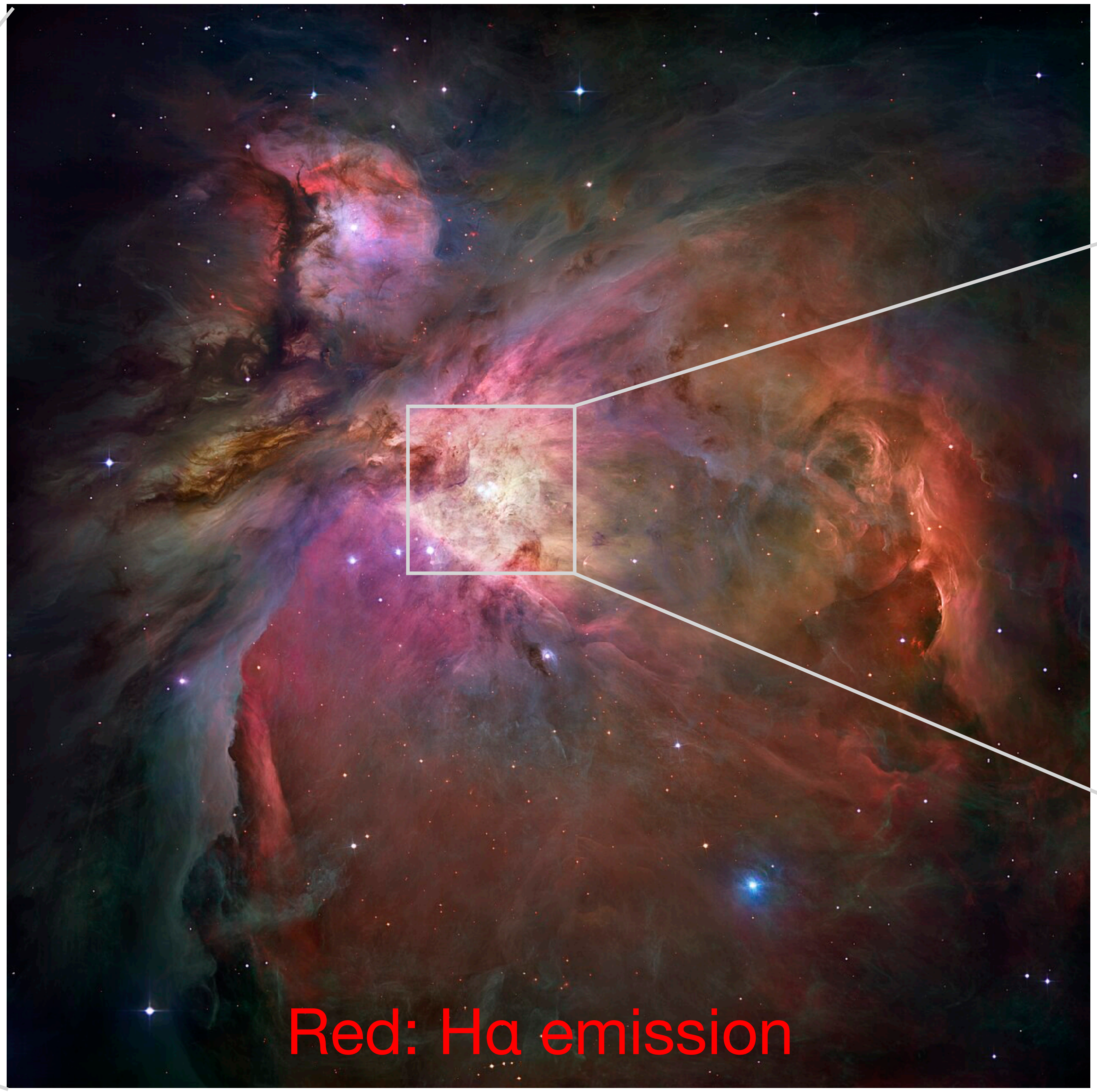
Balmer series
Hα: 6564.6 Å (visible red)
Hβ: 4862.7 Å
Hγ: 4341.7 Å
Hδ: 4102.9 Å

Lyman series
Lyα: 1215.7 Å (far ultraviolet)
Lyβ: 1025.7 Å
Lyman edge: 911.8 Å

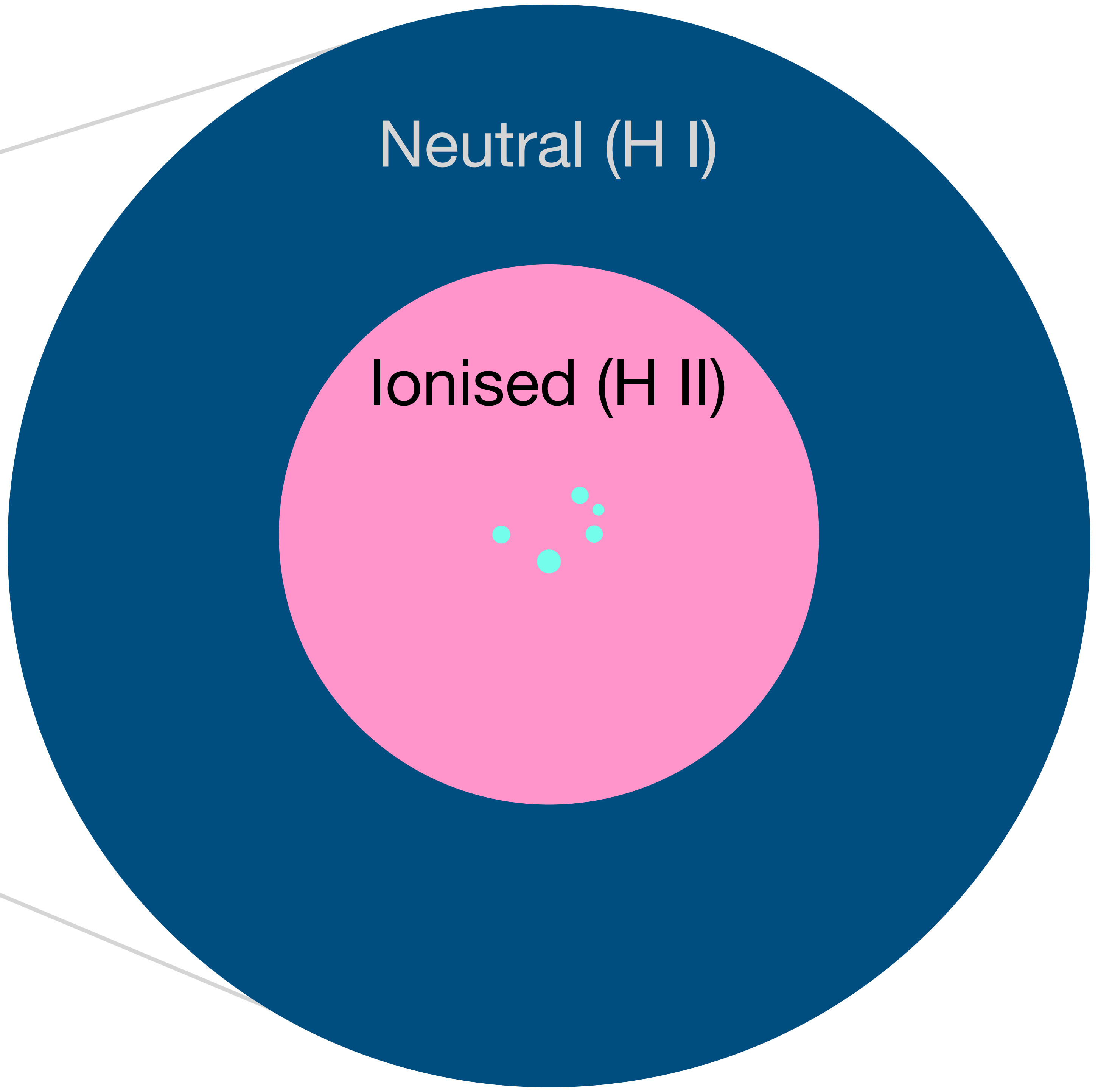
Lyman continuum (LyC) photons (below Lyman edge) are able to ionise neutral hydrogen

H II region example: Orion Nebula

Orion Nebula



H II region



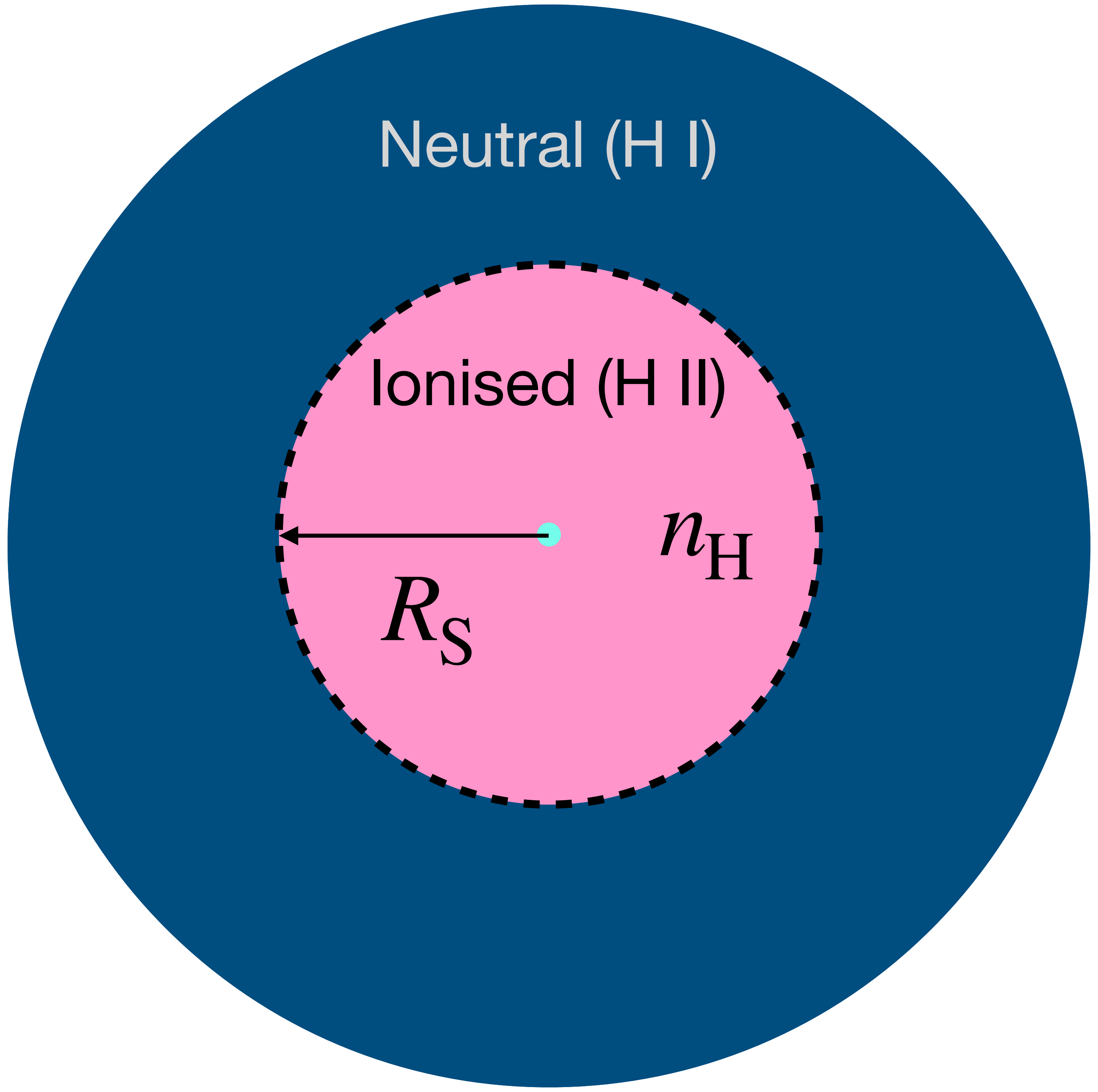
Photoionisation in H II regions

Inside a radius r defining the H II region, ionisations balance recombinations (volumetric rate $\alpha_{\text{rec}}\, n_{\text{HII}}\, n_e$):

$$\dot{N}_{\text{ion}} = \frac{4}{3}\pi r^3\, \alpha_{\text{rec}}\, n_{\text{HII}}\, n_e$$

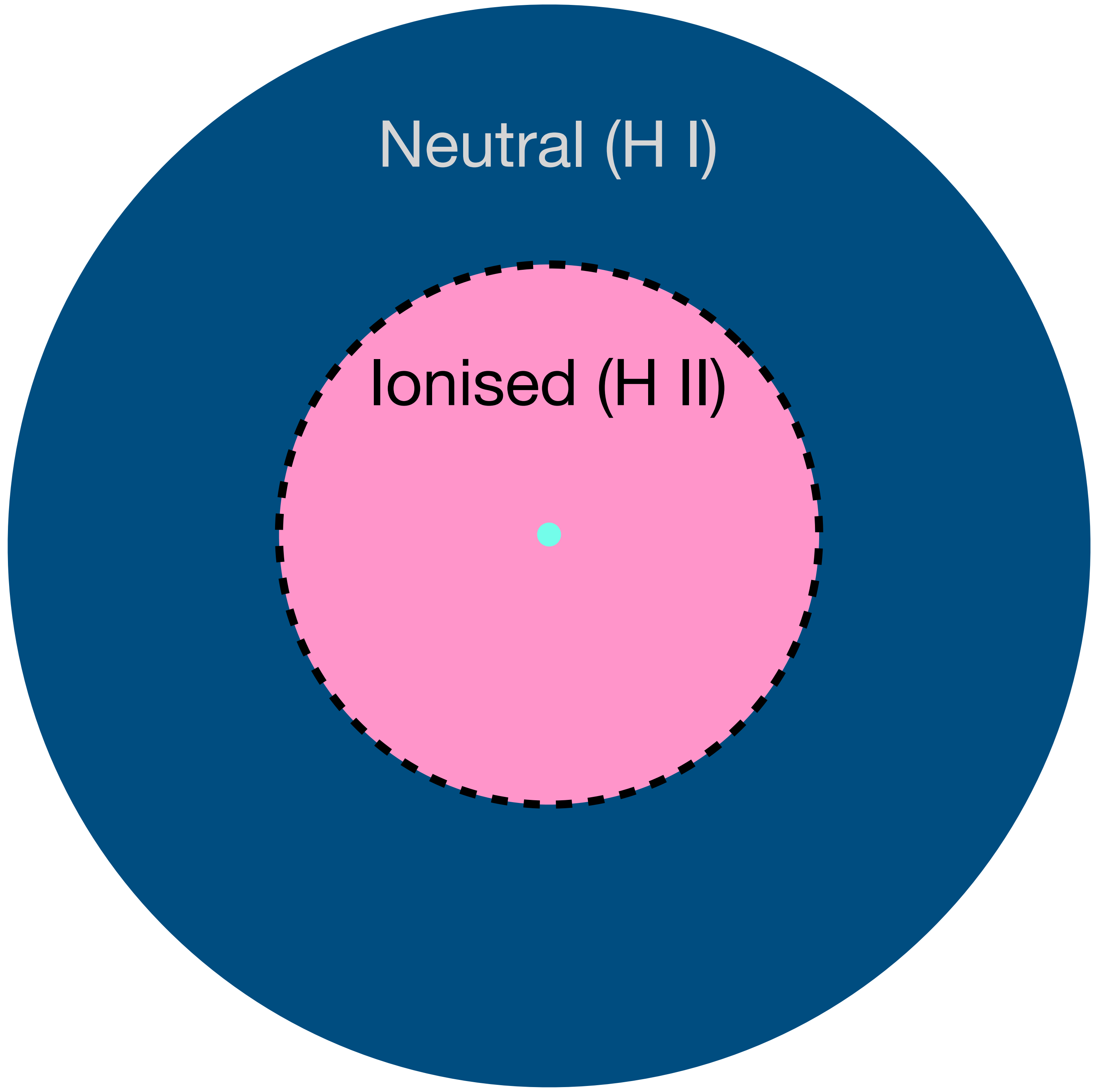
For fully ionised hydrogen ($n_{\text{HII}}\, n_e \approx n_{\text{H}}^2$), we can define the *Strömgren radius*:

$$R_{\text{S}}^3 \equiv \left(\frac{3\dot{N}_{\text{ion}}}{4\pi\alpha_{\text{rec}}\, n_{\text{H}}^2} \right)$$



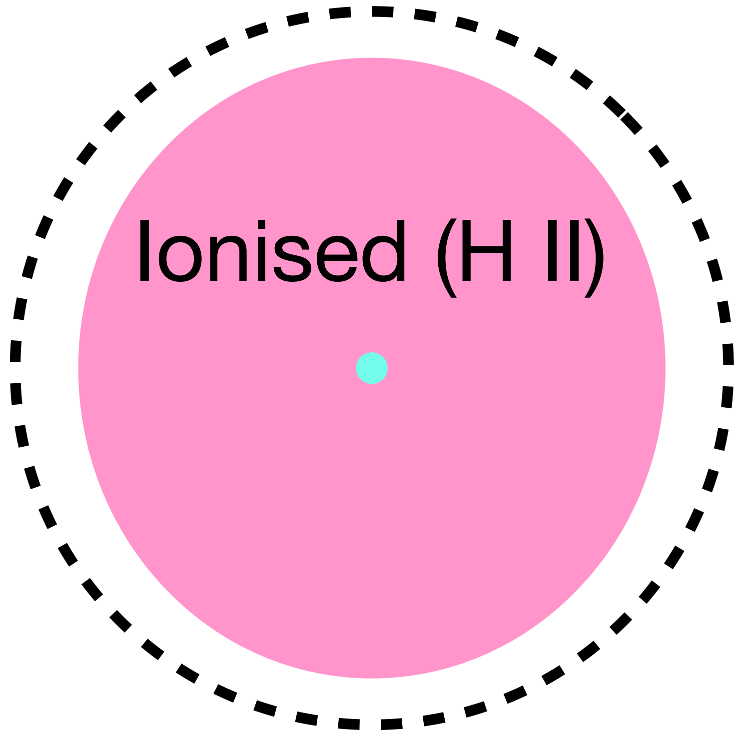
Photoionisation in H II regions

Ionisation bounded ($r > R_\mathrm{S}$)



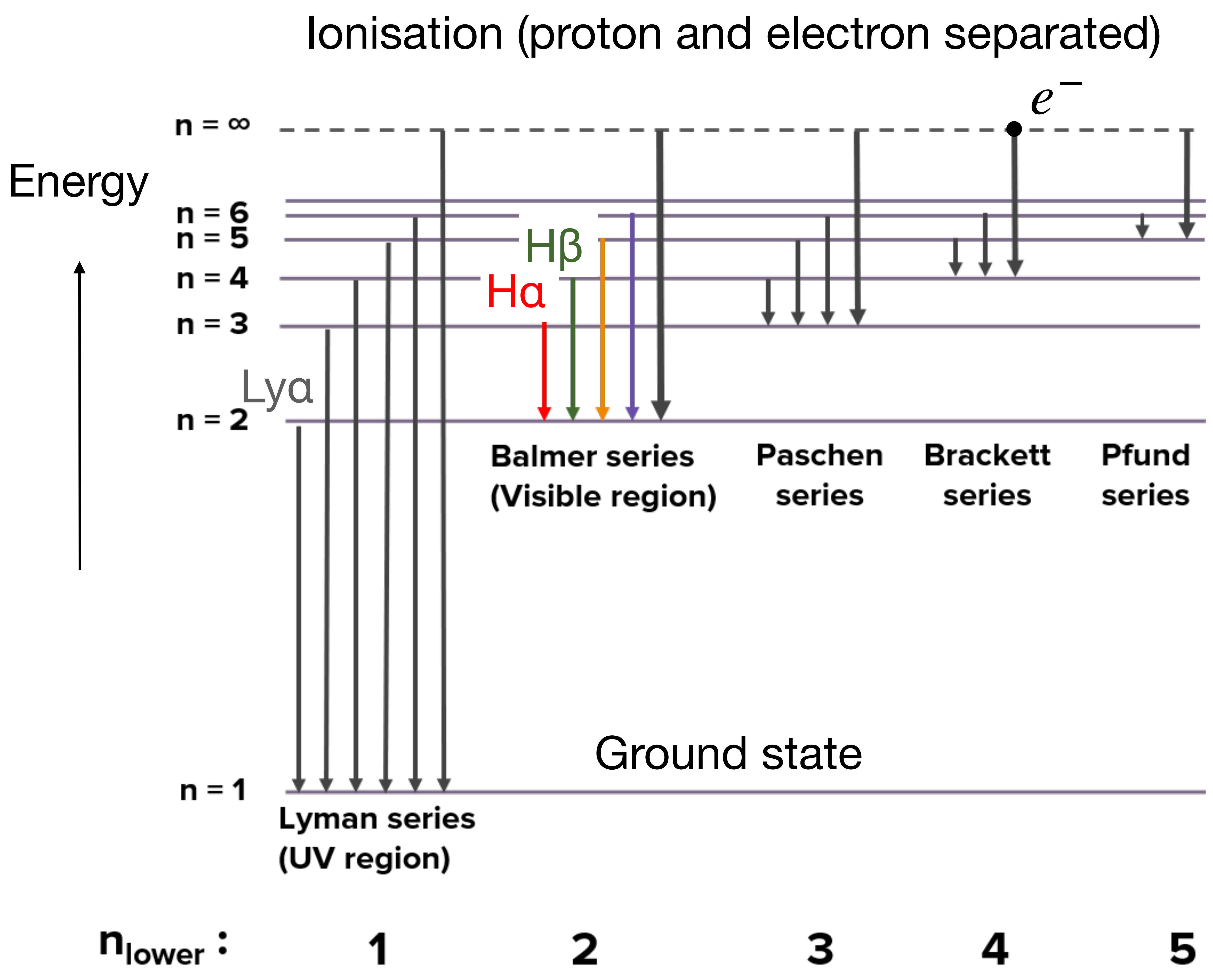
All ionising photons absorbed:
$f_\mathrm{esc} = 0$ (no reionisation!)

Density bounded ($r < R_\mathrm{S}$)



Escape of ionising photons:
$f_\mathrm{esc} > 0$

Hydrogen recombination lines



Recombination radiation

Every time a proton and electron recombine into a hydrogen atom, the electron quickly *cascades* down to the ground state (obeying QM selection rule $|l - l'| = 1$), for instance:

$H^+ + e^- \rightarrow H_{4p} + \gamma_{\infty \rightarrow 4p}$ (free-bound continuum emission)

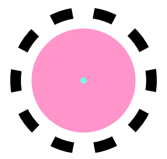
$\rightarrow H_{3s} + \gamma_{\mathrm{Pa}\alpha(4\mathrm{p}\rightarrow 3\mathrm{s})}$ (Paα line emission)

$\rightarrow H_{2p} + \gamma_{\mathrm{H}\alpha(3\mathrm{s}\rightarrow 2\mathrm{p})}$ (Hα line emission)

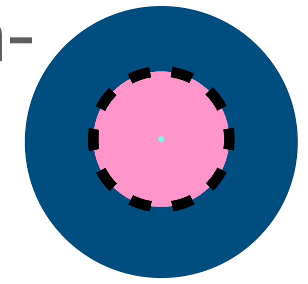
$\rightarrow H_{1s} + \gamma_{\mathrm{Ly}\alpha(2\mathrm{p}\rightarrow 1\mathrm{s})}$ (Lyα line emission)

Simplifying assumptions

Case-A recombination: gas is optically thin to LyC photons (density bound), recombination can result in any energy level



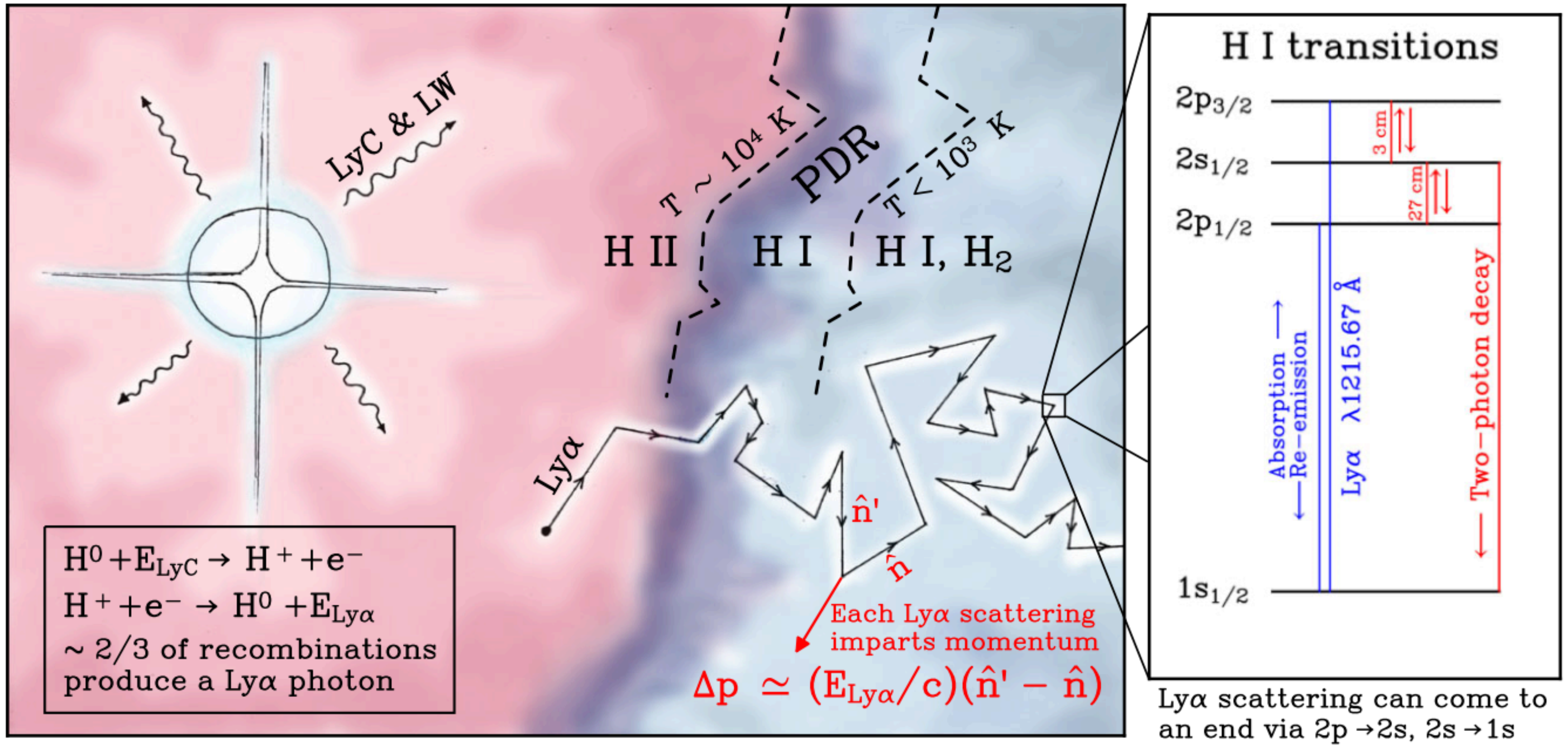
Usual assumption is Case B: gas is optically thick to Lyman-series photons (ionisation bound), recombination cannot result in the ground state (why not?)



Under case B, about 2/3 of recombination events (68.6% at 10 000 K) lead to the emission of a Lyα photon

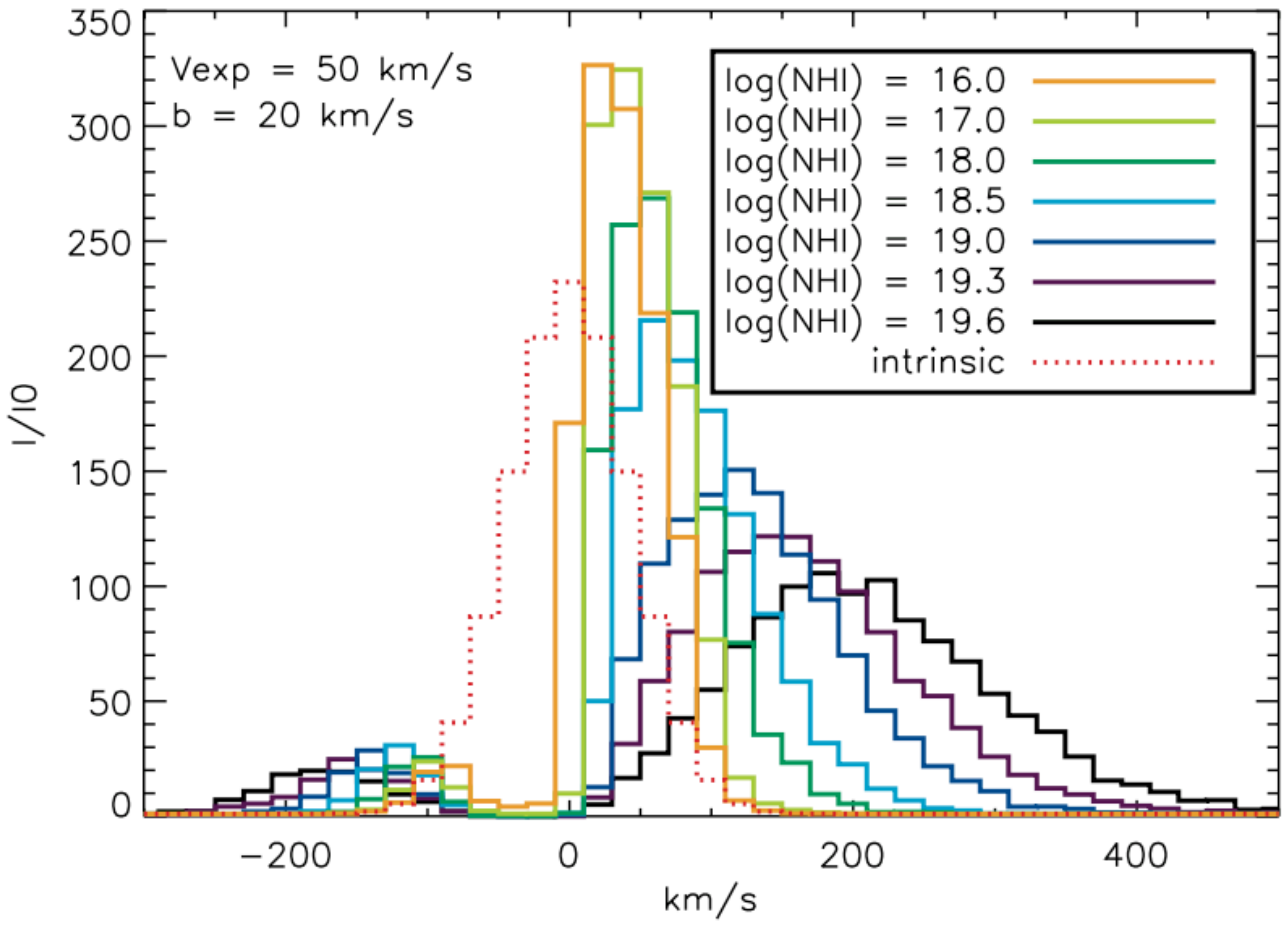
Resonant scattering of Lyα photons

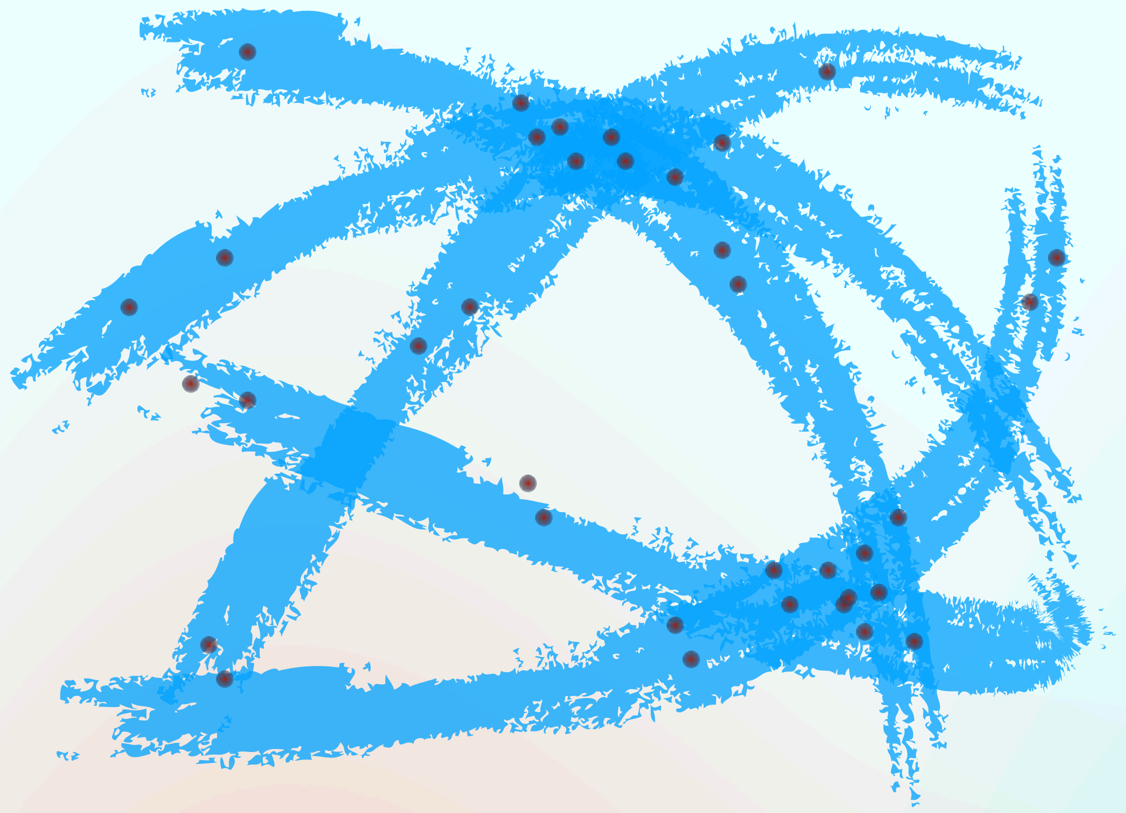
Nebrin et al. (2025)



Lyα scattering can come to an end via 2p→2s, 2s→1s

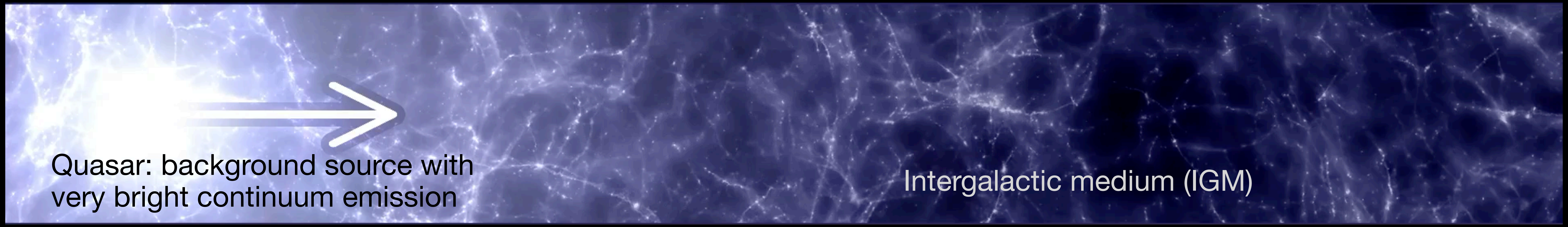
Verhamme et al. (2014)

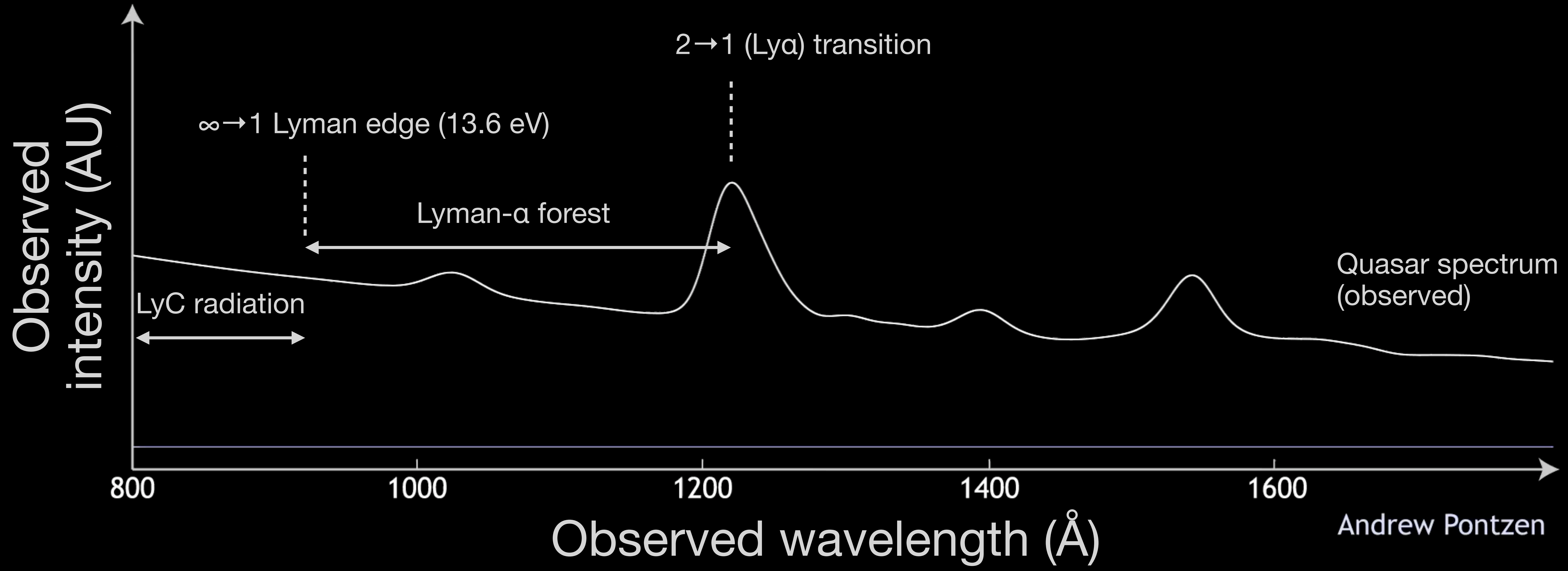




Observationally probing the intergalactic medium

Intergalactic absorption: Lyman-α forest





IGM absorption of Lyman-α

First distance measurement of quasars (Schmidt 1963, 1964, 1965)

NOTES

ON THE DENSITY OF NEUTRAL HYDROGEN IN INTERGALACTIC SPACE

Recent spectroscopic observations by Schmidt (1965) of the quasi-stellar source 3C 9, which is reported by him to have a redshift of 2.01, and for which Lyman-α is in the visible spectrum, make possible the determination of a new very low value for the density of neutral hydrogen in intergalactic space. It is observed that the continuum of the source continues (though perhaps somewhat weakened) to the blue of Ly-α; the line as seen on the plates has some structure but no obvious asymmetry. Consider, however, the fate of photons emitted to the blue of Ly-α. As we move away from the source along the line of sight, the source becomes redshifted to observers locally at rest in the expansion, and for one such observer, the frequency of any such photon coincides with the rest frequency of Ly-α in his frame and can be scattered by neutral hydrogen in his vicinity.

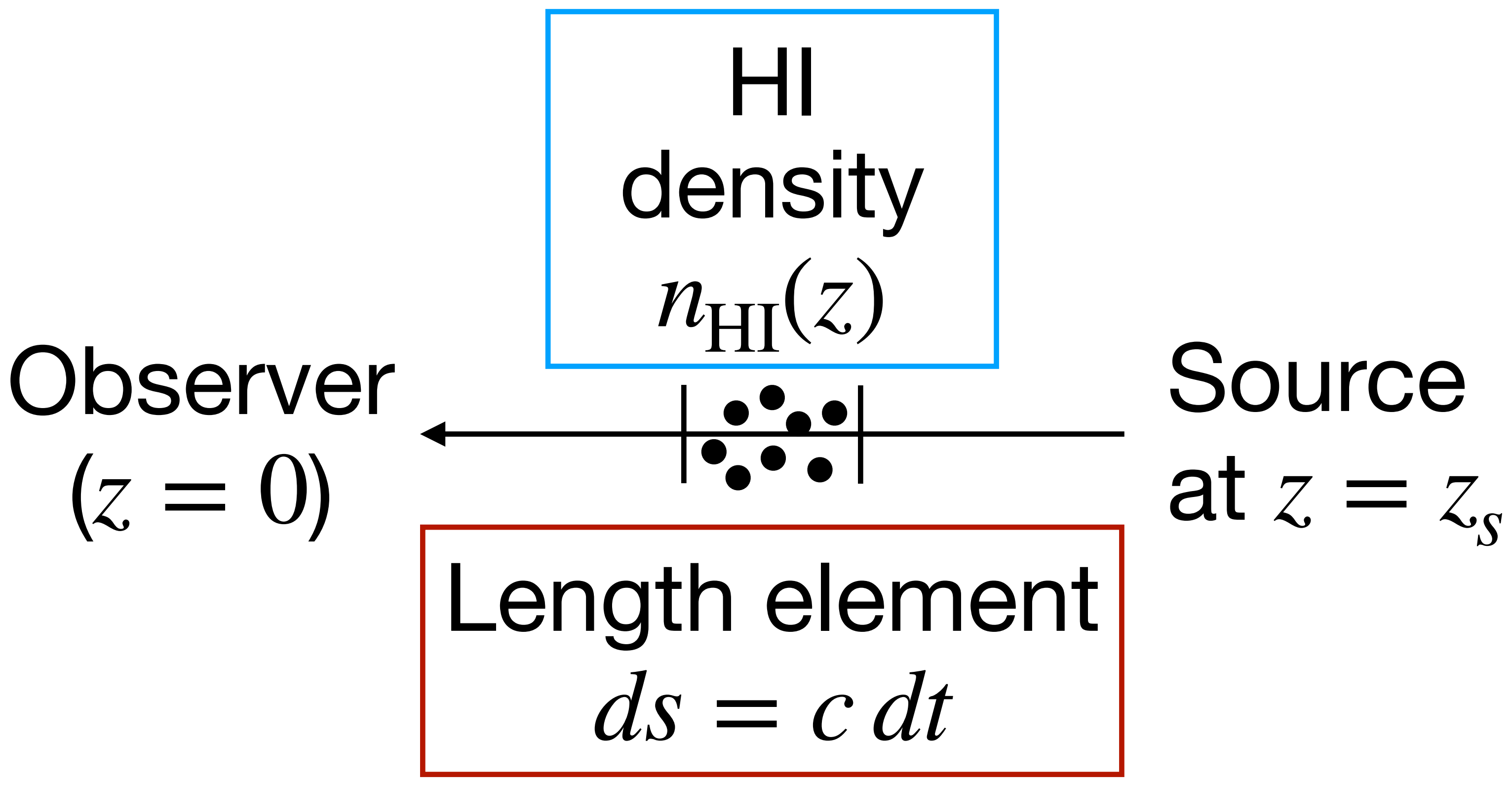
Gunn & Peterson (1965)

IGM absorption of Lyman-α

Consider a distant source with a given redshift z_s.

Given the Lyα cross section $\sigma_{\mathrm{Ly}\alpha}(\lambda, T) \approx 5.9 \times 10^{-14}\, \phi(\lambda) \left(\frac{T}{10^4\,\mathrm{K}} \right)^{-1/2} \mathrm{cm}^2$, the integrated optical depth to Lyα photons from a source at redshift z_s is

$$\tau_{\mathrm{Ly}\alpha}(\lambda_{\mathrm{obs}}) = \int_0^{z_s} \boxed{dz\, \frac{c\, dt}{dz}}\, \boxed{n_{\mathrm{HI}}(z)}\, \sigma_{\mathrm{Ly}\alpha}\left(\frac{\lambda_{\mathrm{obs}}}{1+z}, T \right).$$



Simplifying $\phi(\lambda)$ to be a delta function at $\lambda = \lambda_{\mathrm{Ly}\alpha}$, we obtain the Gunn-Peterson optical depth for the IGM at overdensity $\Delta = n_{\mathrm{H}}/\bar{n}_{\mathrm{H}}(z)$:

$$\tau_{\mathrm{GP}}(z_s) = \frac{f_\alpha \pi e^2}{m_e \nu_\alpha} \frac{x_{\mathrm{HI}}\, n_{\mathrm{H}}(z_s)}{H(z_s)} \approx 2.1 \times 10^4\, x_{\mathrm{HI}}\, \Delta\, \left(1 + z_s\right)^{3/2}.$$

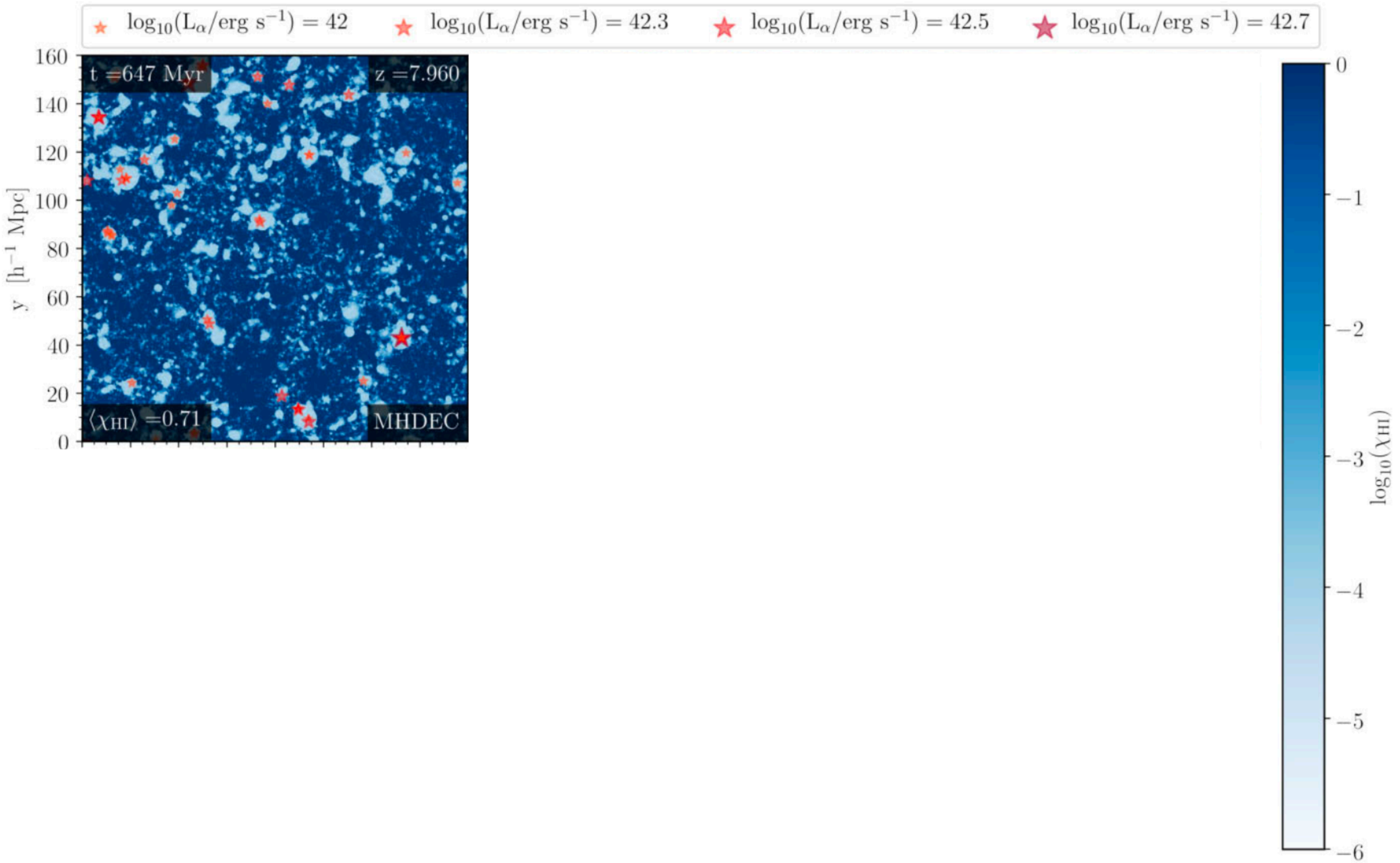
As soon as the neutral fraction of a intervening medium at mean density ($\Delta = 1$) exceeds $x_{\mathrm{HI}} \approx 10^{-4}$, it becomes optically thick to Lyα!

Emergence of Lyman-α emitting galaxies (LAEs)

Reionisation
is driven by…

Low-mass
galaxies

High-mass
galaxies



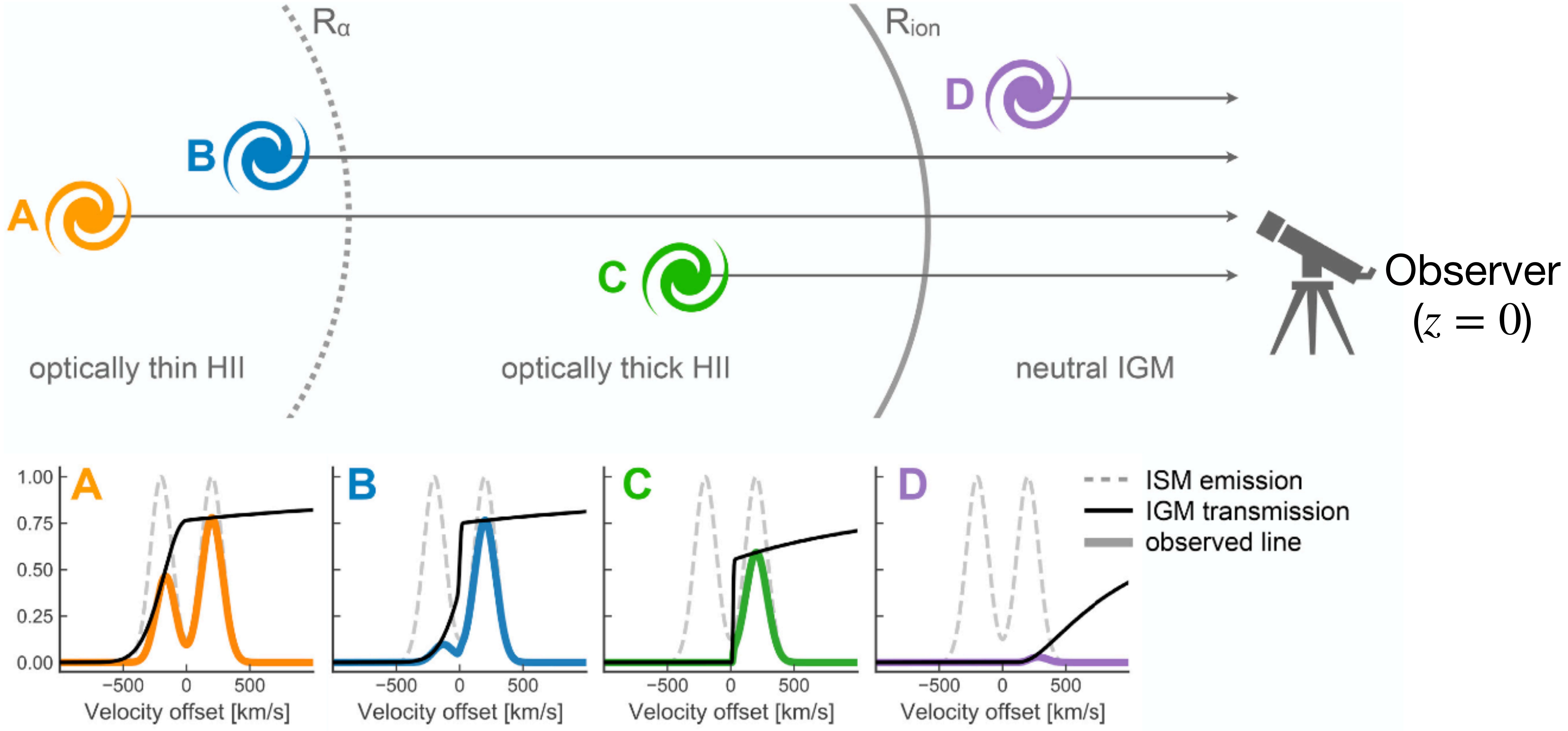
Why do LAEs trace the process of reionisation?

Cosmic time

Astraeus simulations
(Hutter et al. 2023)

Ionised bubbles and Lyman-α escape

Two-zone IGM model: ionised bubble embedded
in neutral medium (Mason & Gronke 2020)



Ionised bubble in an expanding universe

How does the volume of a sphere ($V \propto R^3$) evolve with time, if its radius stays constant in comoving coordinates, $R(t) = a(t)\chi$ with $\chi(t) = \mathrm{const}$. ?

Chain rule: $\dfrac{d(R^3)}{dt} = 3R^2\dfrac{dR}{dt} = 3R^2\dfrac{da}{dt}\chi = 3R^3\dfrac{\dot{a}}{a}$

Evolution of ionised bubble radius $R_{\mathrm{ion}}(t)$ given by Cen & Haiman (2000):

$$\frac{dR^3_{\mathrm{ion}}}{dt} = \underbrace{\boxed{3H(z)R^3_{\mathrm{ion}}}}_{\text{Cosmic expansion}} + \underbrace{\boxed{\frac{3f_{\mathrm{esc,\,LyC}}\,\dot{N}_{\mathrm{ion}}}{4\pi\bar{n}_{\mathrm{H}}}}}_{\text{Escape of ionising photons}} - \boxed{C_{\mathrm{HII}}\bar{n}_{\mathrm{H}}\alpha_{\mathrm{B}}R^3_{\mathrm{ion}}}$$

Recombinations, with 'clumping factor' based on simulations ($C_{\mathrm{HII}} = 3$)

Cosmic expansion

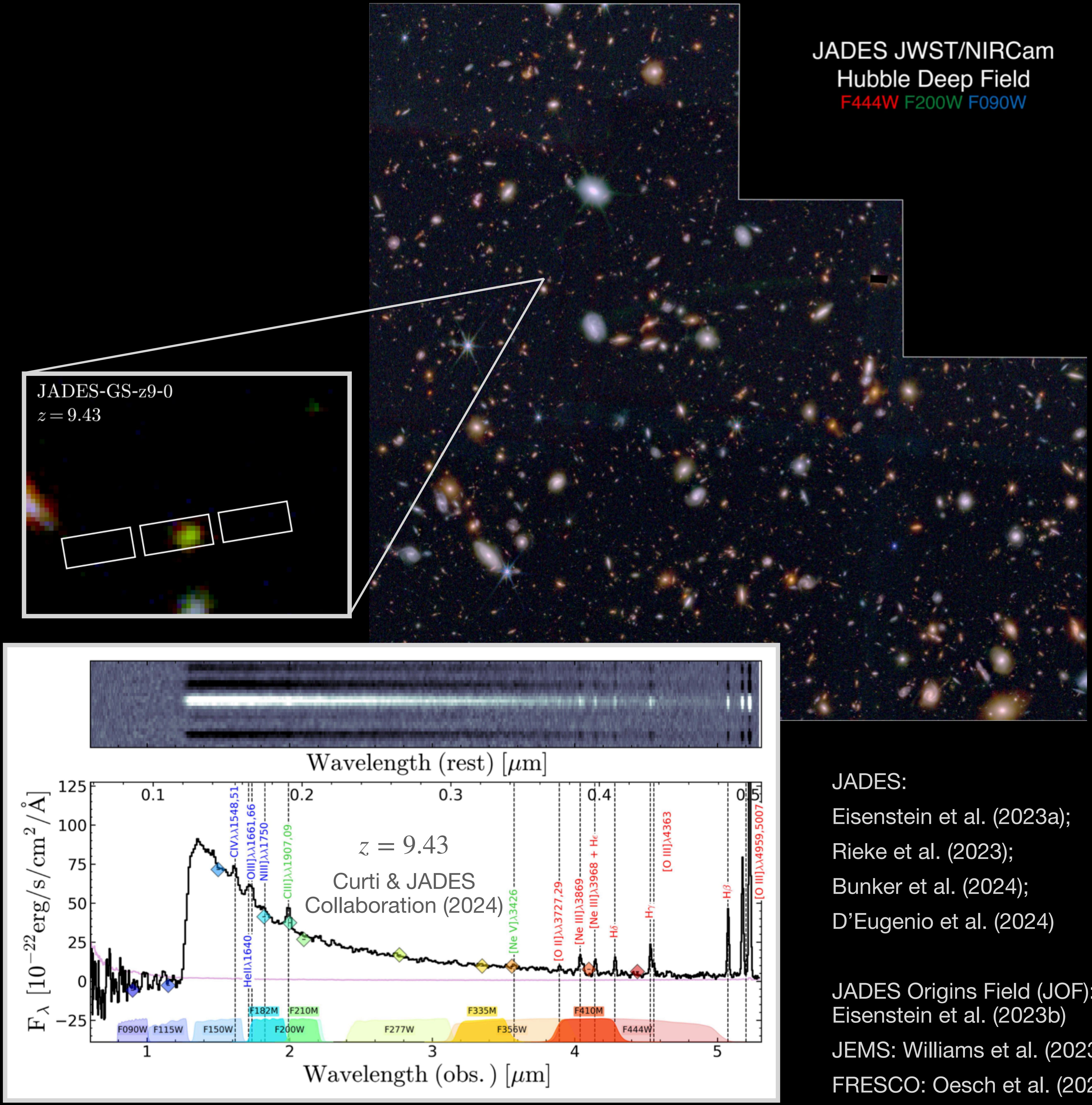
Escape of ionising photons

Observing the process of reionisation with JWST

JADES

JWST Advanced Deep Extragalactic Survey

- Joint GTO programme from NIRCam & NIRSpec instrument teams: https://jades-survey.github.io
- Near-infrared multi-object spectroscopy selected from ultra-deep pre-imaging over the GOODS fields, containing HUDF
- Exposure times of 10 up to 100+ hours (!) per target over different resolution modes, mainly PRISM ($R \approx 100$) and gratings ($R \approx 1000$)



JADES:

Eisenstein et al. (2023a);

Rieke et al. (2023);

Bunker et al. (2024);

D'Eugenio et al. (2024)

JADES Origins Field (JOF): Eisenstein et al. (2023b)

JEMS: Williams et al. (2023)

FRESCO: Oesch et al. (2023)

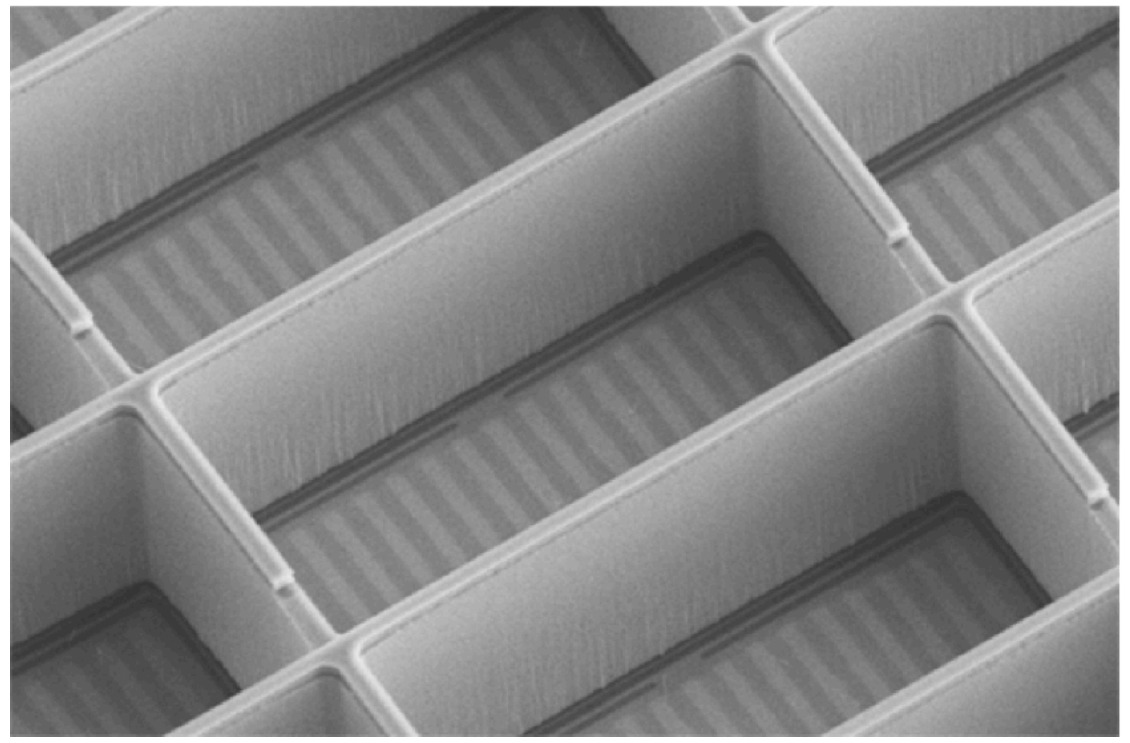
NIRSpec multi-object spectroscopy

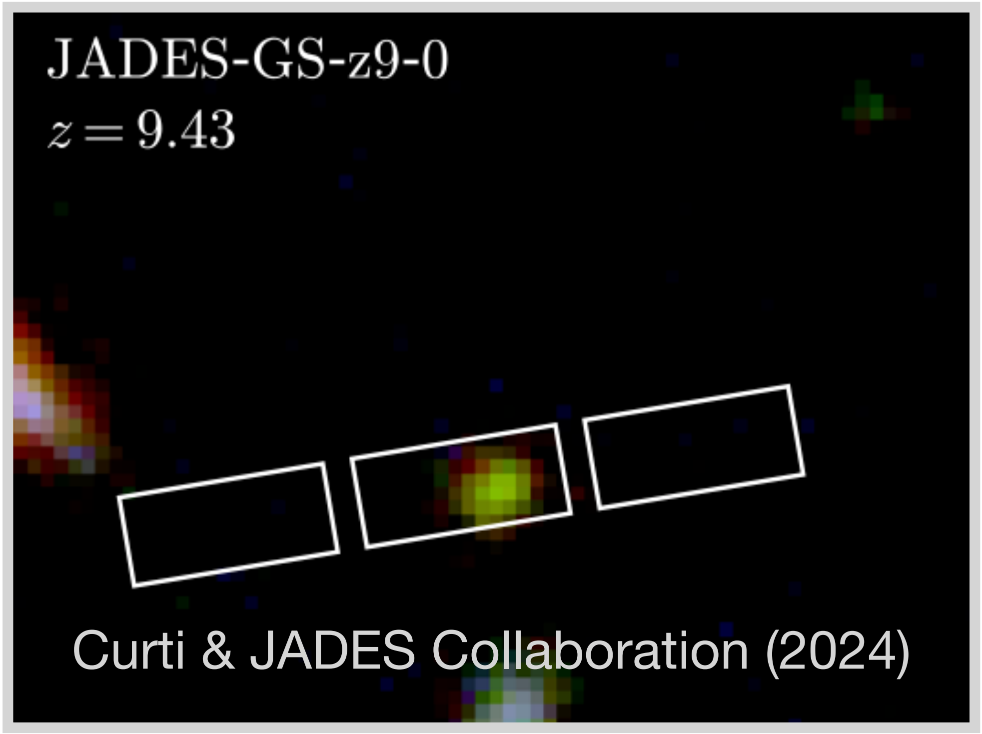
- 250,000 configurable micro-shutters that can be individually opened or closed form the *micro-shutter assembly* (MSA)

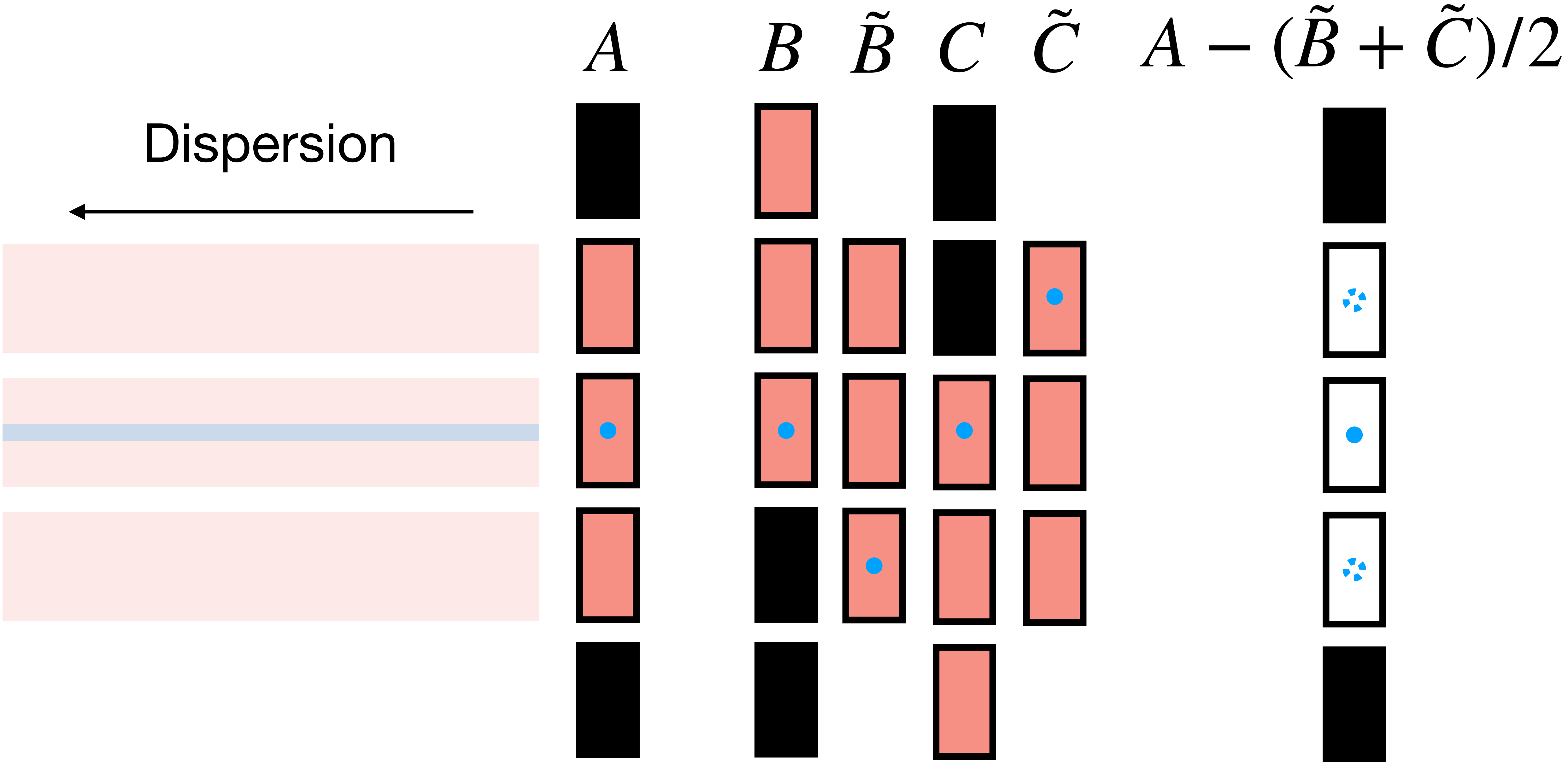
- Light is dispersed onto detector from three adjacent micro-shutters

- Observations are taken in three different positions or *nods*

- Nodding pattern allows background subtraction





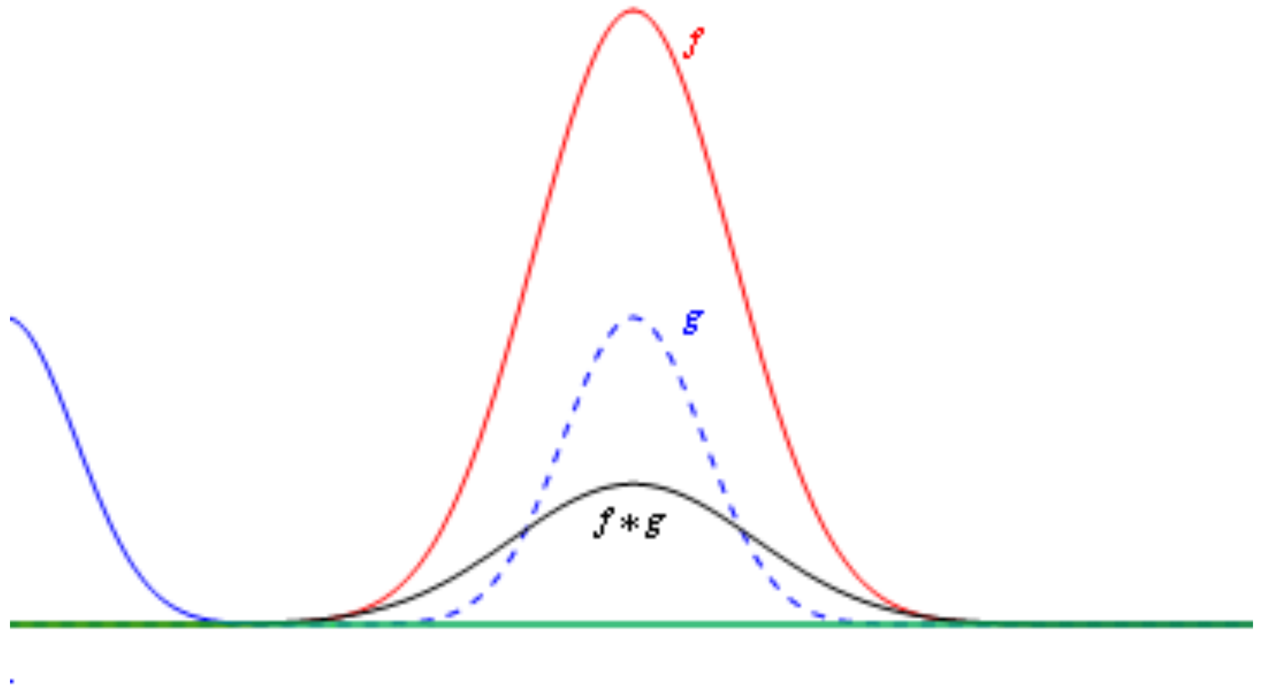


Spectral resolution

- Equivalent to the *point spread function* (PSF) in images, in spectroscopy we have the *line spread function* (LSF): the observed profile of a delta function ('point source')

- The observed spectrum (F_λ) is then simply a convolution of the LSF and the intrinsic spectrum ($F_{\lambda,\,\mathrm{intr}}$):
$$F_\lambda = \mathrm{LSF} * F_{\lambda,\,\mathrm{intr}}$$

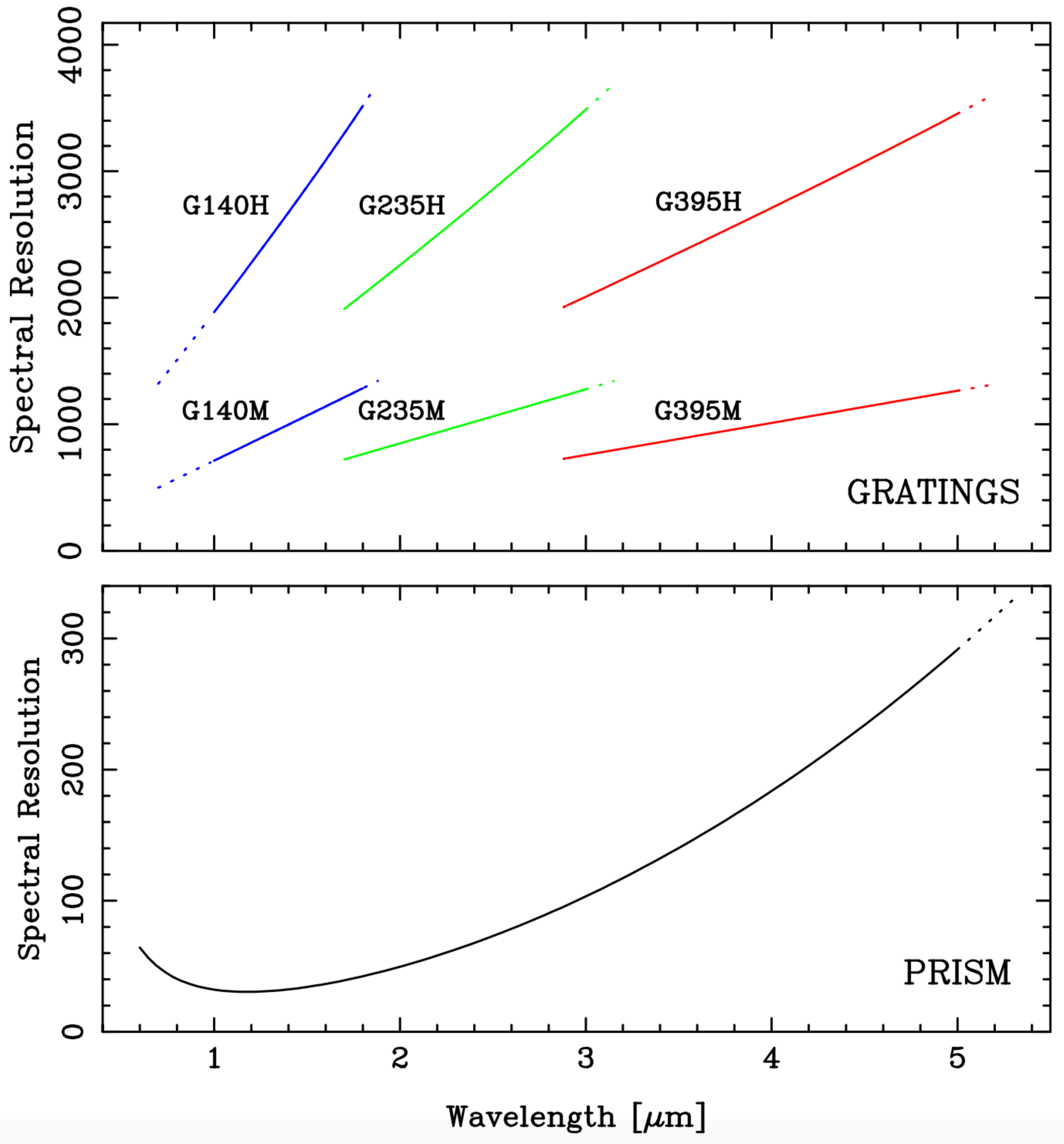
- Both intrinsic line profile and LSF often assumed to be Gaussian, in which case their widths add quadratically (because their Fourier Transforms are still Gaussian):
$$\sigma^2_{\mathrm{obs}} = \sigma^2_{\mathrm{int}} + \sigma^2_{\mathrm{LSF}}$$



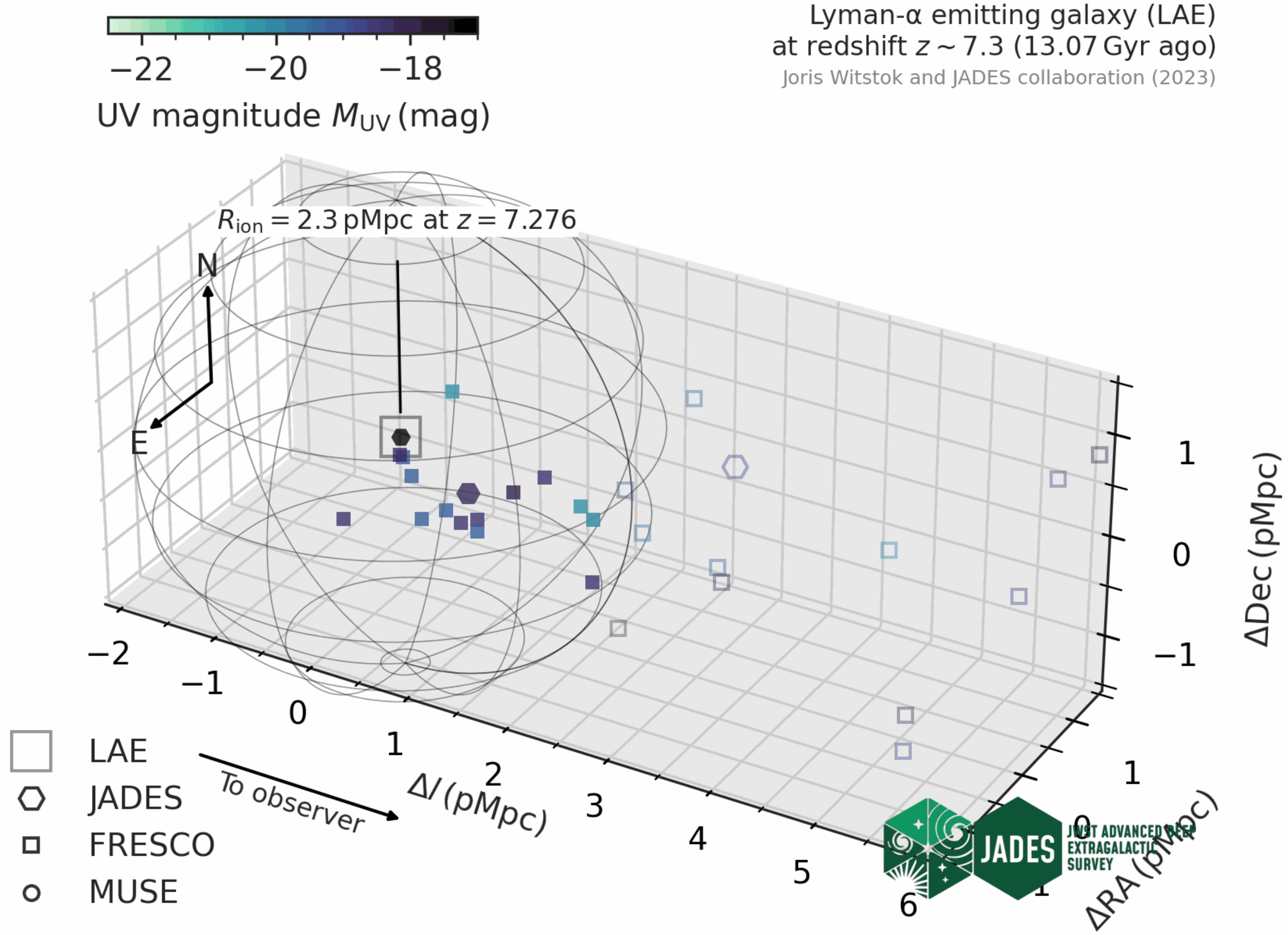
NIRSpec dispersers and filters

- Spectral resolution $R = \lambda / \Delta\lambda$ specifies the FWHM $\Delta\lambda$ of line spread function (LSF)
- NIRSpec instrument has 7 modes:
  - One low-resolution PRISM disperser ($R \approx 100$) covering 0.6-5.3 µm
  - Three medium-resolution gratings ($R \approx 1000$) together covering 1-5 µm
  - Three 'high-resolution' gratings ($R \approx 3000$) together covering 1-5 µm

Jakobsen et al. (2022)



JWST 3D view of the end of the EoR



Summary

- The study of galaxy evolution spans a huge dynamic range of physical scales

- Spectroscopy is a powerful tool to understand the astrophysical conditions in and around galaxies

- Reionisation exemplifies the complex interplay between galaxies and the large-scale matter distribution (IGM)