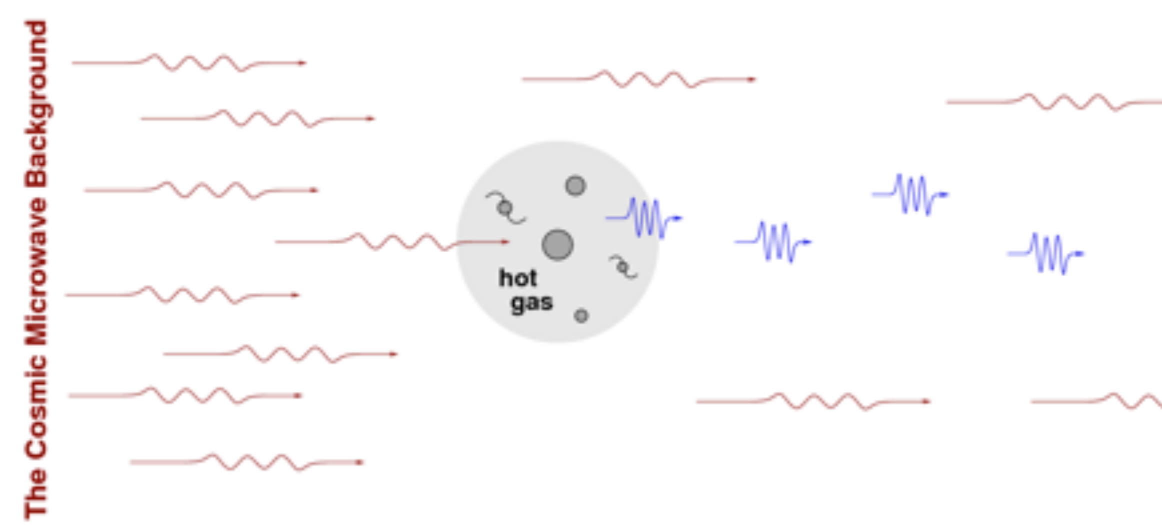
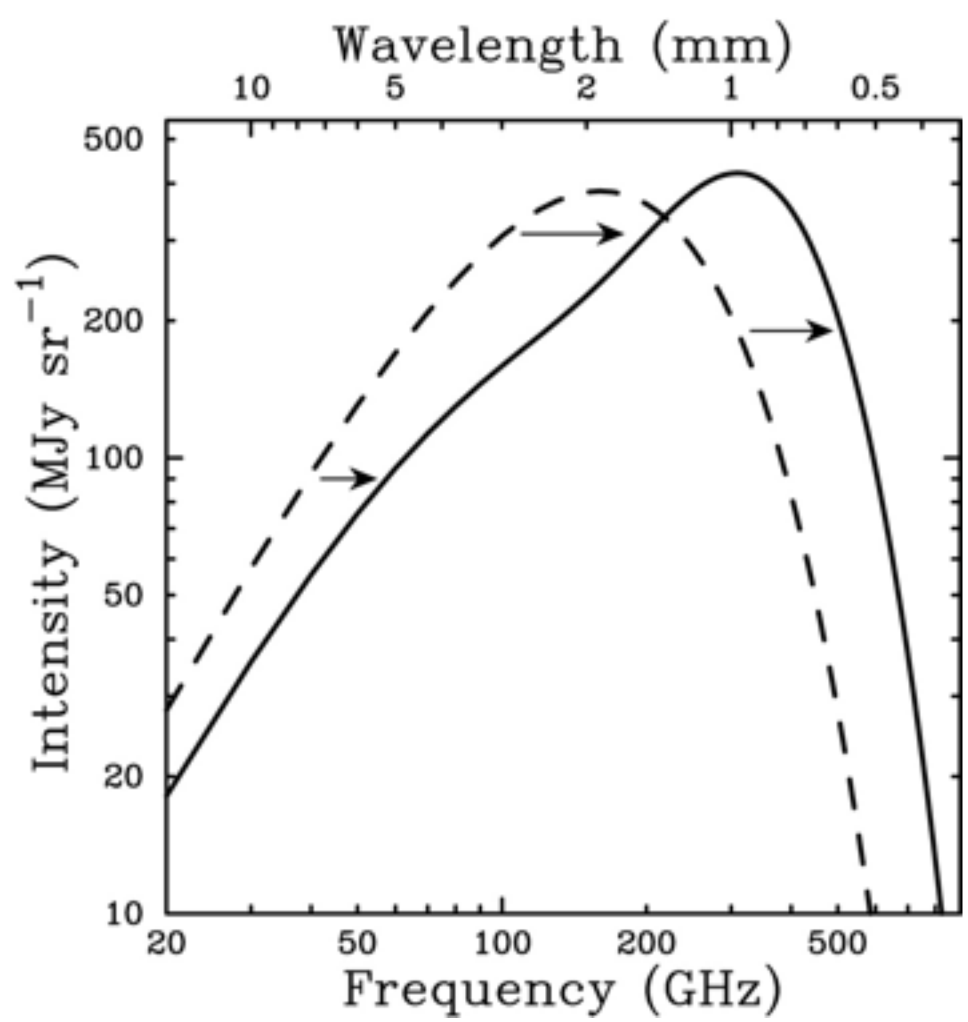
Sunayev-Zeldovich effect

Sunayev-Zeldovich effect

- The Sunyaev-Zel'dovich effect (SZE) is a small spectral distortion of CMB spectrum caused by the scattering of the photons off a distribution of high energy electrons (e.g. cluster hot plasma).
- The *inverse Compton scattering* **boosts** the energy of the CMB photon by roughly kT_e/m_ec^2 causing a small (~1 mK) distortion in the CMB spectrum.

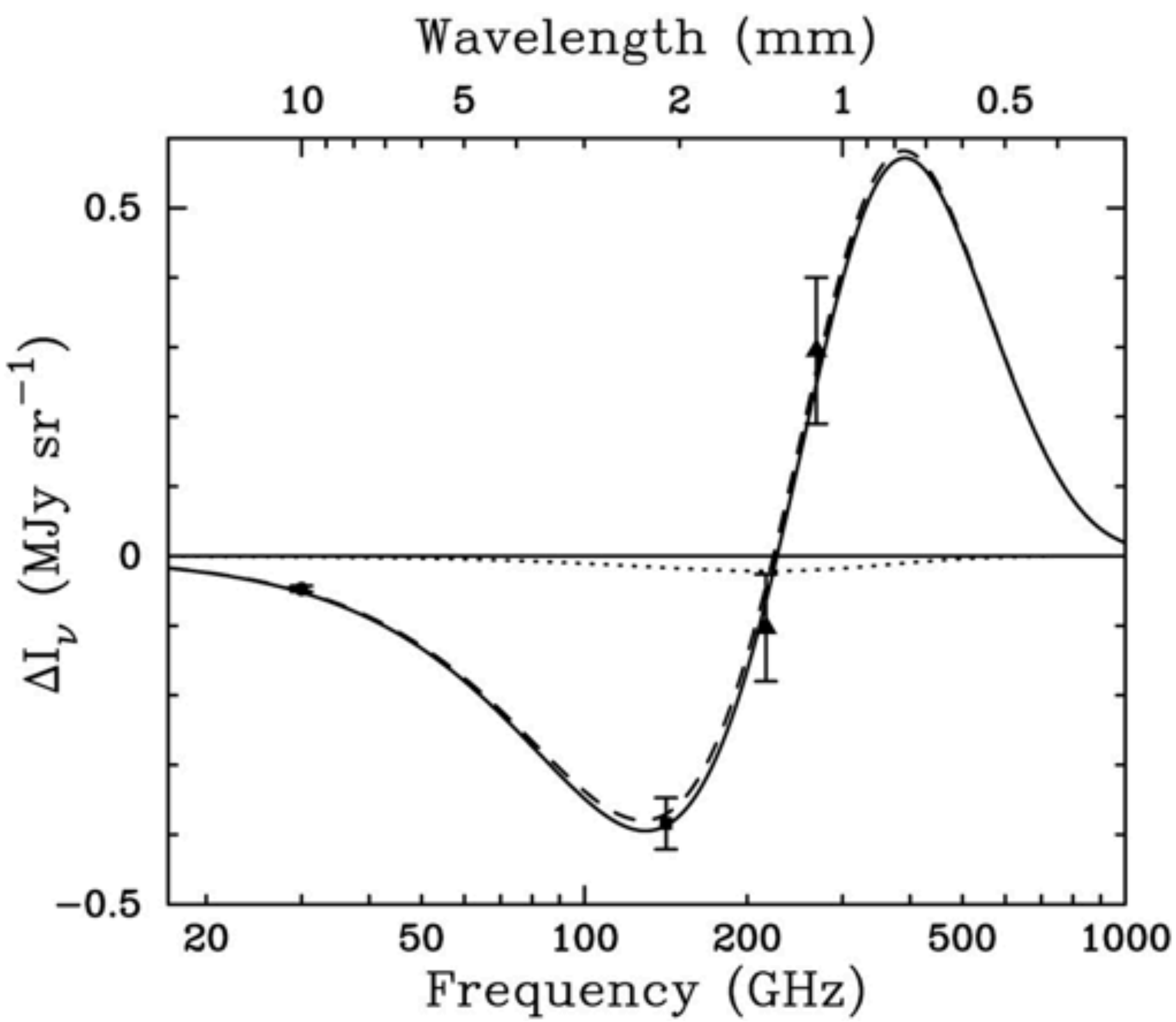
$$\frac{\Delta T_{SZE}}{T_{CMB}} \approx \int n_e \frac{kT_e}{m_e c^2} \sigma_T \, dl$$

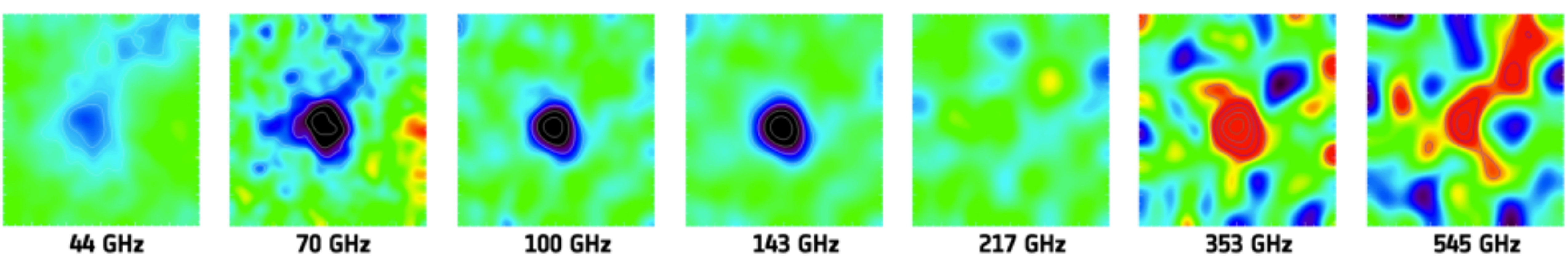




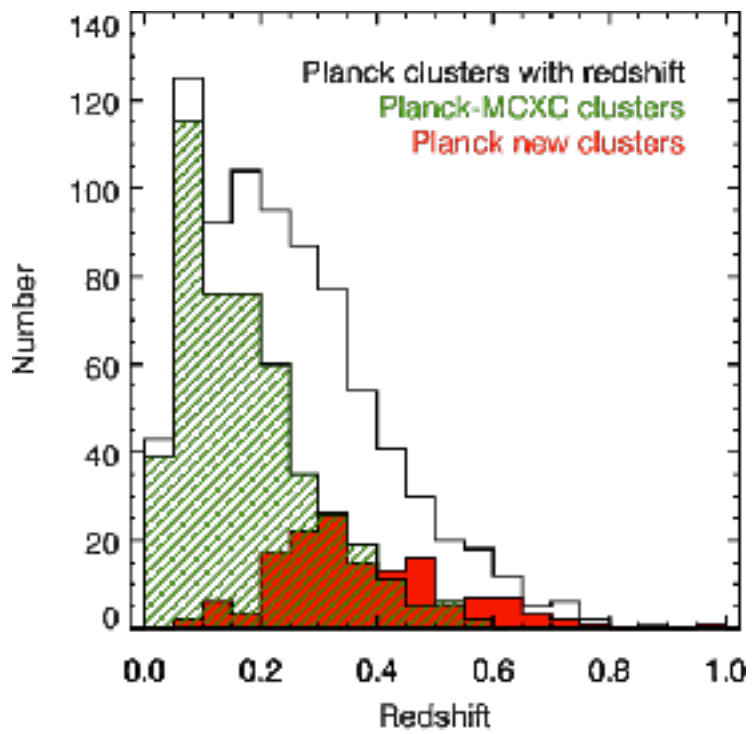
SZ detections

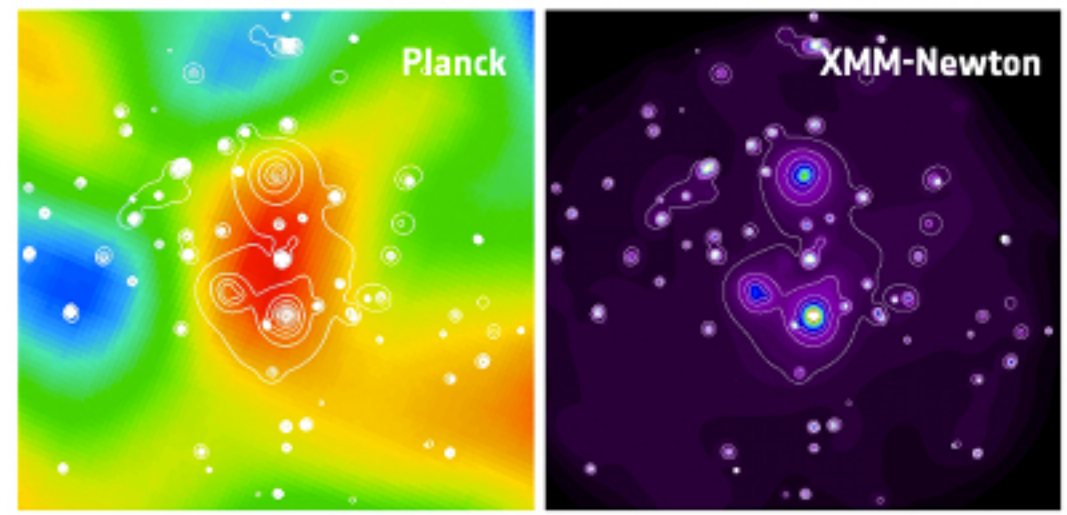
Cluster detection is seen as a positive or negative signal depending on the observation frequency

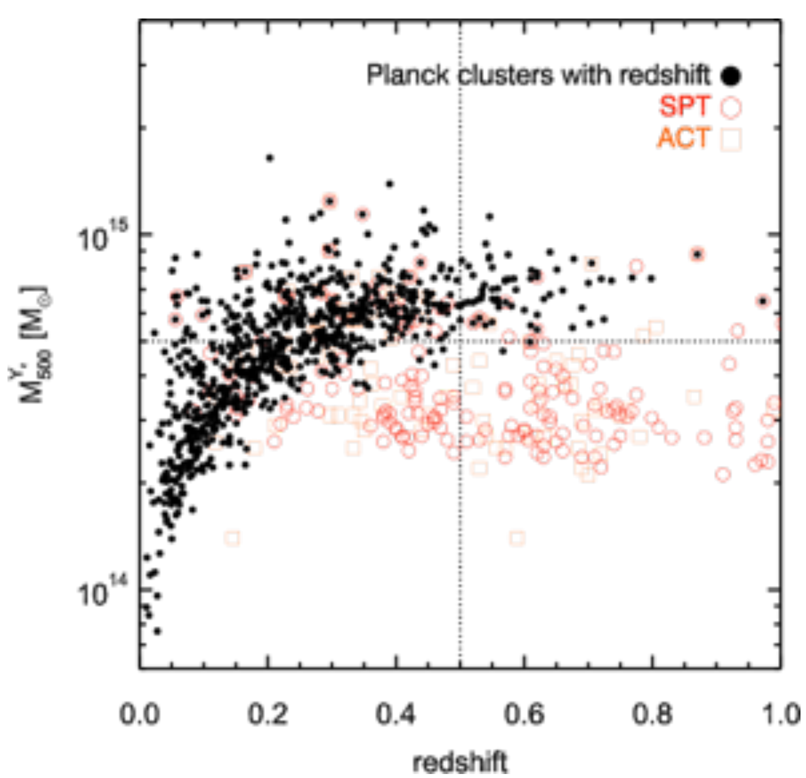


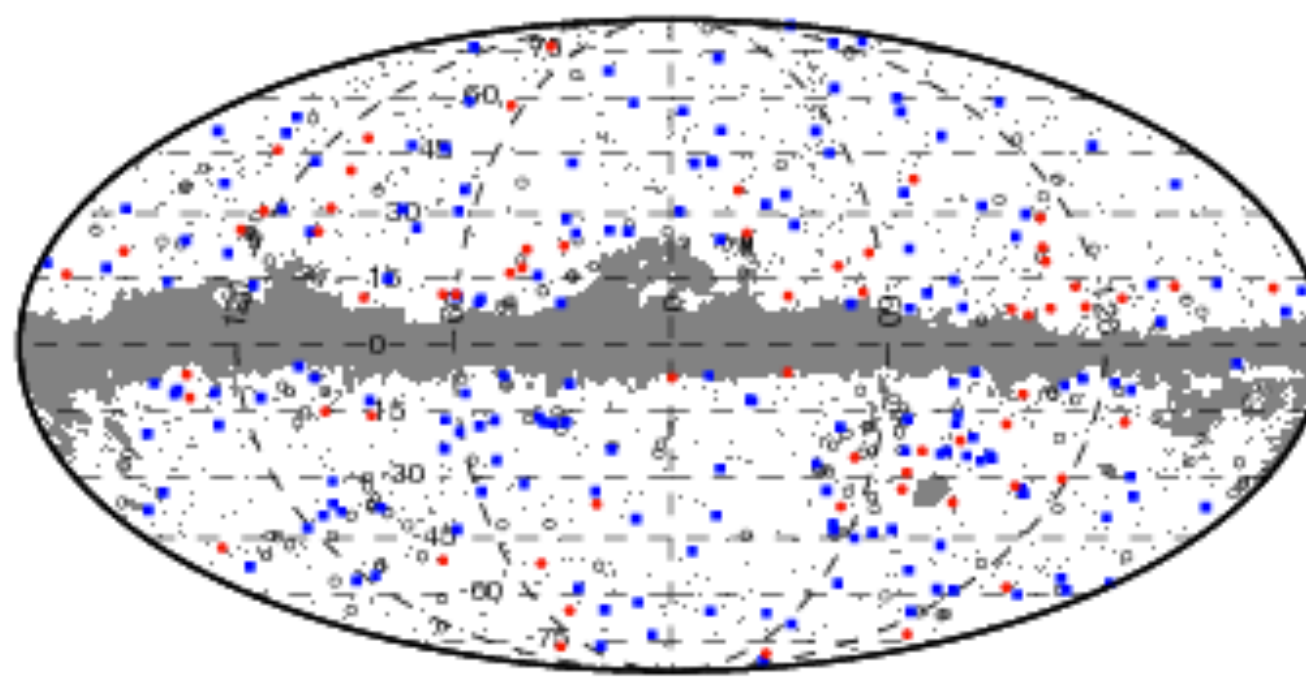


Planck SZ-clusters







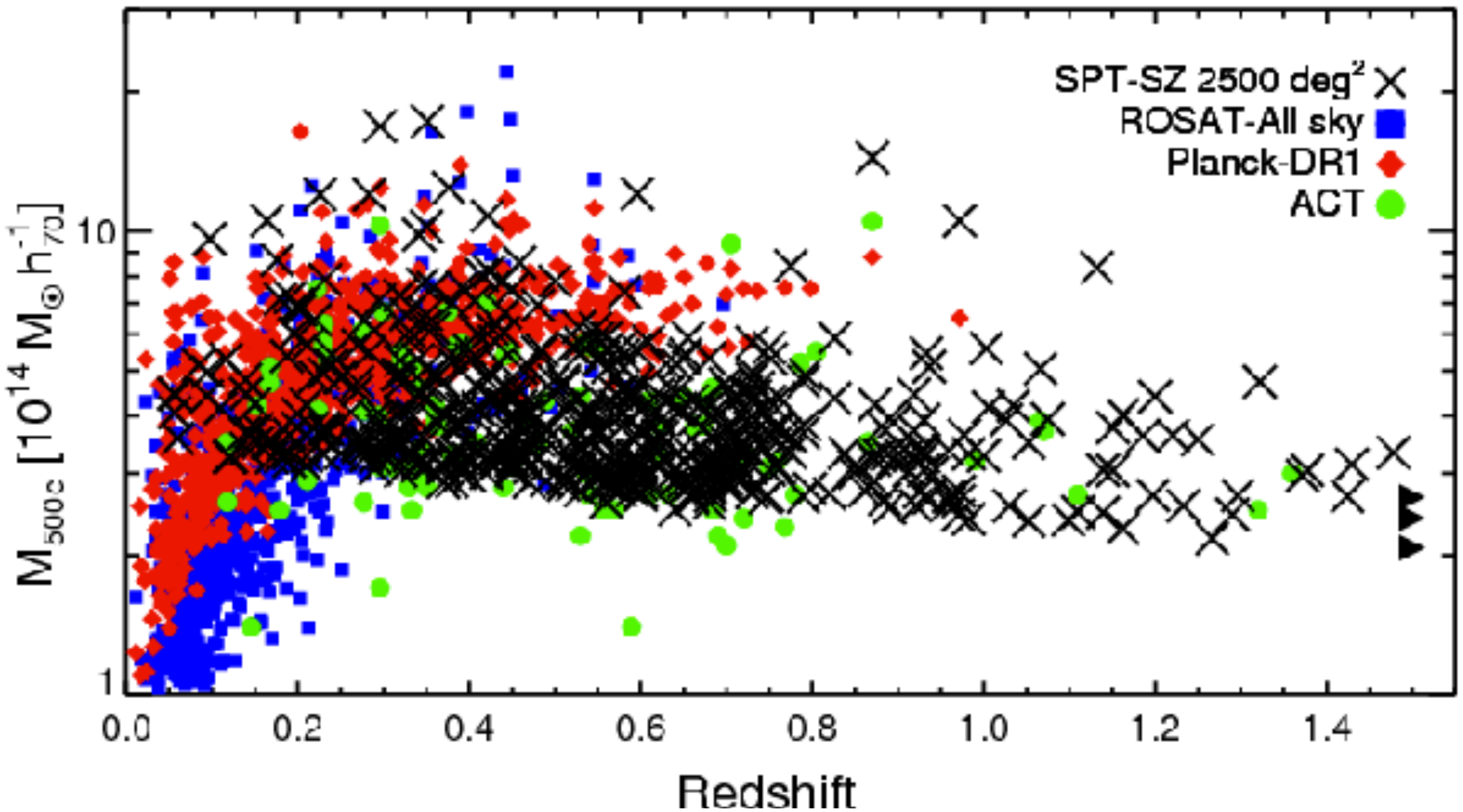


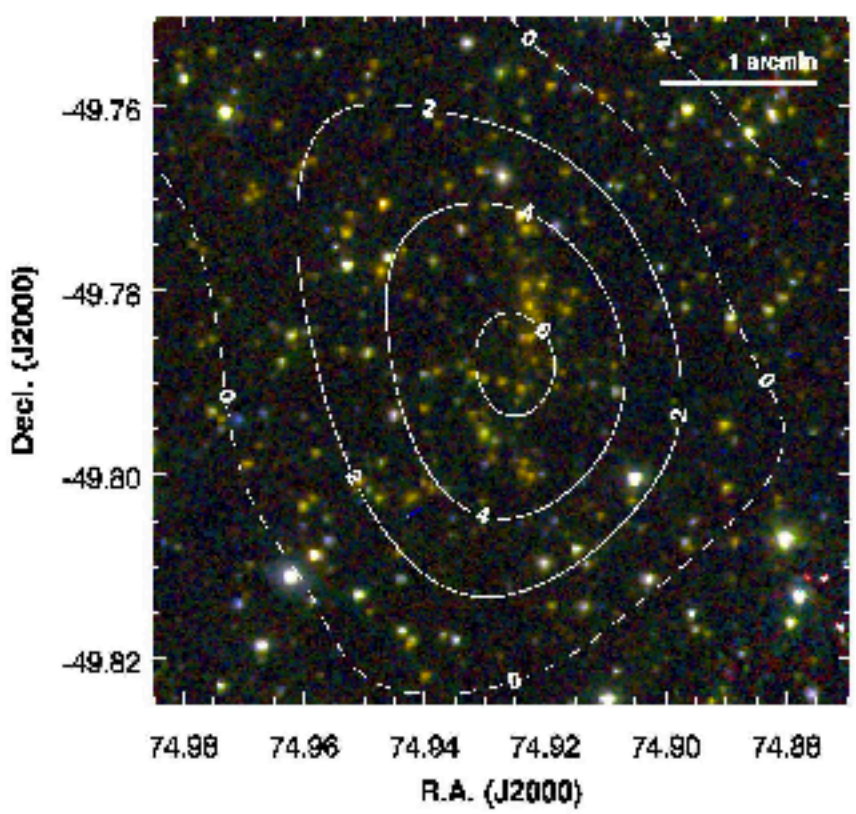
SZ clusters from Planck

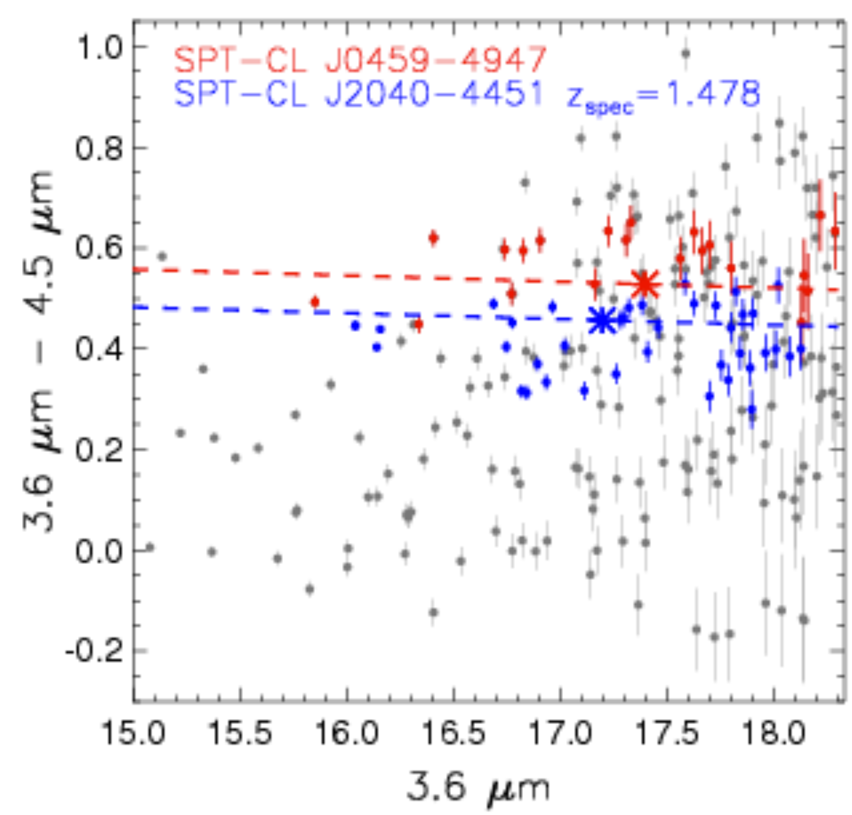
South Pole Telescopes

- South Pole station : CMB telescopes visible in the background include (left to right) the South Pole Telescope, the BICEP2 telescope, and the Keck Array telescope

SPT Clusters

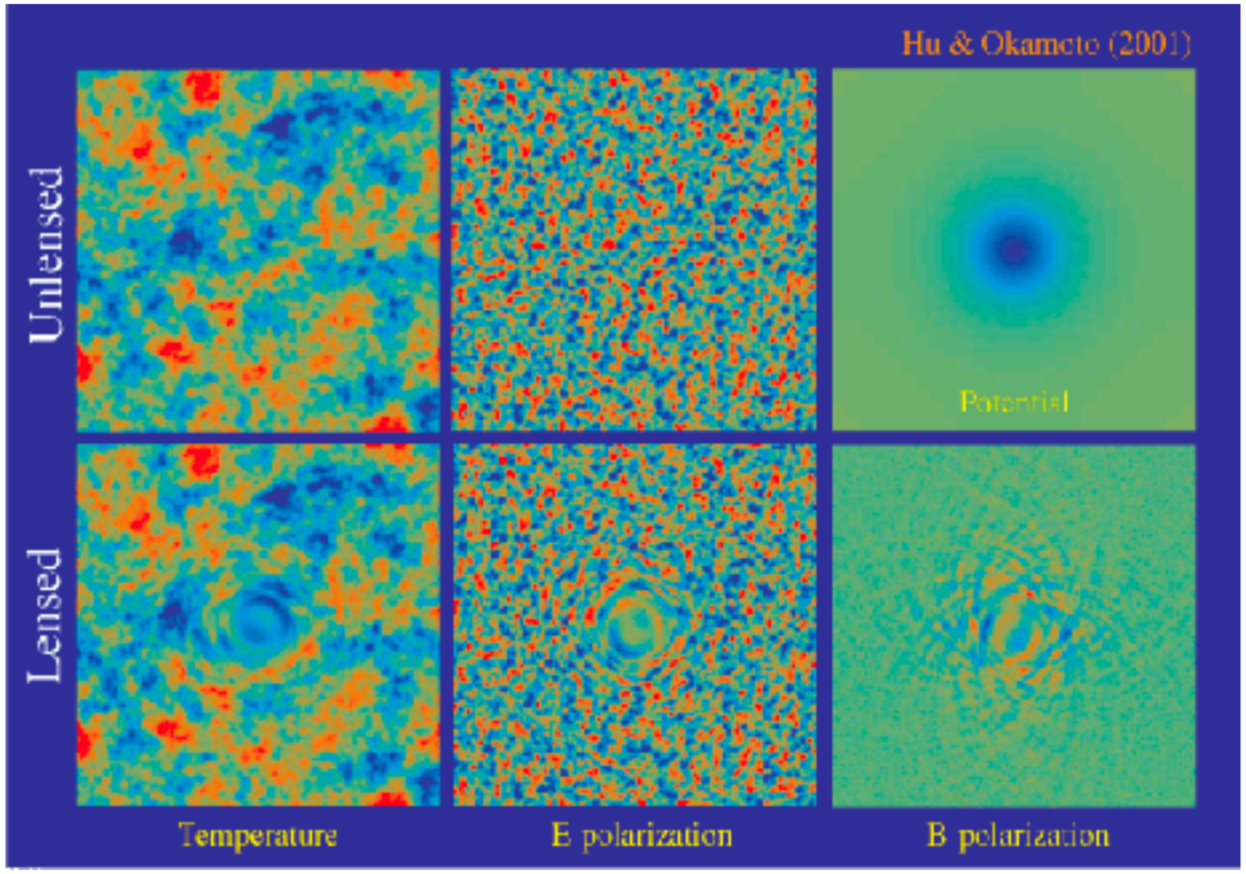


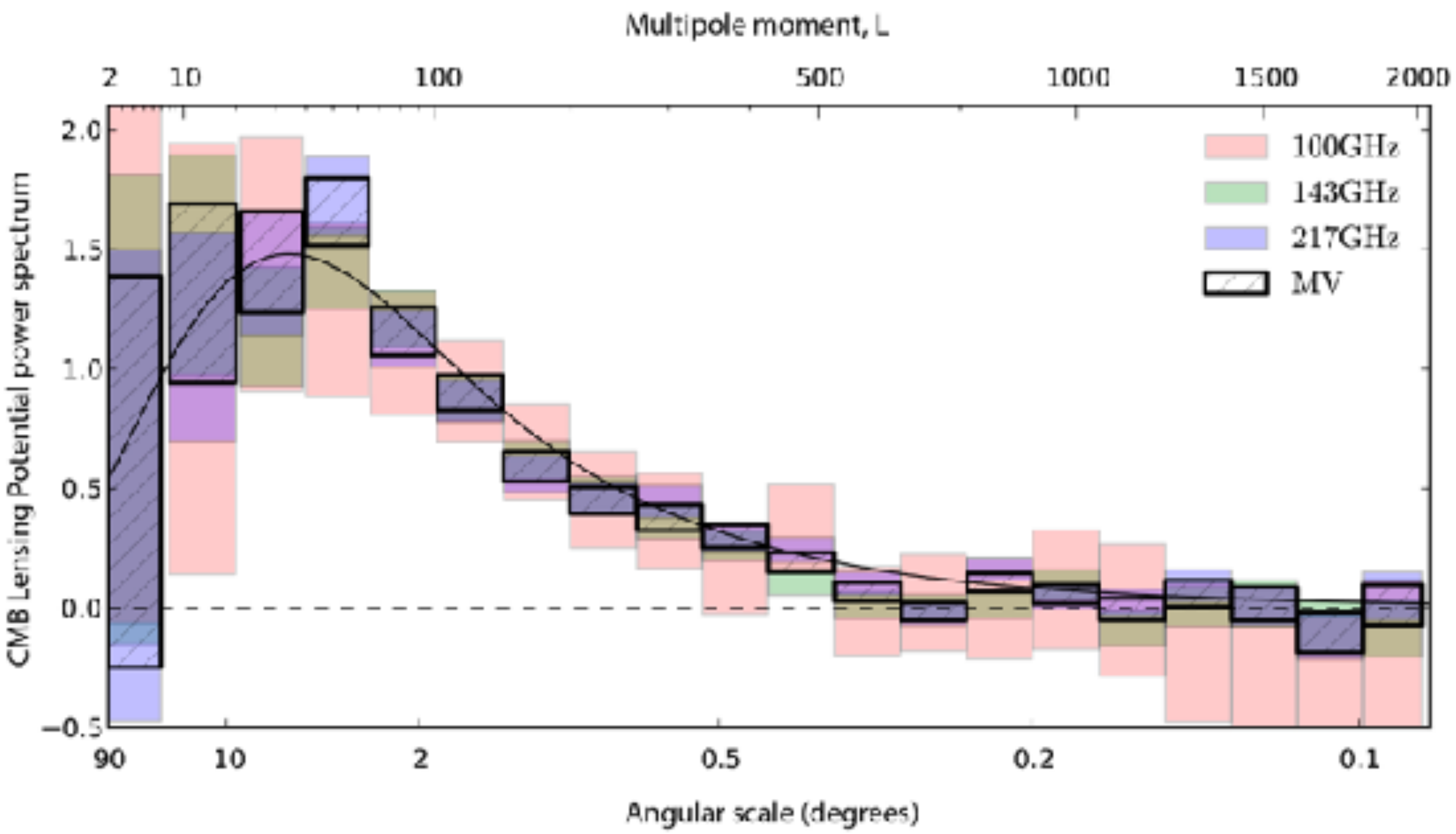




CMB Lensing

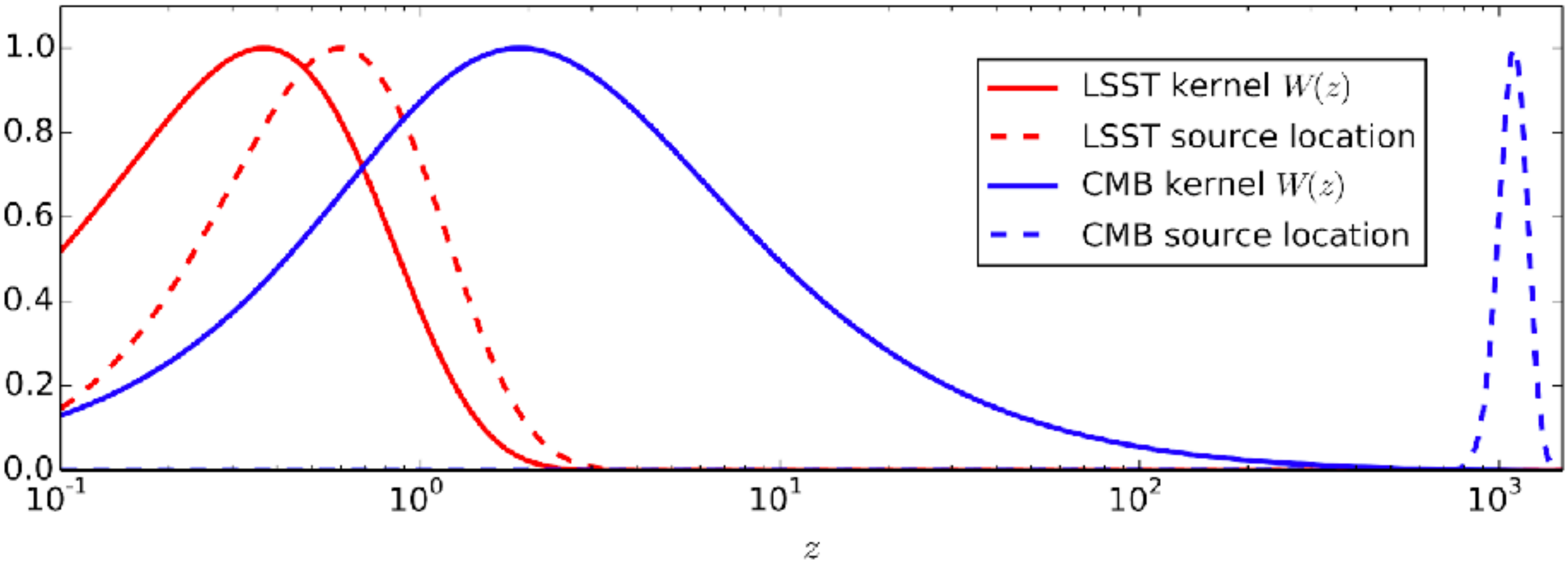
- Mass distribution on the line of sight will distort the CMB light
- Changes in T, E and B polarisation
- Detected in the Planck/SPT/ACT data





https://arxiv.org/abs/1502.01591

CMB and galaxy lensing



CMB S-4 Science book

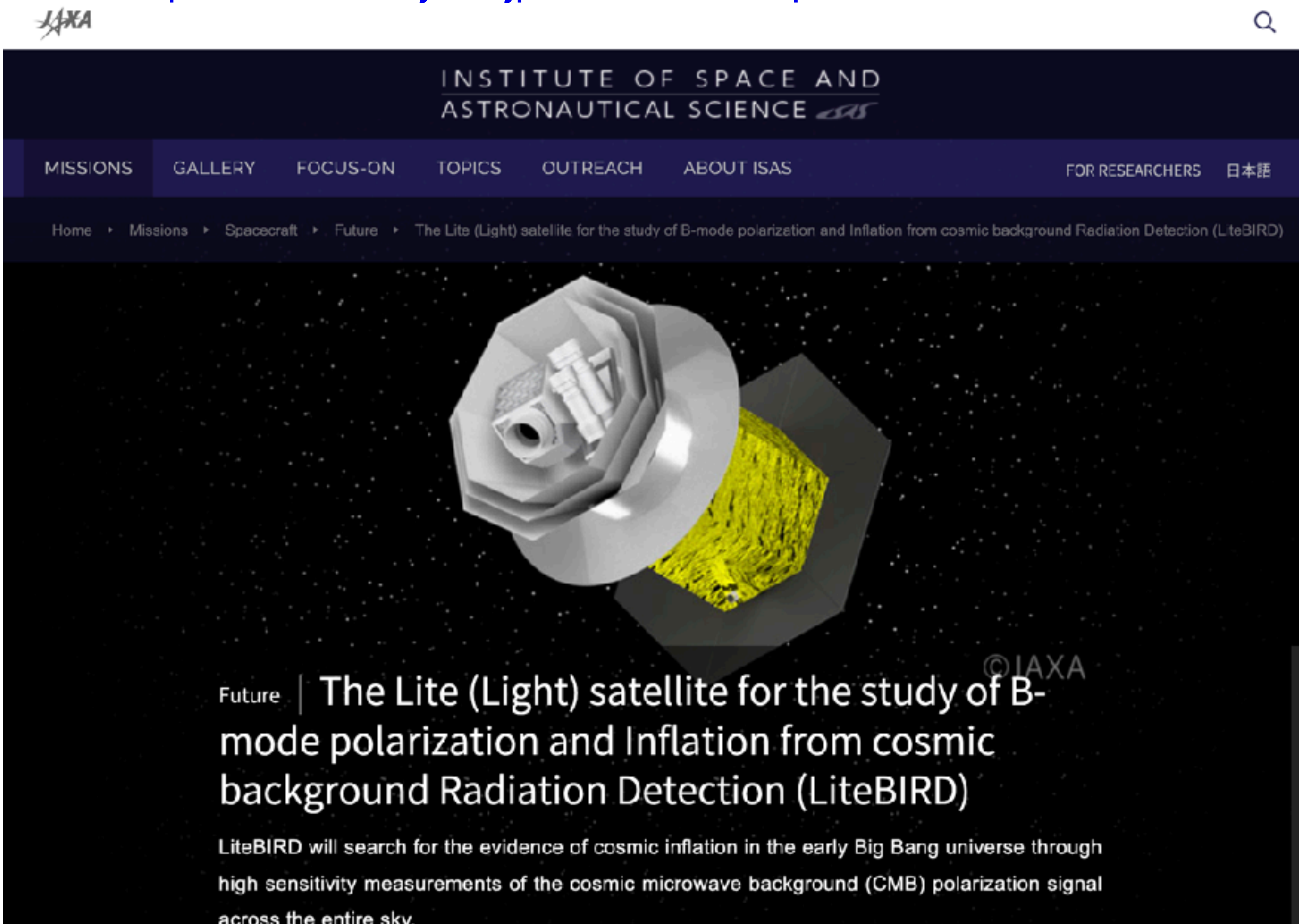
https://arxiv.org/abs/1610.02743

Future of CMB observations

- Better polarisation measurement.
- Primordial B-modes? (test inflation)
- Higher resolution images (larger telescope)
- Space-based projects (proposed but not successful yet)
- Ground based project: "Stage-IV" project led/motivated by US DOE. (Simons Observatory in the near future)
- Mars 2025: first light of the large telescope of the "Simons Observatory": https://simonsobservatory.org/
- http://xxx.lanl.gov/abs/1610.02743 CMB-S4 Science Book
- https://cmb-s4.org/

LiteBIRD Space Mission

https://www.isas.jaxa.jp/en/missions/spacecraft/future/litebird.html



Quiz

- What are the first atoms (ions) formed ~3minutes after the BigBang?
- When the first neutral Hydrogen atoms form? At which redshift? Temperature?
- Can you deduce then the Temperature of the Cosmic Microwave Background?
- From which equation can we deduce the temperature of the CMB?
- What is the density of CMB photons today? And the density of baryons?
- Who first detected the CMB?
- What are the main parameters we can constraints using the CMB anisotropies?
- **What is the SZ-effect? What is it sensitive to?**

The Intervening Universe

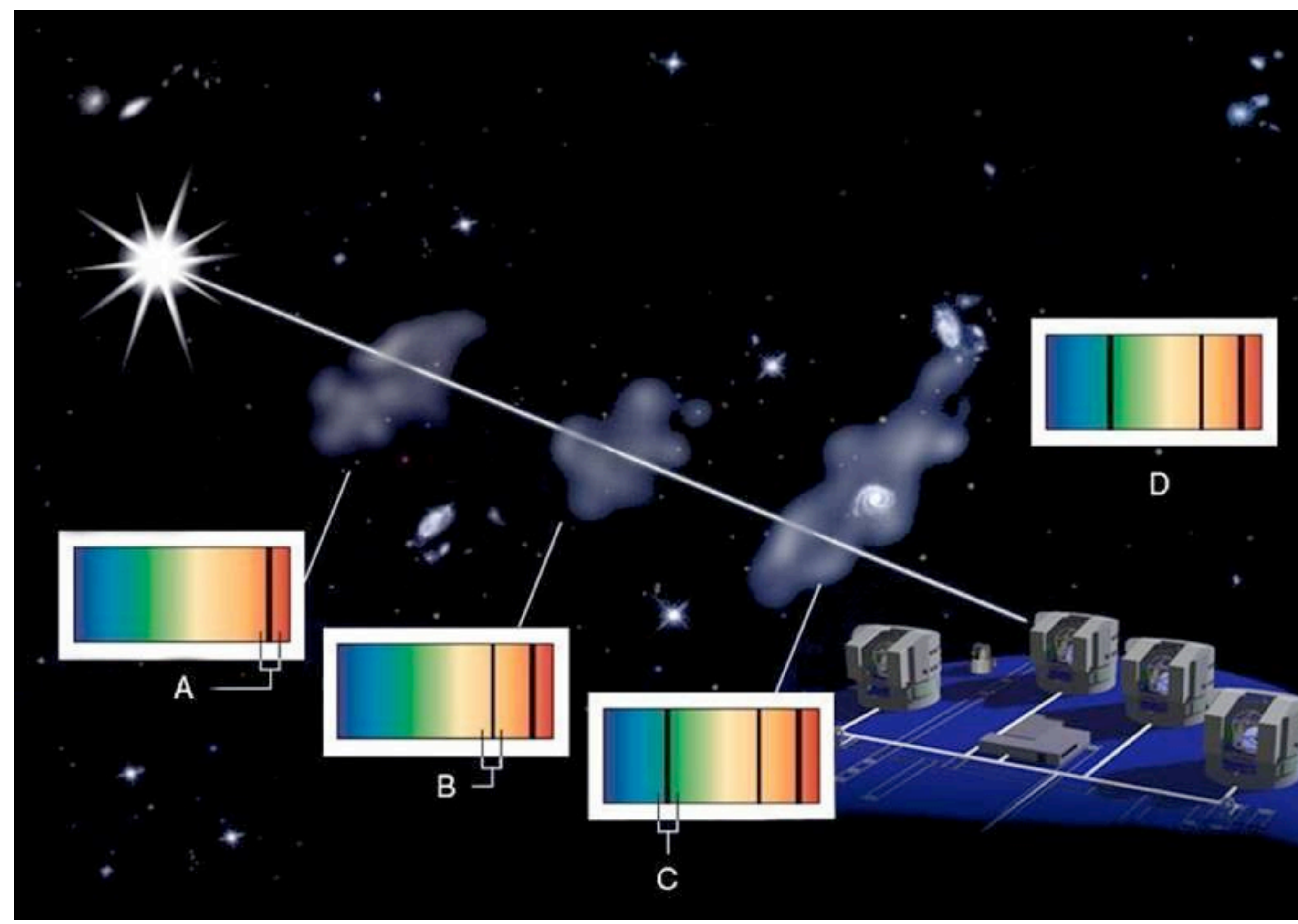
Jean-Paul KNEIB

Introduction

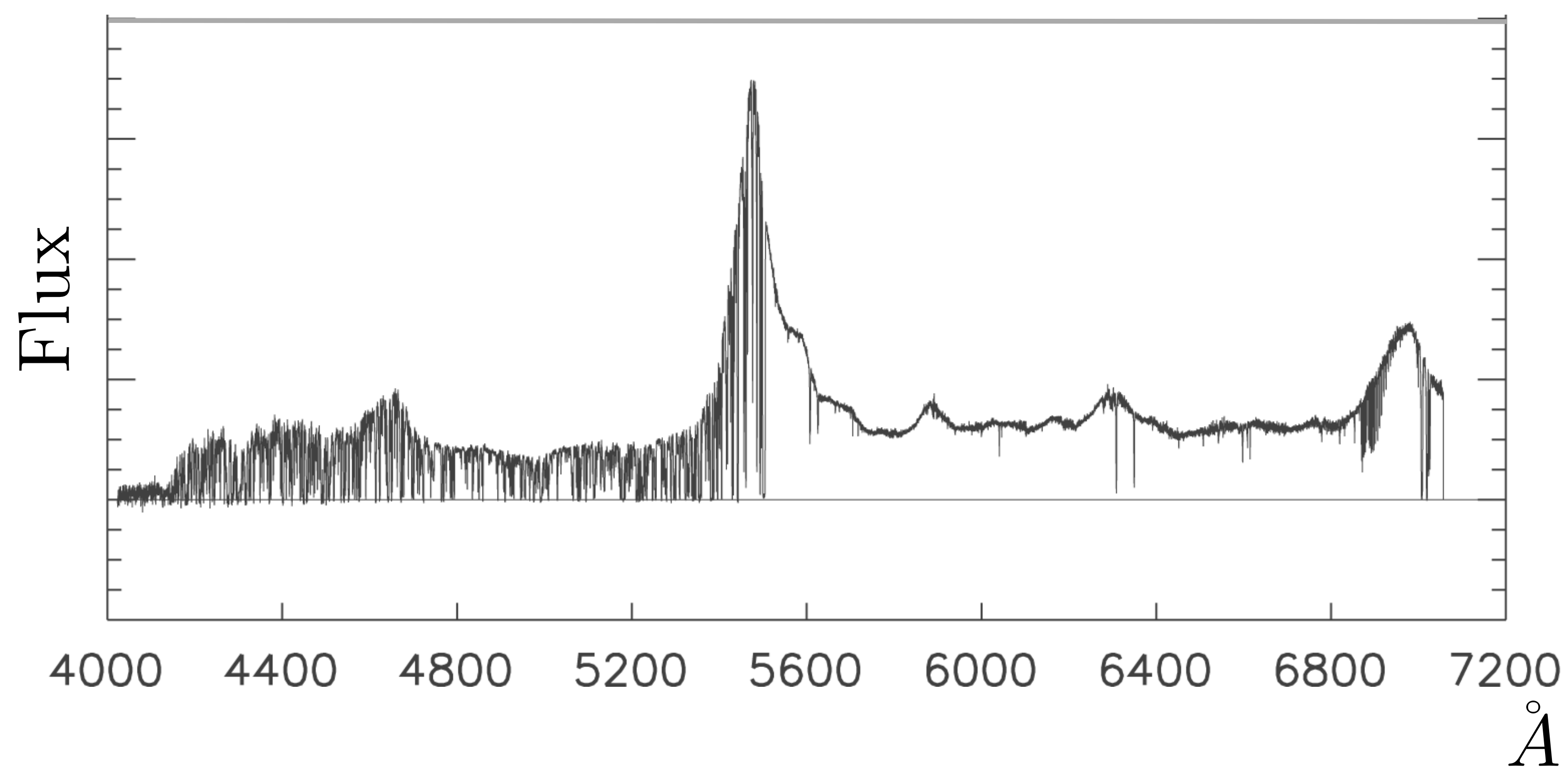
- **Direct Mass estimate** is possible through:
  - measuring the **mass of galaxies**, clusters
  - different techniques can be used: **dynamics**, gravitational lensing, but also X-ray, SZ ...
- **Indirect Mass estimate** is the topic today *through the absorption of light in the spectrum of distant bright objects* (mainly quasars, but also GRB optical counterpart)

The light of quasars is absorbed during its travel towards us

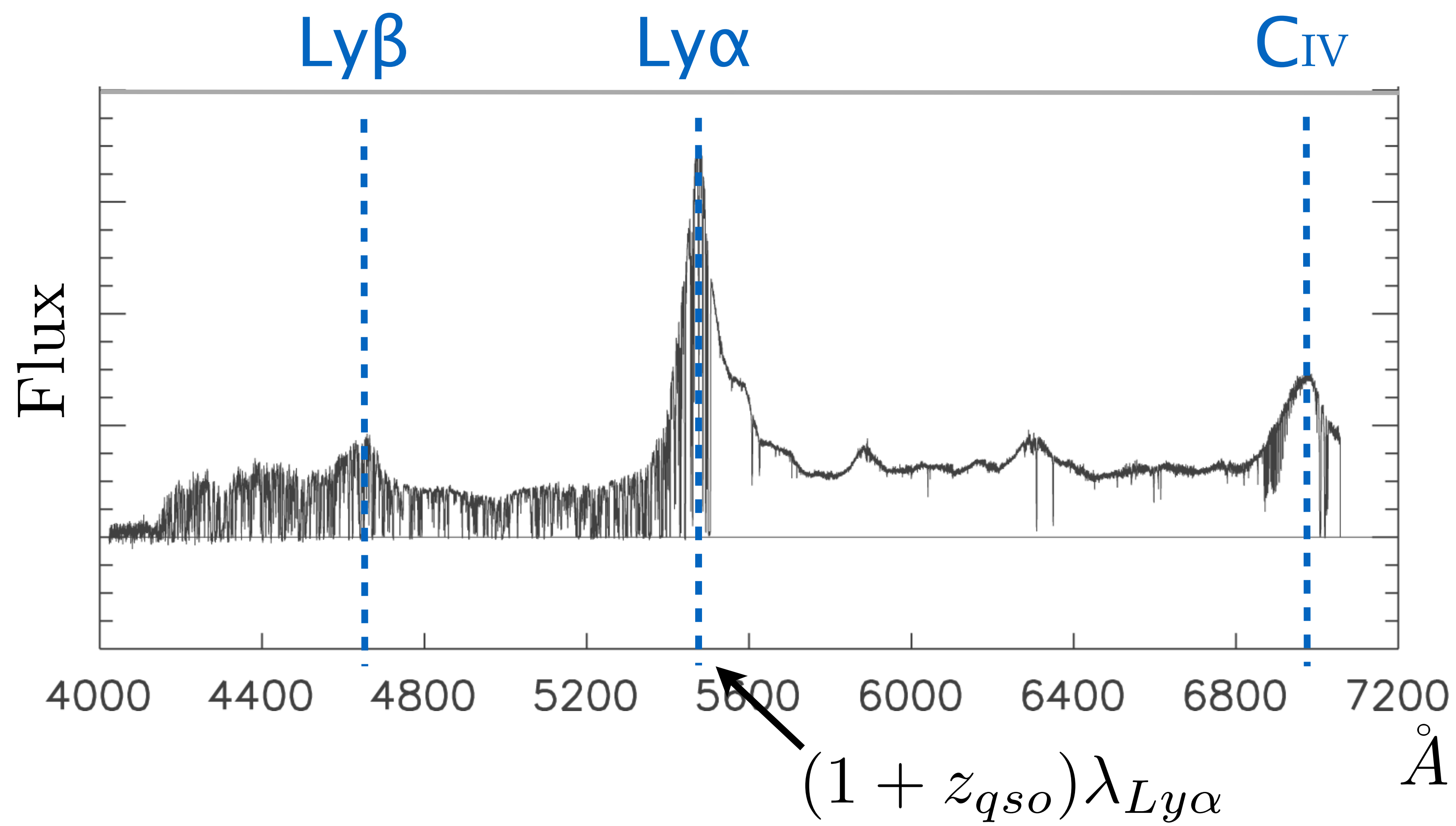
- Quasars *(SMBH accreting mass)* are used as background light sources
- Neutral hydrogen creates absorption lines in their spectra (Lyman-alpha line: 1216 Angstrom)



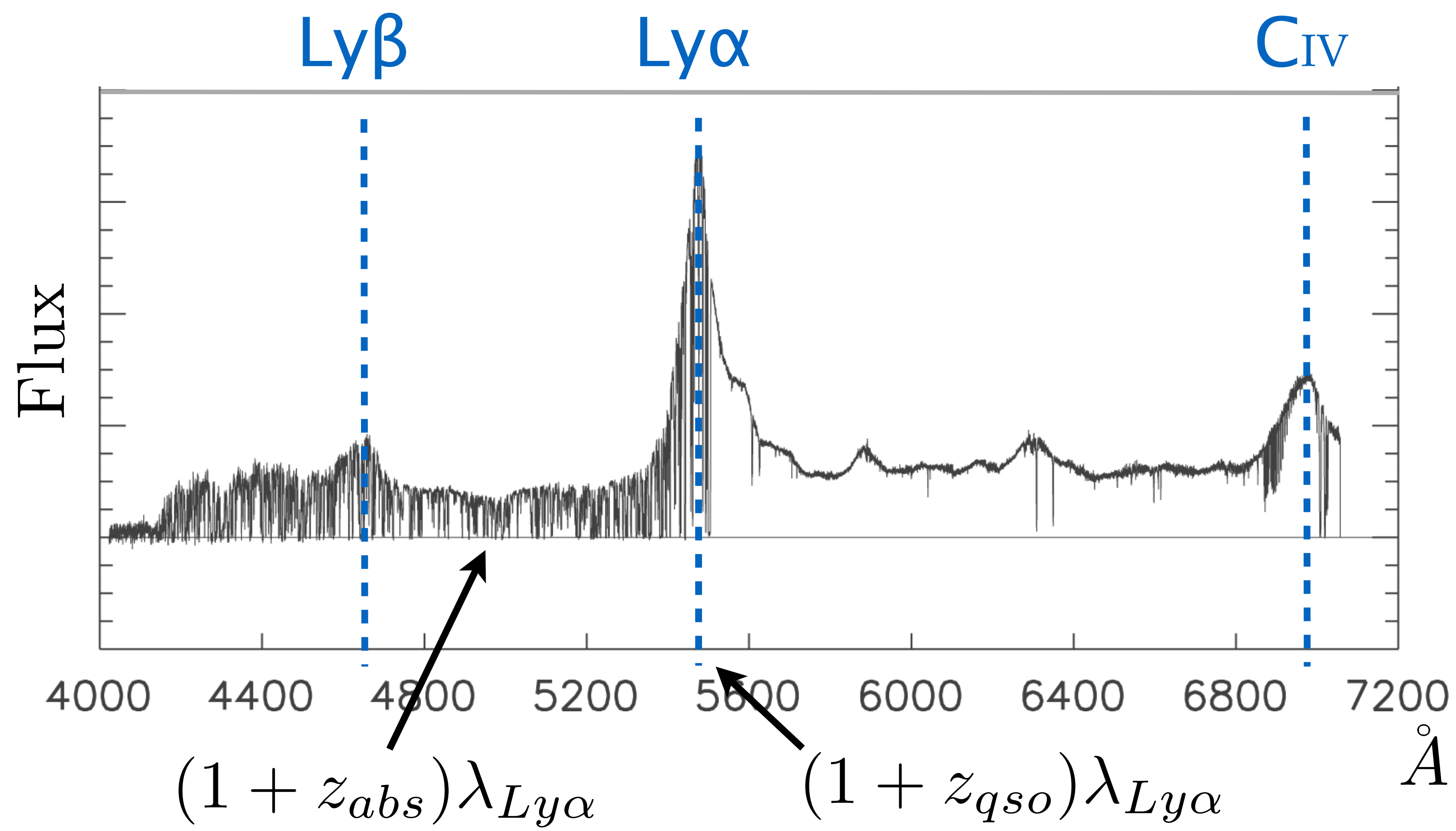
High z quasar spectra tell us about the H I density along their line of sight



High z quasar spectra tell us about the HI density along their line of sight

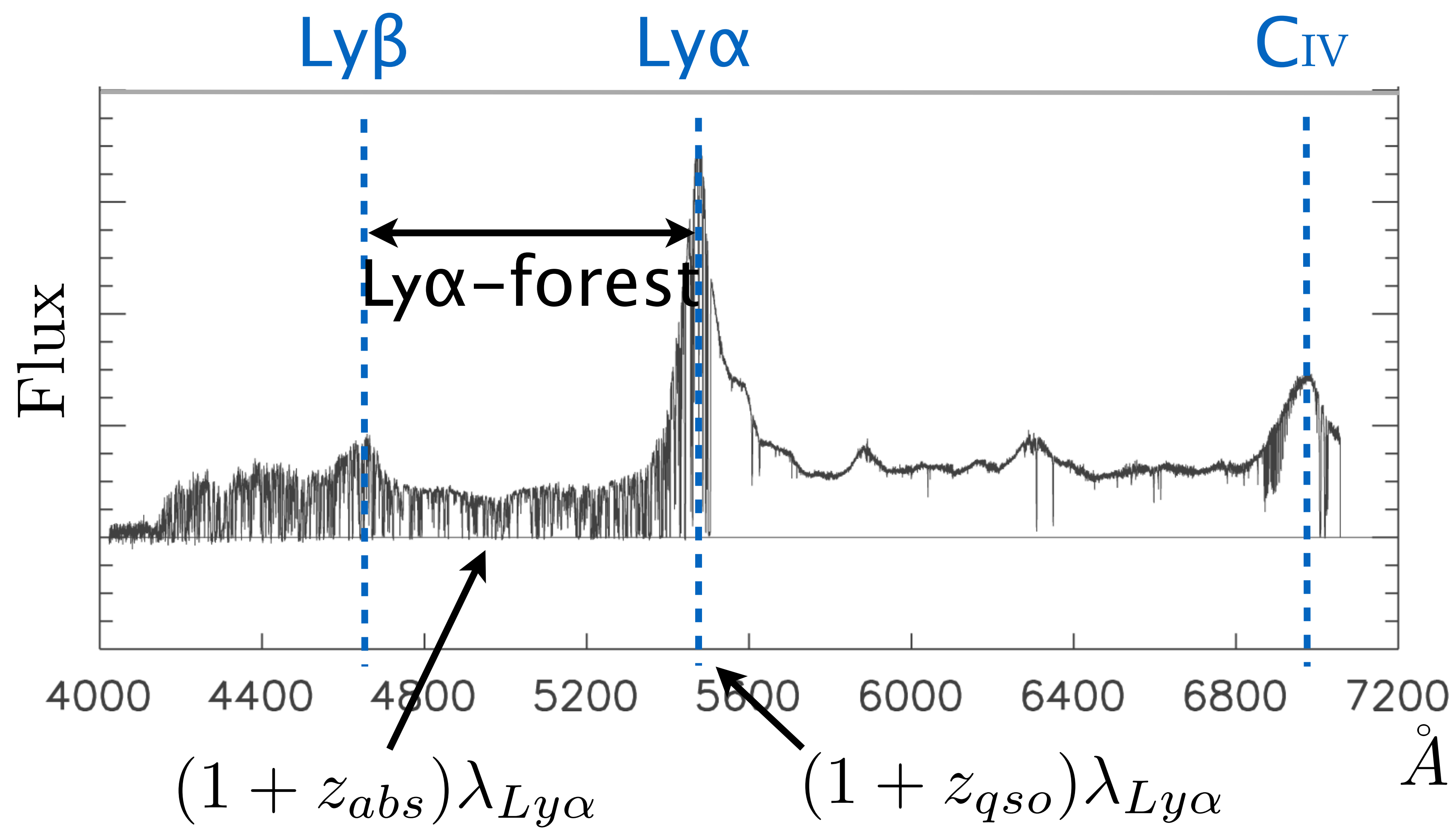


High z quasar spectra tell us about the HI density along their line of sight



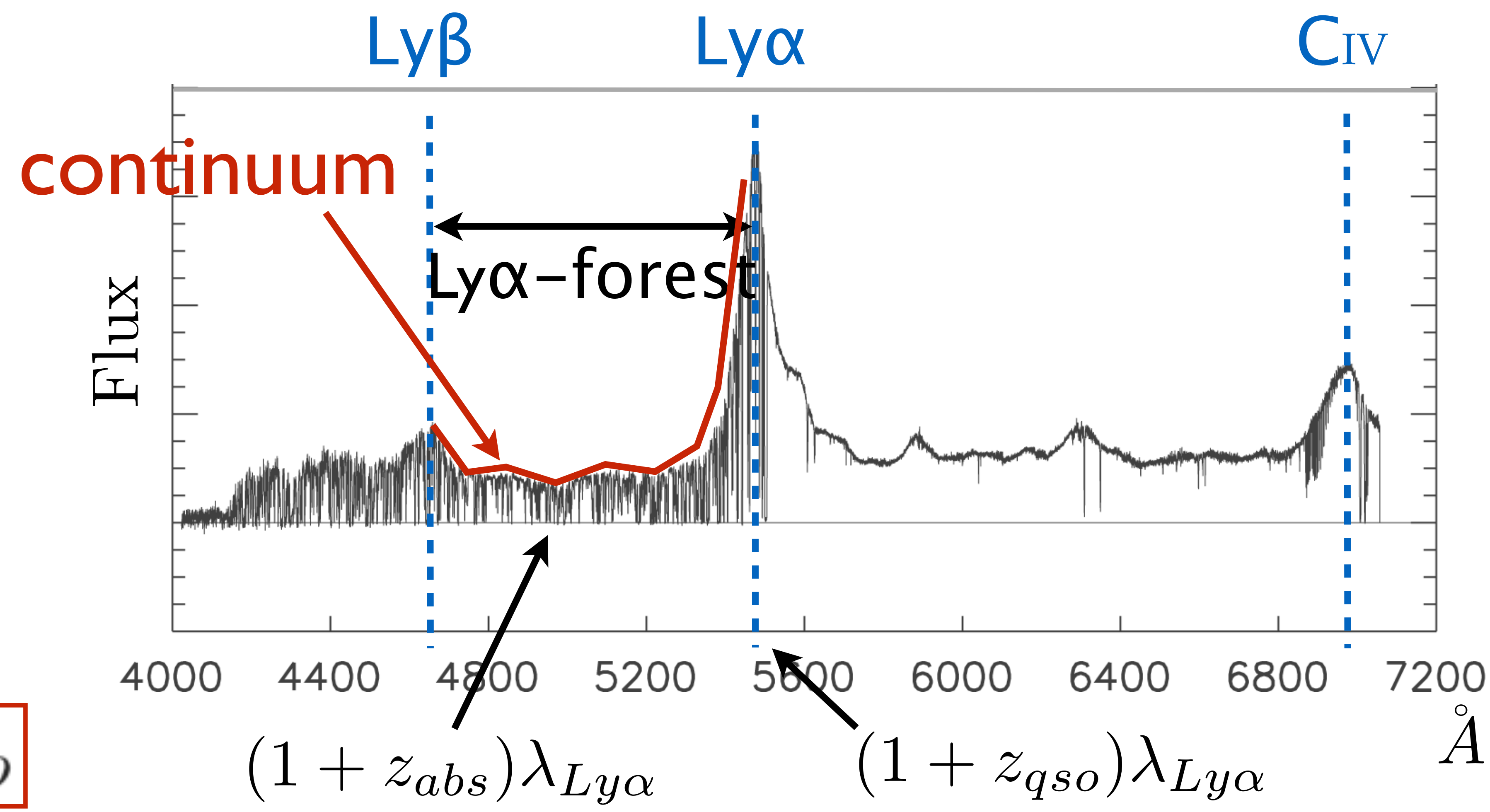
$z_{abs} < z_{QSO}$

High z quasar spectra tell us about the H I density along their line of sight



$z_{abs} < z_{QSO}$

High z quasar spectra tell us about the HI density along their line of sight



$z_{abs} < z_{QSO}$

- Transmitted flux fraction :

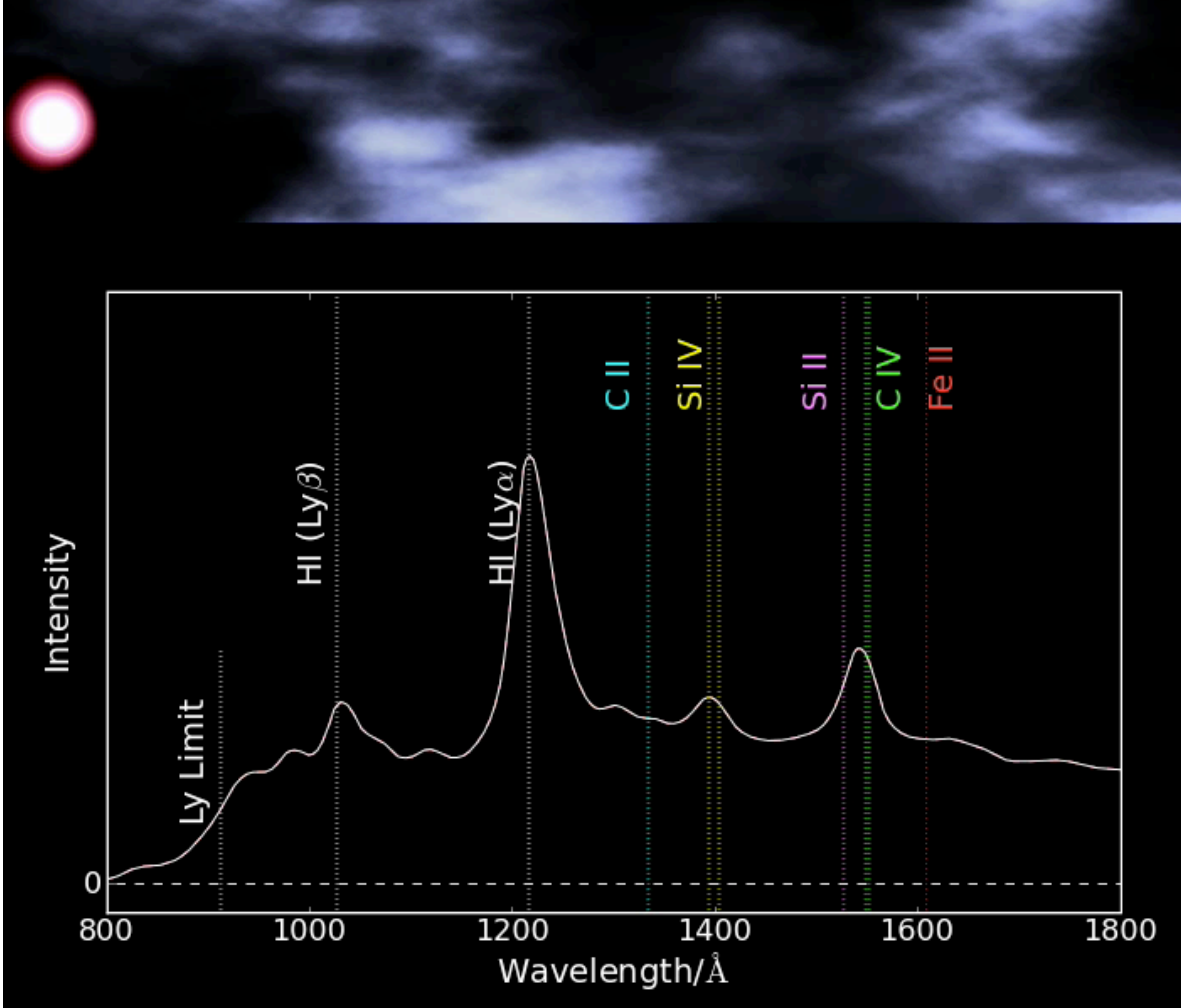
$$F(\lambda_{obs}) = \frac{Flux}{Continuum} = e^{-\tau}$$

- Optical depth :

$$\tau(\lambda_{obs}) \propto n_{\mathrm{HI}}(z_{abs})$$

$\tau > 1$

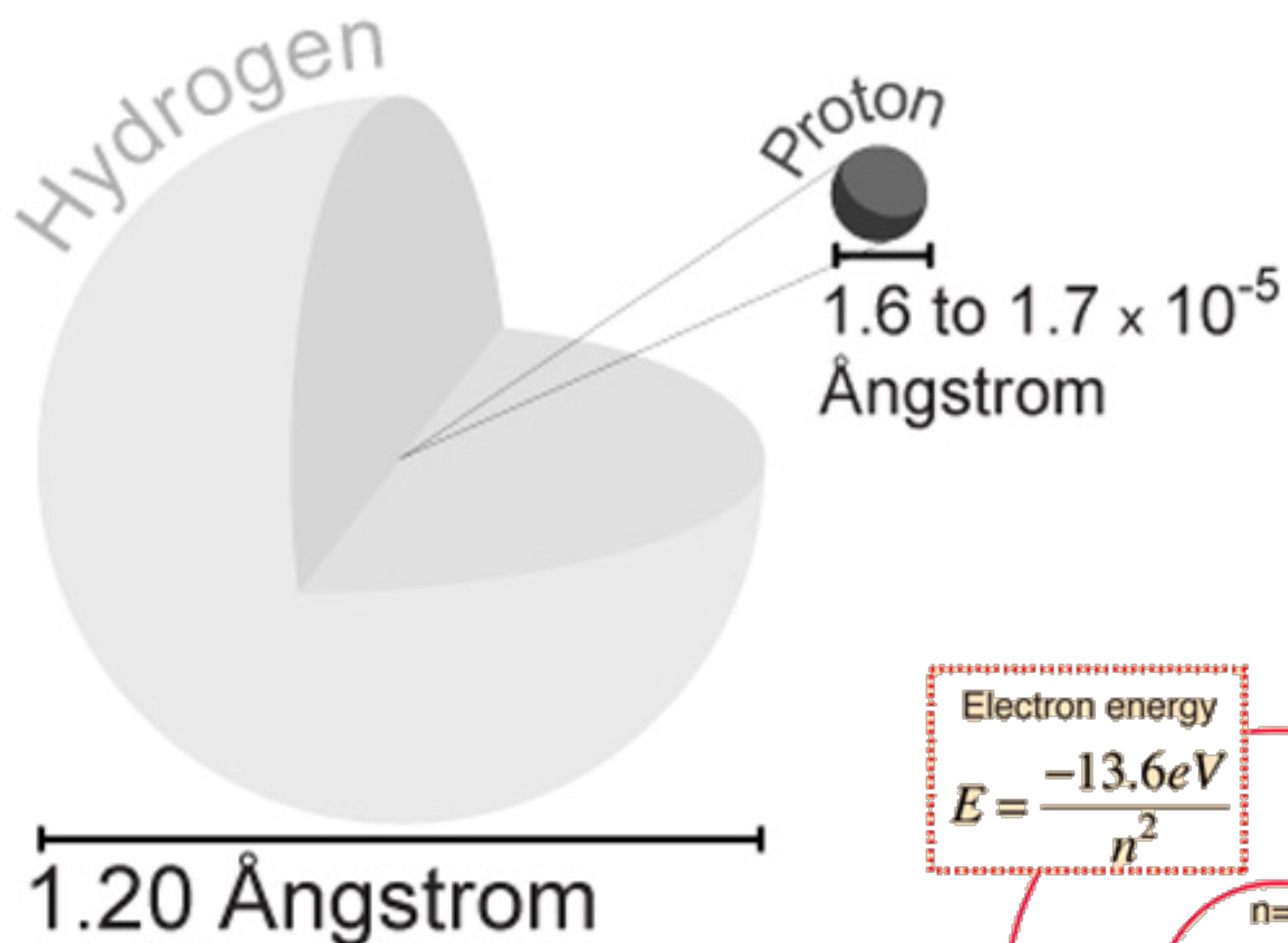
Opaque

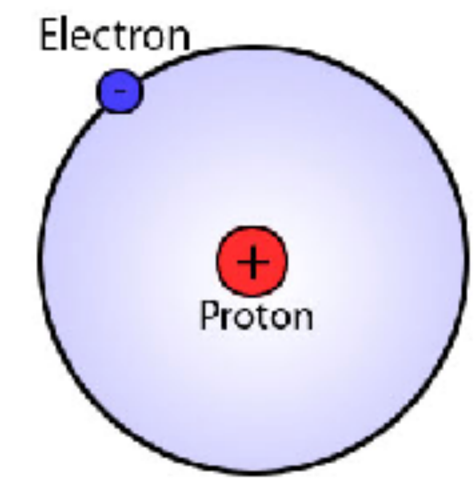

C II
Si IV
Si II
C IV
Fe II
HI (Lyβ)
HI (Lyα)
Ly Limit
Intensity
0
800
1000
1200
1400
1600
1800
Wavelength/Å

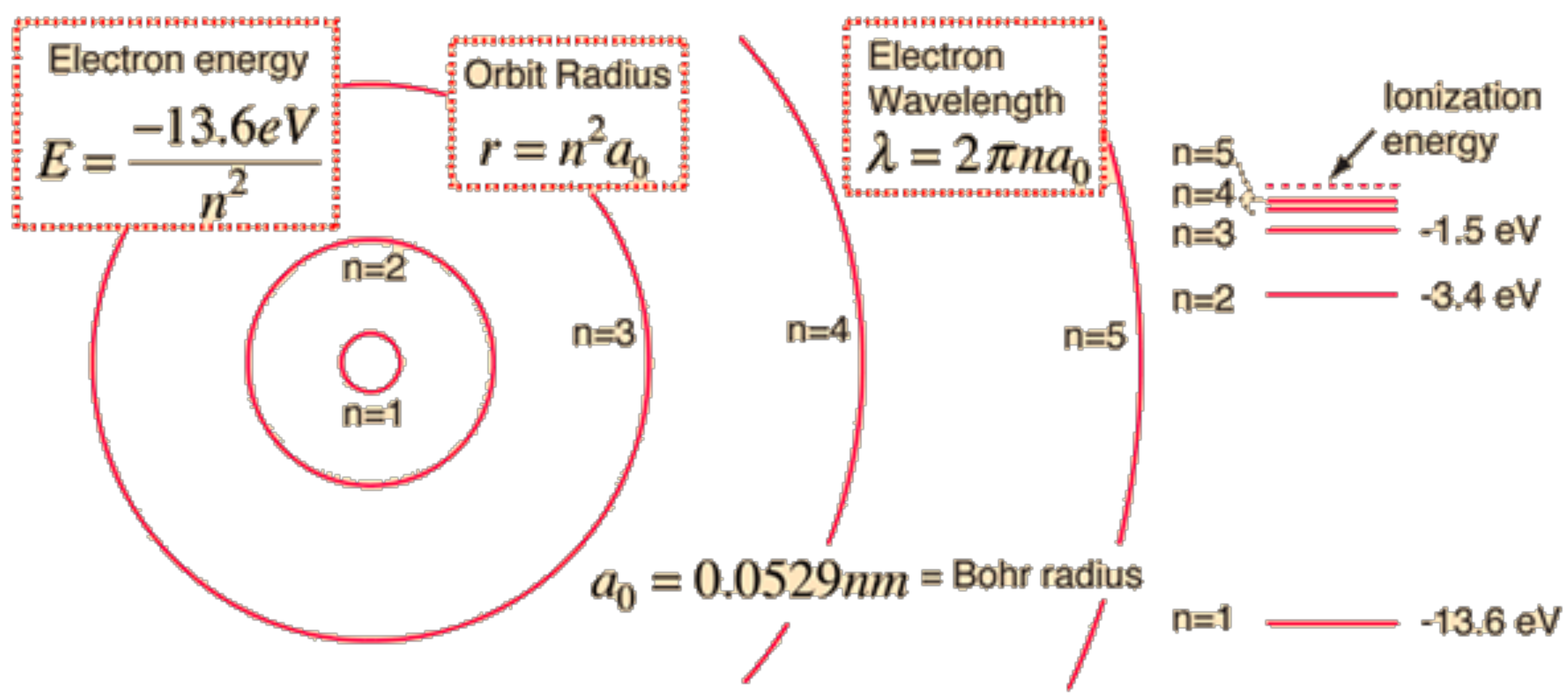
Line Transitions

Line	Angstrom
Lyman Limit	912
Ly-gamma	972,5
Ly-beta	**1025,7**
Ly-alpha	**1215,7**
Si IV 1393	1393,7
Si IV 1402	1402,8
C IV 1549	**1459**
Fe II 2382	2382,8
Fe II 2600	2600,2
Mg II 2796	2796,4
Mg II 2803	2803,5

Hydrogen Atom

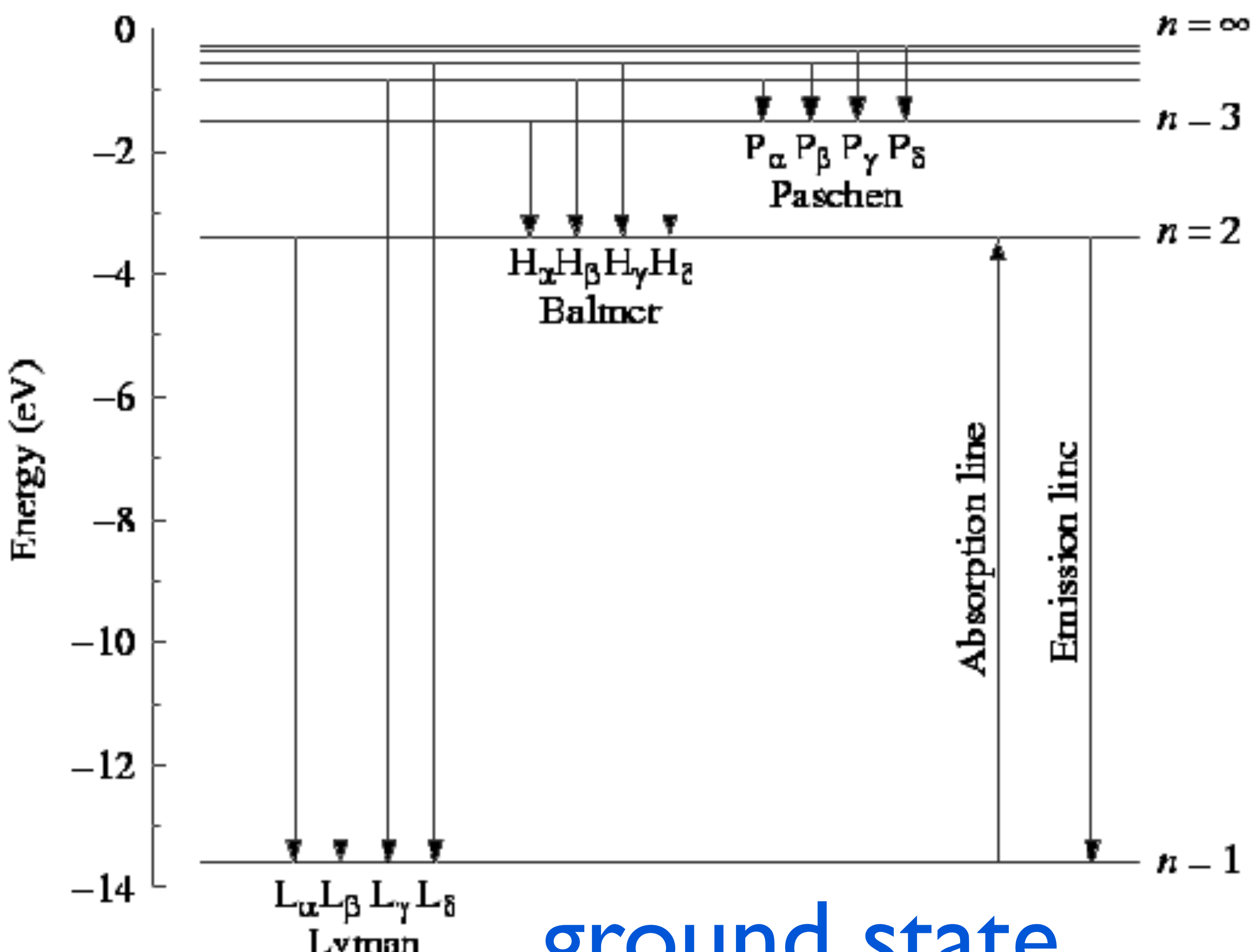




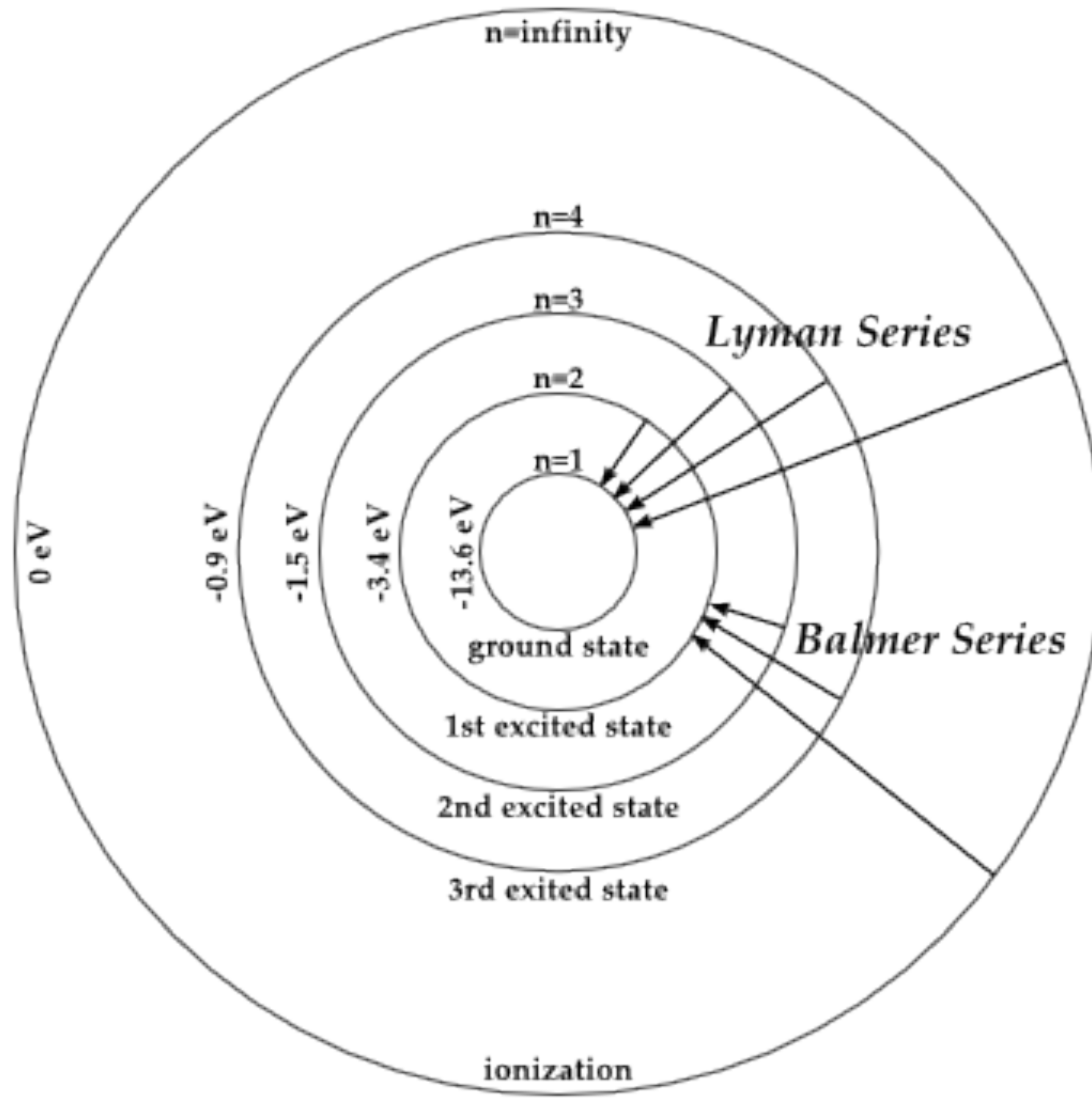


Hydrogen energy levels

ionised



ground state



Absorbing Photons

Hydrogen energy levels are quantised:

$$E_n = -\frac{E_0}{n^2}$$

with $E_0 = 13.6$ eV (1 eV = 1.602×10^{-19} Joules) and $n = 1,2,3\ldots$

- Energy is a negative number because it takes that much energy to ionise the electron from the nucleus.
- *Unbound electron has zero (binding) energy* [ionised state]
- Bound electron can only absorb photons of energies matching exactly the energy difference, or "quantum leap", between 2 energy states.

Absorbing Photons

- *When an electron absorbs a photon it gains the energy of the photon.*
- An electron in the ground state has an energy of -13.6 eV. The second energy level is -3.4 eV. Thus it takes $E_2 - E_1 = -3.4 - -13.6 = 10.2$ eV to excite the electron from the ground to the first excited state.
- *If a photon has more energy than the binding energy of the electron, then it will* ***ionise*** *the atom.*
- The ground state is the most bound state and therefore takes the most energy to ionise.

Emitting Photons

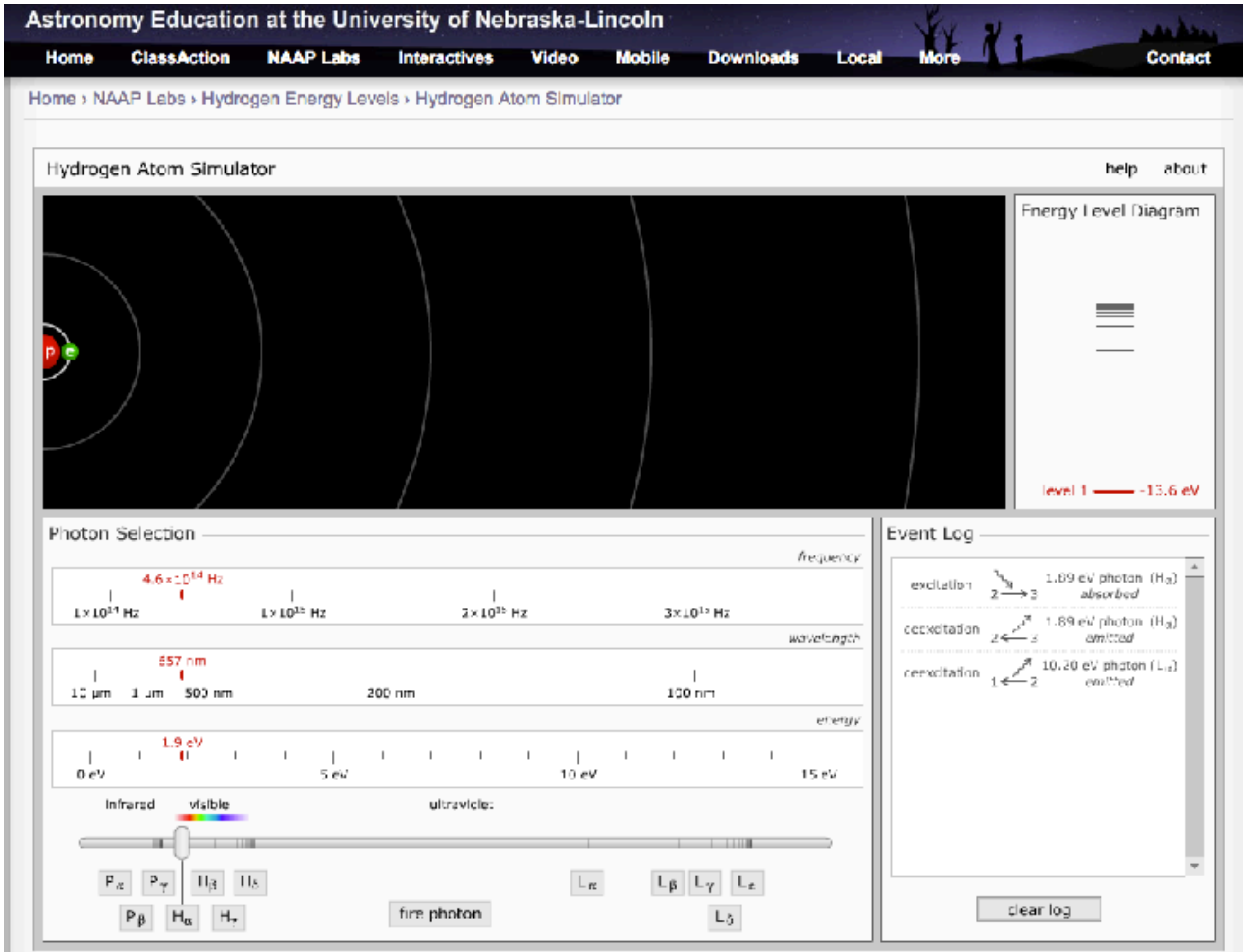
- Excited state is not the most stable state of an atom.
- An electron has a certain probability to ***spontaneously*** drop from one excited state to a lower (*i.e.* more negative) energy level.
- When an electron drops to a lower level it *transforms the excess energy, by emitting a photon*, of energy given by the ***Rydberg Formula***:

$$\Delta E_{n,m} = E_0\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \qquad n<m$$

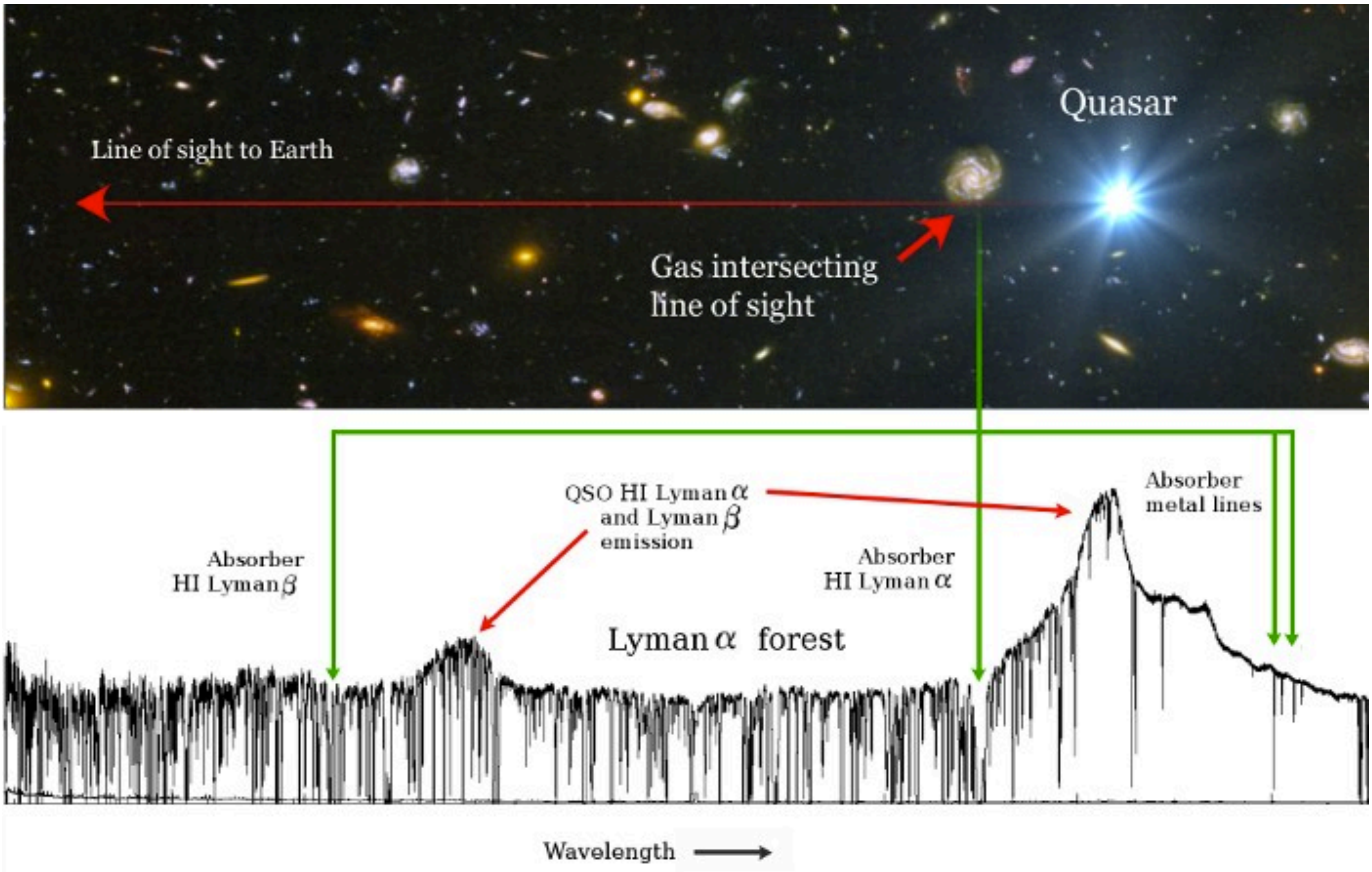
Hydrogen Atom Simulator

http://astro.unl.edu/naap/hydrogen/hydrogen.html

http://astro.unl.edu/naap/hydrogen/animations/hydrogen_atom.html



Quasar absorbers



Optical Depth

The optical depth (OD) is given by the probability of scattering of a photon:

$$d\tau = n.\sigma.ds$$

- where $\boldsymbol{n}$ is the *number density* of neutral hydrogen atoms, $\boldsymbol{\sigma}$ is the *cross-section* for the Ly-alpha transition and $\boldsymbol{ds}$ is the distance element.
- If OD is large ($\tau>1$), the region is *optically thick* -- light is readily absorbed.
- If OD is small ($\tau<1$), the region is *optically thin*, and light passes through easily.

Column Density

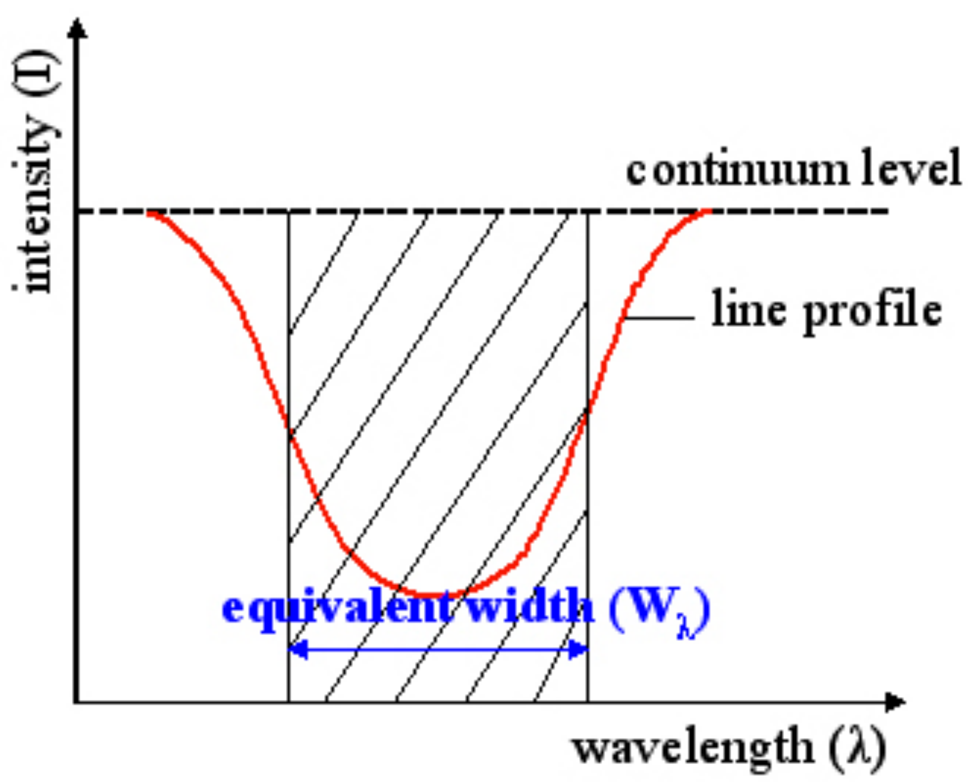
The column density (a.k.a. surface density) of material is the projected density of the material on the observation plane.

Then the number of absorbers per unit surface area is given by the column density:

$$\Sigma = \int n.ds$$

Equivalent Width

The shape of an absorption line depends on the number of photons that are absorbed at a particular wavelength.
To compare the strengths of the absorption lines we can use the equivalent width.



$$W_{\lambda_0} = \int (1 - F(\lambda)/F_c)\, d\lambda$$

$$A = F_c W_{\lambda_0}$$

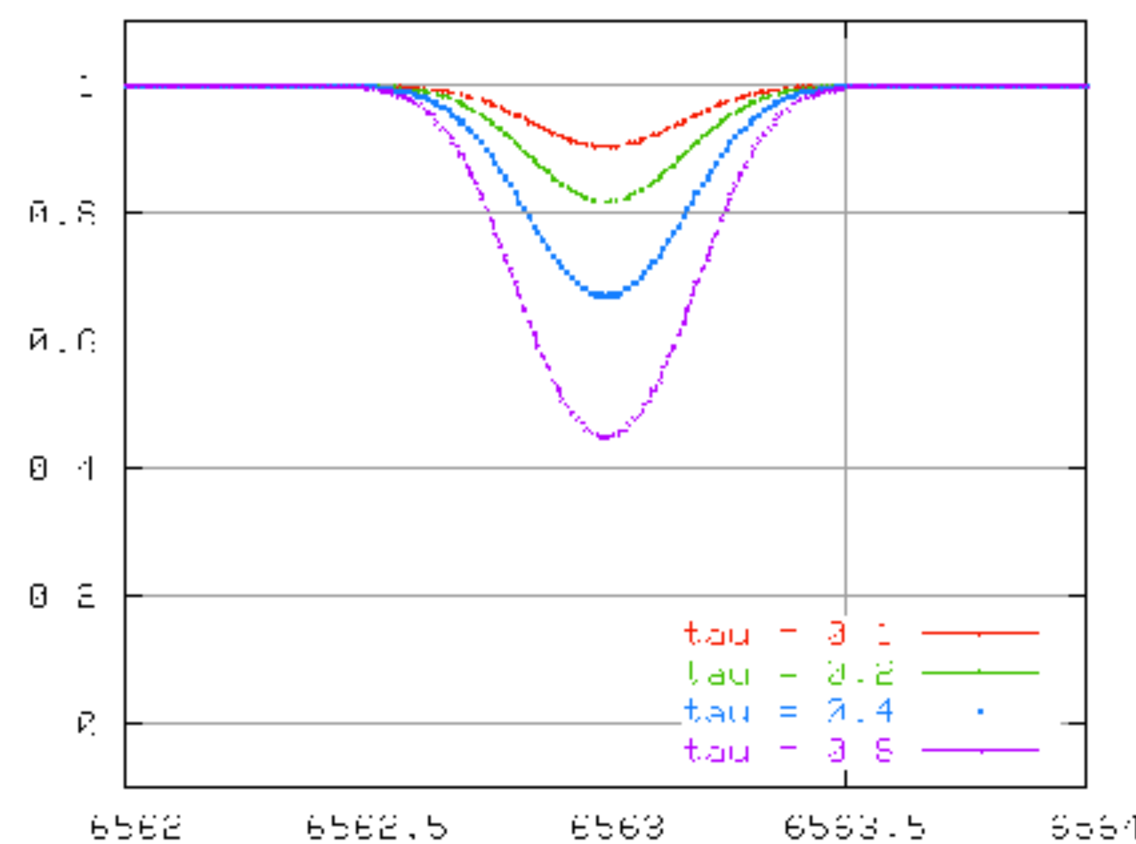
Flux absorption

In the case of **optically thin** medium (τ<1):

$$dF=-F.d\tau=-F.n.\sigma.ds$$

$$F_{out}=F_{in}e^{-\tau}$$

$$F_{out}\sim F_{in}(1-\tau)$$

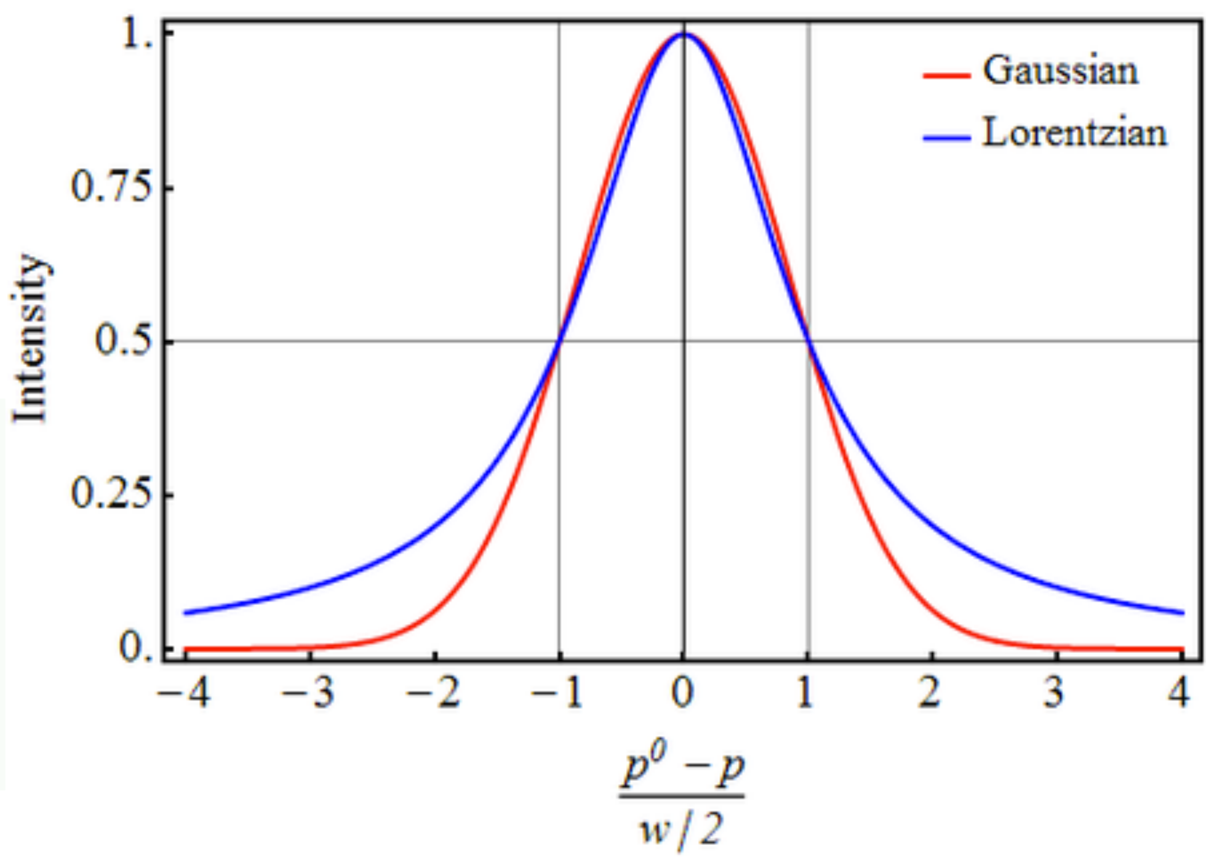


Line Shape

- **Gaussian**: random velocity broadening
- **Lorentzian**: natural broadening/collision broadening (uncertainty principle)

$$\tau(\lambda) = \tau(\lambda_0)\left(\frac{Q^2}{(\lambda-\lambda_0)^2+Q^2}\right)$$

- **Voigt** convolution of Gaussian and Lorentzian



Gaussian Line

Thermal broadening, due to random thermal motions of atoms.
For a Maxwellian velocity distribution,
the 1-D projected velocity distribution is Gaussian.

- Mean value: μ
- Dispersion (standard deviation): σ
- Gaussian profile:

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- Width at half maximum:

$$FWHM = 2\sigma\sqrt{2\ln 2} \sim 2.35\sigma$$

Lorentzian Line

Natural broadening, intrinsic to the transition and resulting from the Heisenberg uncertainty principle. *This gives rise to a Lorentzian absorption cross-section.*

- Lorentzian profile: $$L(x) = \frac{1}{1+x^2}$$
- Width at half maximum: $$FWHM = 2$$
- Normalised abscisse: $$x = \frac{p^0 - p}{w/2}$$

Voigt Line

- Convolution of a Gaussian and a Lorentzian:

$$V(x;\sigma,\gamma) = \int_{-\infty}^{\infty} G(x';\sigma)L(x-x';\gamma)\,dx'$$

- Width of Gaussian and Lorentzian: σ, γ

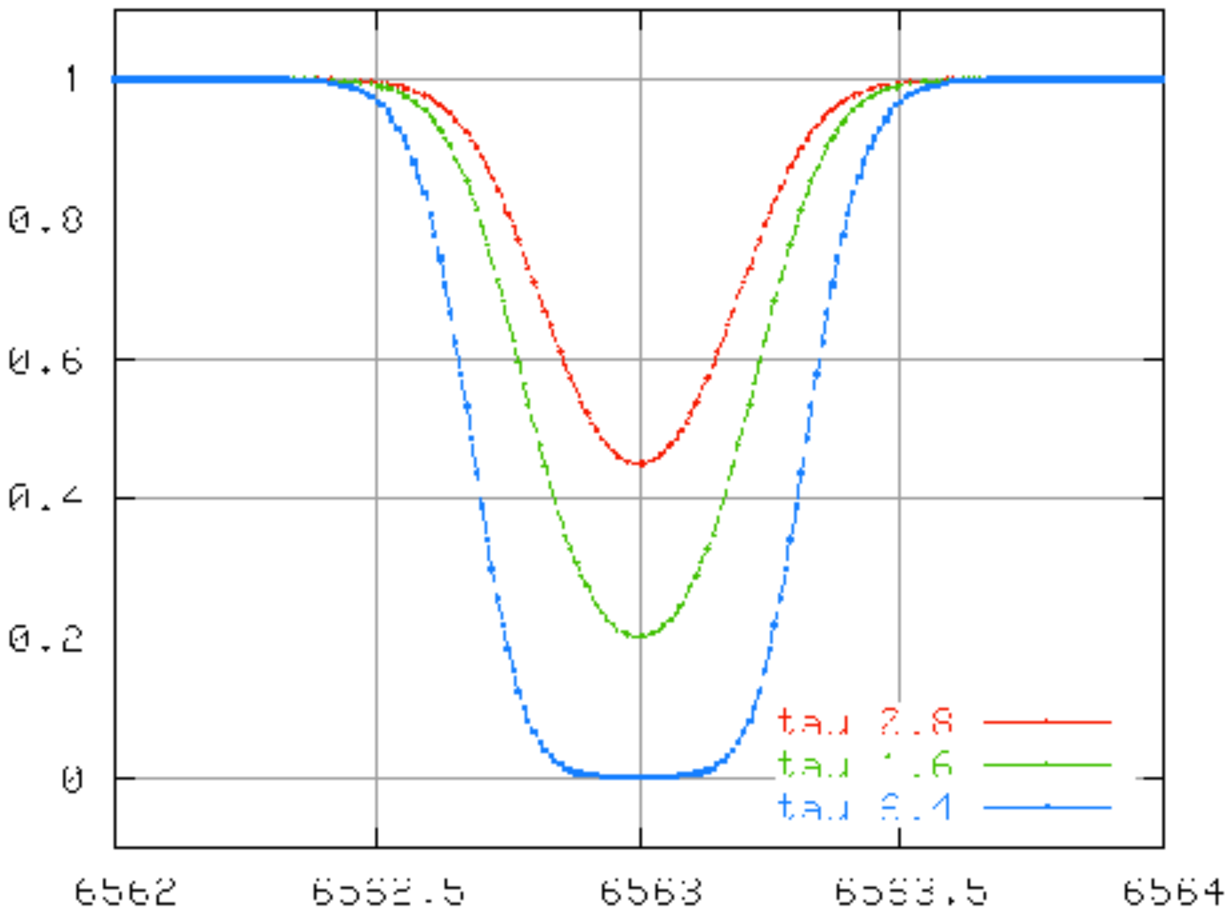
Link between velocity and Doppler shift

- Link between the Doppler velocity shift and the variation in wavelength:

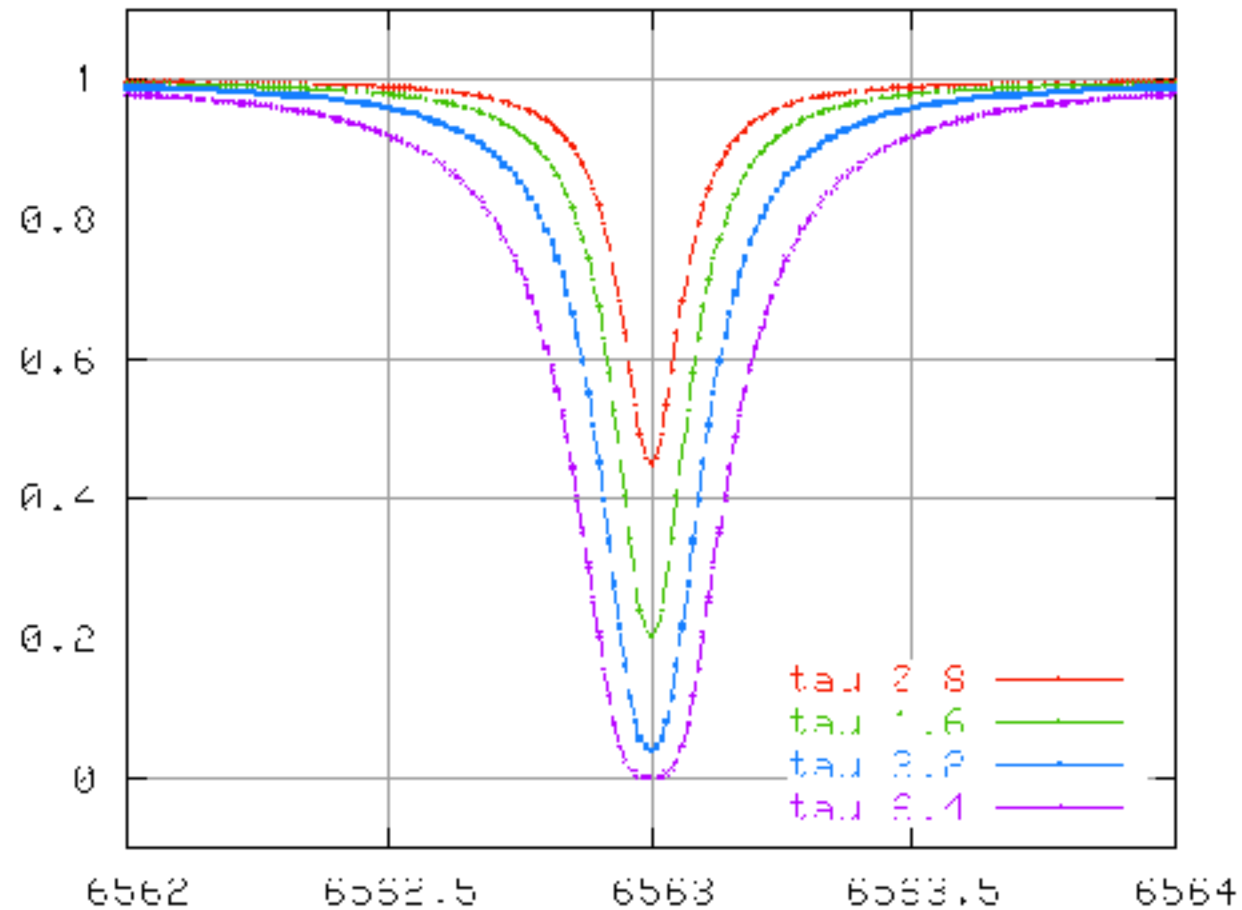
$$\frac{\Delta v}{c} = \frac{\Delta \lambda}{\lambda}$$

Width as a function of optical depth

Gaussian

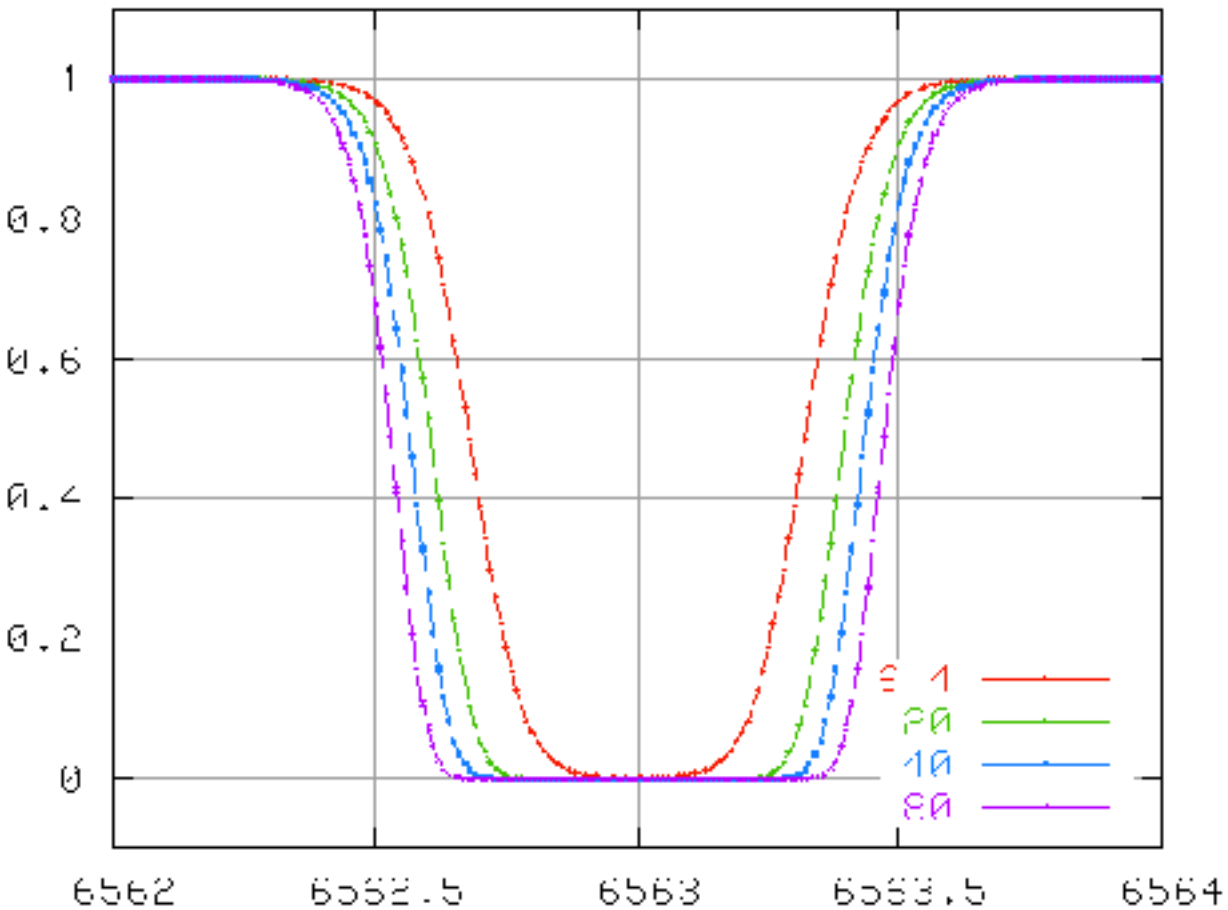


Lorentzian

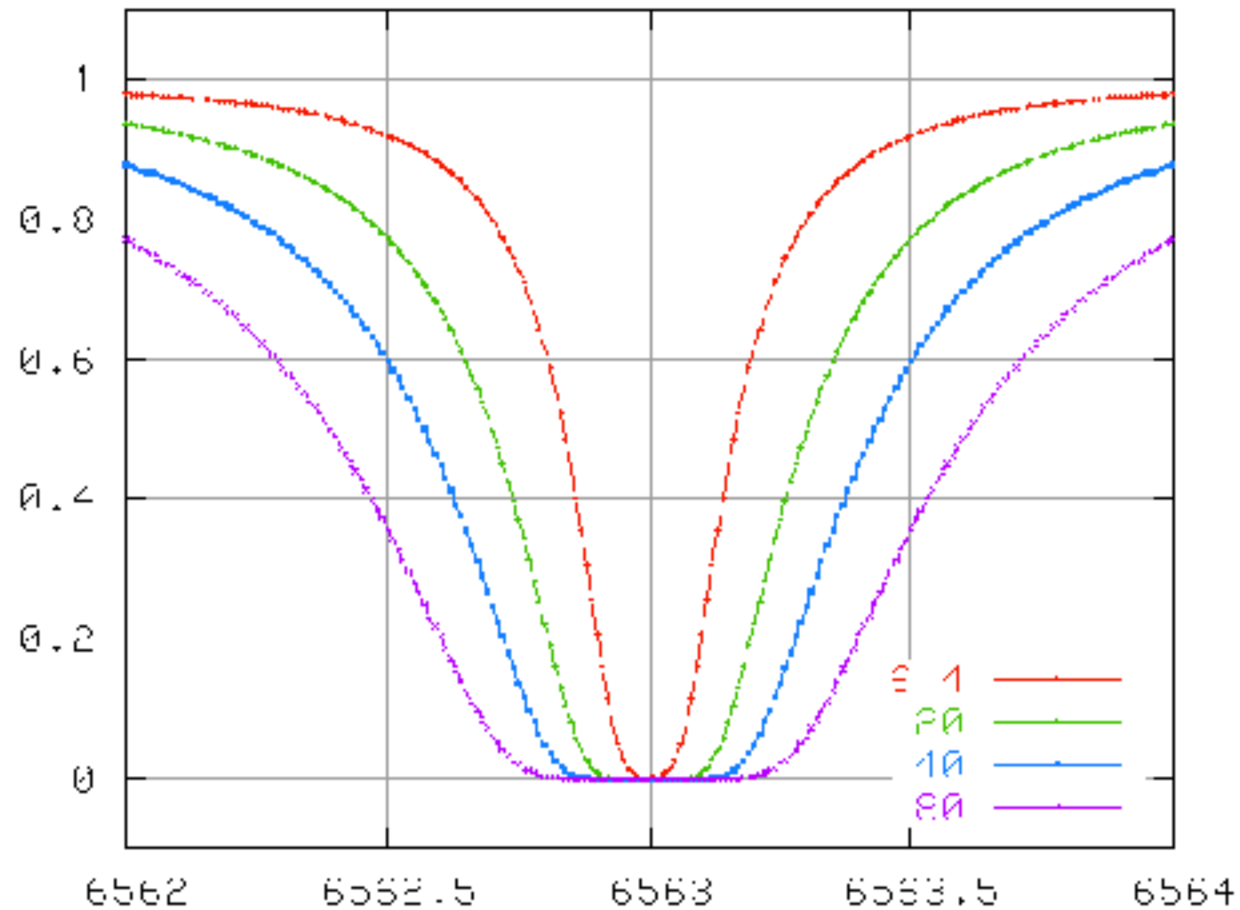


Width as a function of optical depth

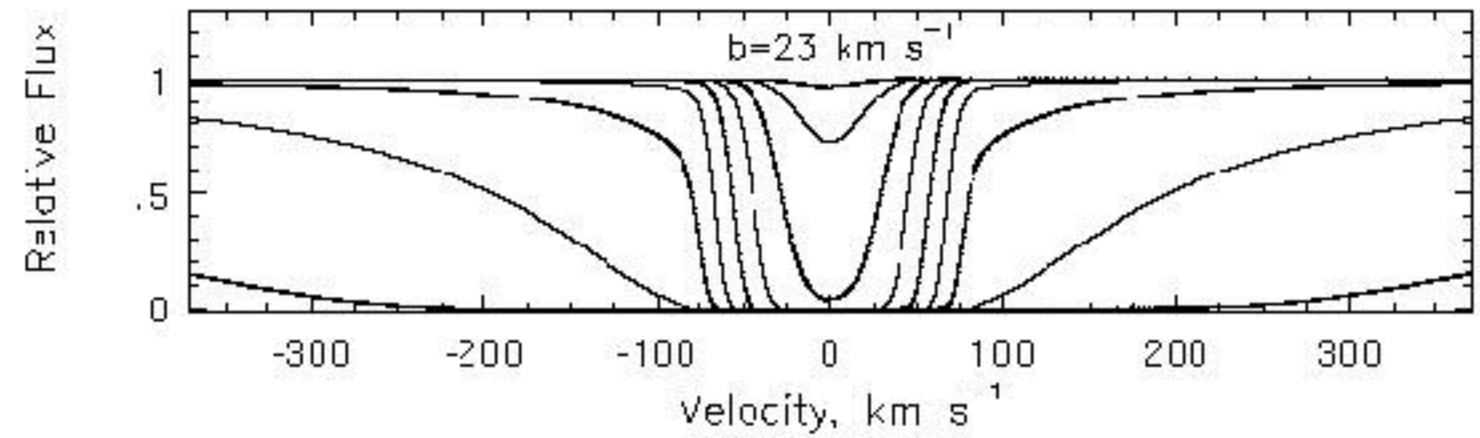
Gaussian

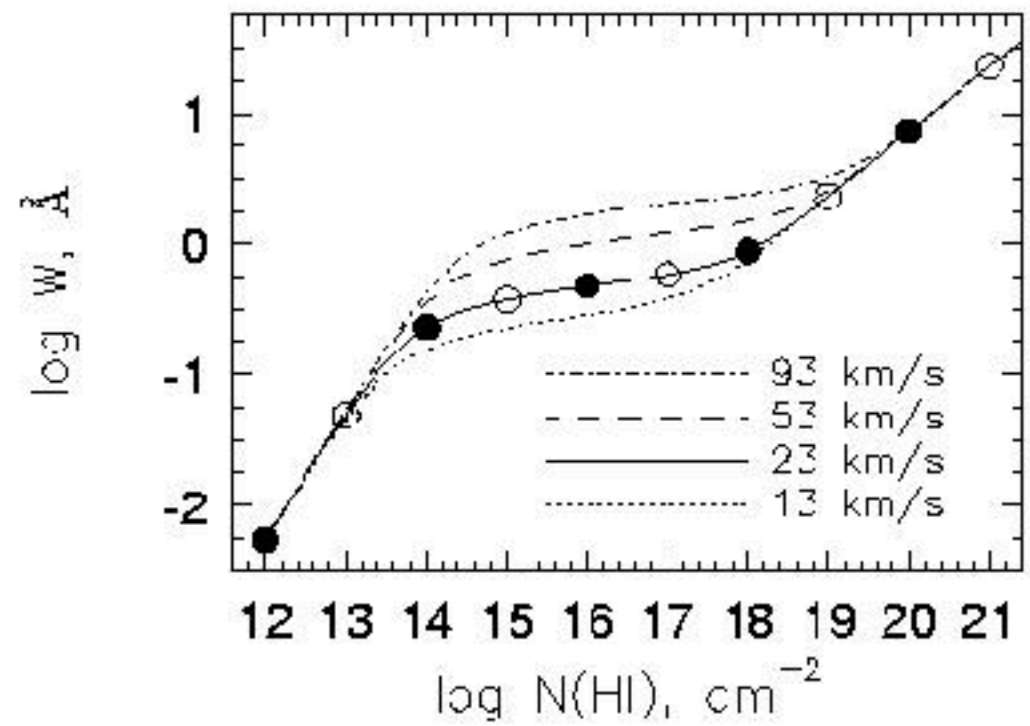


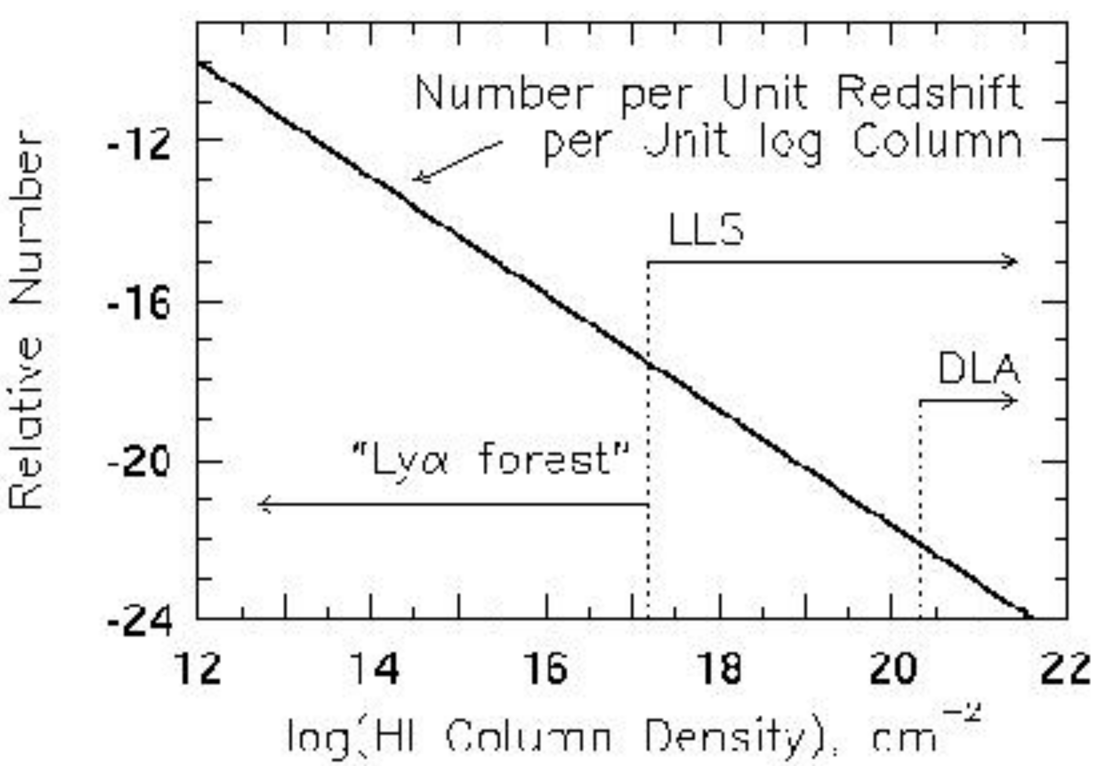
Lorentzian

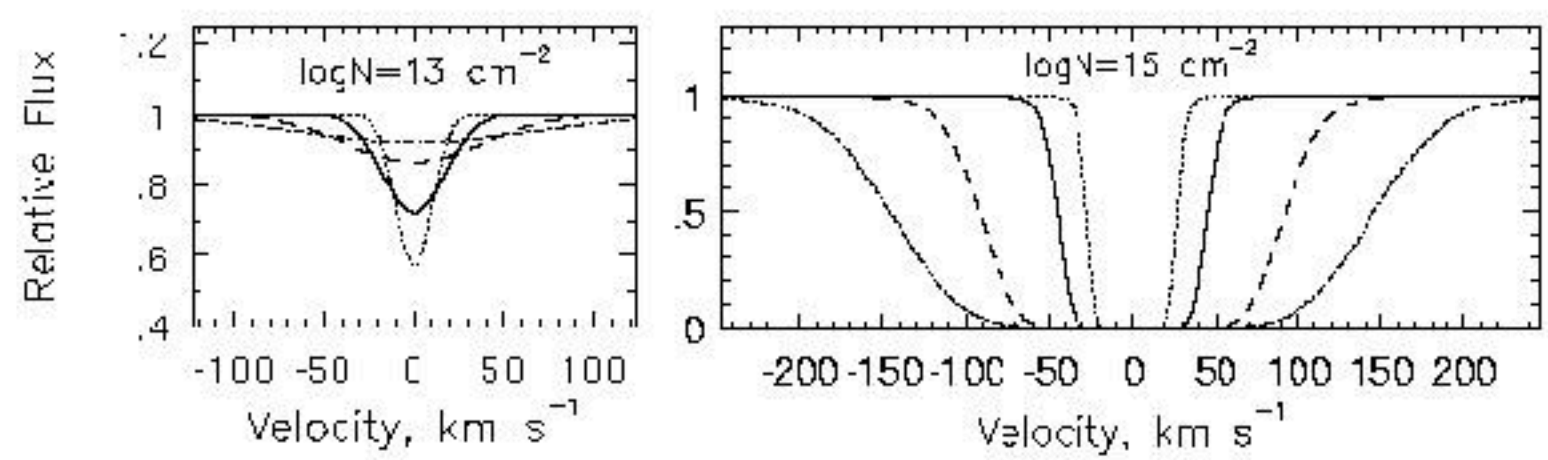


Equivalent Width as a function of column density





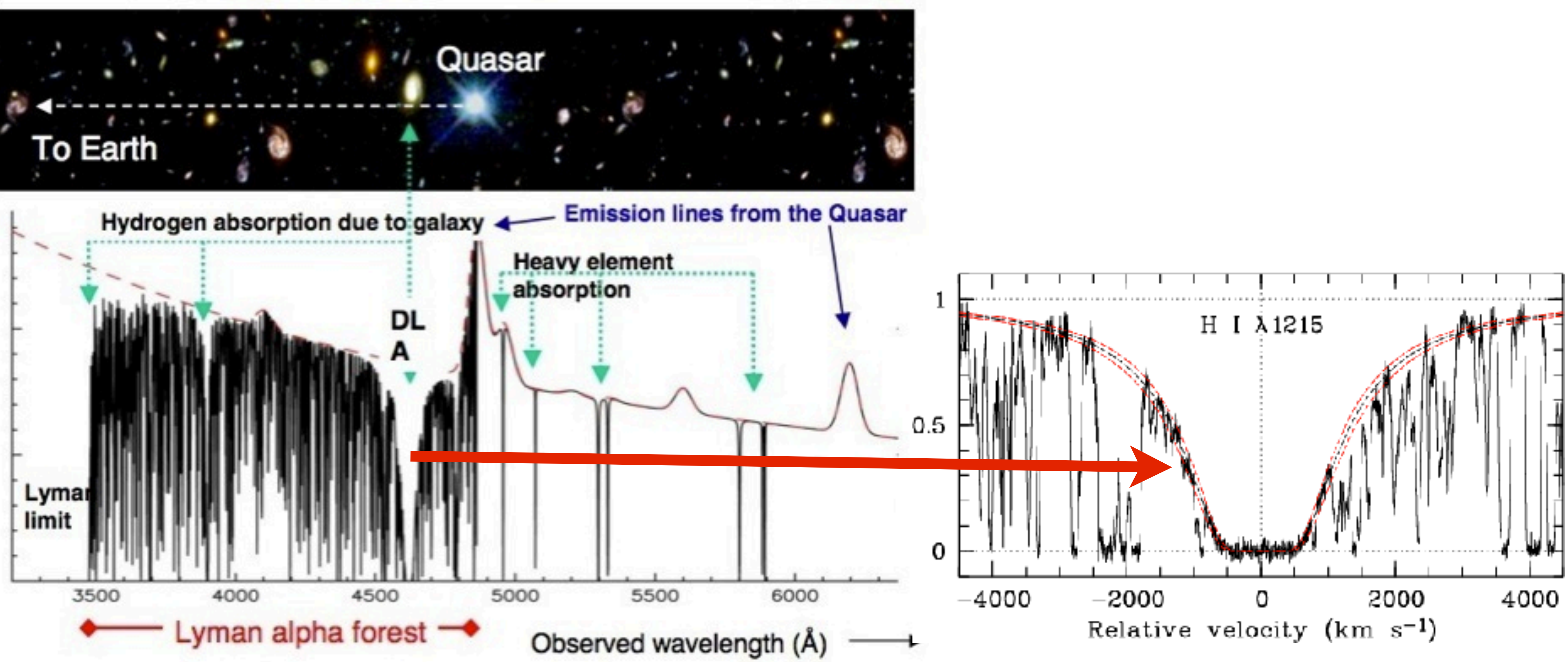




https://ned.ipac.caltech.edu/level5/Charlton/Charlton1_1.html

Damped Lyman-alpha (DLA) system

Damped Lyman alpha systems are concentrations of neutral hydrogen gas, detected in the spectra of quasars. They are defined to be systems where the column density (density projected along the line of sight to the quasar) of hydrogen is larger than 2 x 10^{20} atoms/cm^2



The neutral hydrogen density parameter

We can define the HI density parameter:

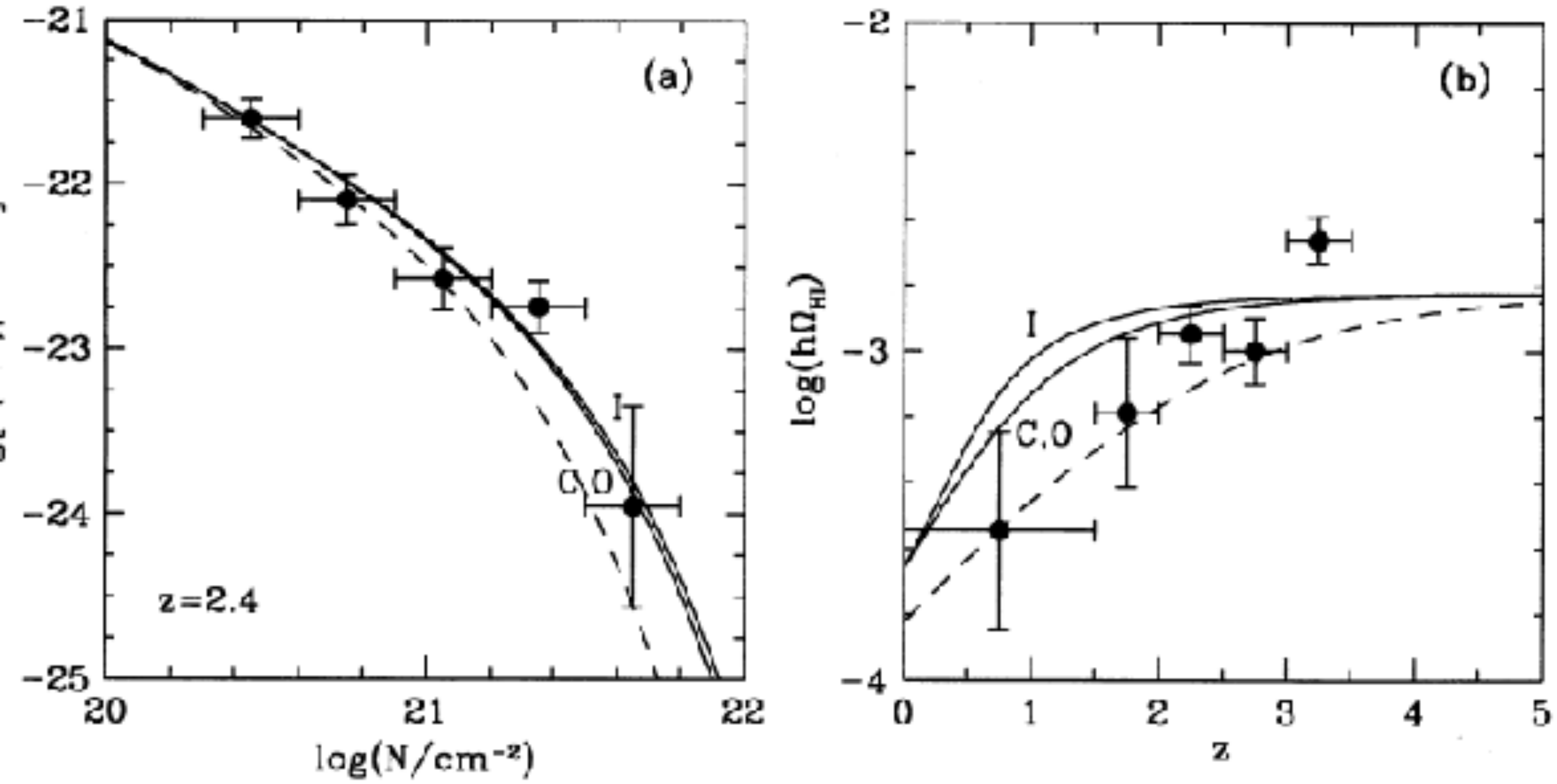
$$\Omega_{HI} = \frac{8\pi G.\rho_{HI}}{3H^2}$$

The volume density of HI can be expressed by:

$$\rho_{HI}(z) = \frac{H_0 \mu m_H}{c} \int N_{HI} f(N_{HI}, z) dN_{HI}$$

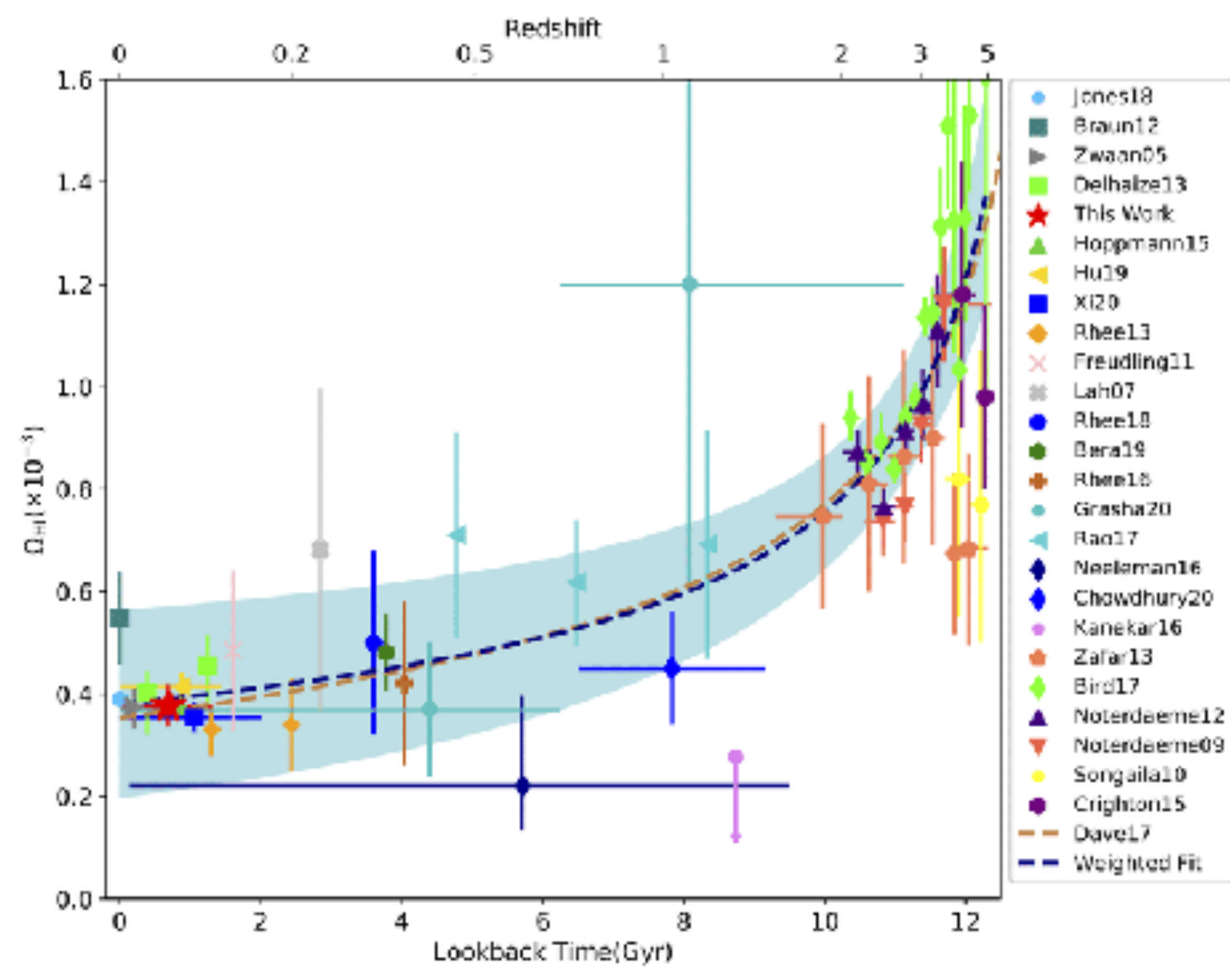
Where f is the column density distribution of Lyman-alpha clouds as a function of HI density and redshift.

The neutral hydrogen density parameter



Pei & Fall 1995

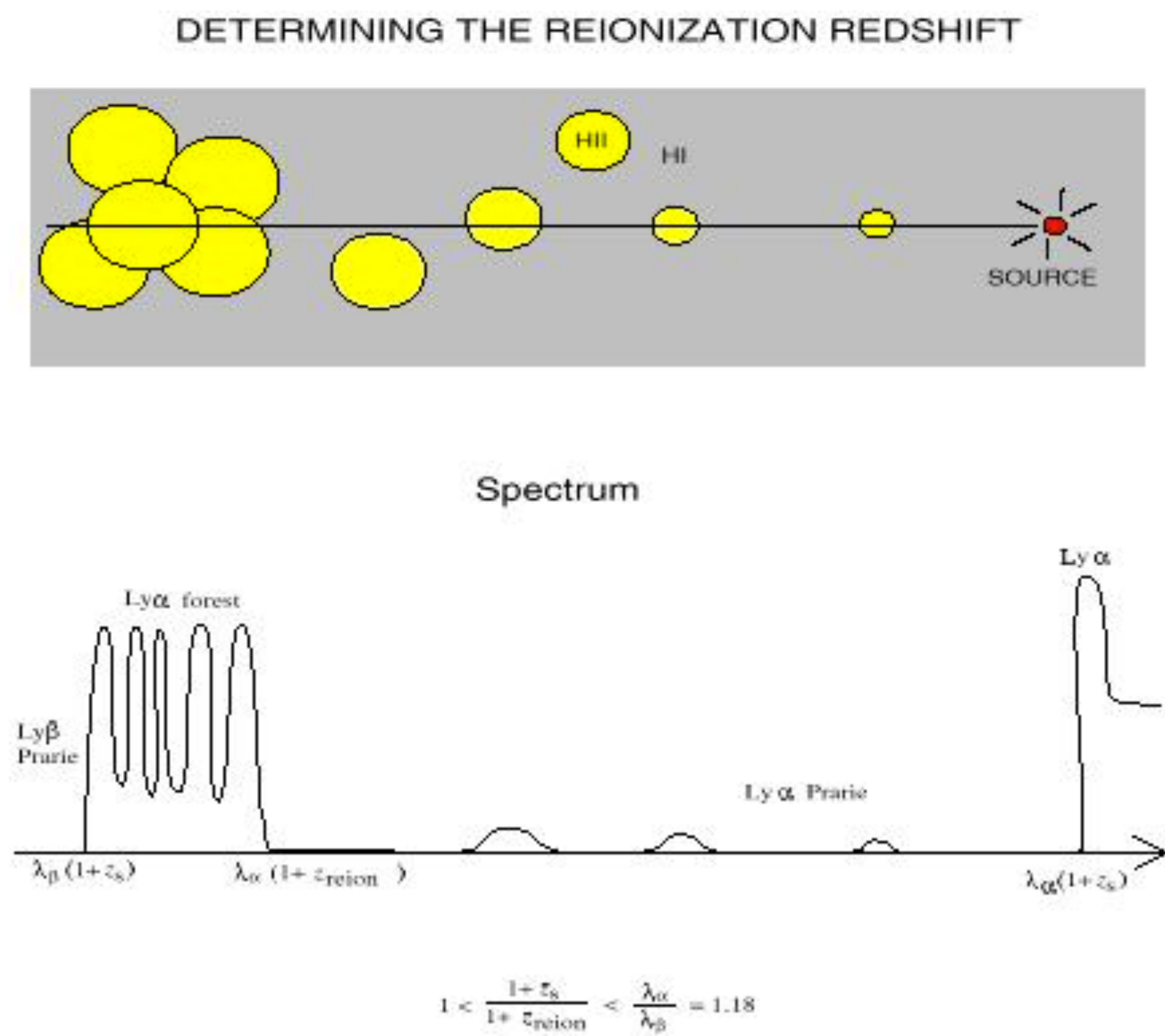
Chen et al 2021



Gunn-Peterson effect

The **Gunn–Peterson trough** is a feature of the spectra of quasars due to the presence of neutral hydrogen in the Intergalactic Medium (IGM). The **trough is characterized by suppression of electromagnetic emission from the quasar** at wavelengths less than that of the Ly-alpha line.

This effect was originally predicted in 1965 by James Gunn and Bruce Peterson.

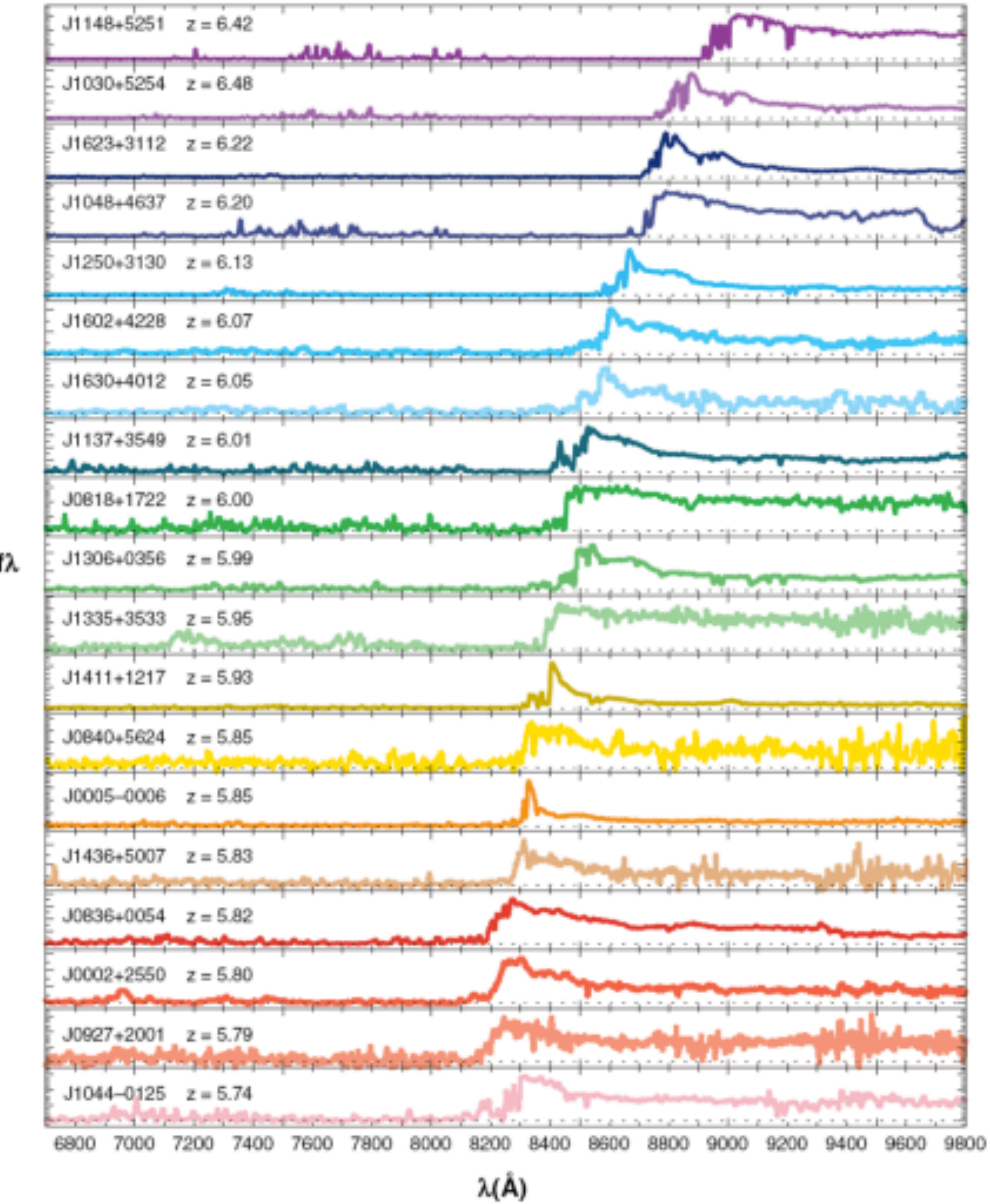


Lyman-forest as a function of redshift

High redshift SDSS quasars.

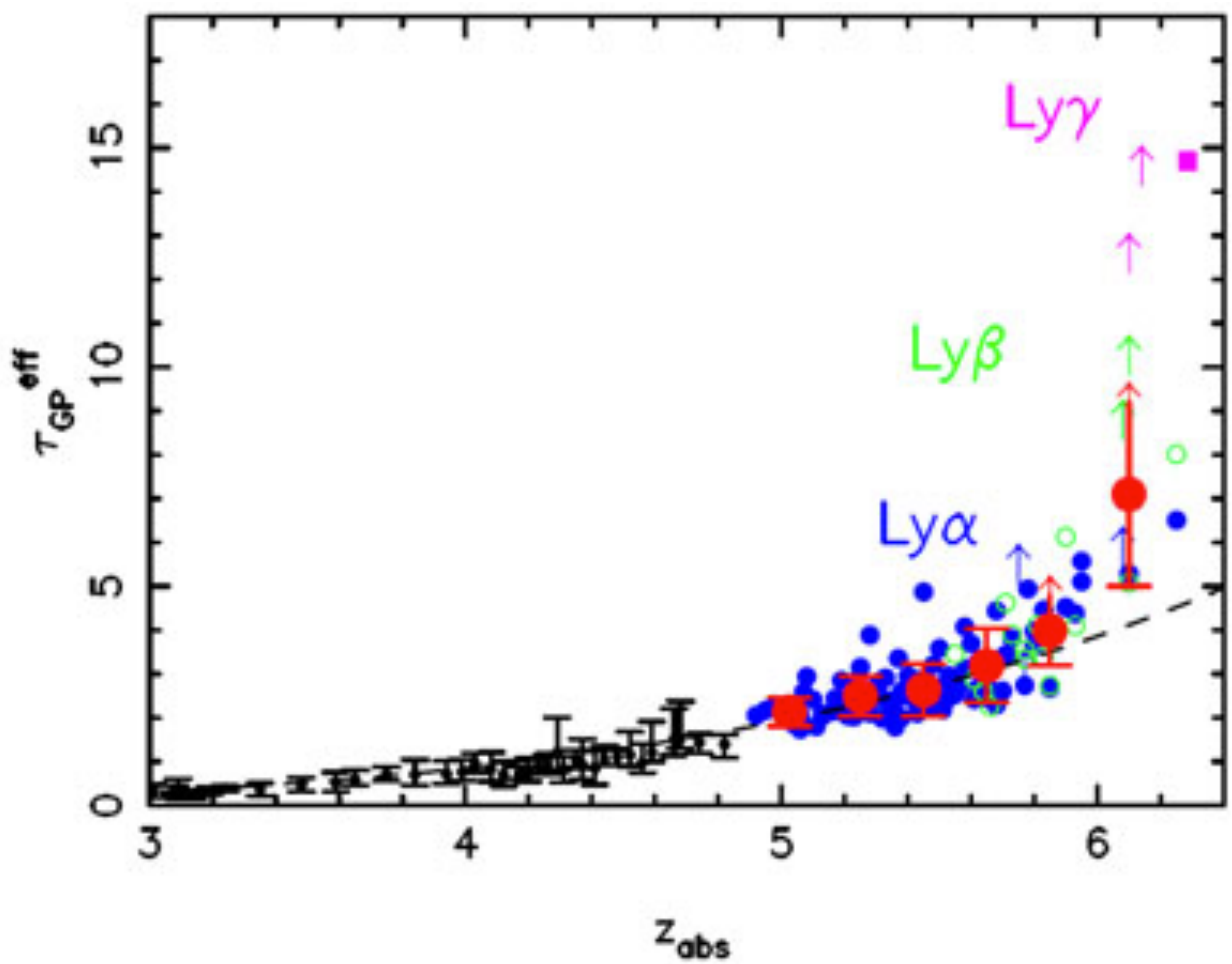
The Gunn-Peterson trough blue-wards of the QSO Lyman emission that is clearly apparent in the highest redshift ones.

It indicates that the Universe has become somewhat more neutral at these redshifts. A similar behaviour is also seen blue-wards of the QSO Lyman-beta region.



Optical Depth as a function of redshift

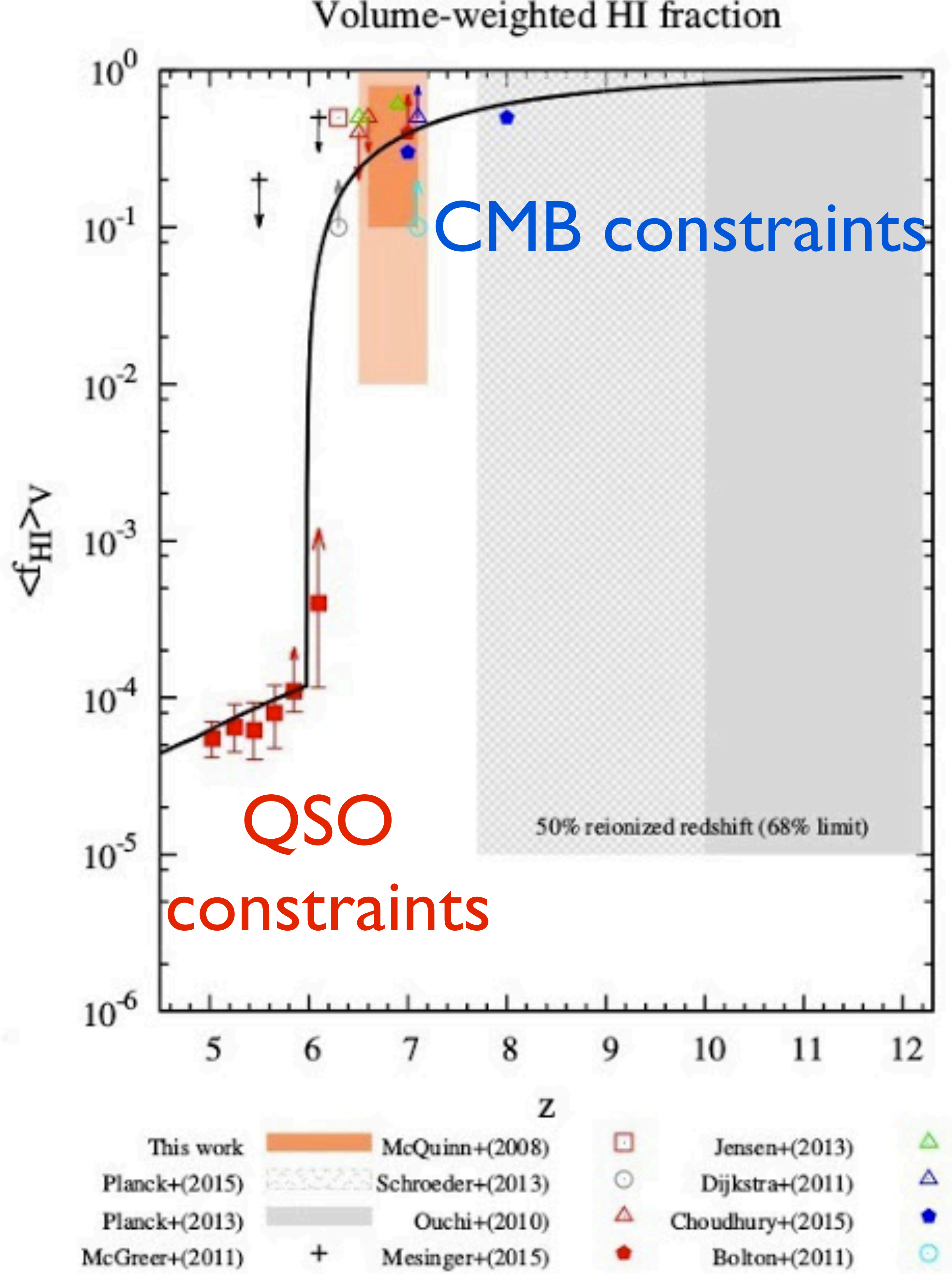
Evolution of the optical depth from the high redshift Sloan quasars.
The dashed line shows a redshift evolution of ≈$(1+z)^{4.3}$.
At z > 5.5, the best-fit evolution has ≈$(1+z)^{>10.9}$, indicating an accelerated evolution.



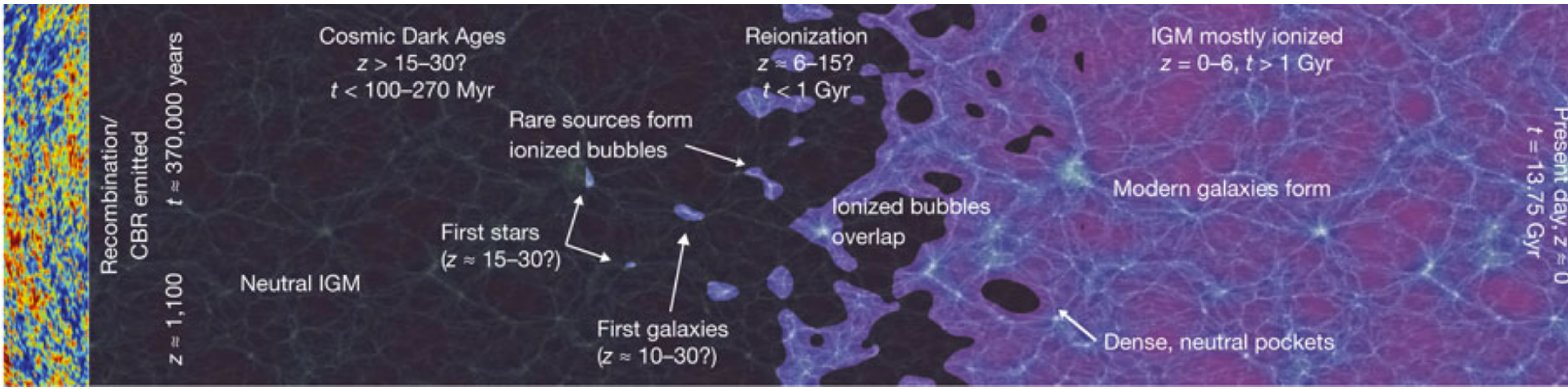
HI fraction evolution

The cosmological fraction of neutral hydrogen (HI) in the diffuse intergalactic medium as a function of redshift.

For higher redshift, the universe is increasingly neutral.
A late and rapid reionisation is favoured.



Reionization

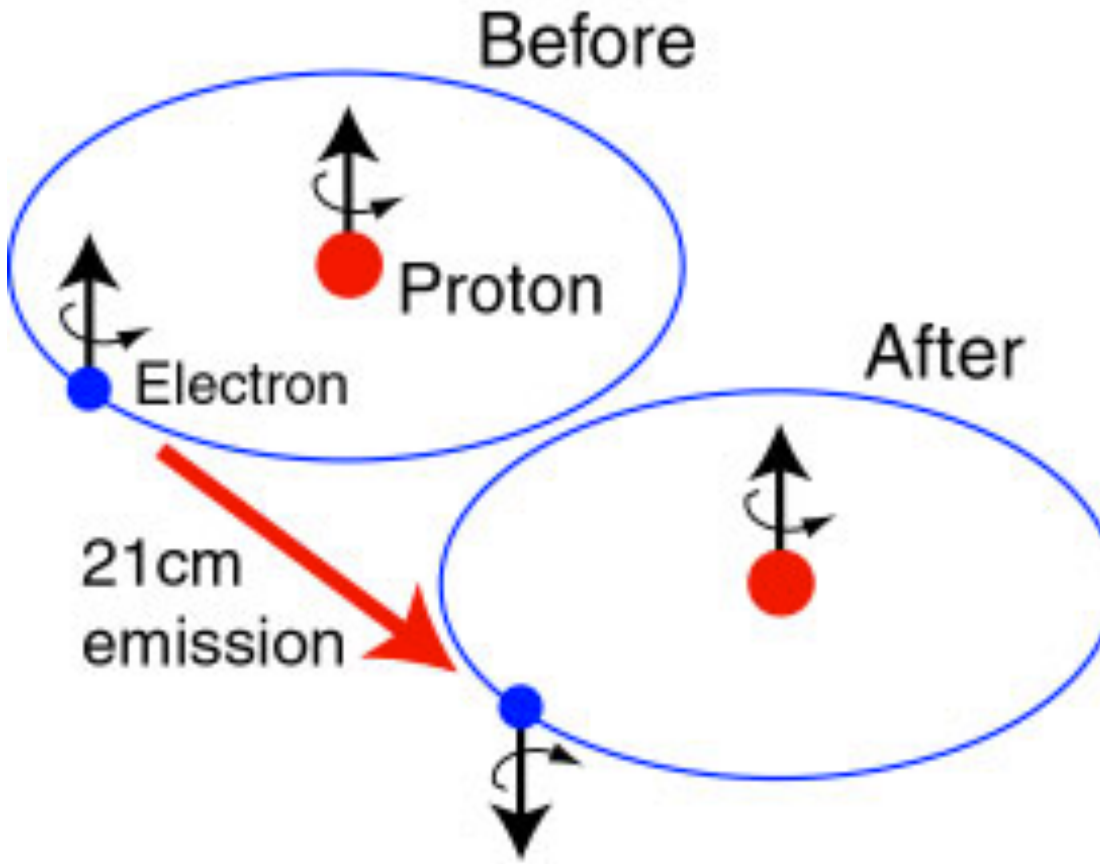


Reionization is the process that reionized the matter in the universe after the "dark ages". It is now believed to happen at z~7-9.

As the majority of baryonic matter is in the form of hydrogen, reionization usually refers to the reionization of hydrogen gas.

21cm spin-flip transition

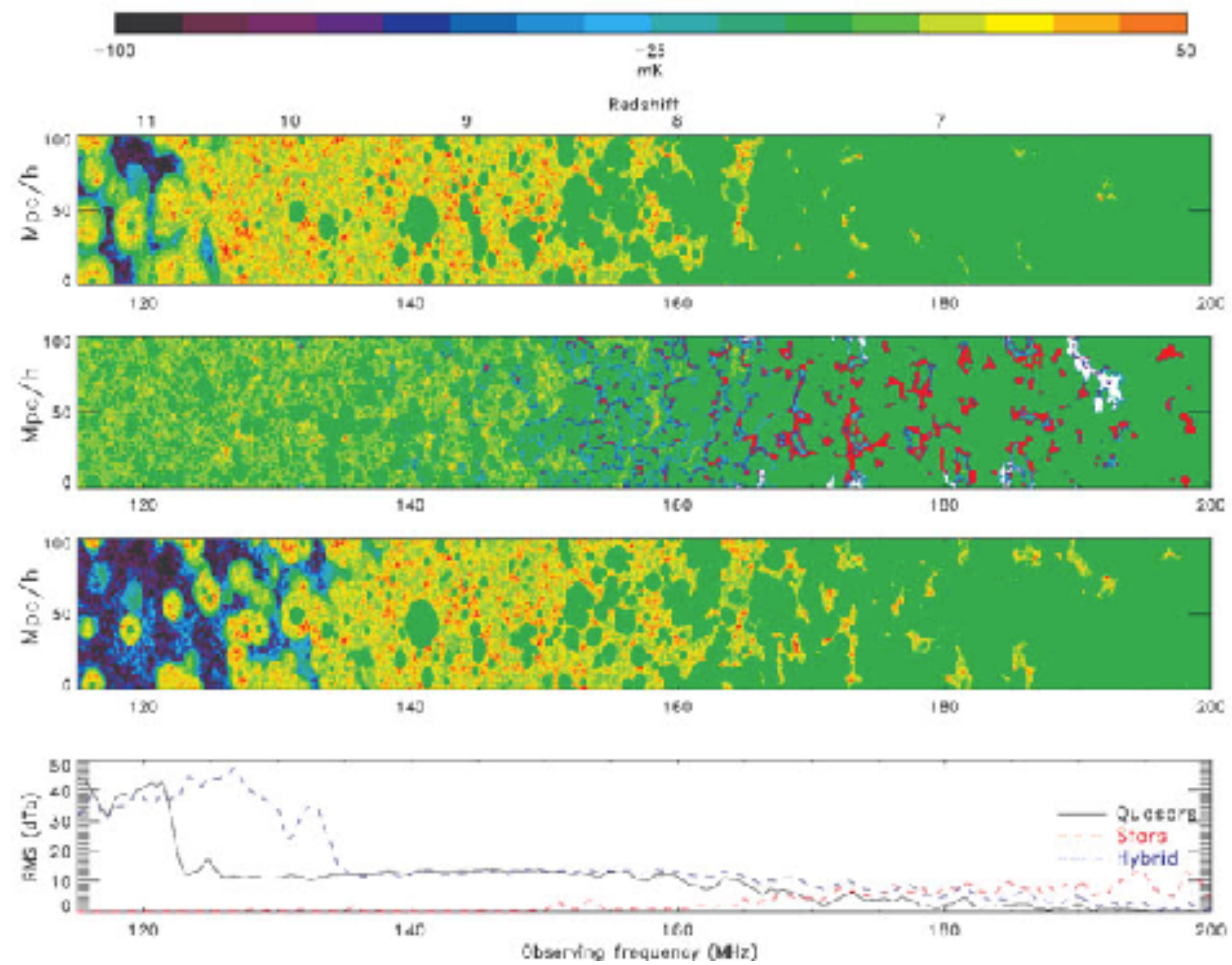
- *There is a slight difference in energy of the ground state depending whether the spins of the proton and electron are in the same or opposing sense.*
-
- *The transition between them gives rise to a line close to 1.42 GHz - 21cm in wavelength.*
- *This is called the 21cm line and is a most powerful tool for studying the dynamics of galaxies.*



Energy difference is $\sim 10^{-6}$ eV

21cm reionisation

- *The 21cm line is observable in radio domain, even when redshifted to z>10.*
- *During reionization, the 21cm line could be in emission or in absorption depending on the thermal history of the gas.*
- *We expect a 21cm-forest analogous to a Lyman-alpha forest.*



Reionization histories (T_b in mK as a function of frequency or redshift) are plotted for mini-qso, stellar and hybrid sources, respectively.

21cm spin-flip transition

- *The 21cm line is observable in radio domain, even when redshifted to z>10.*
- *During reionization, the 21cm line could be in emission or in absorption depending on the thermal history of the gas.*
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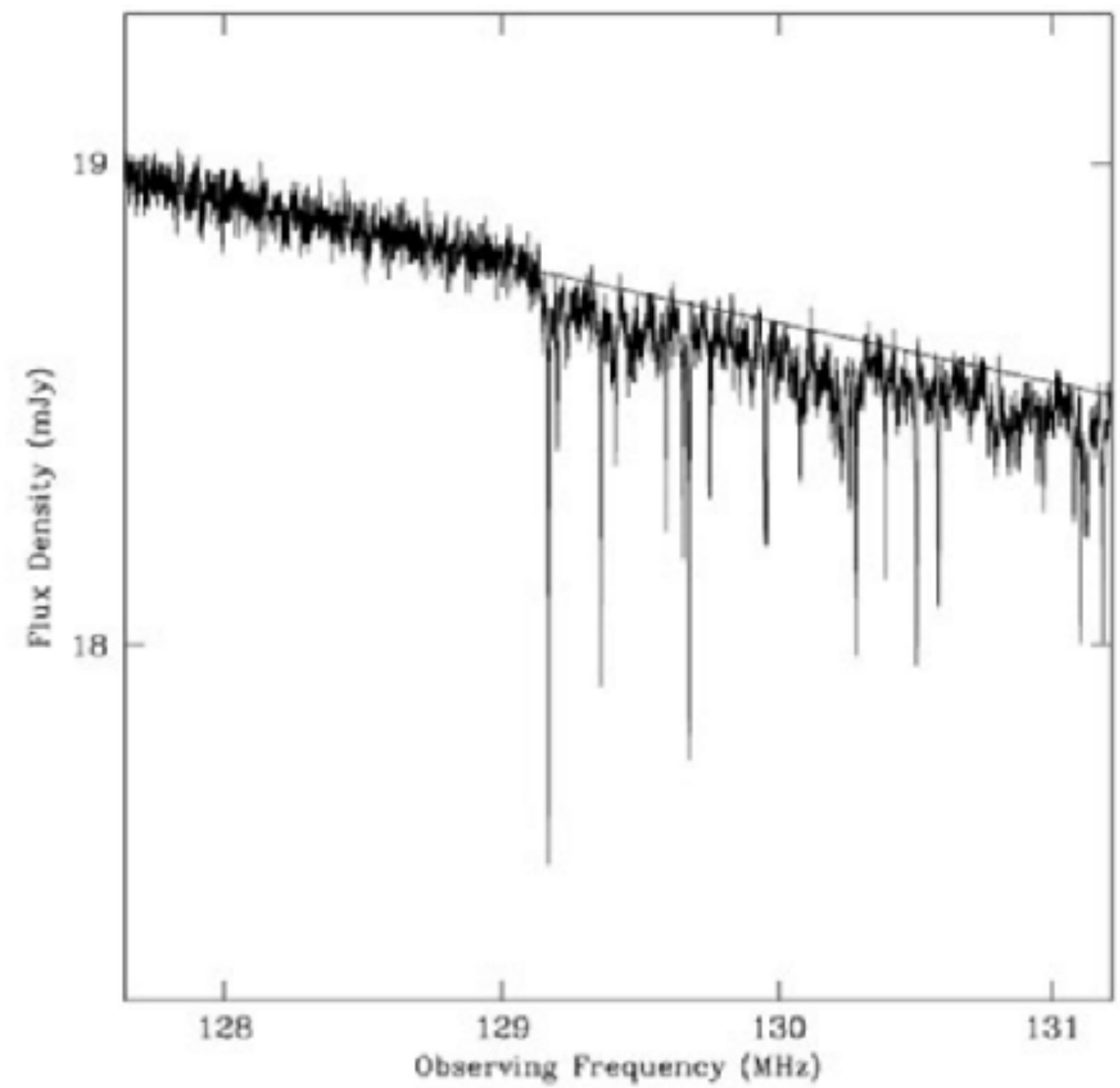
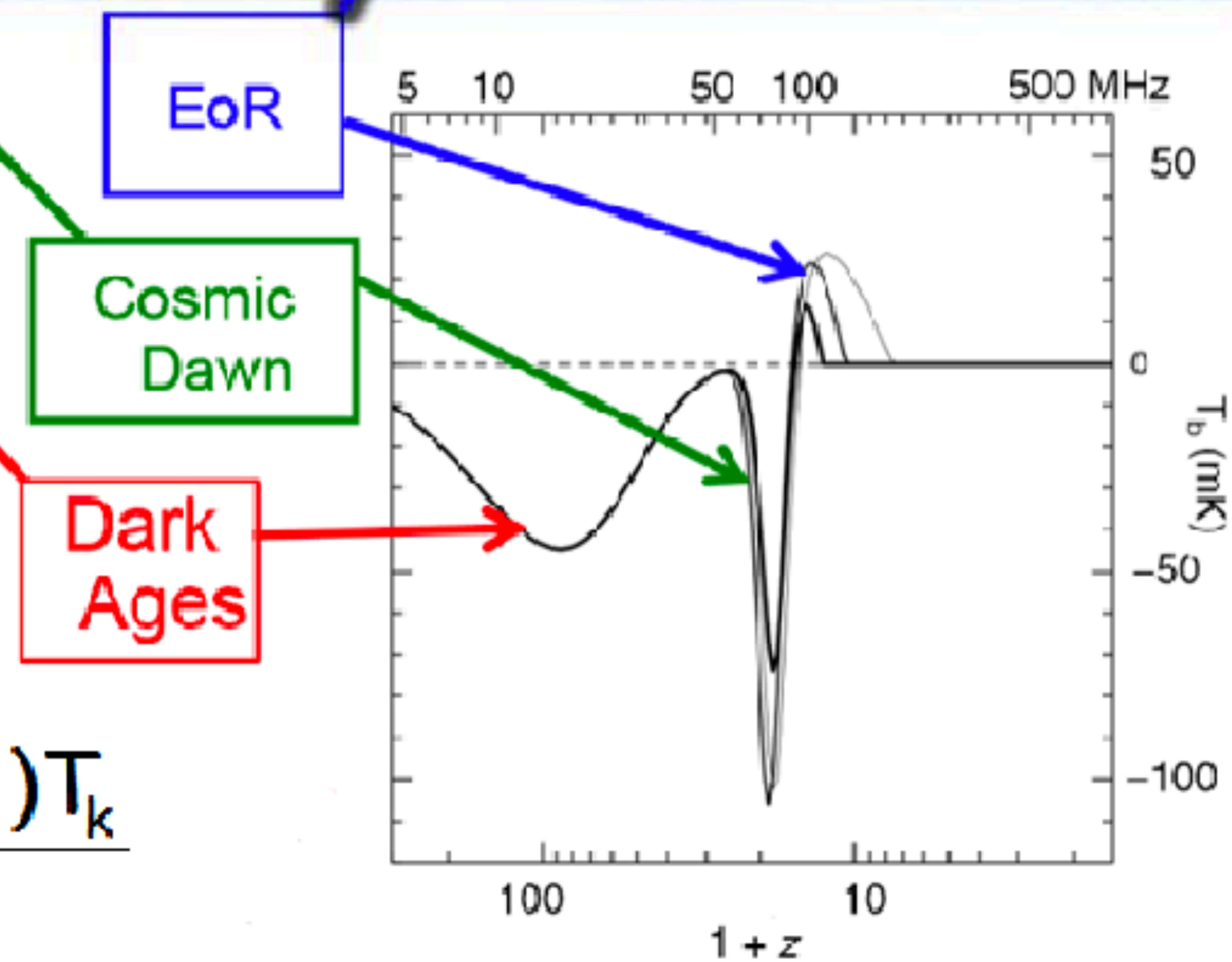


Dark age: the gas cools faster than the CMB, is thermalised by collisions (y_c)

Cosmic dawn: after the first stars, the Lyα by WF effect (y_α) couples T_s to T_k

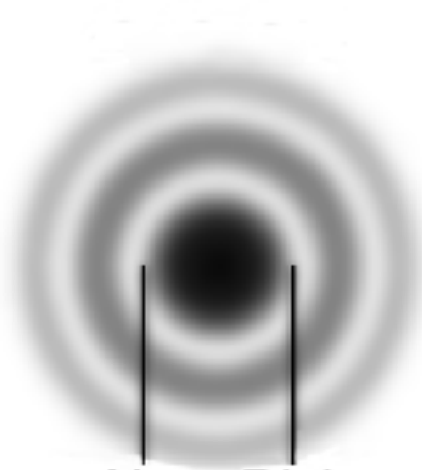
EoR: gas is heated by the stars



$$T_s = \frac{T_{CMB} + (y_\alpha + y_c)T_k}{1 + y_\alpha + y_c}$$

WF: Wouthysen Field

Specifics of Radio Astronomy



- The airy disk is given by:

$$\theta = 1.220\frac{\lambda}{D}$$

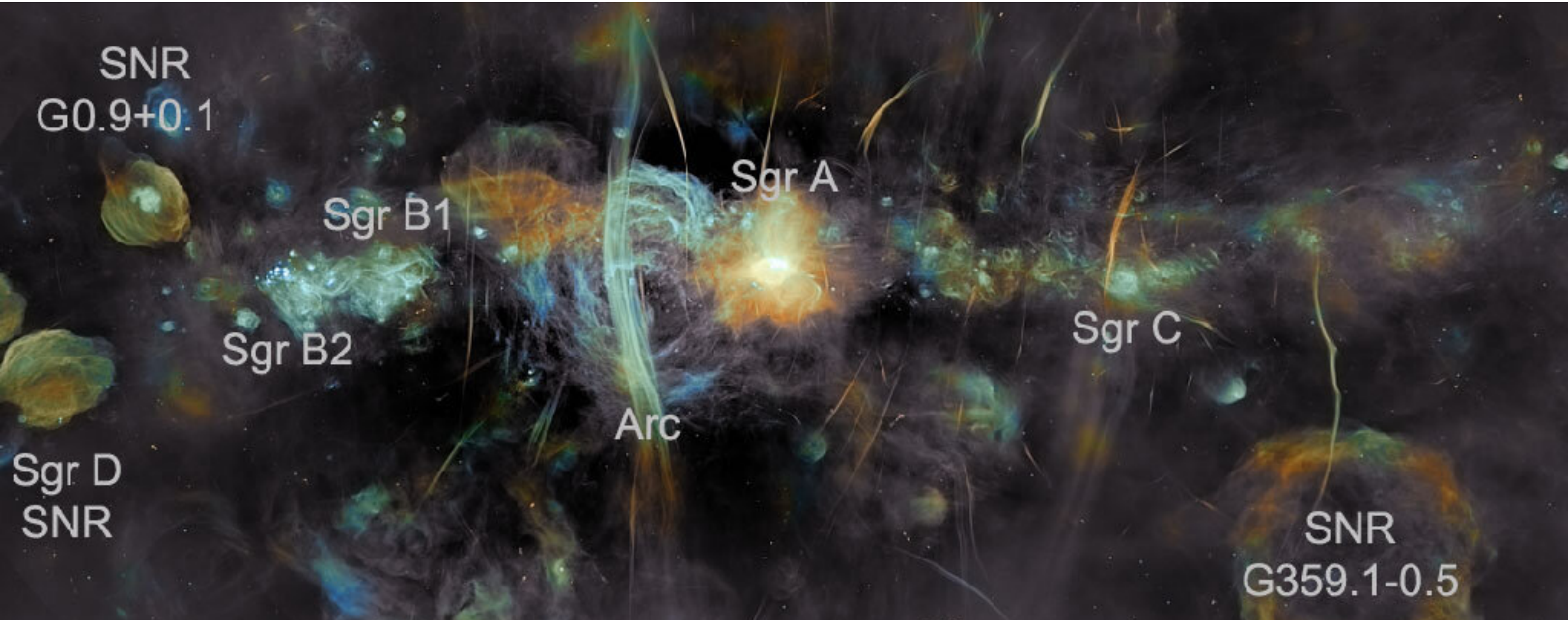
- At 1cm wavelength, D=2.5km to resolve 1"
- At 21cm (Hydrogen Line), D=50km
- At 1m, D=250km (to resolve the hydrogen line in a galaxy at z~5)

• https://www.edx.org/course/radio-sky-1
• https://www.edx.org/course/the-radio-sky-ii-observational-radio-astronomy

China FAST radio telescope = 500m 1cm => 5”

Jansky Very Large Array (JVLA)

MeerKat (South Africa)



Square Kilometer Array Observatory

The SKAO will be the largest and most complex astronomical instrument, with individual antennas spread over continental scales.

Collecting surface area of ~ <1 km^2

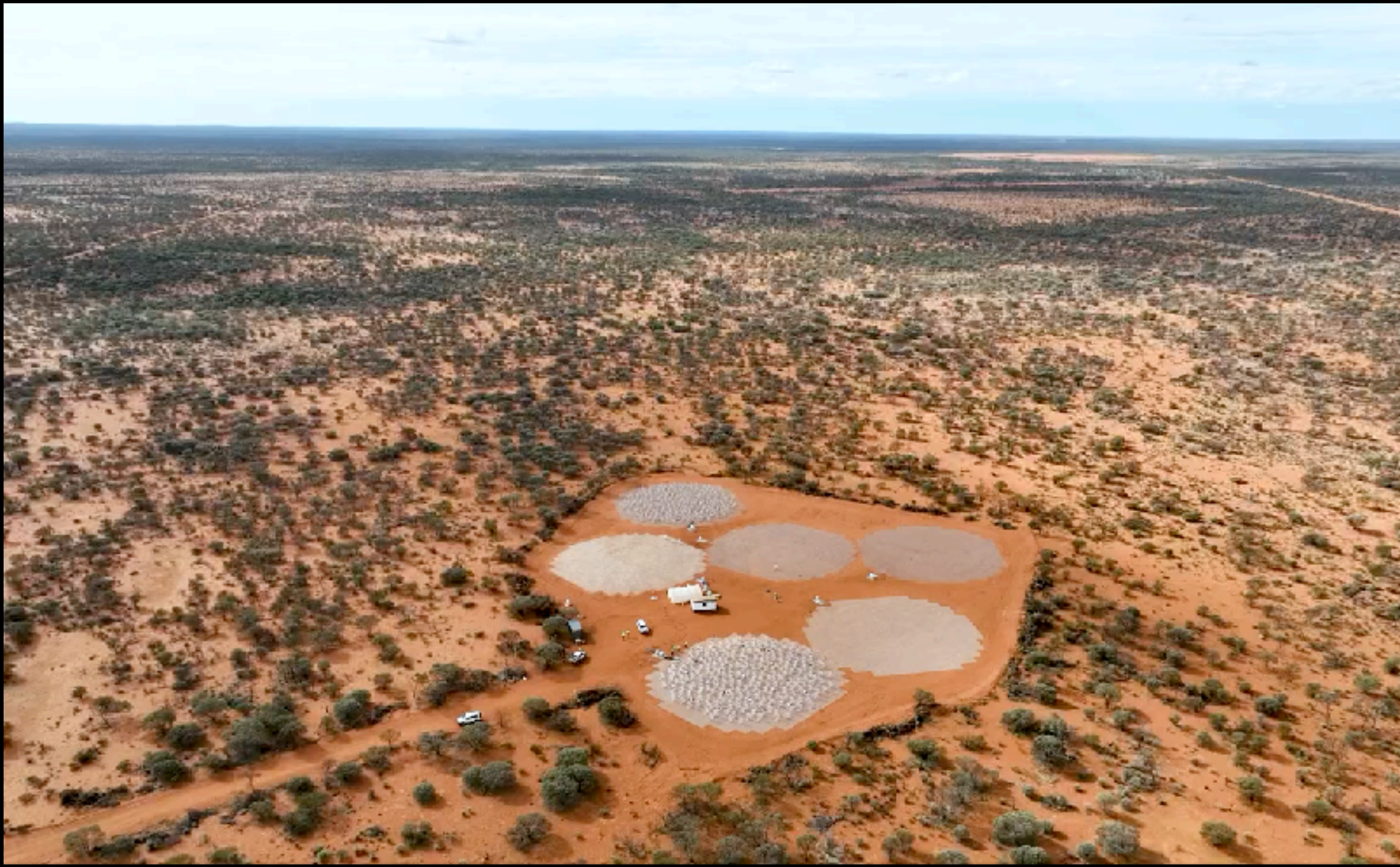
Switzerland joined the SKAO on January 2022

512 stations of 256 antennas

SKAO Low frequency telescope
Across 65km

Epoch of Reionization

Western Australia



To be completed in 2029

144 dish antennas of 15m diameter

SKAO Mid frequency telescope

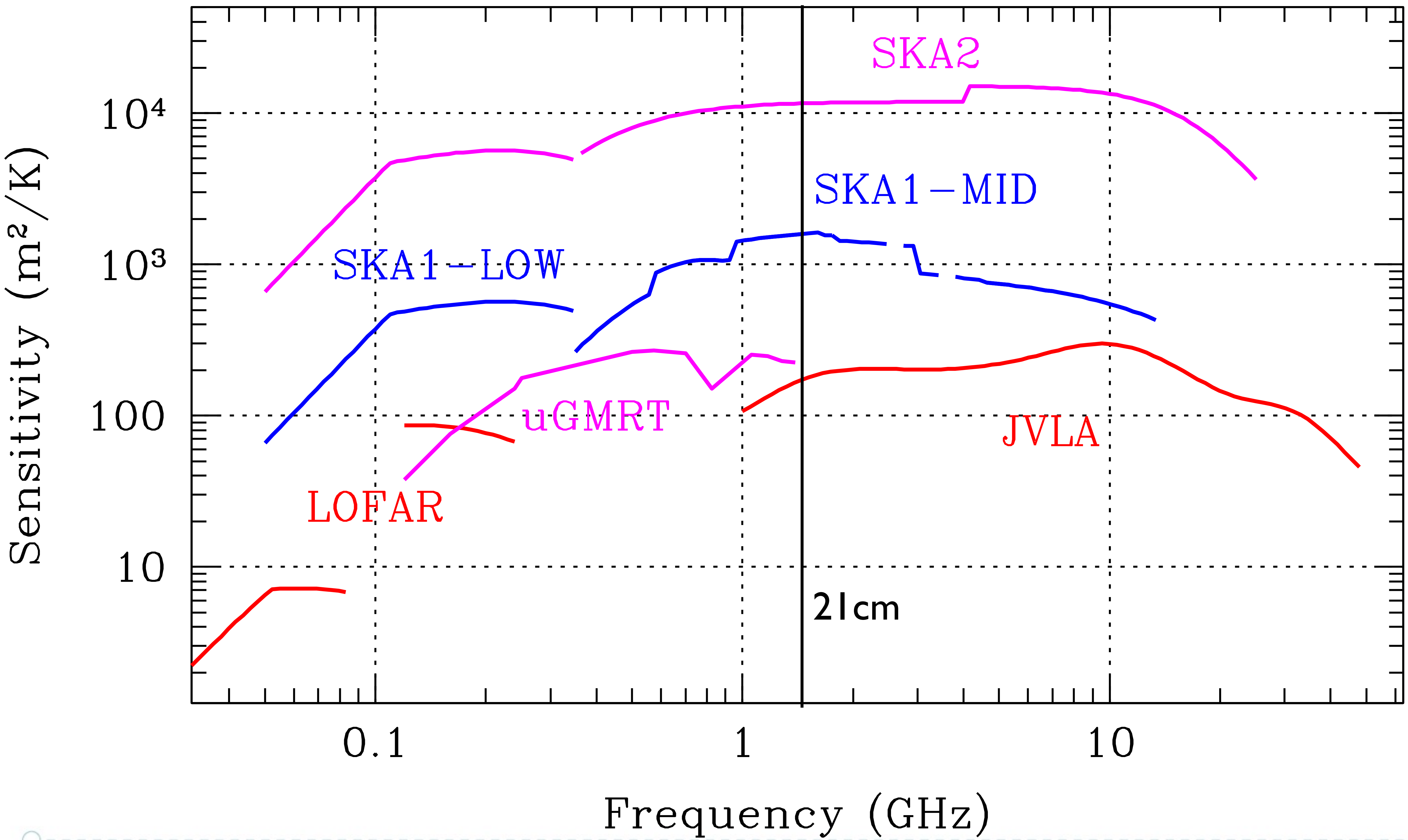
Across 150km

Magnetism, galaxy mapping

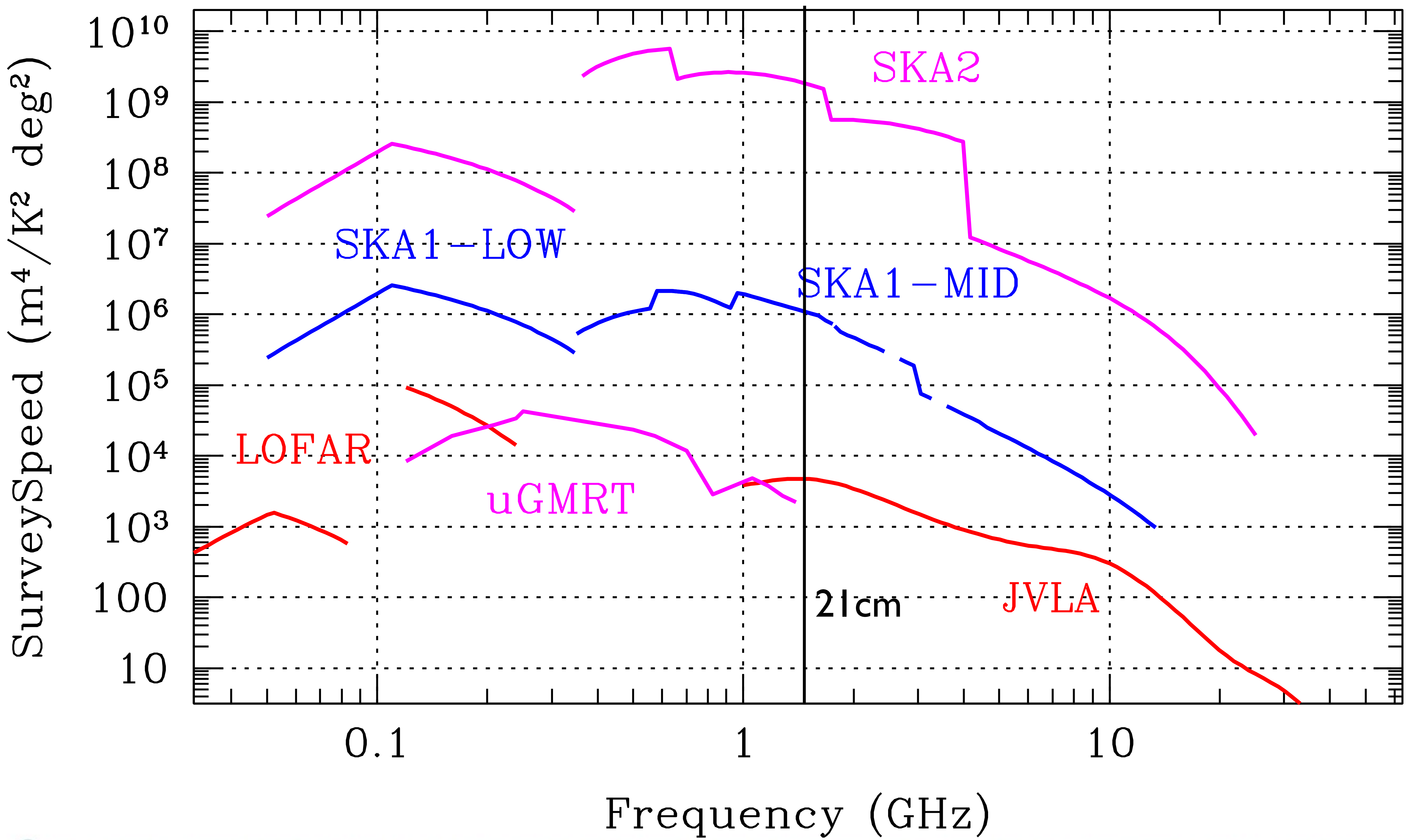
South Africa

To be completed in 2029

Sensitivity Comparison



Survey Speed Comparison



Resolution Comparison

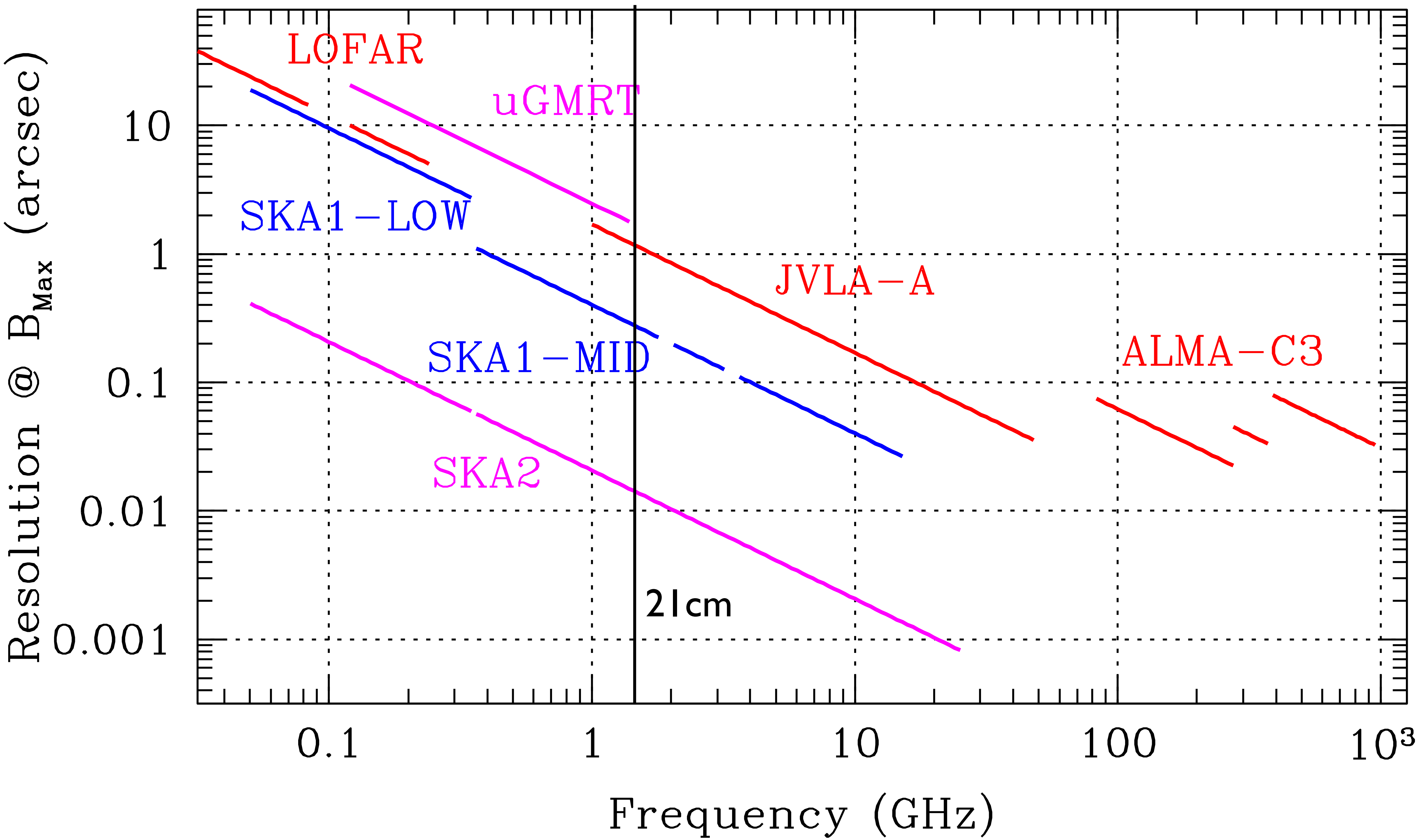
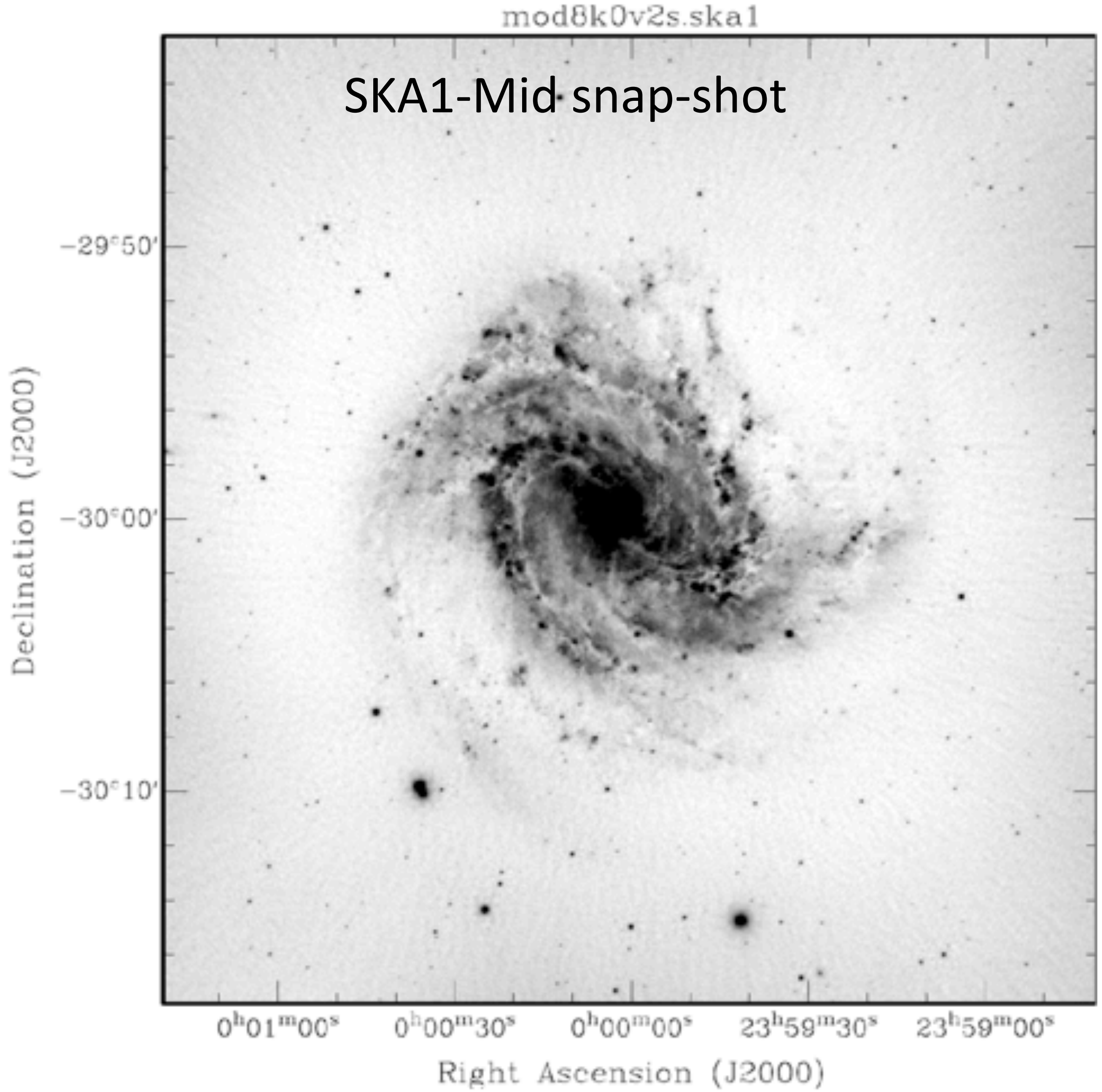
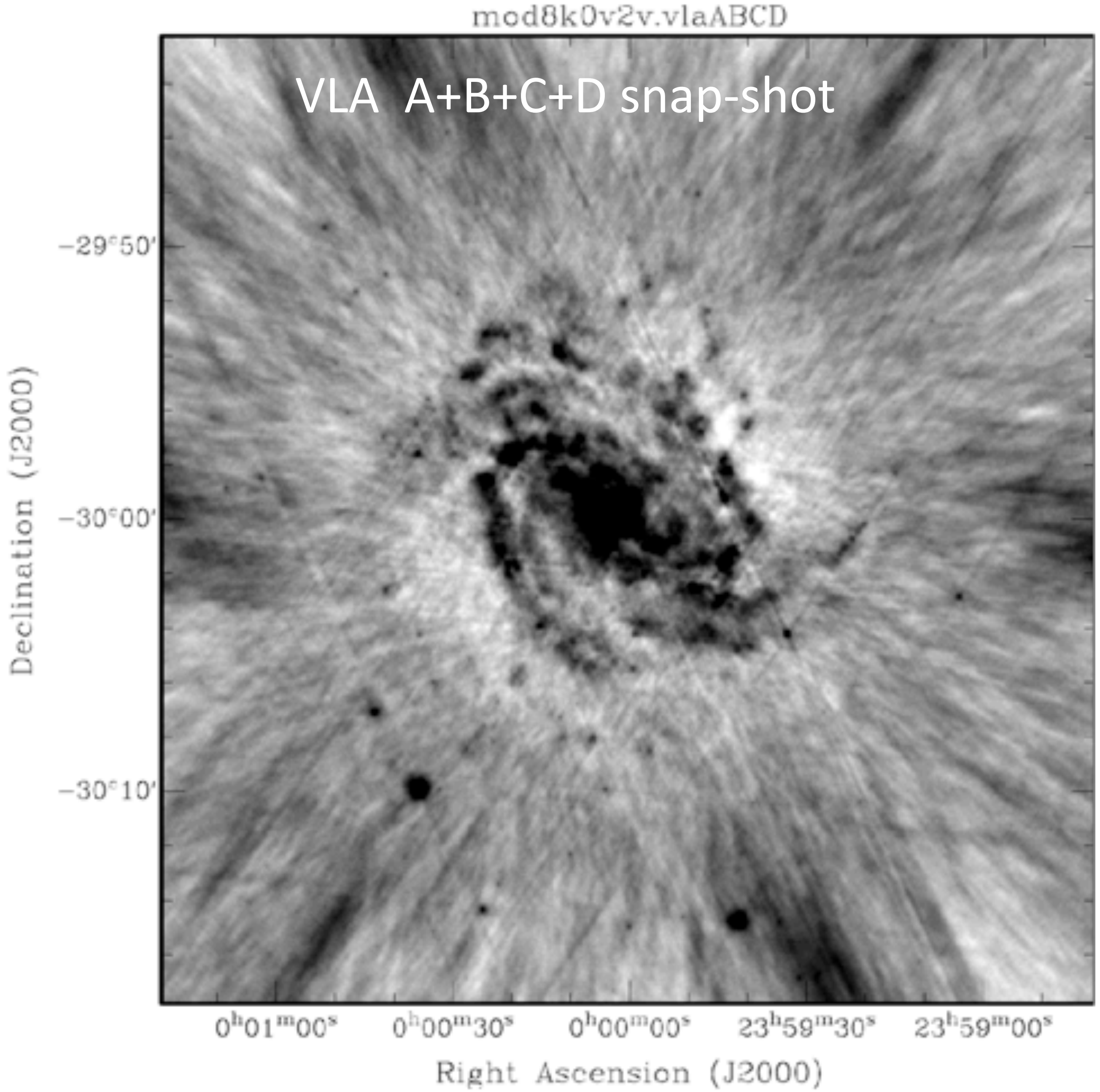


Image Quality Comparison





- Single SKA1-Mid snap-shot compared to combination of snap-shots in each of VLA A+B+C+D