The physics of the HI 21cm line
Observing the early Universe

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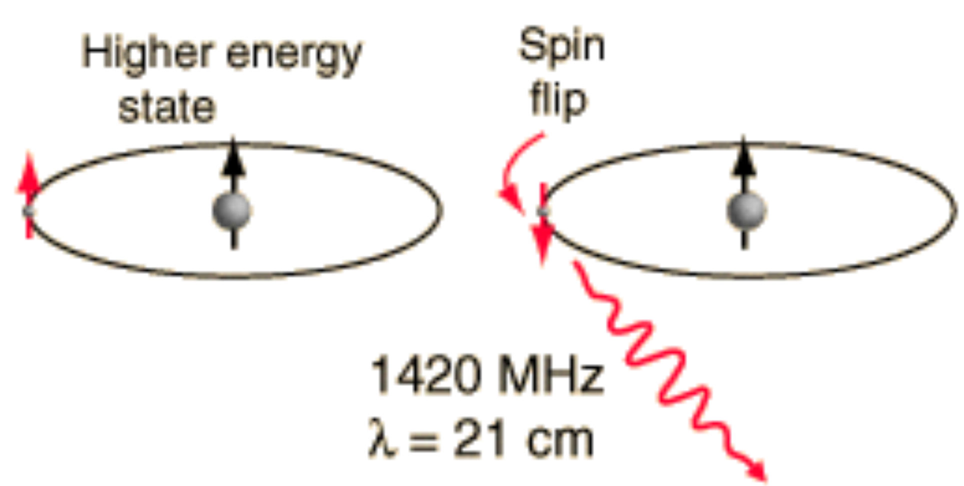
6ª Escola Avançada de Astrofísica do INPE
Cosmologia de 21 cm no século 21



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html

The HI 21cm line
The first light in the Universe

Lecture 1

i) The 21 cm line

ii) CMB Formation

iii) The mean 21cm line signal

Lecture 2

iV) Cosmic Dawn/ The First Stars

V) Reionization

Vi) Observing the EoR

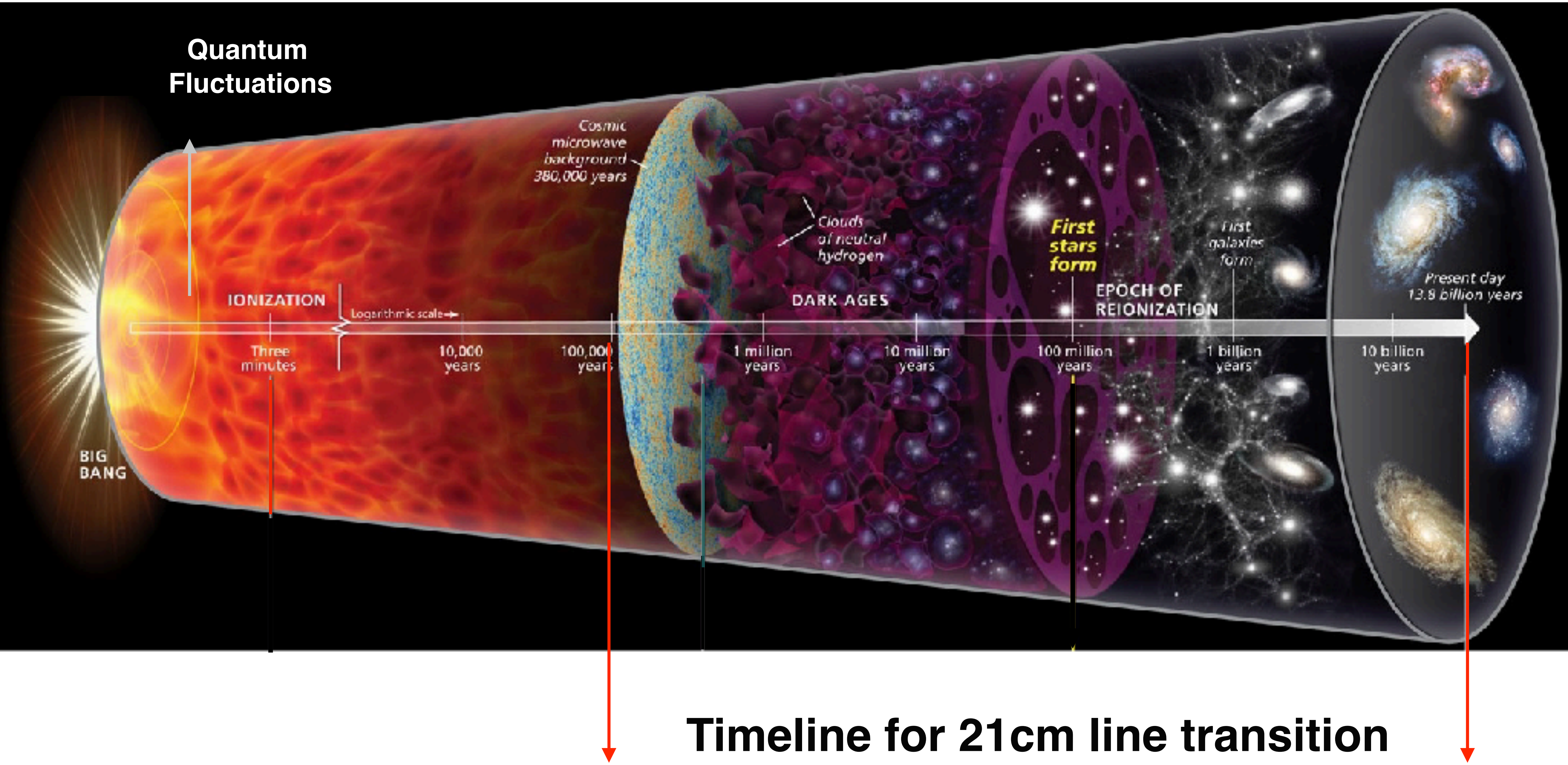
Lecture 3

Vii) Impact of the EoR on the CMB

Viii) Other probes of the EoR

ViV) 21cm line in the post EoR

Highlights Lectures 1,2



Timeline for 21cm line transition

Credit - http://discovermagazine.com/~/media/Images/Issues/2014/April/21-centimeter-cosmology.jpg

Highlights Lectures 1/2

21 cm line Brightness Temperature

$$\delta T_b \approx 28\text{mK} (1+\delta) x_{HI} \frac{T_s - T_{CMB}}{T_s} \frac{\Omega_b h^2}{0.02} \left[\frac{0.24}{\Omega_m} \left(\frac{1+z}{10} \right) \right]^{\frac{1}{2}}$$

Astrophysics

Cosmology

Lecture 3

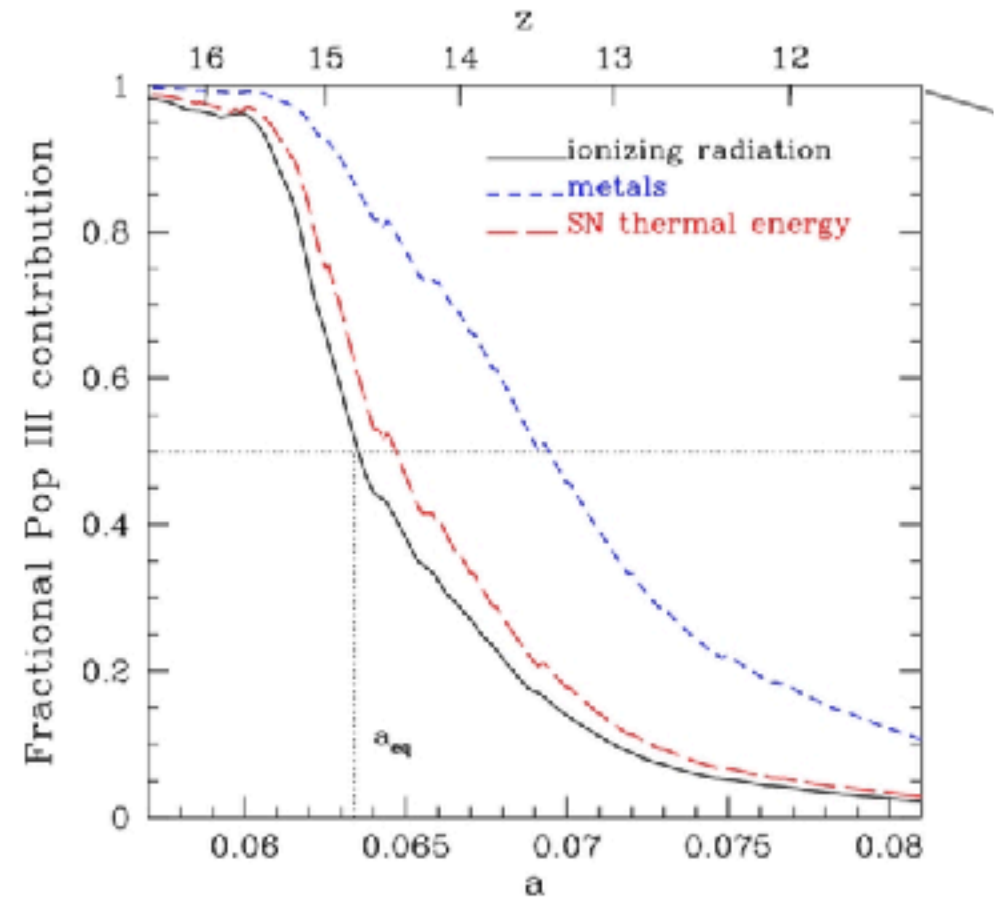
Vii) Impact of the EoR on the CMB

Viii) Other probes of the EoR

ViV) 21cm line in the post EoR

POP III stars

- Uncertain IMF: 0.1-1000 Msun
- Massive stars have short life's
- Galaxies stable at $T_{virial} = 10^4$ K
- First metals produced in the cores of these stars
- Production of Lyman-Werner photons (11.2 to13.6 eV)
- Ionisation of its surroundings



The duration of Pop III era is less than 100-200 Myr in a given galaxy

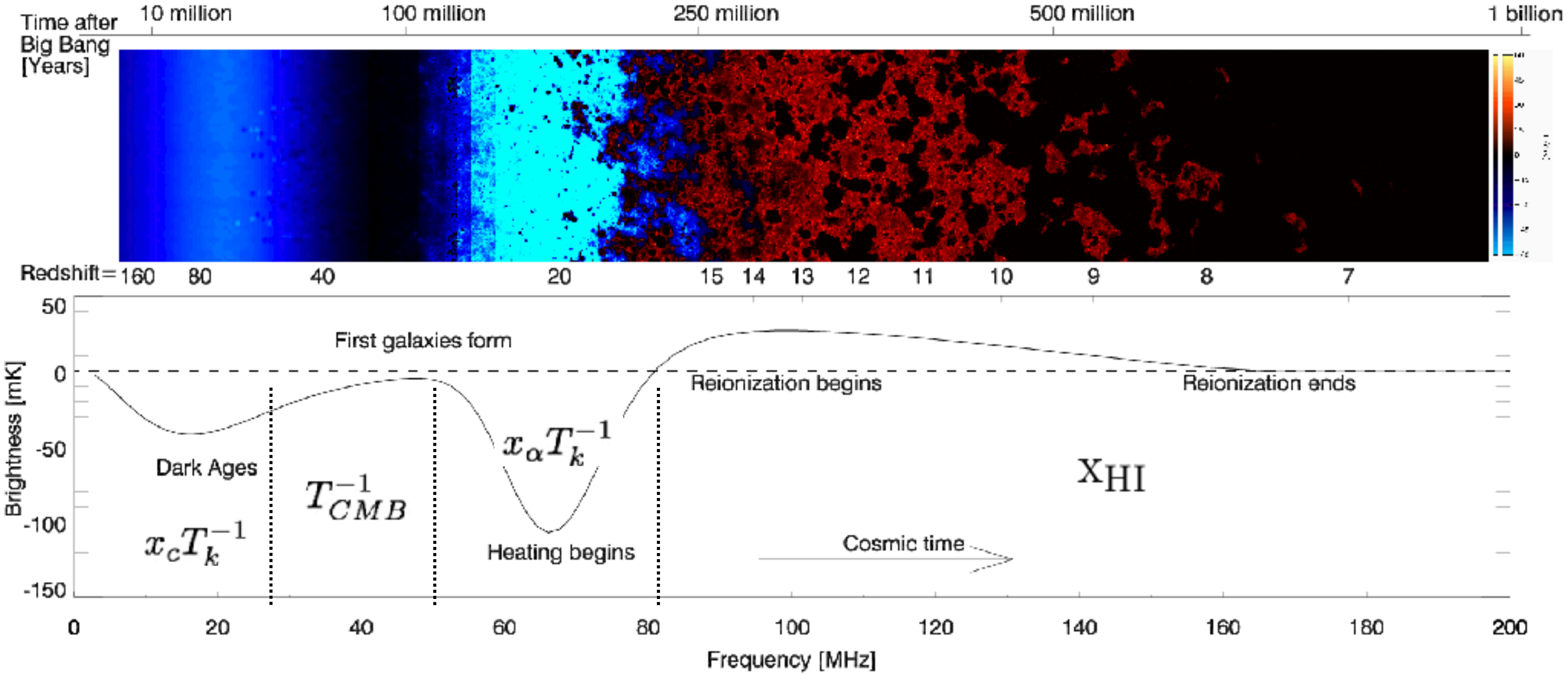
SN explosion

X-rays heat, ionise and excite the IGM

Metals produced in the start ejected into the IGM

POP II stars (Formed with metals)

The evolution of the Tb



$$\delta T_b(z) = C(z)(1+\delta)\left(\frac{1}{1+H(z)dv_r/dr}\right)x_{HI}\left(\frac{T_S - T_{CMB}}{T_S}\right)$$

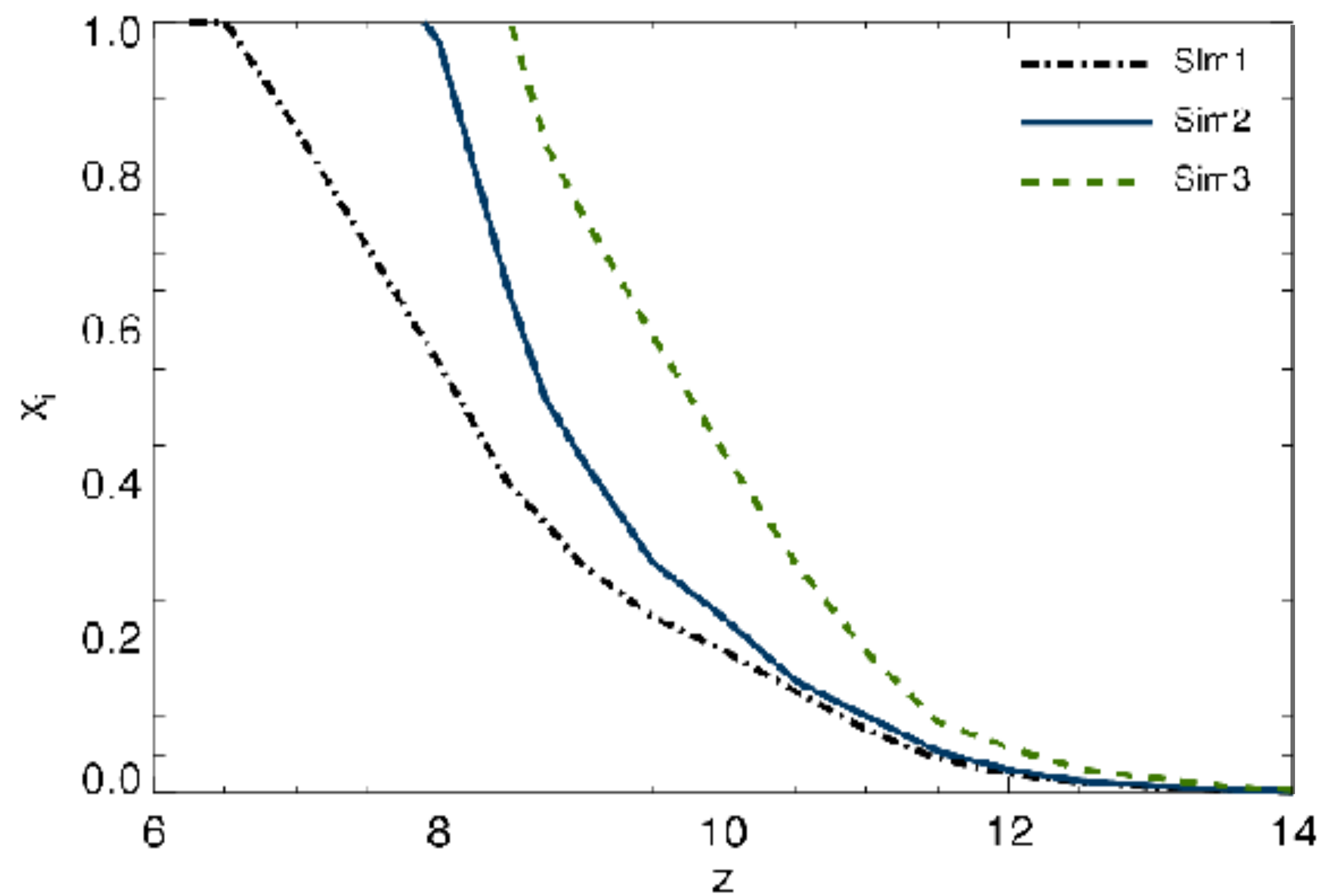
The Epoch of Reionization

Sources:

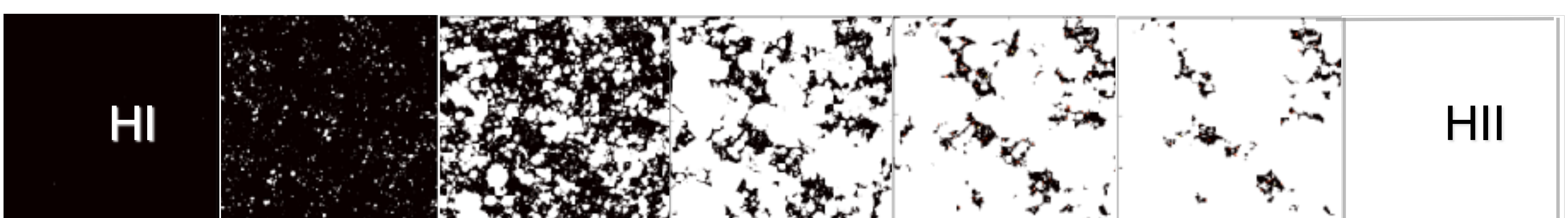
- POP II
- POP III stars
- Quasars

Probes:

- CMB
- Ly-alpha Forest
- LAE
- Lyman break Gal
- IM of the 21cm line
- IM of Galaxy lines
- etc.



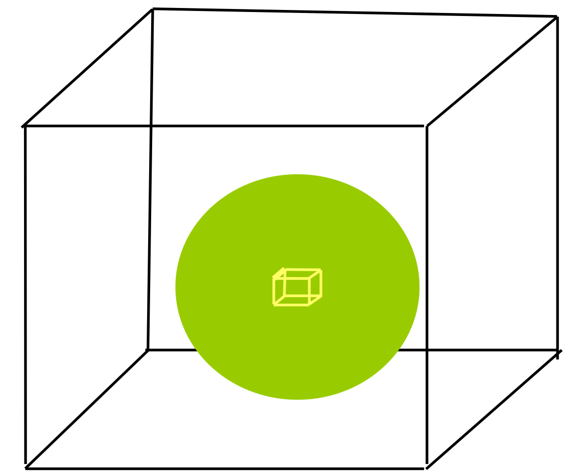
Timeline: z~14-6



Ionizing emissivity vs recombinations

Ionized when:

Ionizing rate	≥	Recombination rate



$$\dot{n}_{\rm ion} = A_{\rm He} \times SFRD \times Q_{\rm ion} \times f_{\rm esc}$$

Ionisation rate

$$\dot{n}_{\rm rec} = \alpha_{\rm rec}(T_{\rm K}) \times C \times n_{\rm e} \times n_{\rm HII}$$

Recombination rate

Line Intensity Mapping

- **Integrated line intensity**
- High volumes
- low resolution
- Fast

- **Constraints on:**
  - Cosmology
  - Global astrophysical quantities

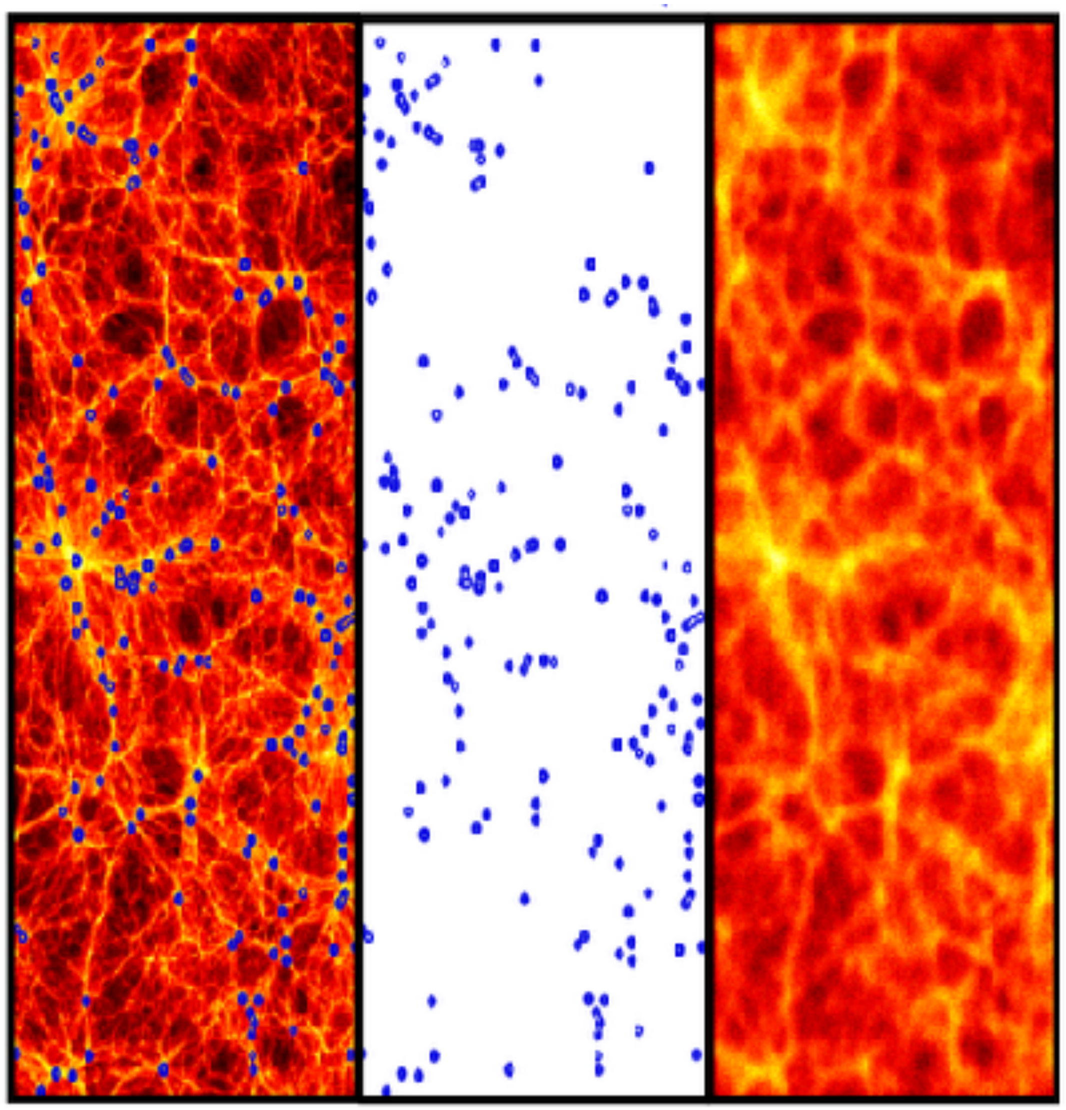
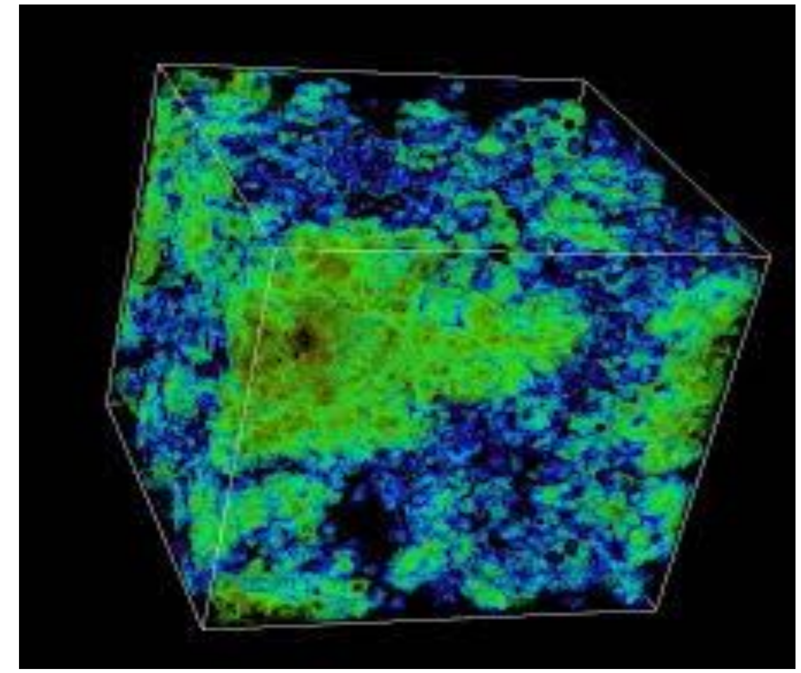


Image from
Dore & Bock 2014

The Line-IM Technique

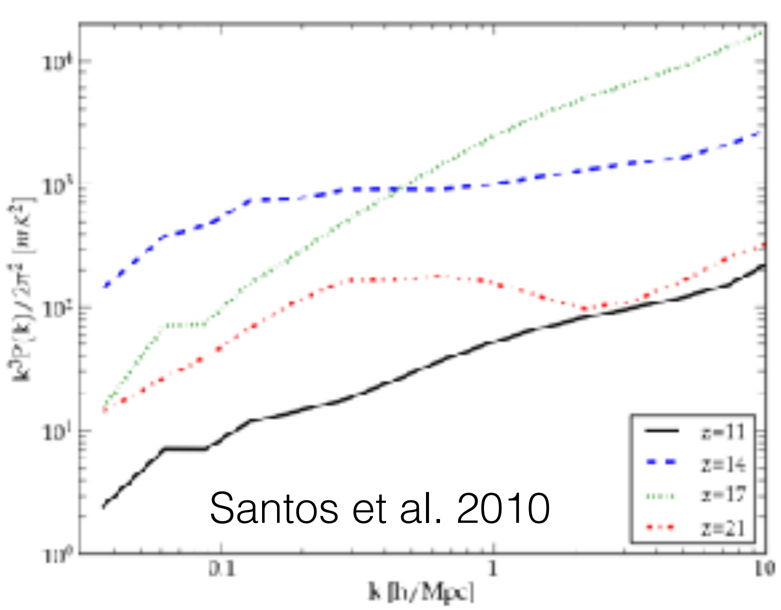
- High S/N ➜ Tomography
- Low S/N ➜ Statistical detection
  (no need to be well above noise)



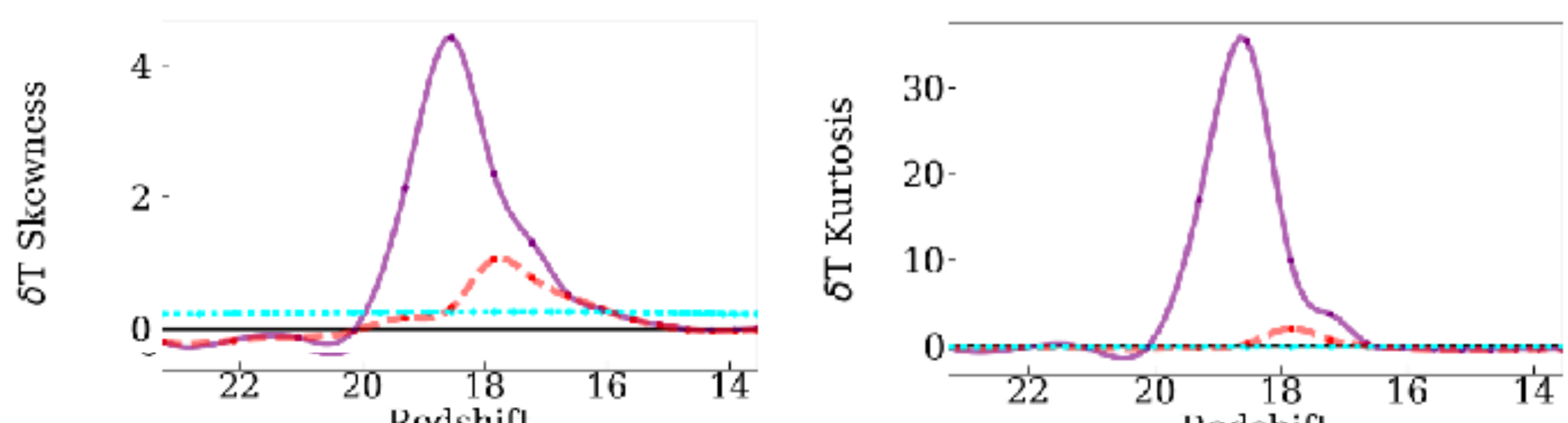
CEA-Irfu

Statistical analysis

- Power Spectra (2 point correl. function)
- Redshift space effect
- Bispectrum, Skewness, Kurtosis (The 21 cm signal is not Gaussian)



Santos et al. 2010

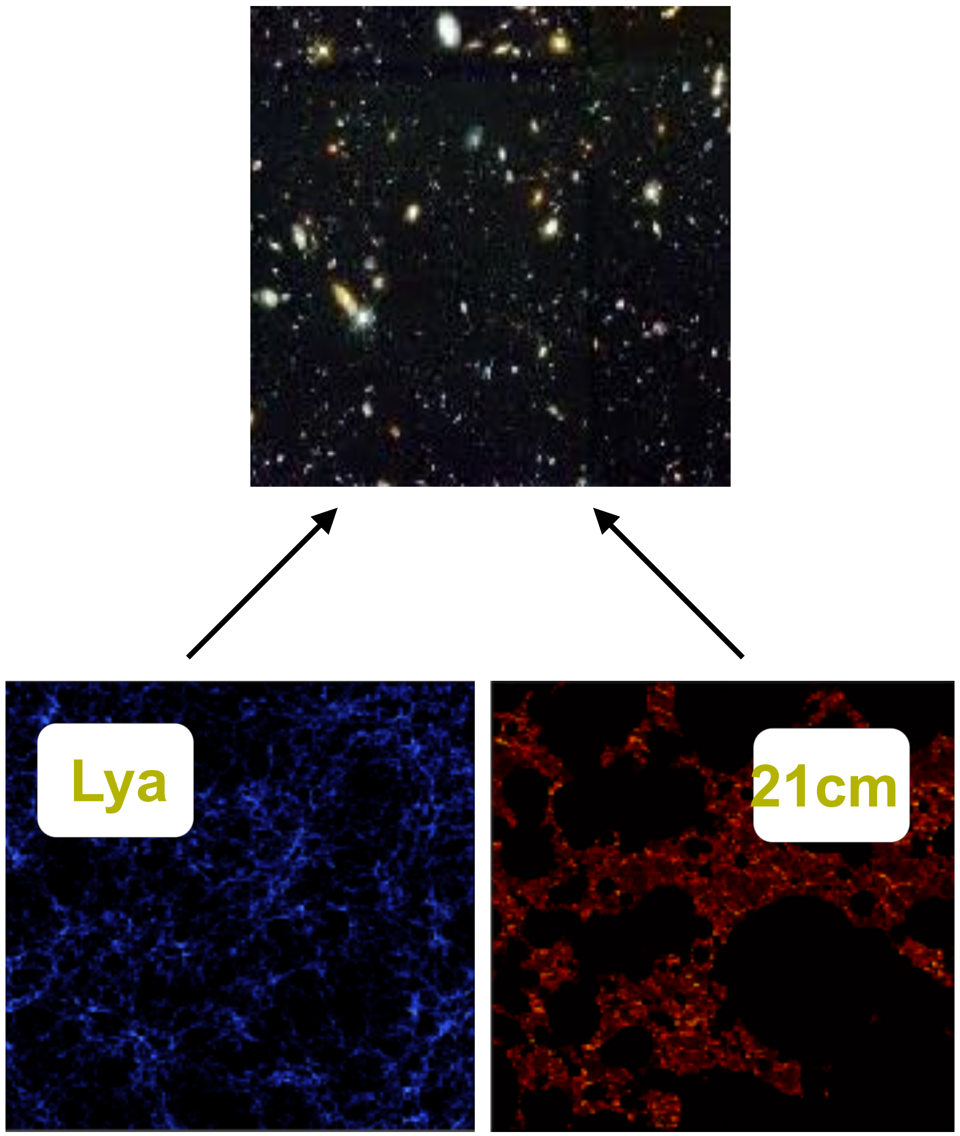


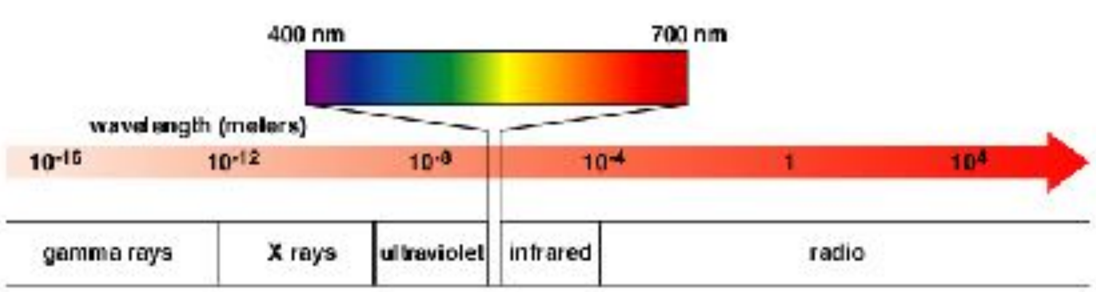
Ross et al. 2018

How to confirm a statistical detection?

Can we use cross correlations?

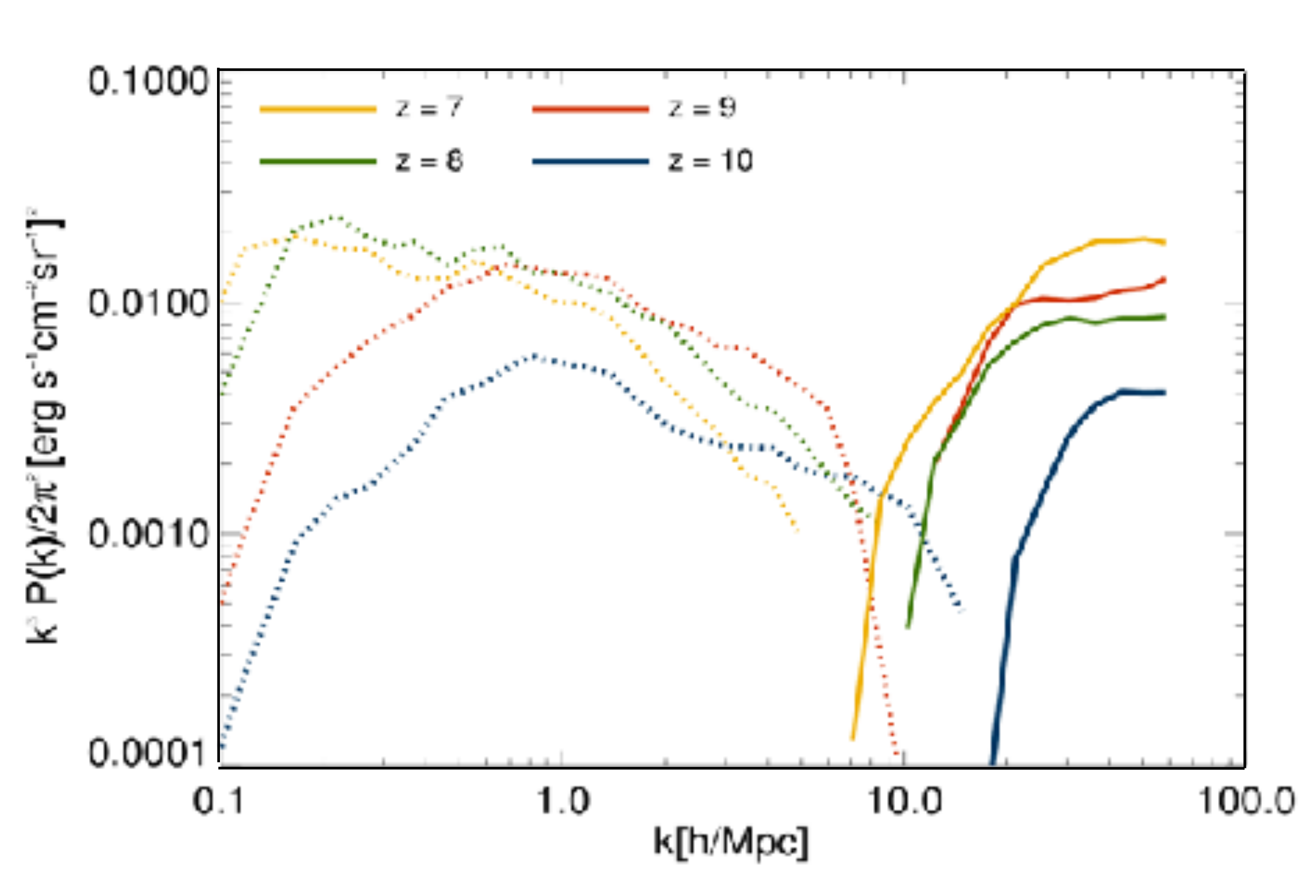
Cross correlations avoid foregrounds





Two independent observations of the same volume in space will be to first order free of foregrounds

≠ observations are made in ≠ freq. bands so they have ≠ foregrounds



The 21cm line and Lyα are anti correlated on low scales

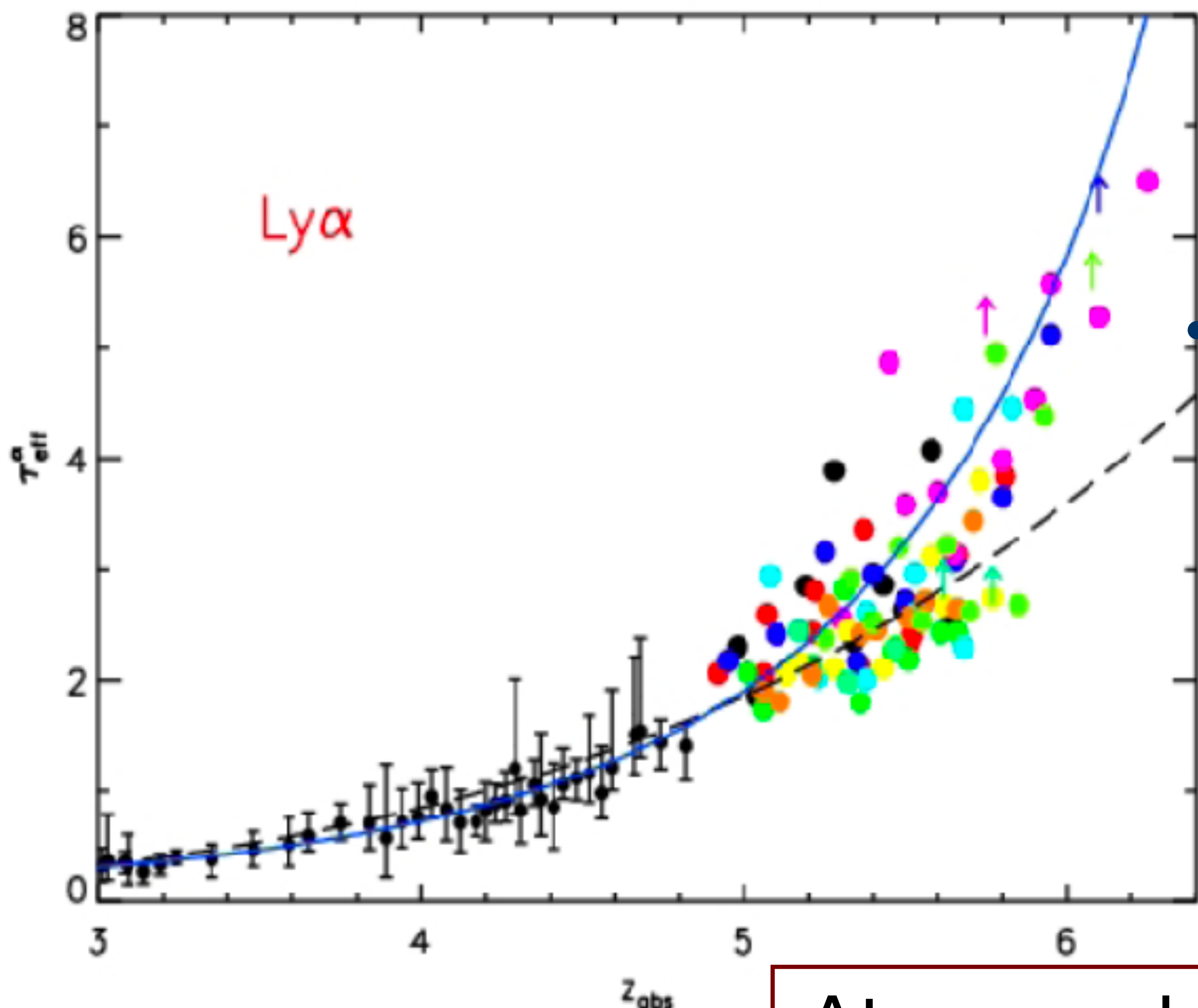
Lecture 3

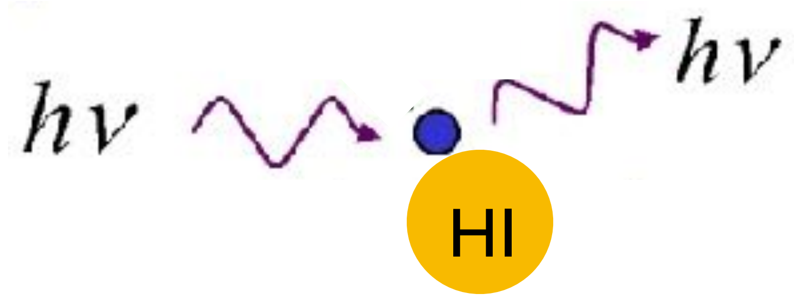
Vii) Probes of the EoR: Lyα Forest and the CMB

Viii) Other probes of the EoR

ViV) 21cm line in the post EoR

Lyman alpha Forest and the end of the reionization process



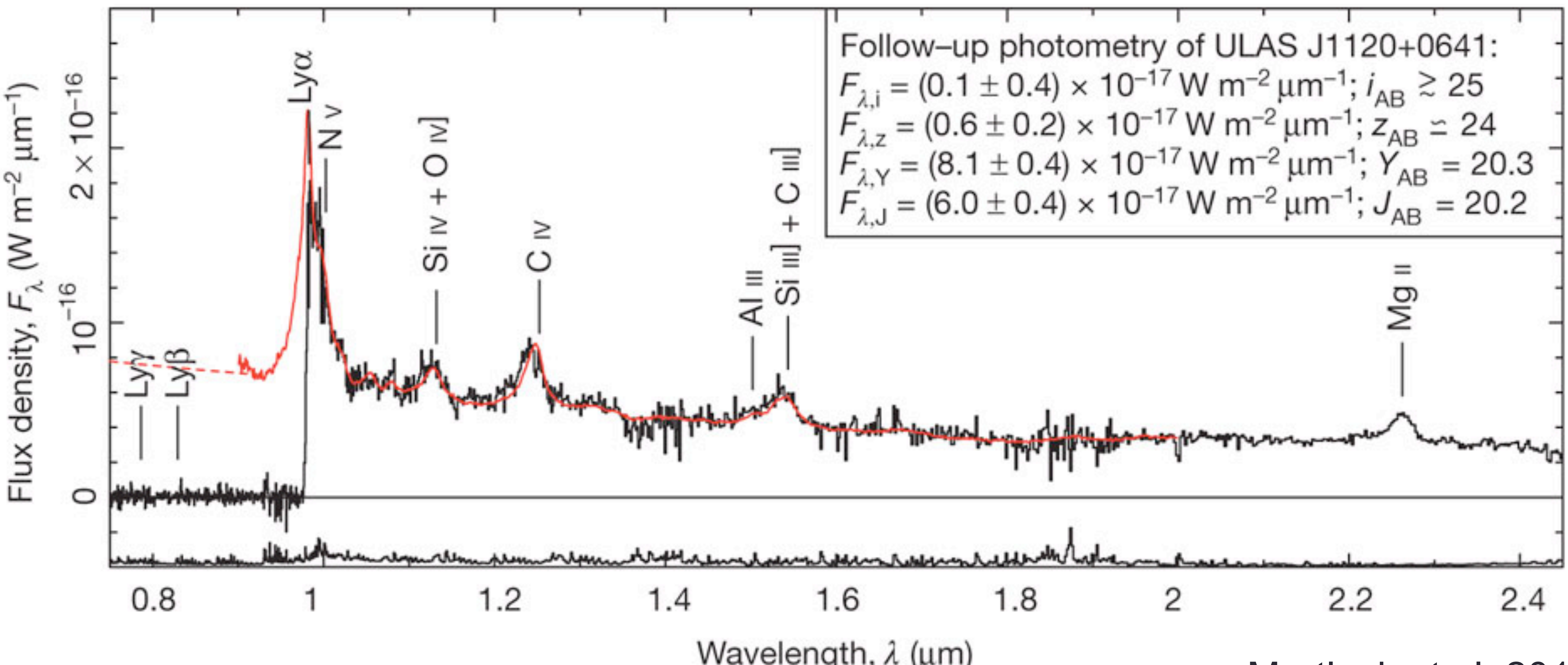


- The Lyman-alpha forest: At z<6 he Universe is completely ionized

$$\tau_\alpha(\nu_0) = \int_{x_A}^{x_B} n_{HI}\sigma_\alpha dx/(1+z)$$

At mean density $x_{HI} = n_{HI}/n_H > 10^{-5}$ is enough to scatter Lyα

Neutral fraction probed by a high redshift Quasar (z = 7.085)



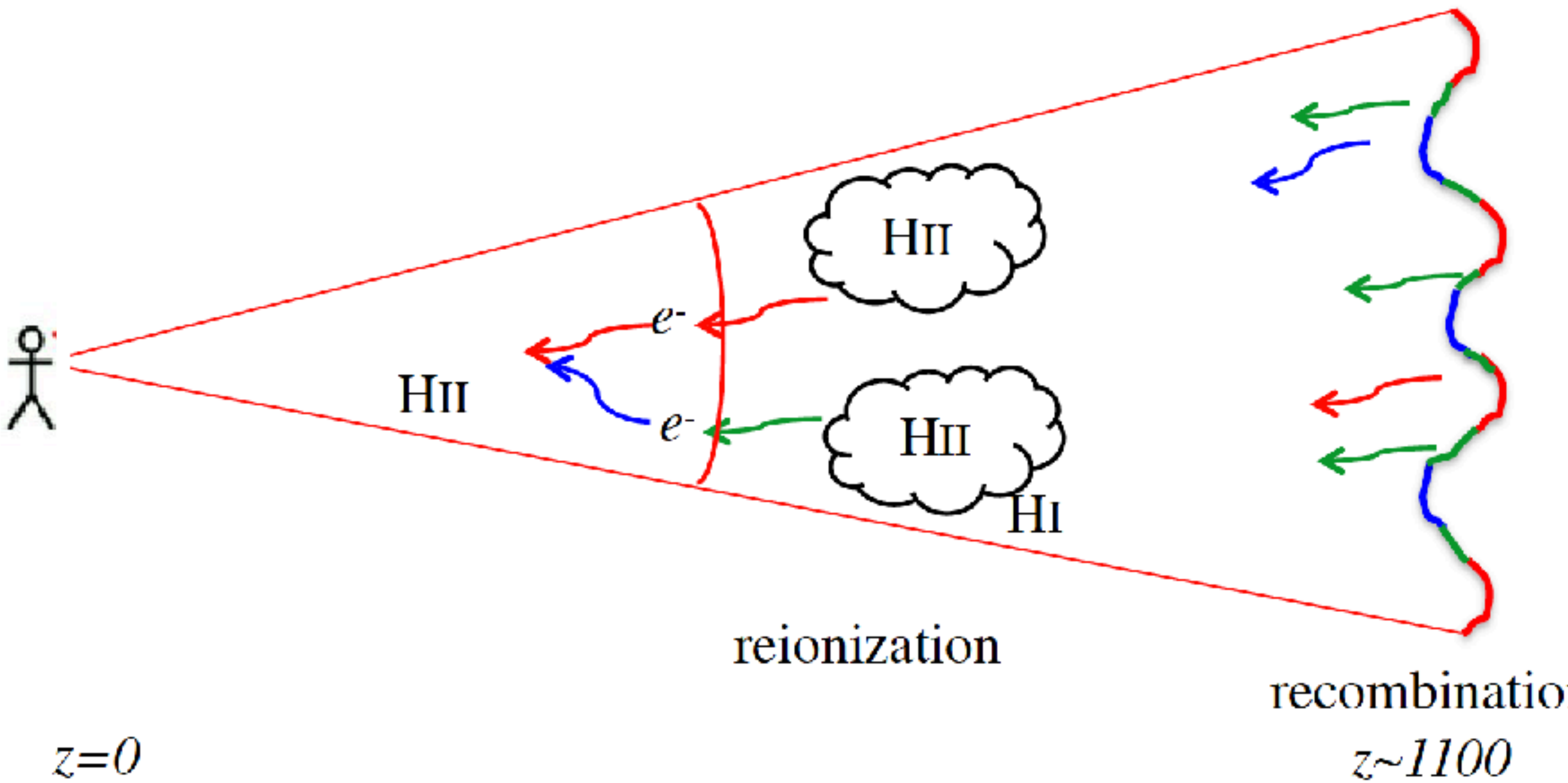
Mortlock et al. 2011

Near zone profile suggests neutral fraction >0.1
(However, depending on assumptions about the medium the neutral fraction can be as low as 10^{-4})

Probes of the EoR the CMB

Impact of reionization on CMB observables

CMB photons Thomson scatter off free electrons in HII regions

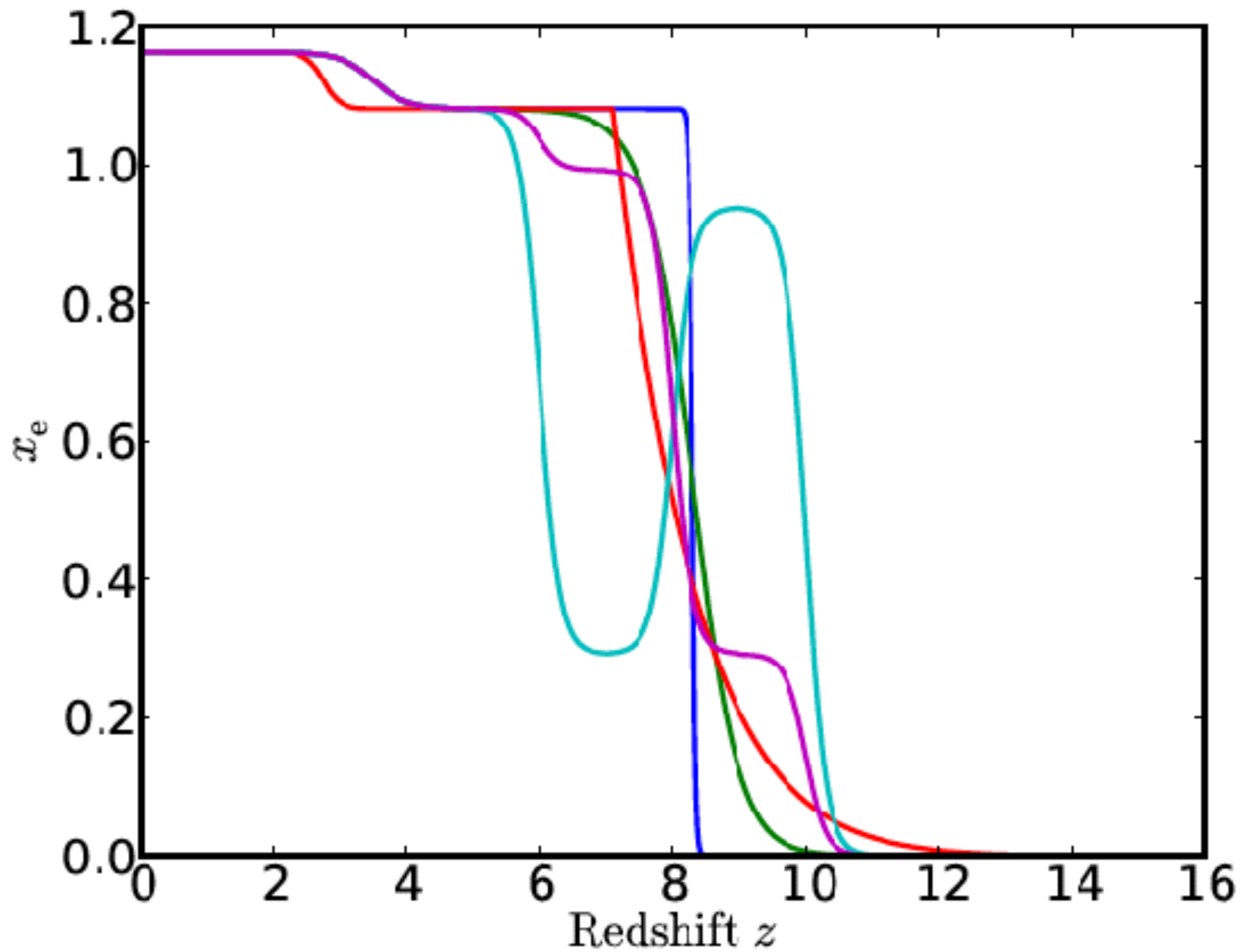


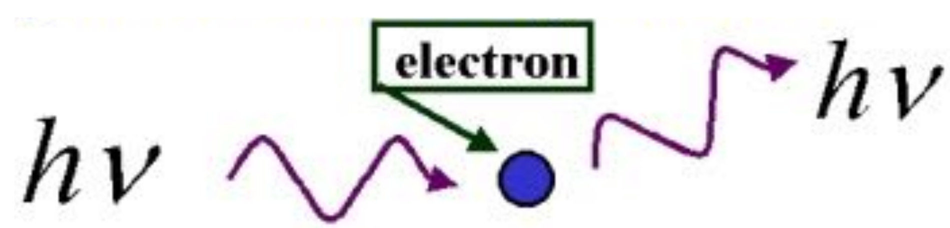
CMB optical depth constrain on the fraction of free electrons

$$\tau_e(z_r) = \int_0^{z_r} n_e \sigma_T (1+z)^{-1} \, [c/H(z)] \, dz$$

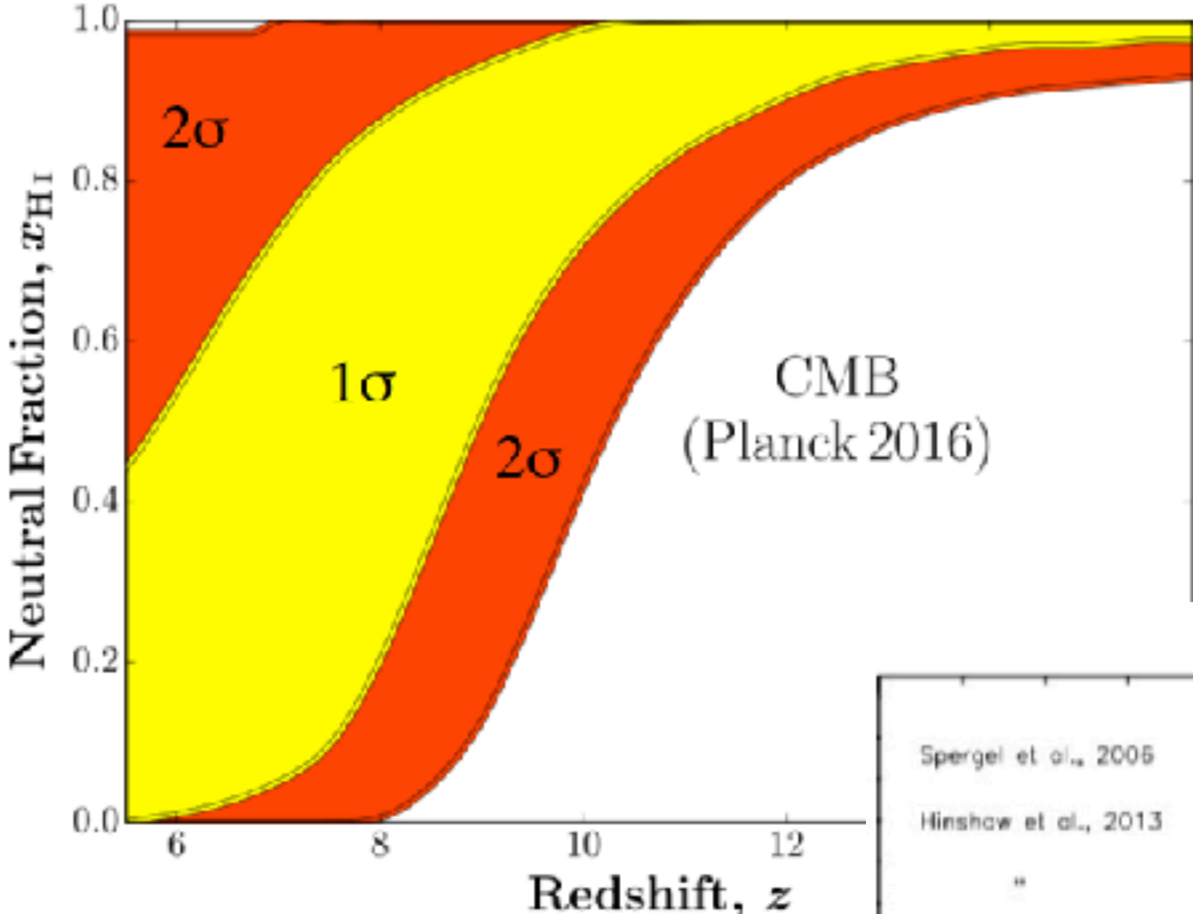
$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2$$

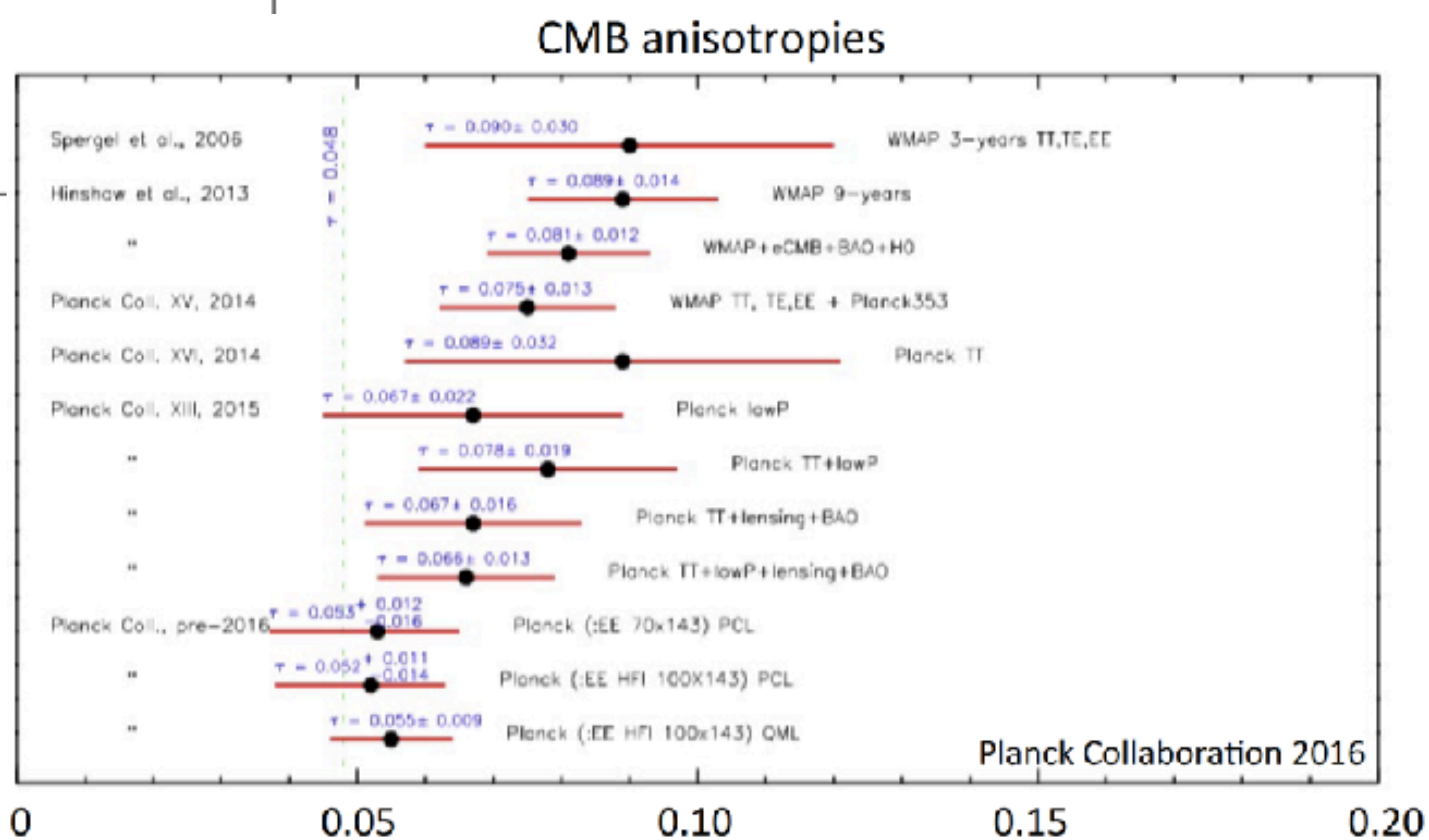
$$= 6.65 \times 10^{-25} \ \ \mathrm{cm}^{-2}$$





The Timeline: Optical depth



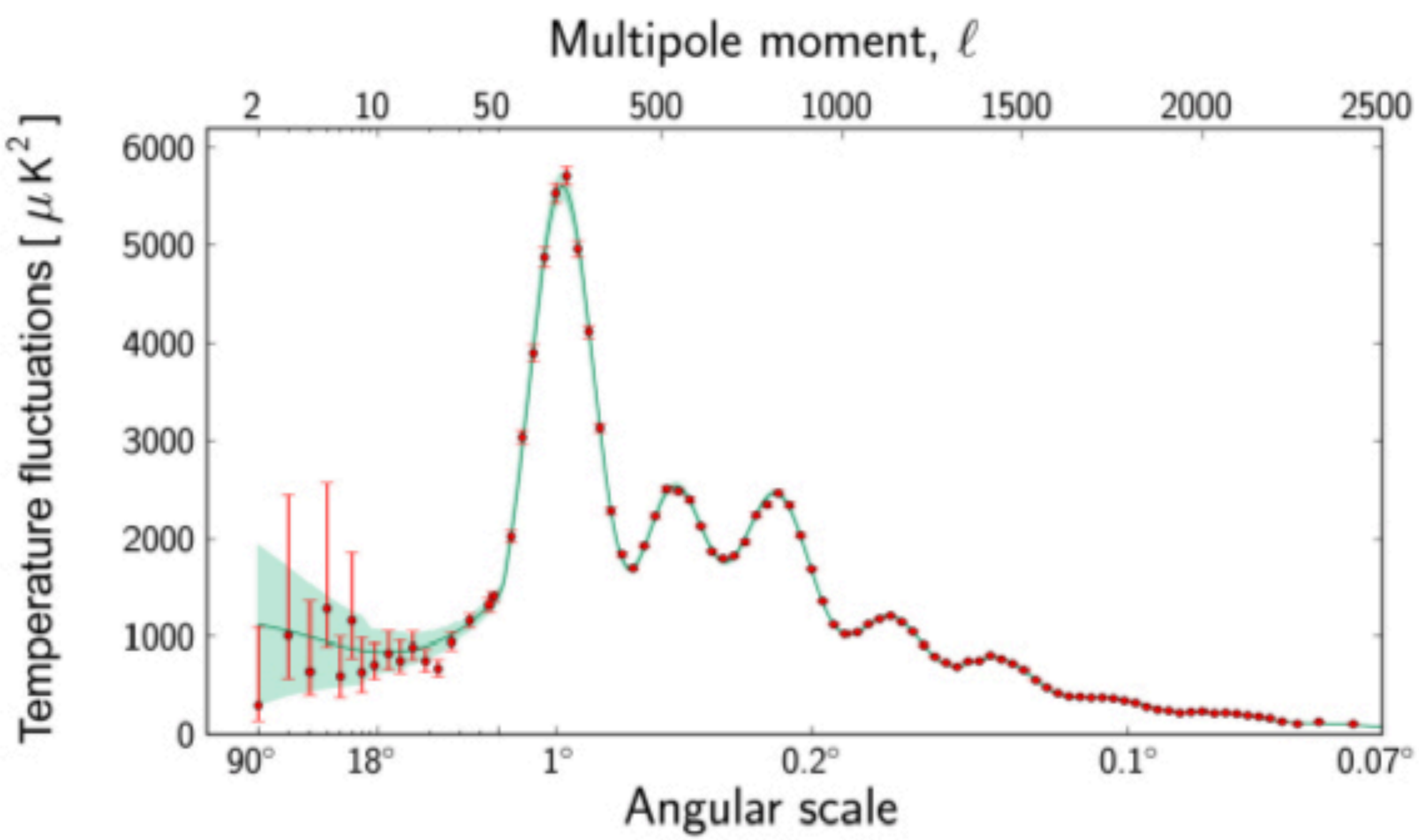


How is the EOR signal encoded in the CMB spectra?

Two signatures of the EoR on the CMB spectra

1) Smoothing of temperature anisotropies

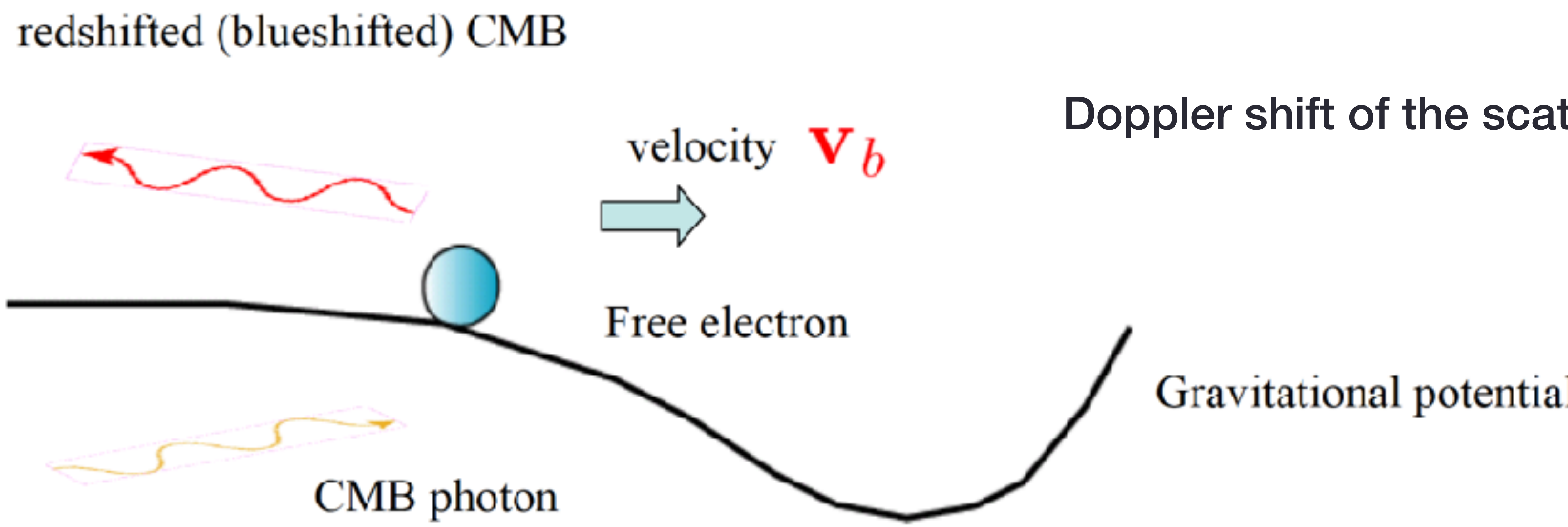
2) Increase in the polarisation of the CMB



Credit: ESA and Planck collaboration

1) Temperature anisotropies generated during reionization

Doppler shift of the scatterers



1) Temperature anisotropies generated during reionization

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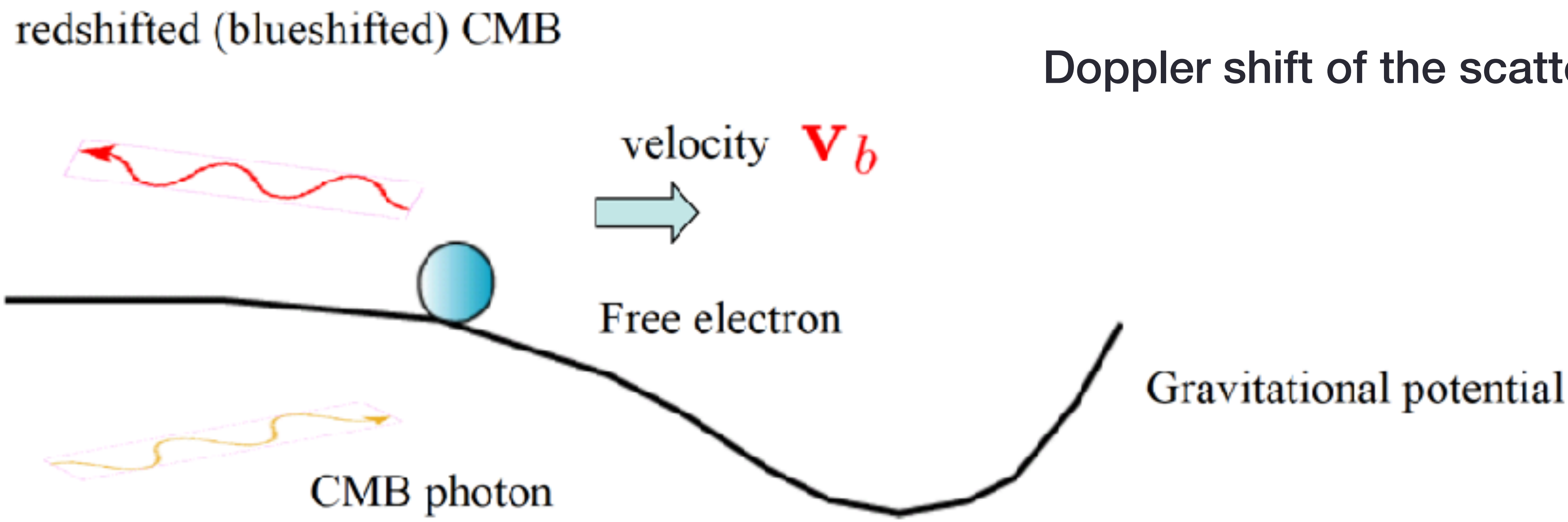


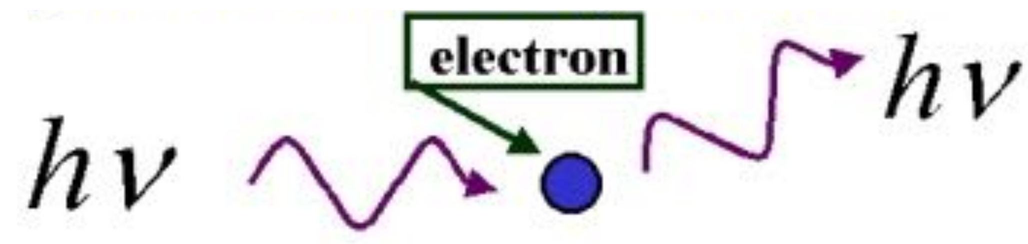
$$T_D(\hat{\mathbf{n}}) = -T_{\rm cmb} \int_0^{\eta_0} d\eta\, g(\eta)\, \hat{\mathbf{n}} \cdot \mathbf{v}_b(\hat{\mathbf{n}}, \eta)$$

$$g(\eta) = \dot{\tau} e^{-\tau}, \;\; \tau = x_e n_b \sigma_T$$

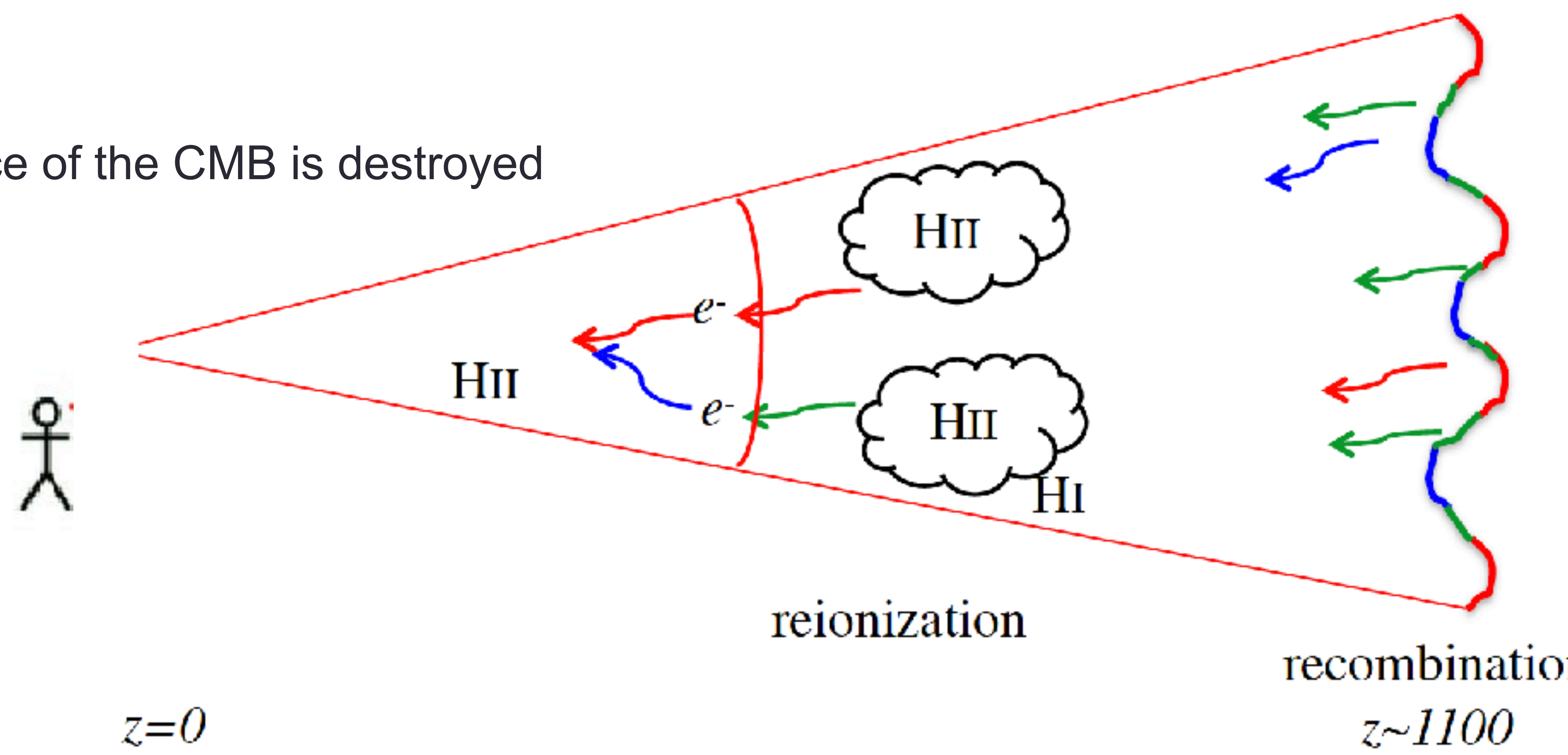
Visibility: Optical depth times velocity of the scatter

The CMB and Reionization: Temperature

Imprint on CMB anisotropies governed by the visibility – or probability that a photon scatters out of the line of sight:



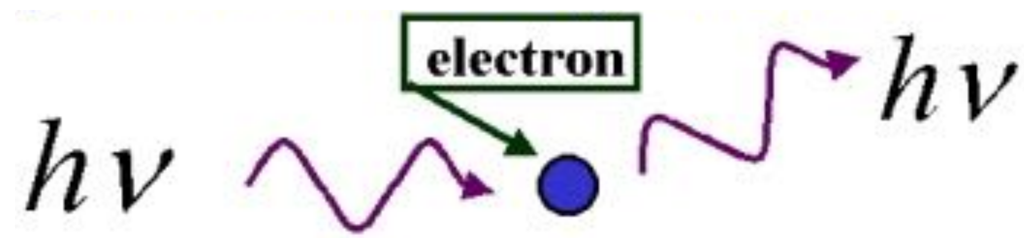
The coherence of the CMB is destroyed

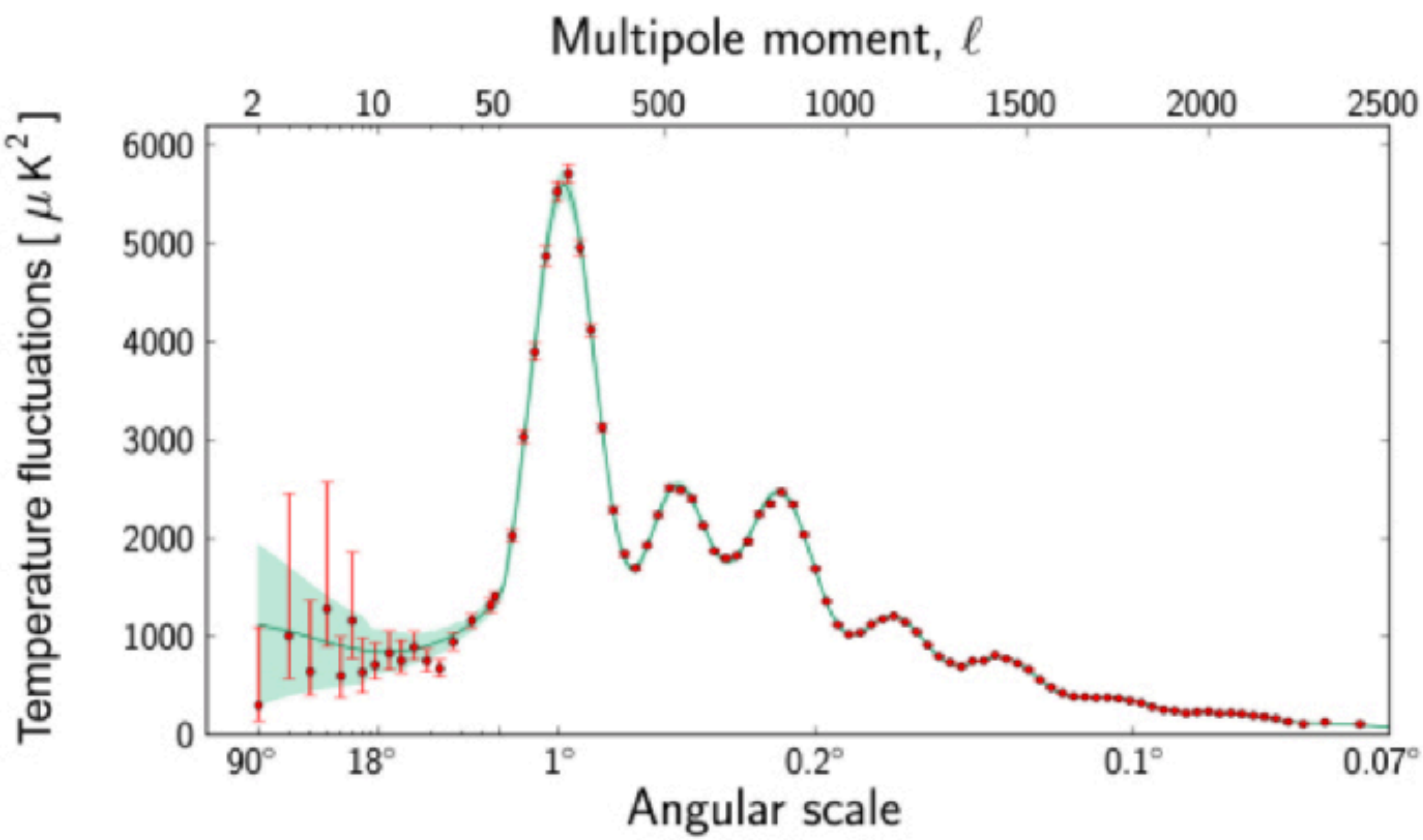


The CMB and Reionization: Temperature

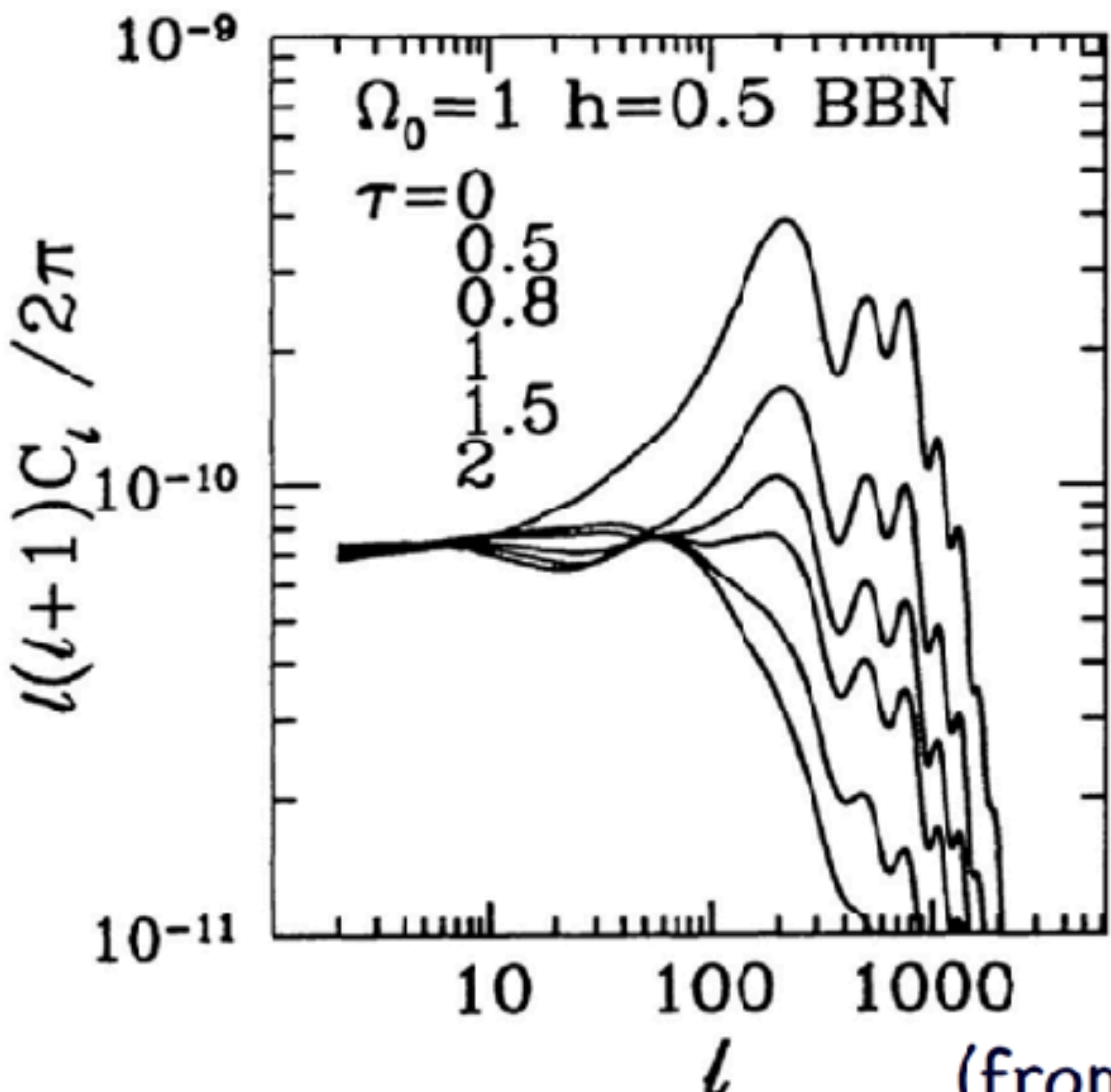
The large power on certain scales means that there is coherence of the CMB on these scales

Thomson scattering lowers/destroys this coherence by changing the direction of the CMB photons

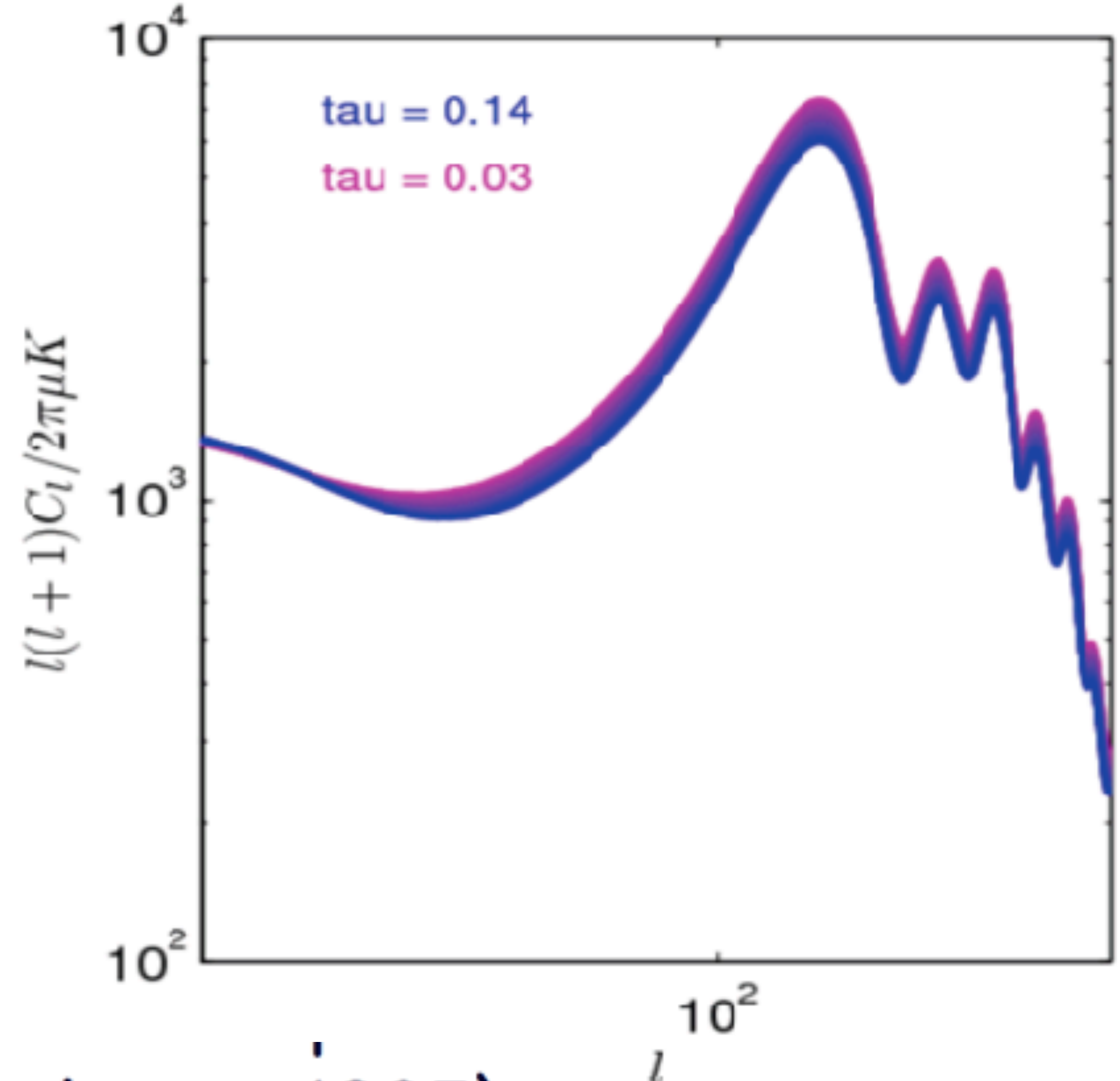




The influence of the EoR on the CMB temperature angular power spectrum



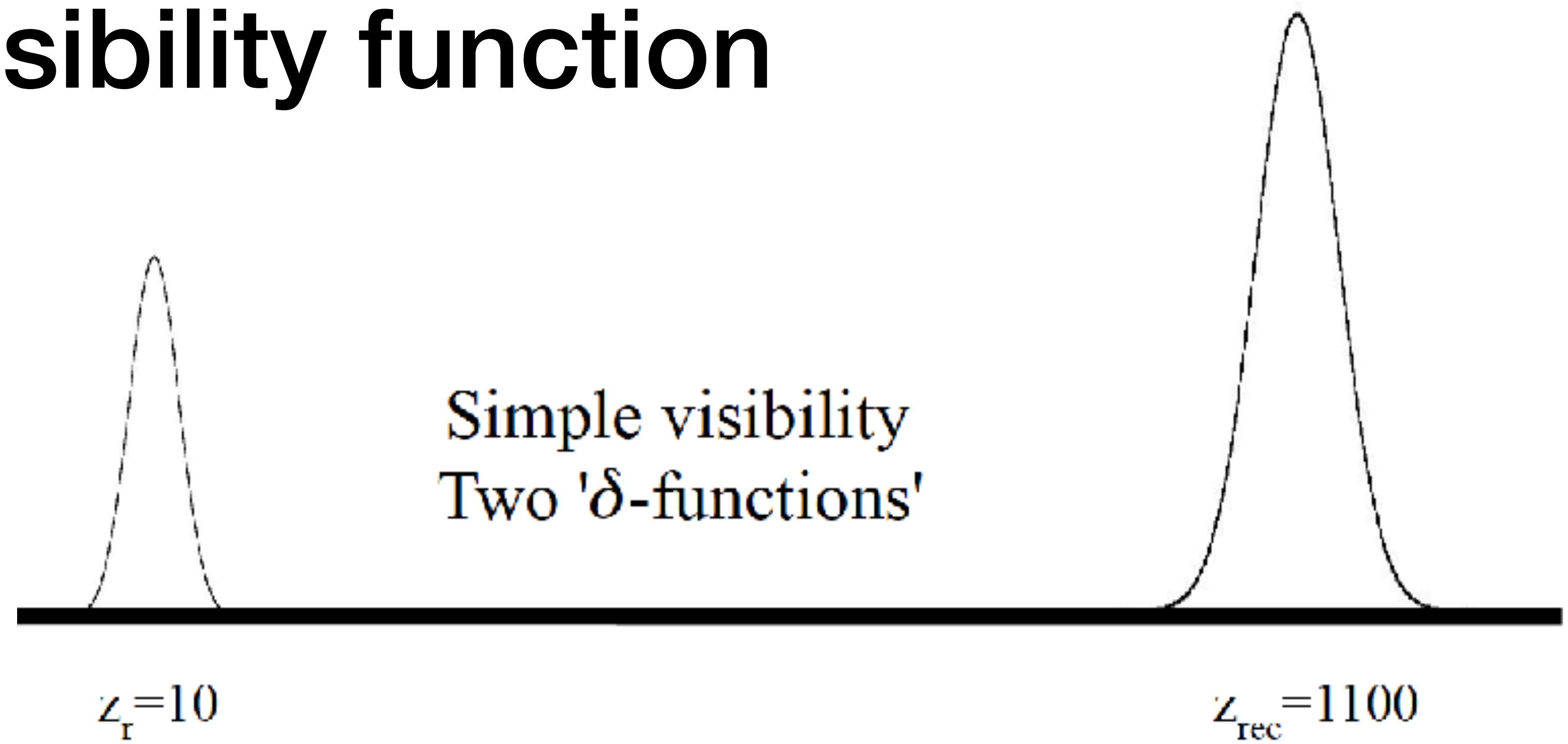
(from Sugiyama 1995)



Large scales not affected since they are above the horizon at recombination

Small scales are the most affected

The visibility function



Assuming that the visibility is given by two delta Functions, the CMB is given by the following expression:

$$\Delta_l = e^{-\tau(z_r)} F_l(z_{rec}) + \left[1 - e^{-\tau(z_r)}\right] F_l(z_r) + ISW + \ldots$$

CMB Photons on our line of sight from z_{rec}

Photons scattered towards the line of sight at z_r

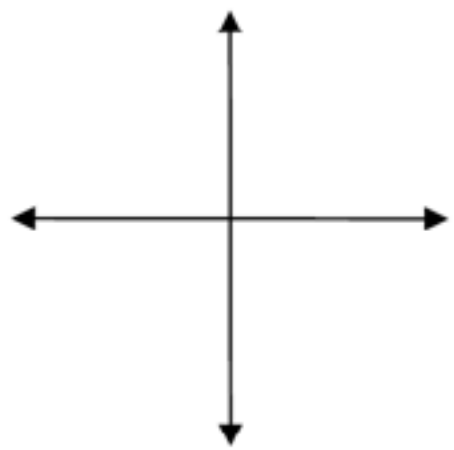
CMB photons gravitationally redshifted (importante for large scales)

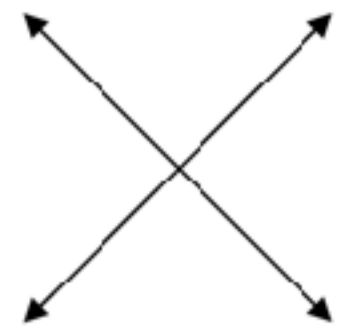
For the astrophysical reionization scenarios (low optical depth) second term negligible

2) CMB and Reionization: Polarization

Stokes parameters: The polarisation state of the radiation

Q





U

Polarization: Stokes parameters

Q → -Q, U → -U under 90 degree rotation
Q → U, U → -Q under 45 degree rotation

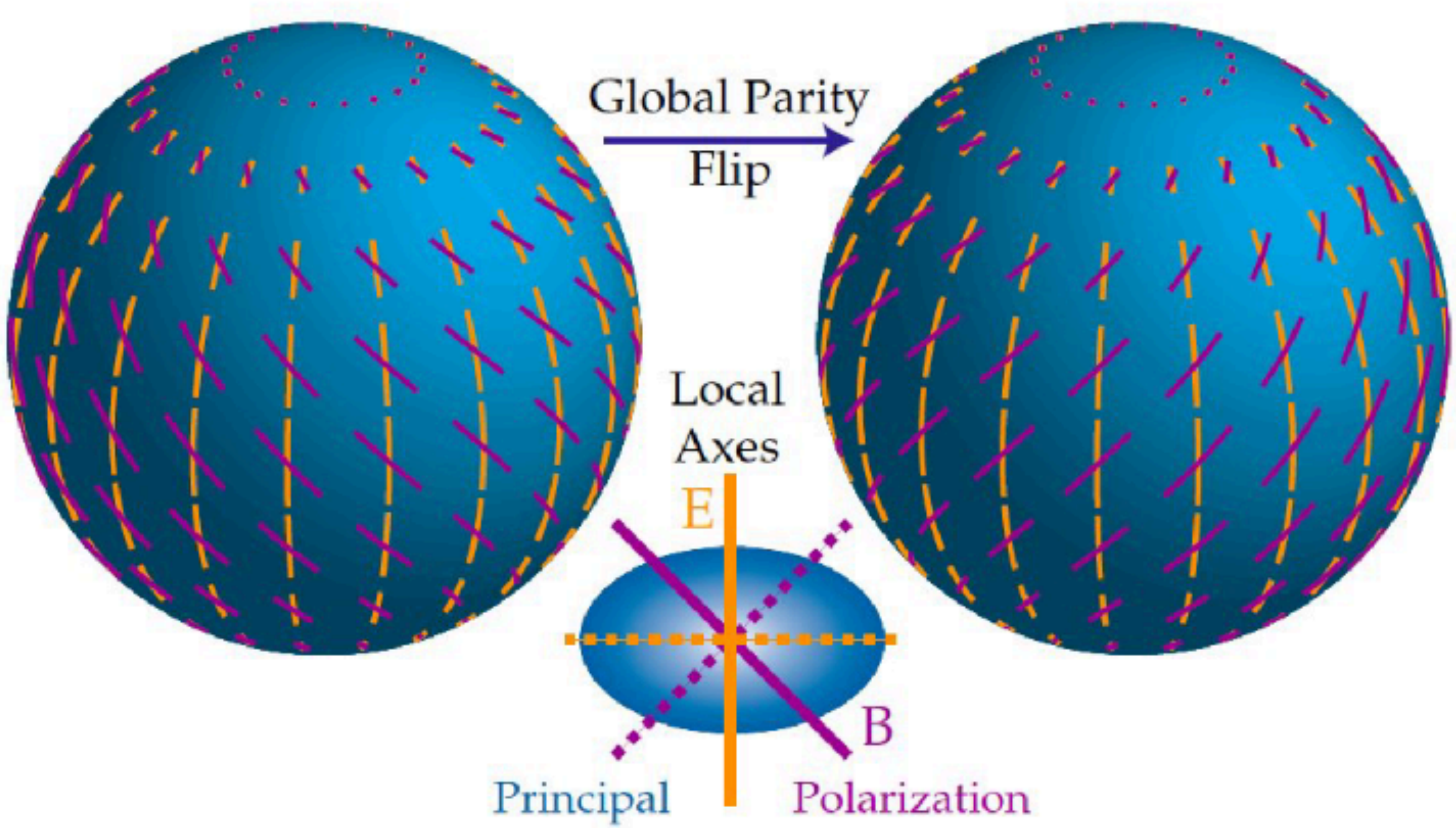
symmetries

$$P = \sqrt{Q^2 + U^2} \quad \text{and} \quad \alpha = \frac{1}{2}\arctan(U/Q).$$

amplitude — angle

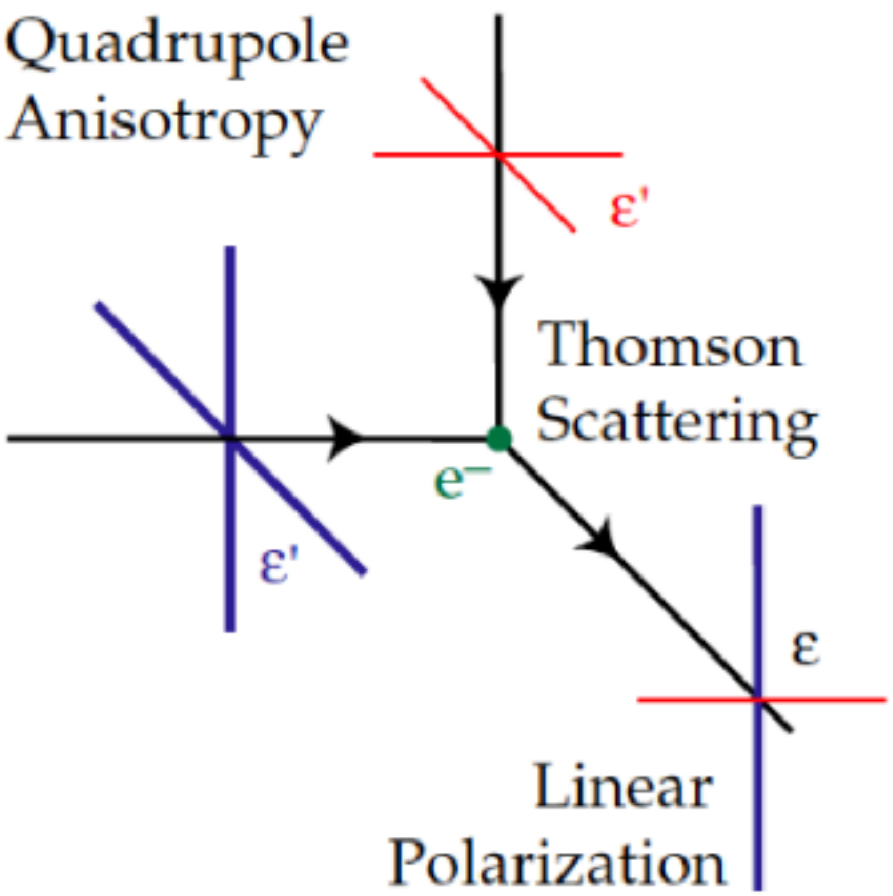
Stokes I - Total intensity
Stokes V - Circular polarisation (Not important here)
Stokes Q,U - Linear polarisation

E and B polarization modes: transformation of Q and U used in CMB studies



E-mode has $(-1)^l$ parity whereas B-mode $(-1)^{l+1}$

Thomson scattering

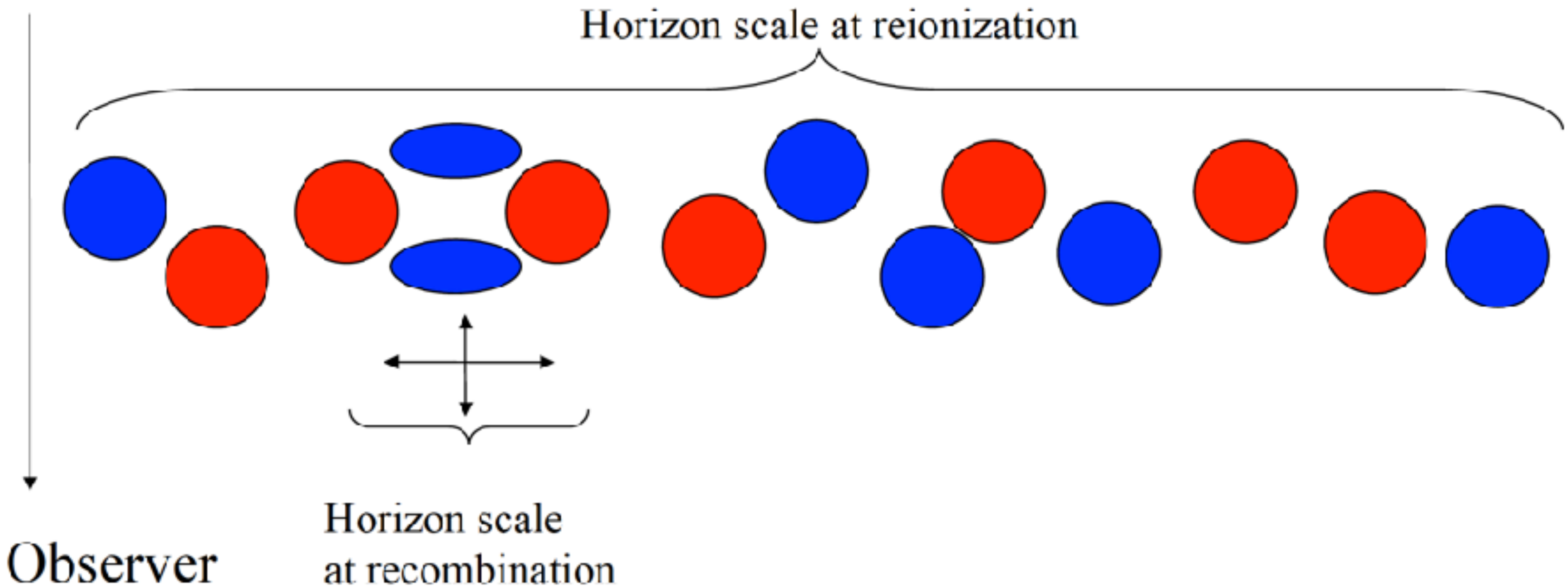


Q and U are generated by Thomson scattering of unpolarized light. Notice no V (circular polarization) is generated.

CMB polarisation arises from Thomson scattering of high energy photons at the LSS and it is amplified on large scales during the EoR by free electrons

$$\frac{d\sigma_T}{d\Omega} = \frac{e^4}{m_e^2 c^4} |\vec{\epsilon} \cdot \vec{\epsilon}'|^2$$

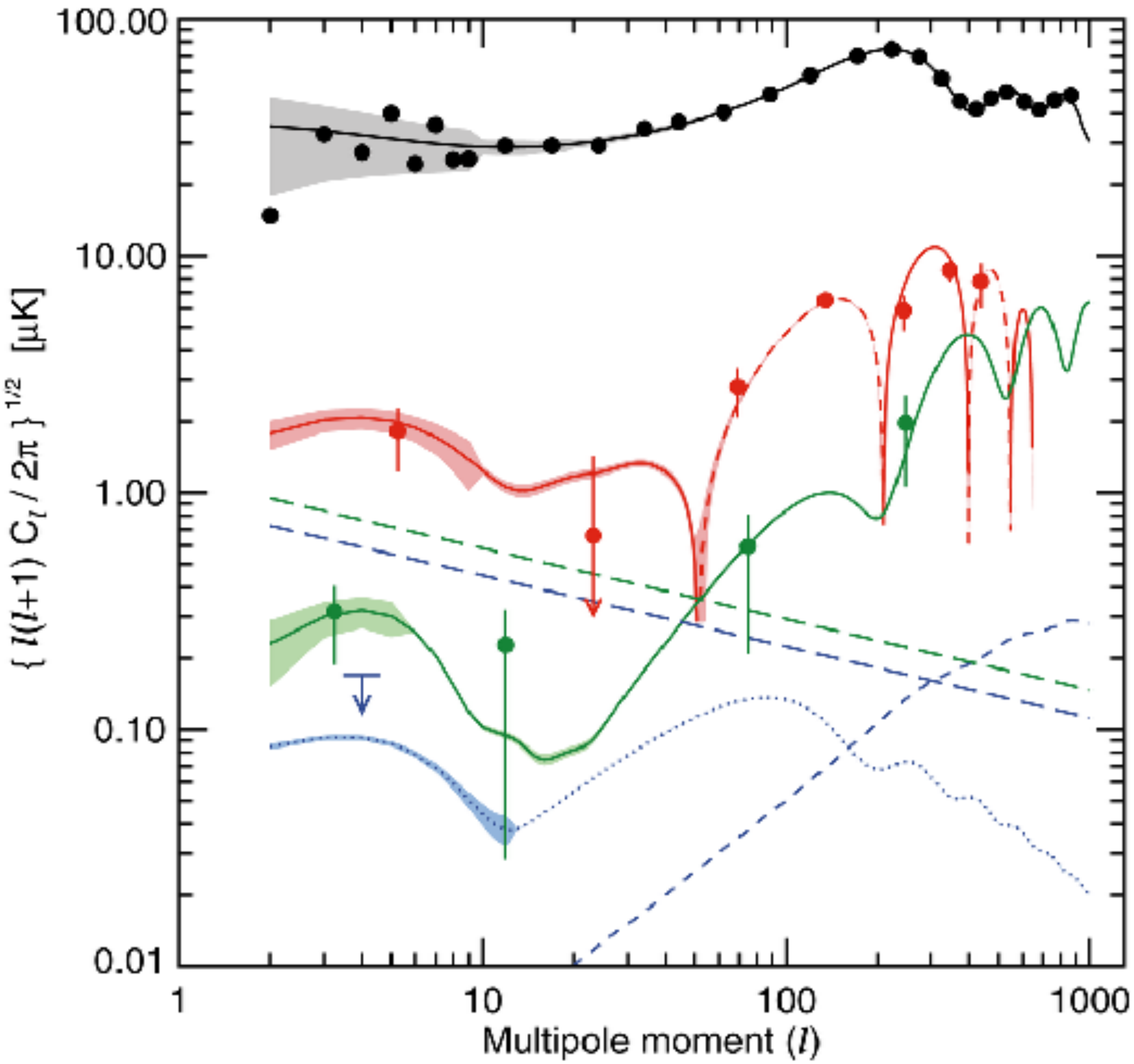
Polarization and Horizon scales during Recombination and Reionization



1 deg l=200 (higher l's are not causally connected)

Given the geometry of linear polarization the amplitude of the signal at any scale depends on the local quadrupole that scatters the photons. However, at scales larger than horizon scales (either at recombination or during reionization) there is no coherence and the signal decays.

The WMAP constraint

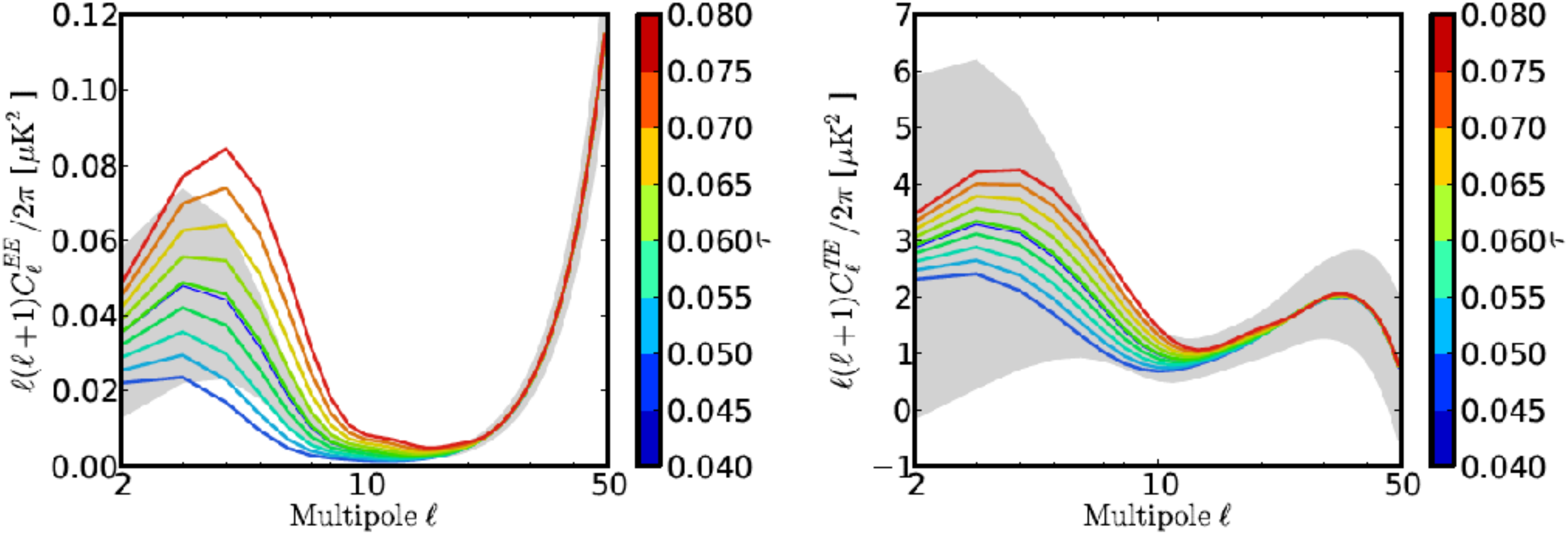


t~ 0.088

The WMAP polarization measurement tells us only about the optical depth not about exact ionization redshift. For that one needs a reionization history model.

For l<200 the signal should decay if it was originated at the LSS (last scattering surface)

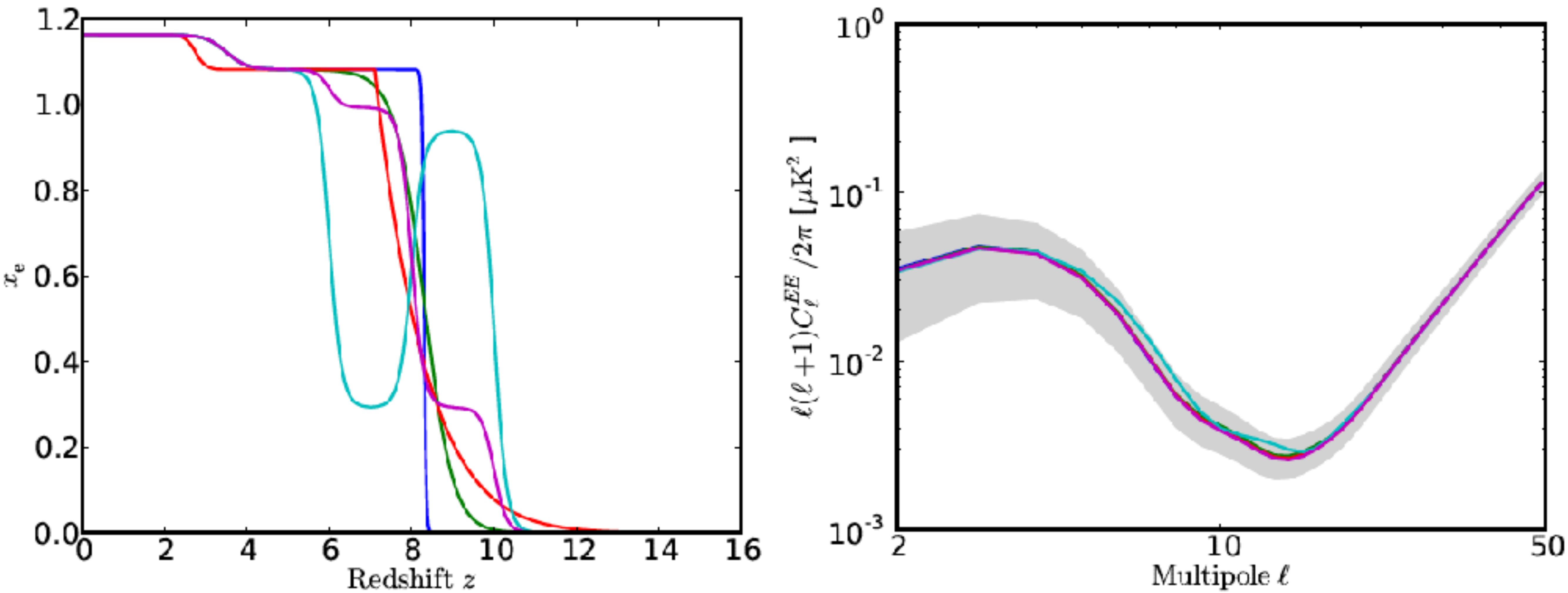
The influence of τ on EE and TE



Constraints from the amplitude and the ℓ of the peak of the fluctuation

Planck XLVII paper

It is and Integral constrain

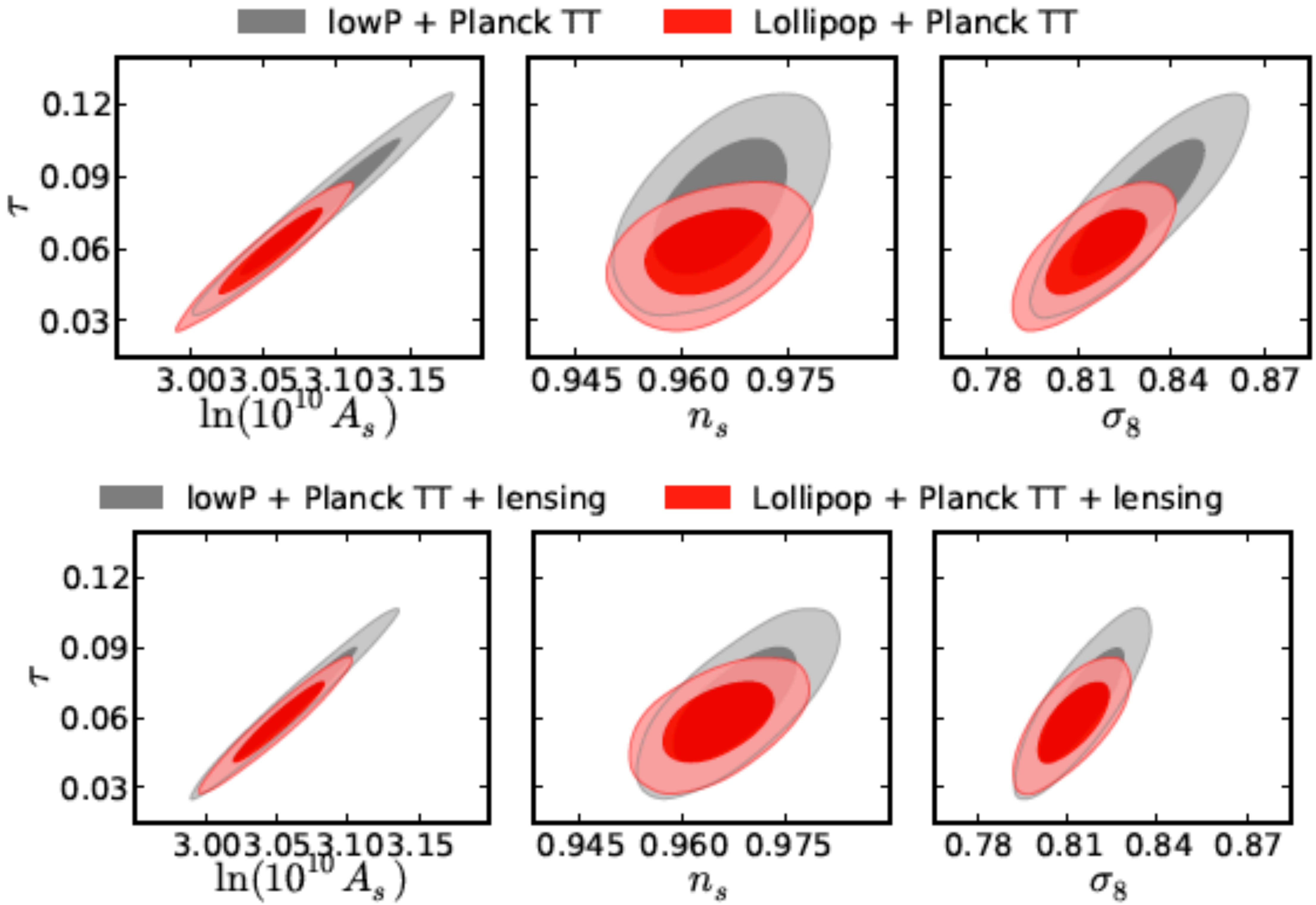


Very different reionization histories result in almost the same polarisation signal

Planck XLVII paper

The Planck constraint:

lollipop = likelihood based on polarisation data



$\tau = 0.053^{+0.014}_{-0.016}$, lollipop[5]

$\tau = 0.058^{+0.012}_{-0.012}$, lollipop+PlanckTT

$\tau = 0.058^{+0.011}_{-0.012}$, lollipop+PlanckTT+lensing

$\tau = 0.054^{+0.012}_{-0.013}$, lollipop+PlanckTT+VHL

Probes of Reionization:

- CMB
- Lyman alpha Forest
- Global Tb
- IM of 21cm line
- IM of other lines
- Lyman alpha emitters
- The temperature of the IGM
- Galaxies

Intensity Mapping of multiple lines

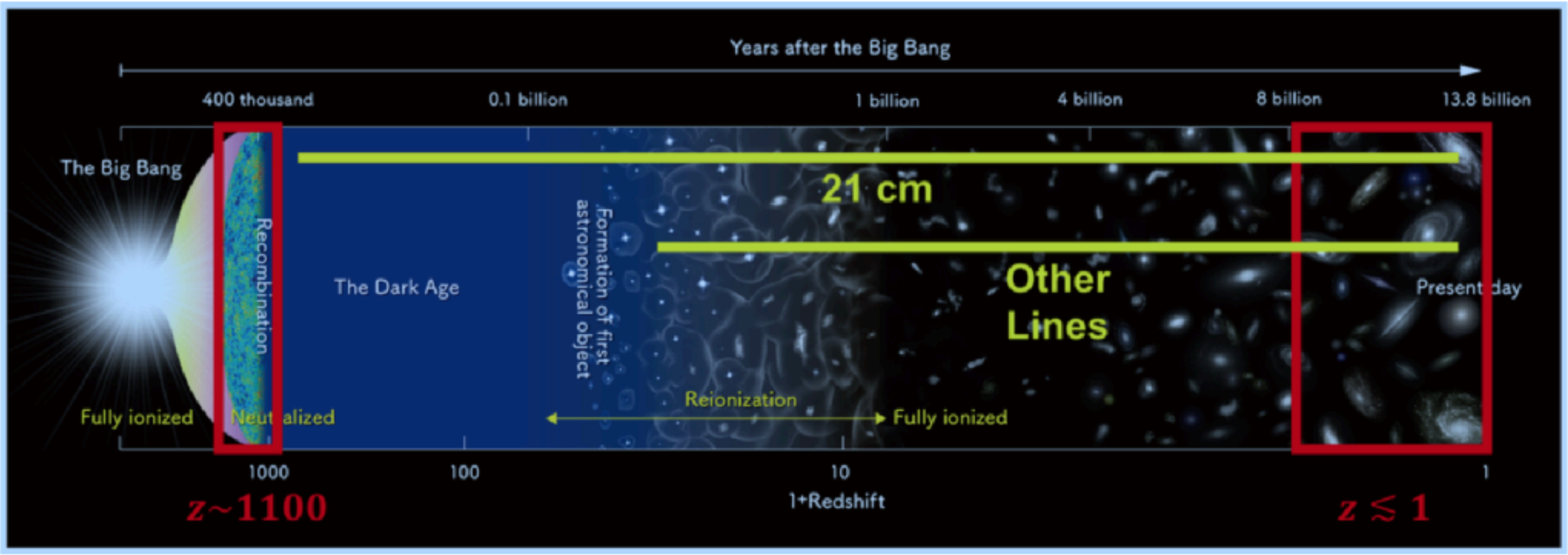
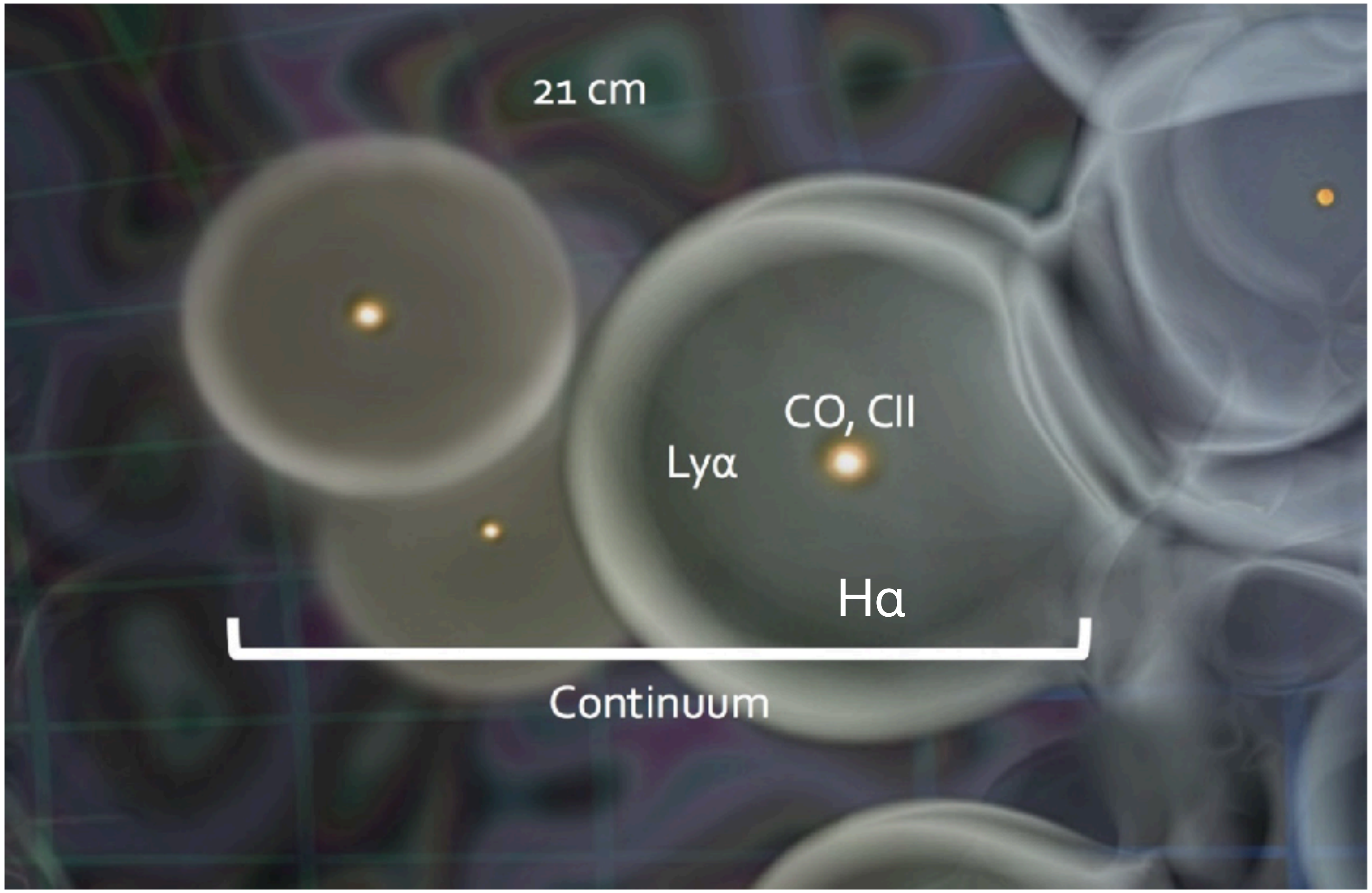


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

Intensity Mapping of multiple lines

Physics of reionization: synergy of lines will give the complete picture



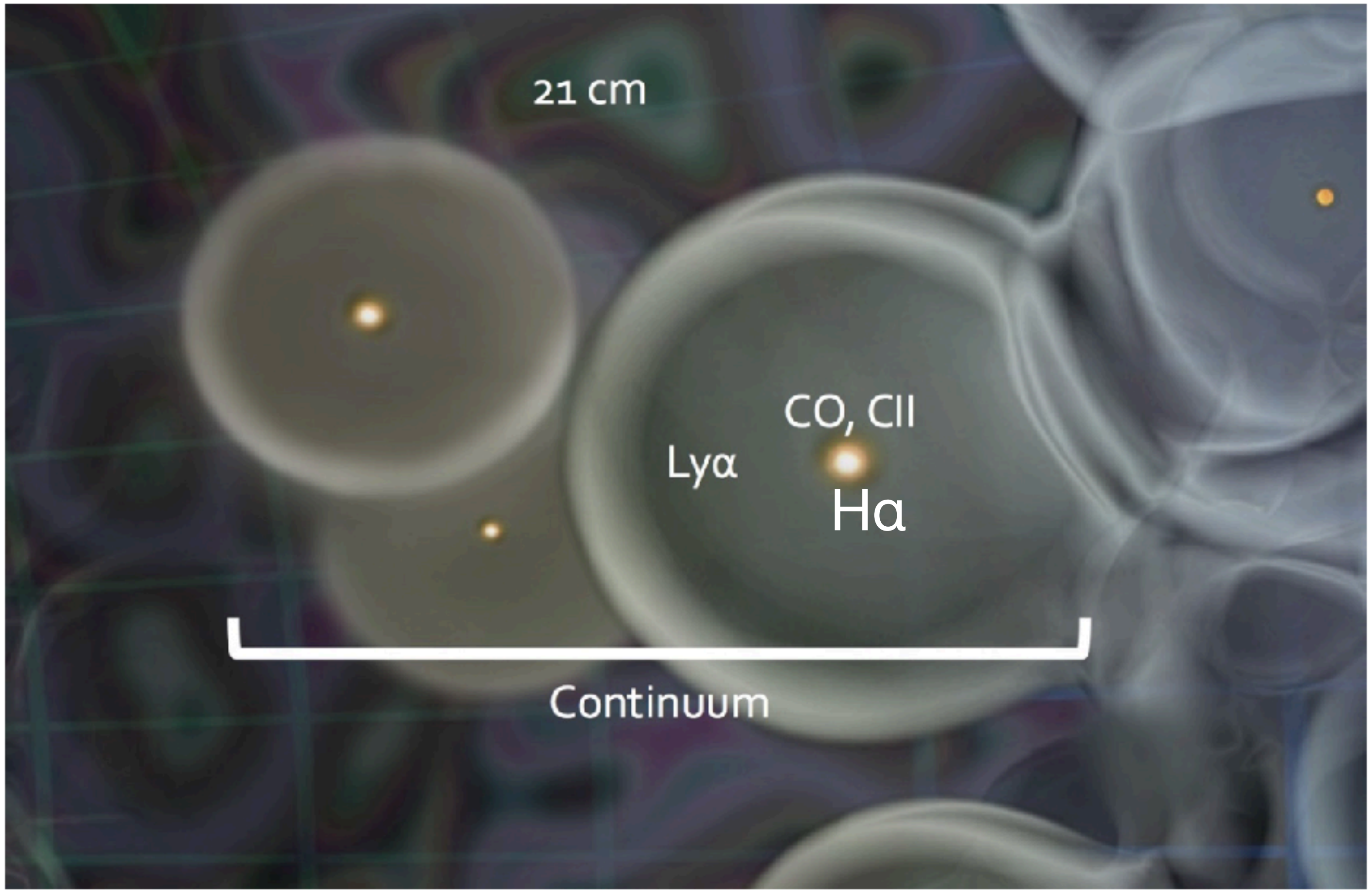
(Courtesy of P. Breysse, Background: Sci. Am.,)

- HI (21cm): maps the neutral IGM, outside of the ionized bubbles.
- CO/[CII] /Hα trace the star-forming galaxies that source the ionizing photons.
- Lyman-α: probes the galaxies along with the halos around them.

Intensity Mapping of multiple lines

Origin of the emission:

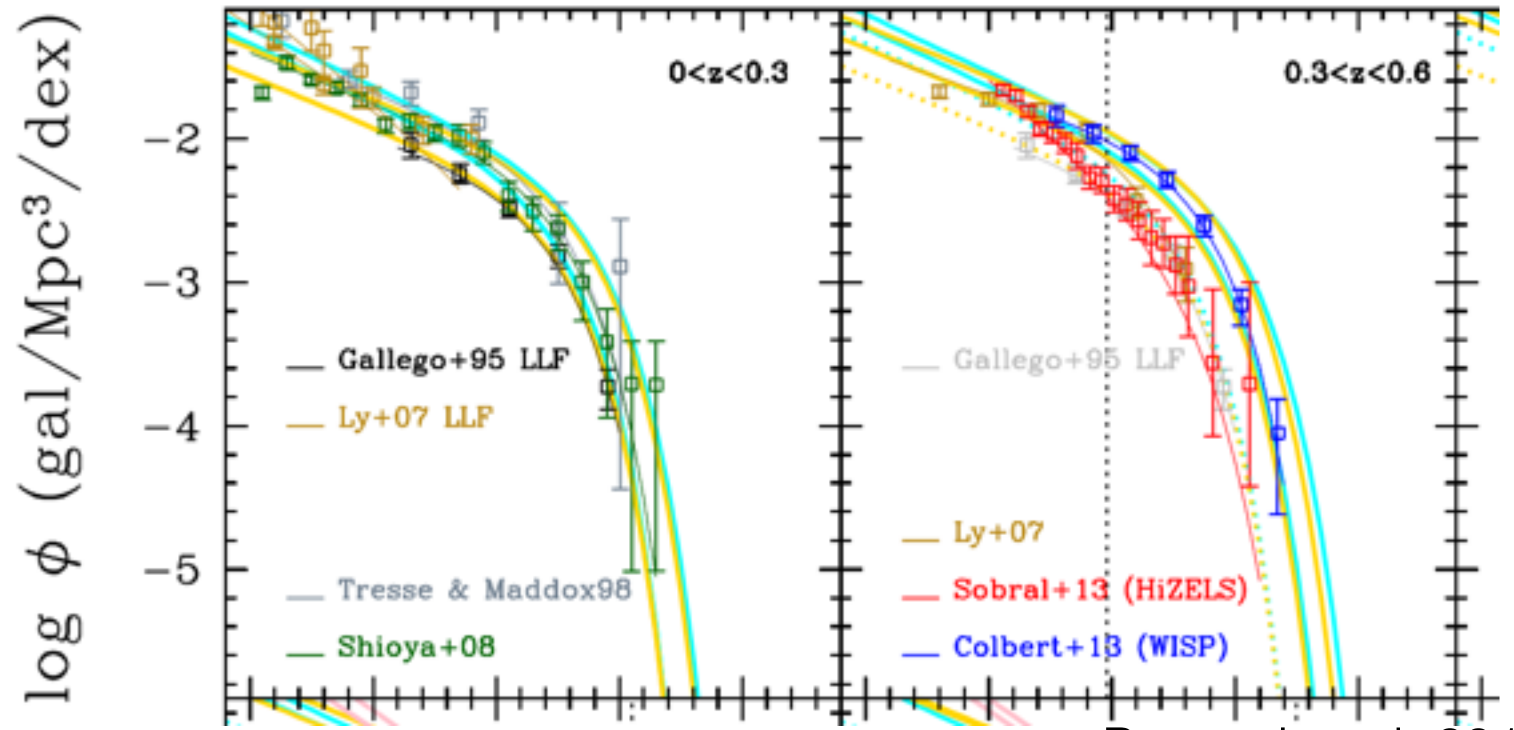
- CO - Molecular gas
- 21 cm - Neutral gas
- CII - PDRs/Ionized gas
- Hα, Lyα - Ionized gas /partially



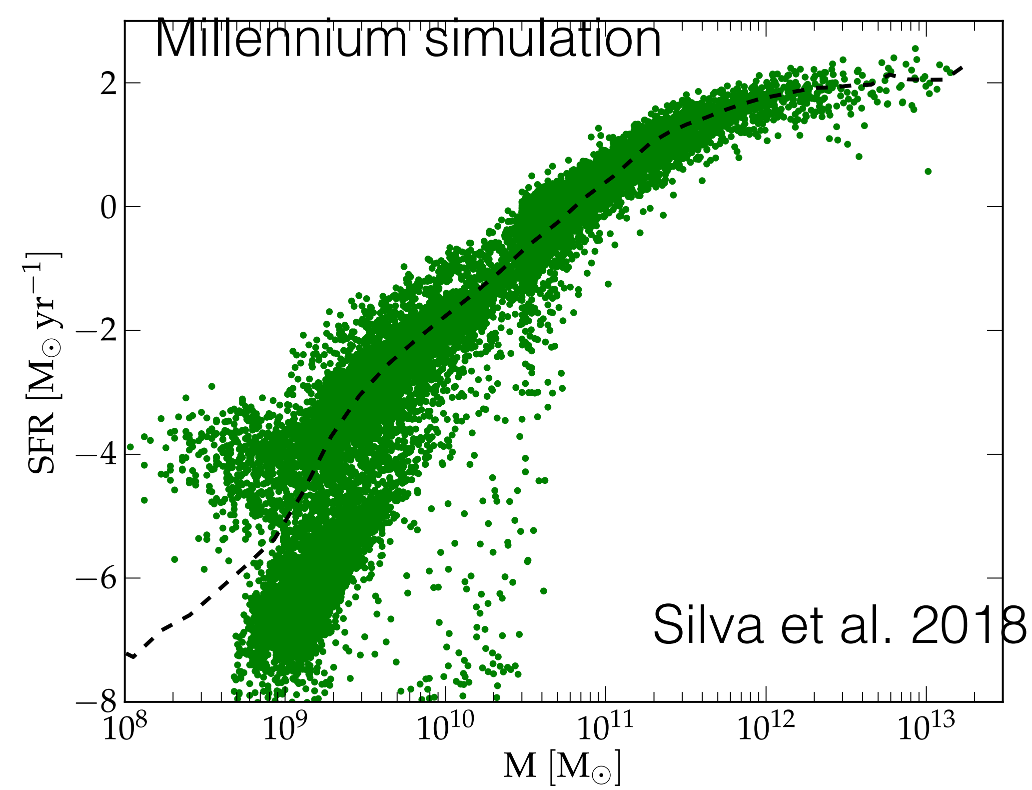
(Courtesy of P. Breysse, Background: Sci. Am.,)

Modelling Galaxy emission for IM studies: Observations + simulations

- Stellar mass
- SFR
- Line excitation
- Metallicity
- Dust extinction
- Gas temperature



Pozzetti et al. 2018



Silva et al. 2018

Intensity Mapping experiments

Experiment	Line	Frequency	Redshift range	Location
HERA	HI	50 – 250 MHz	5 – 27	South Africa
SKA-LOW	HI	50 – 350 MHz	3 – 7	Australia
Lofar	HI	115 - 189 MHz	6.5 -11.4	Europe
CCAT-prime	[CII]	185 – 440 GHz	3.3 – 9.3	Chile
TIME	[CII]	200 – 300 GHz	5.3 – 8.5	North America
CONCERTO	[CII]	200 – 360 GHz	4.3 – 8.5	Chile
COPSS	CO	27 – 35 GHz	2.3 – 3.3	North America
mmIME	CO, [CII]	300, 100, 30 GHz	1 – 5	various
AIM-CO	CO	86 – 102 GHz	1.2 – 1.7, 2.4 – 3.0	China
COMAP	CO	26 – 34 GHz	2.4 – 3.4, 5.8 – 7.8	North America
STARFIRE	[CII], NII	714 – 1250 GHz	0.5 – 1.5	Sub-orbit (balloon)
SPHEREx	Hα (Hβ, [OII], [OIII]), Lyα	60 – 400 THz	0.1 – 5, 5.2 – 8	Space
CHIME	HI	400 – 800 MHz	0.8 – 2.5	North America
HIRAX	HI	400 – 800 MHz	0.8 – 2.5	South Africa
SKA-MID	HI	350 MHz – 14 GHz	0 – 3	South Africa
BINGO	HI	939 – 1238 MHz	0.13 – 0.48	South America

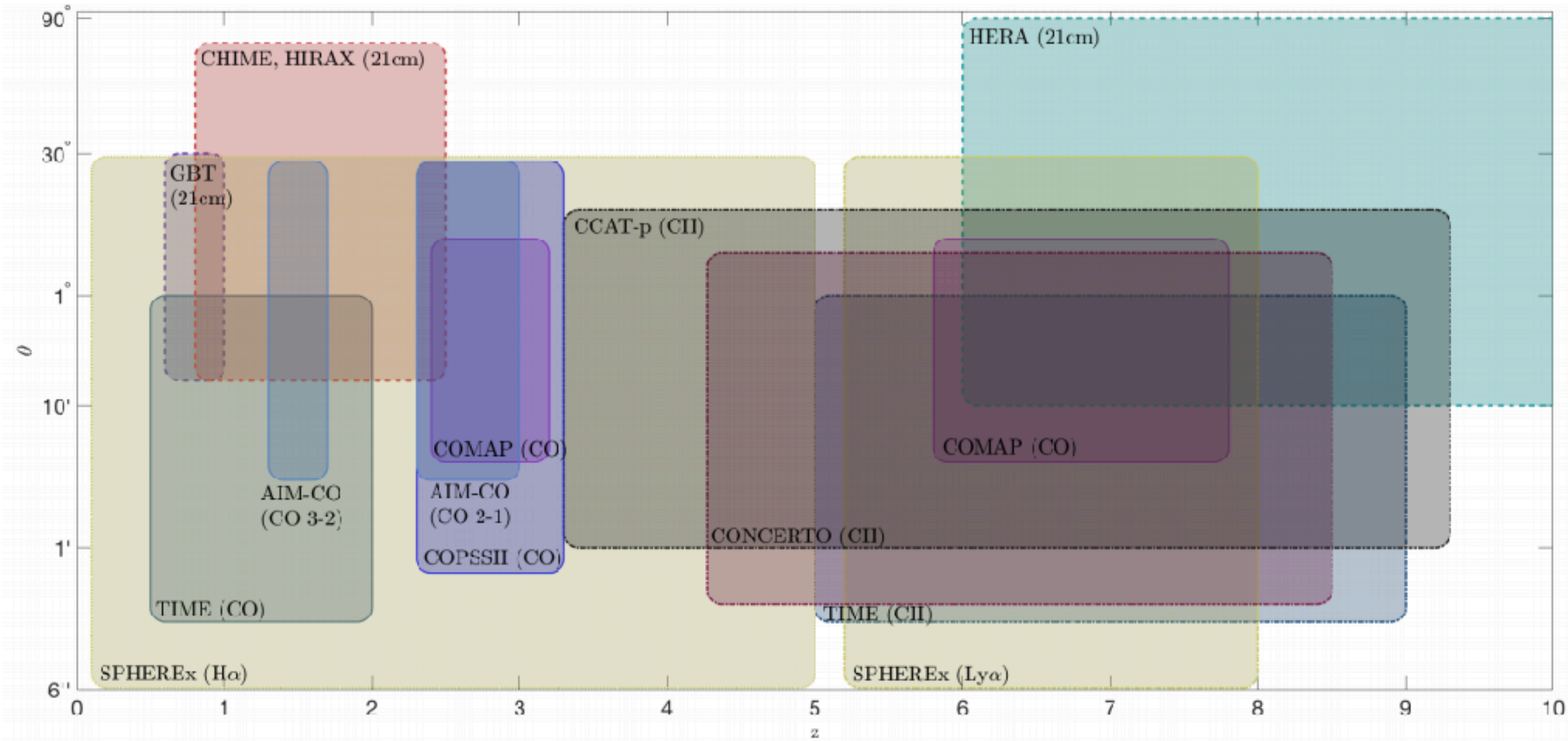
credit: Abigail Crites

Intensity Mapping experiments status

Probe		Results Published	Currently Observing / Under Construction		Planned
HI	Low z	GBT Parkes	CHIME HIRAX → PRIZM TAINLAI →	SKA BINGO GBT-HIM	
	Med. z	PAPER	HERA →		
Lyalpha Hbeta Halpha					SPHEREX
CO		COPSS	mmIME	AIM-CO COMAP	
[CII]				TIME CONCERTO	CCAT-p PIXIE
[NII] [OI]				STARFIRE	

credit: Abigail Crites

Intensity Mapping Surveys: redshift range vs accessible scales



Courtesy of Ely Kovetz and Patrick Breysse

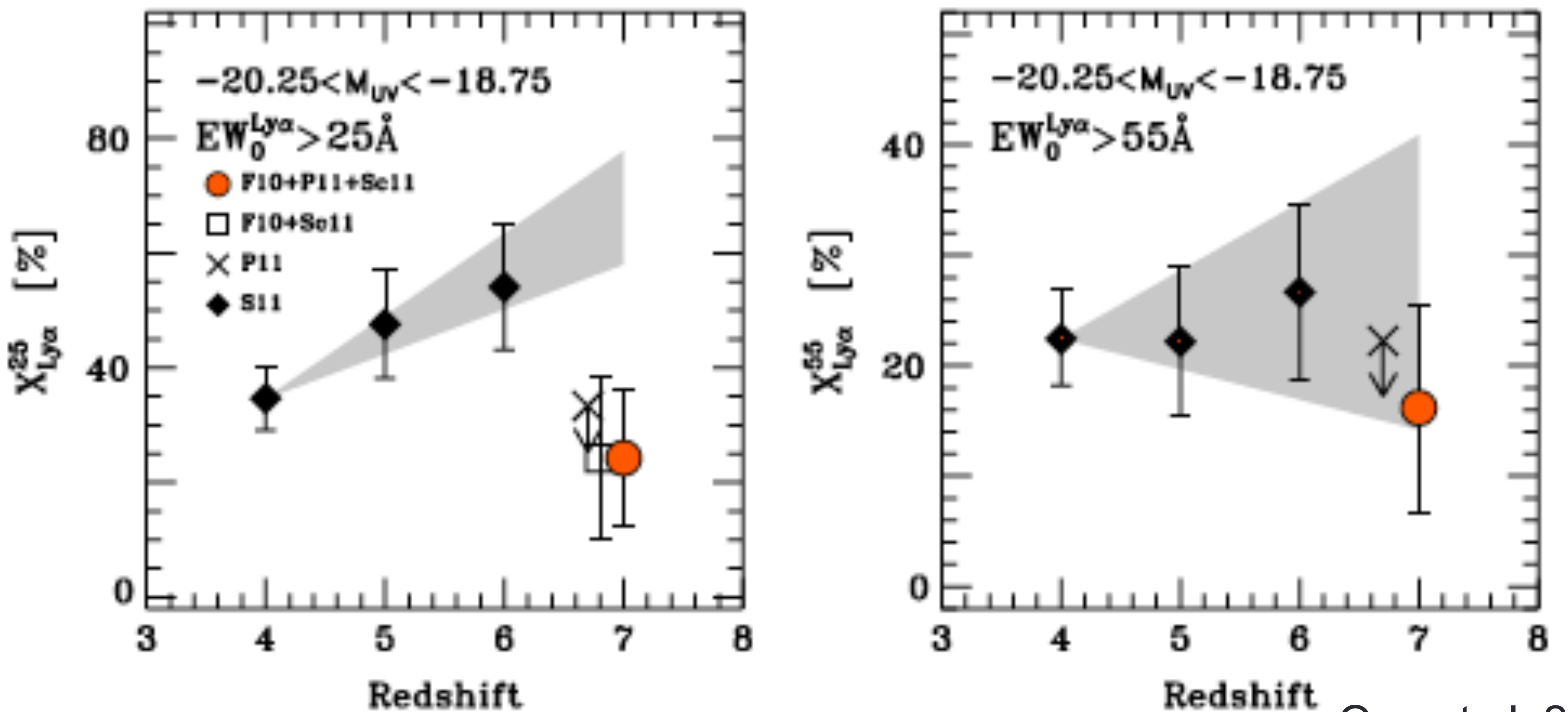
Probes of Reionization:

- CMB
- Lyman alpha Forest
- Global Tb
- IM of 21cm line
- IM of other lines
- Lyman alpha emitters
- The temperature of the IGM
- Galaxies

Lyman alpha emitters

- Galaxies with strong Lyα emission
- Usually they are dust poor (dust destroys Lyα)
- Selected through narrow band filters (Subaru has been very useful for these studies)
- They probe reionization because the
- Their clustering is also used to measure the neutral fraction.
- They usually live in relatively low mass haloes (10^{10}-10^{11} M_{sun})

Drop in the Ly-α emitters fraction at z=6-7

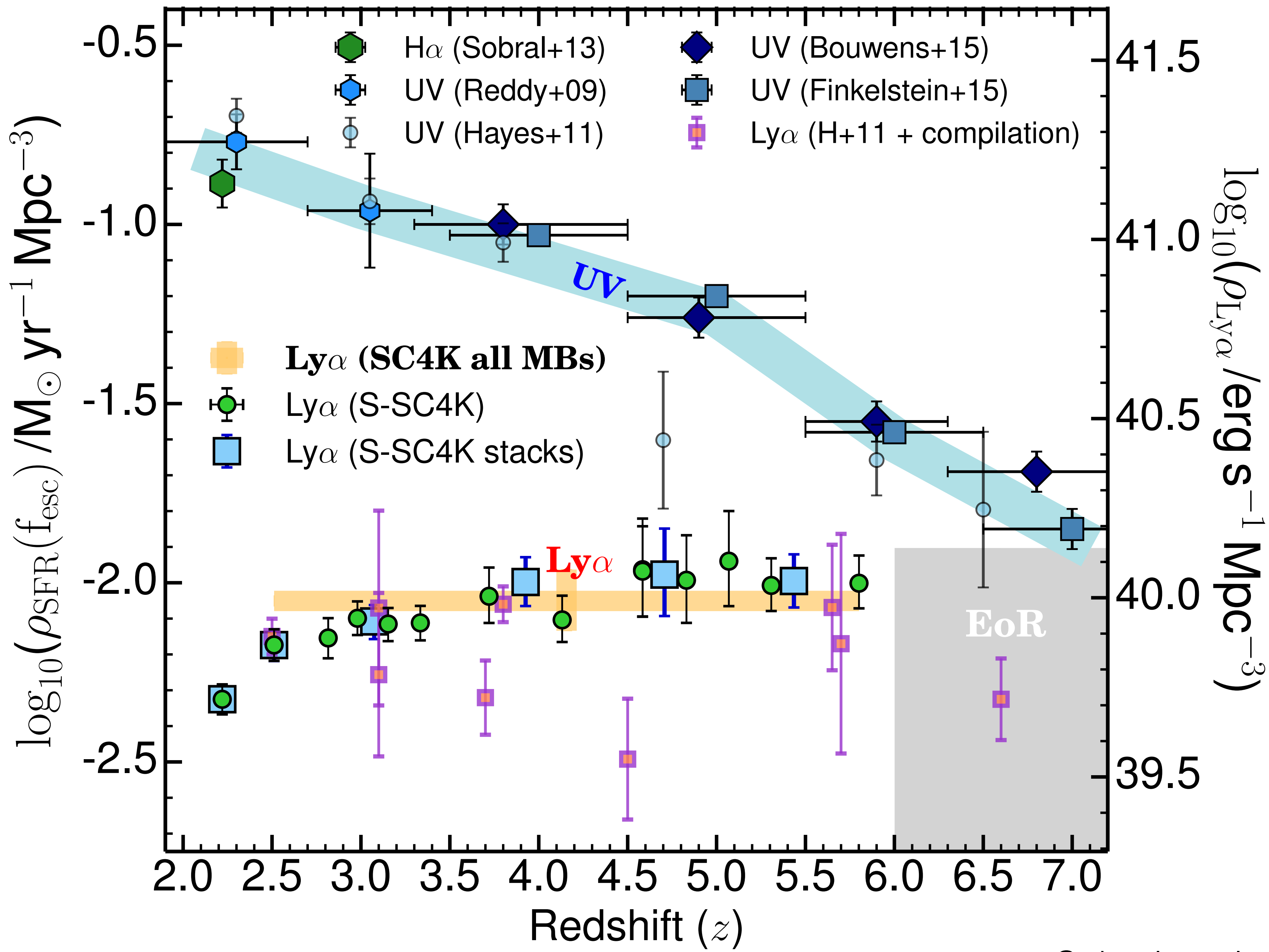


Ono et al, 2012

1. Evolution in the Neutral HI fraction
2. Evolution in the Galaxy properties
3. Evolution on the ionizing background
4. other

Lyα/ UV increase indicates higher escape fractions o

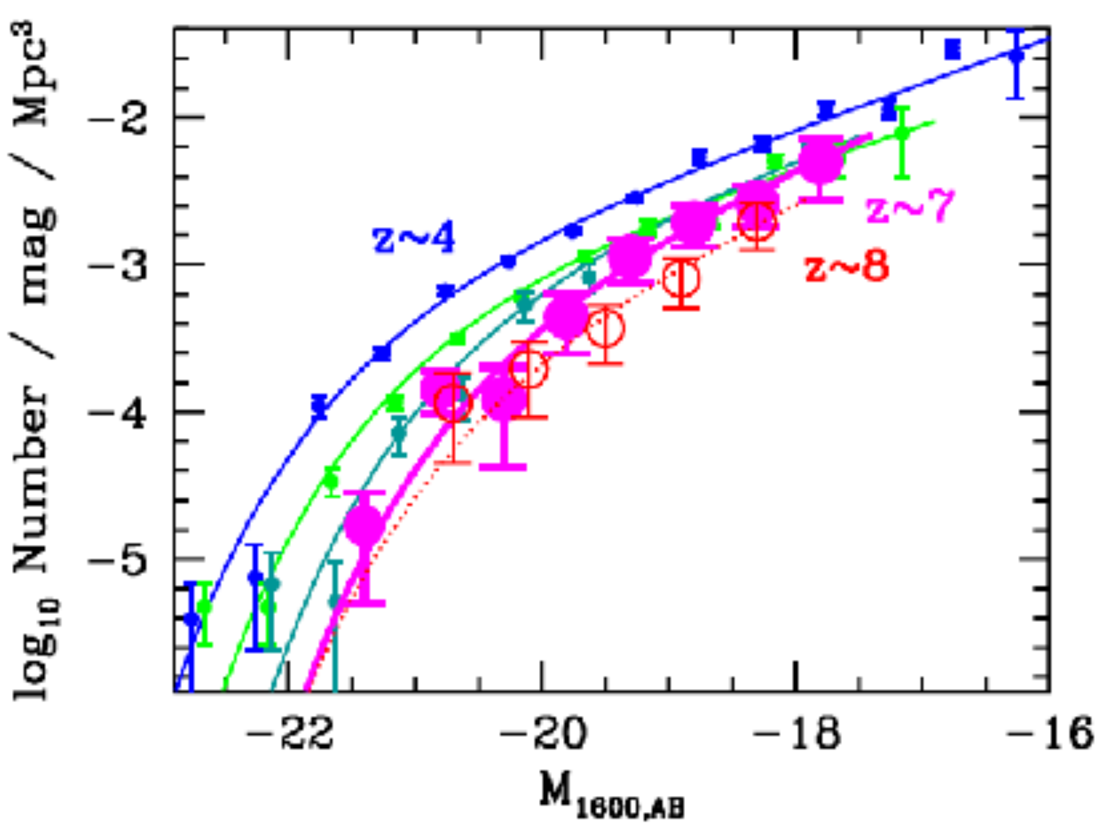
Lyα/Ionizing photons at high z

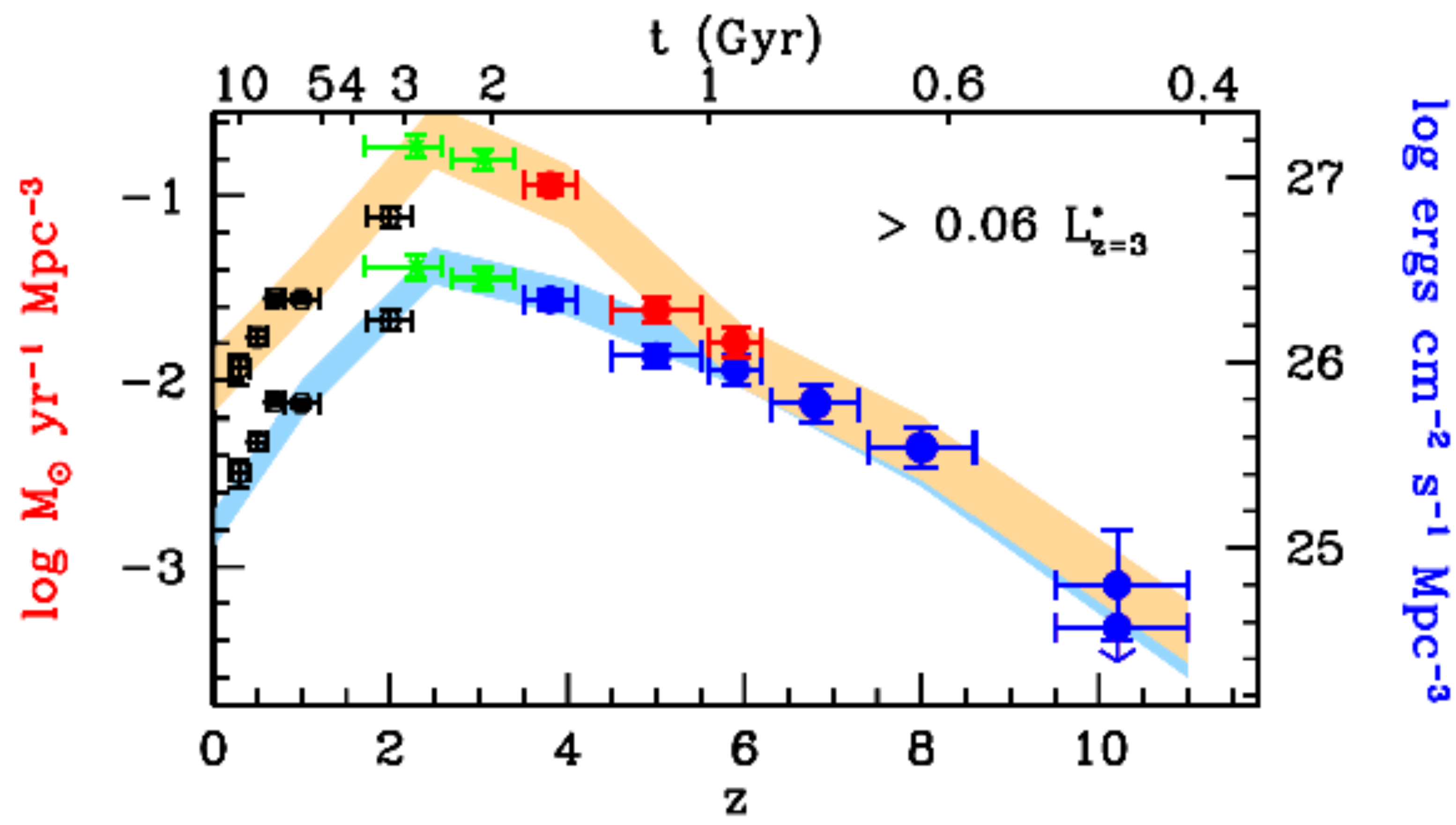


Sobral et al. arXiv 1712.04451

Galaxies

Galaxies appear to become bluer and show more Lyα with decreasing luminosity and increasing redshift.

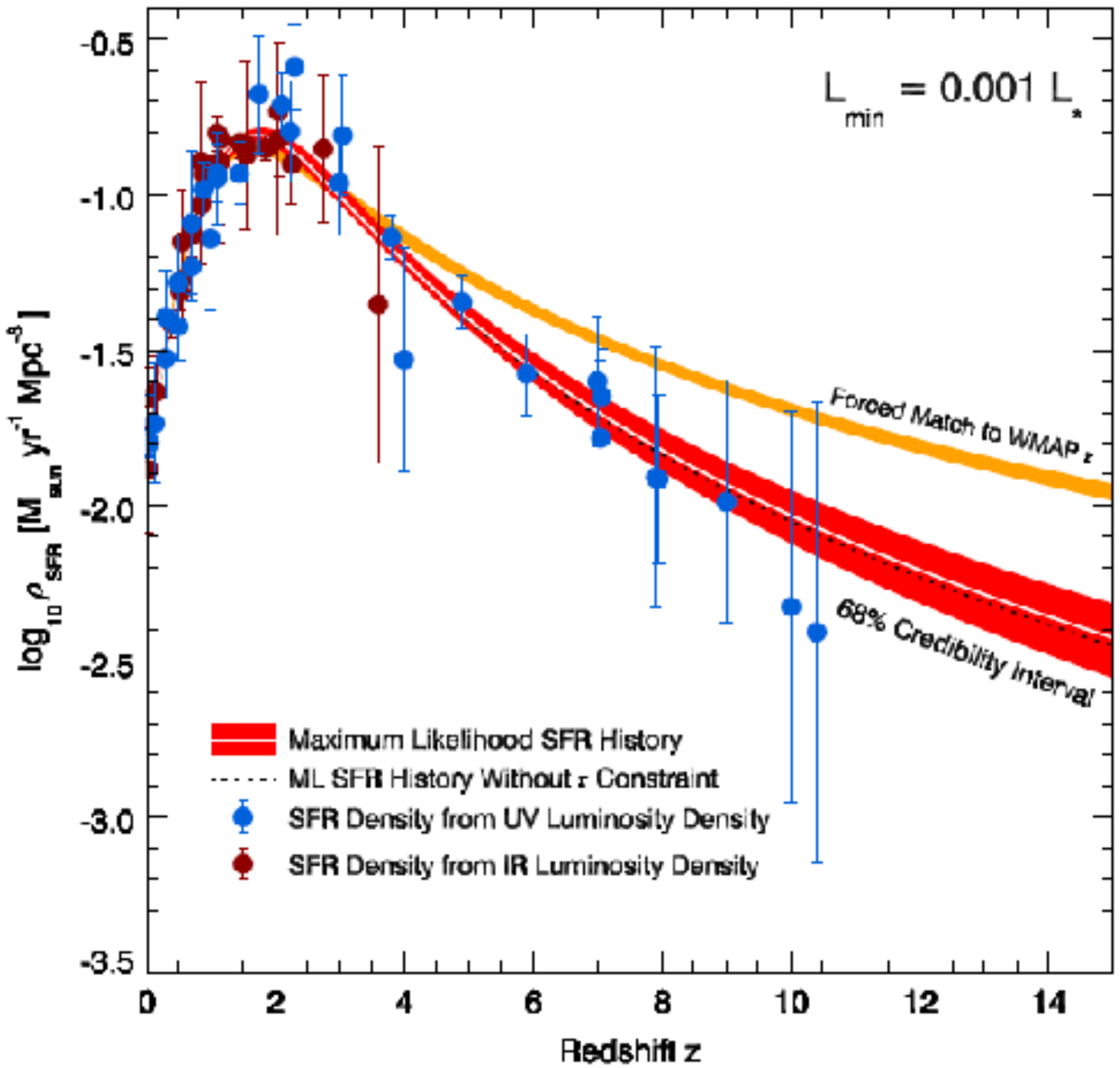


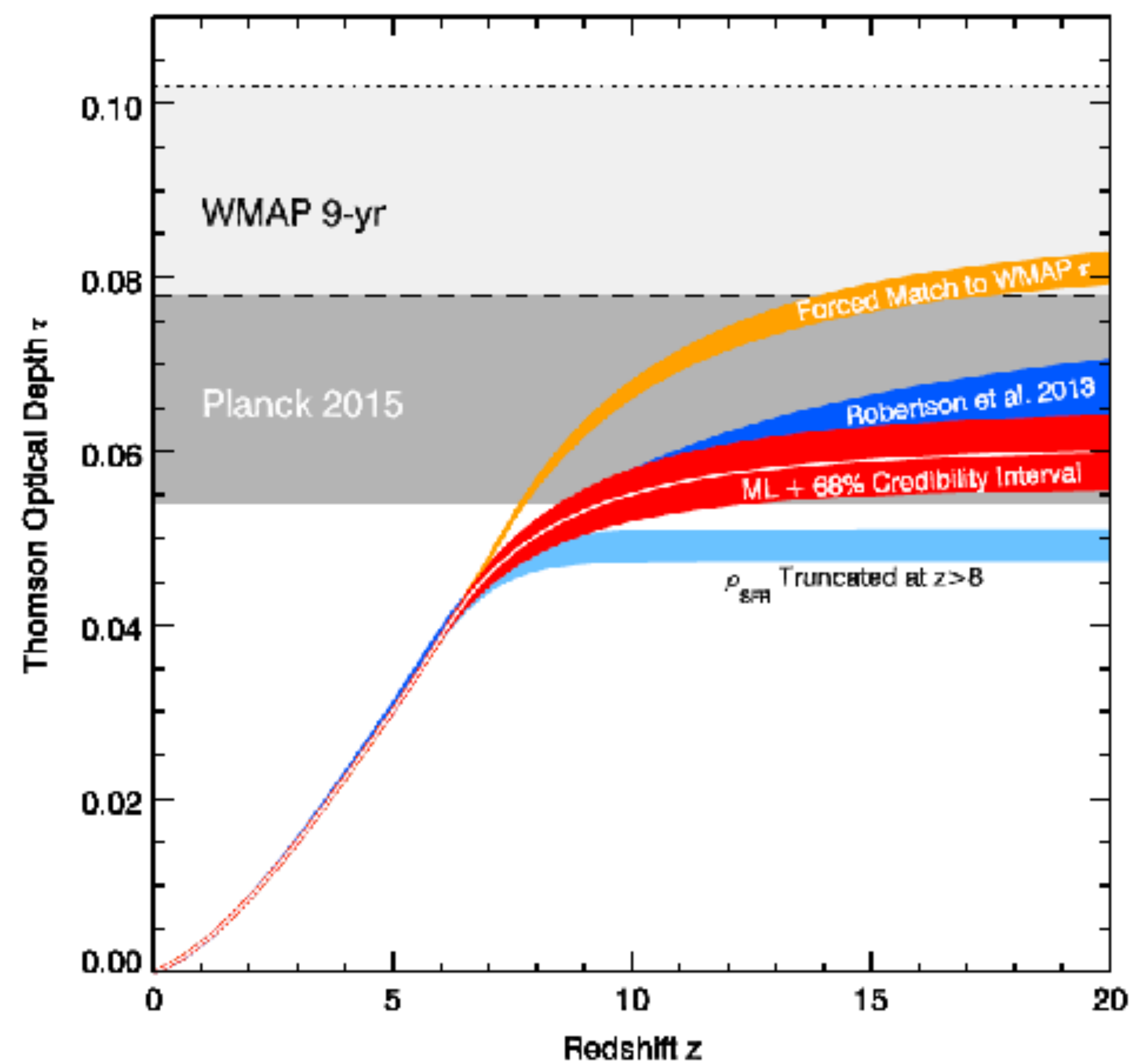


Bouwens et al. 2010

The current status: Star formation history.

f_{esc}=0.2, ξ_{ion} (β=-2), and LF down to M_{UV}=-13





Implies rapid reionization

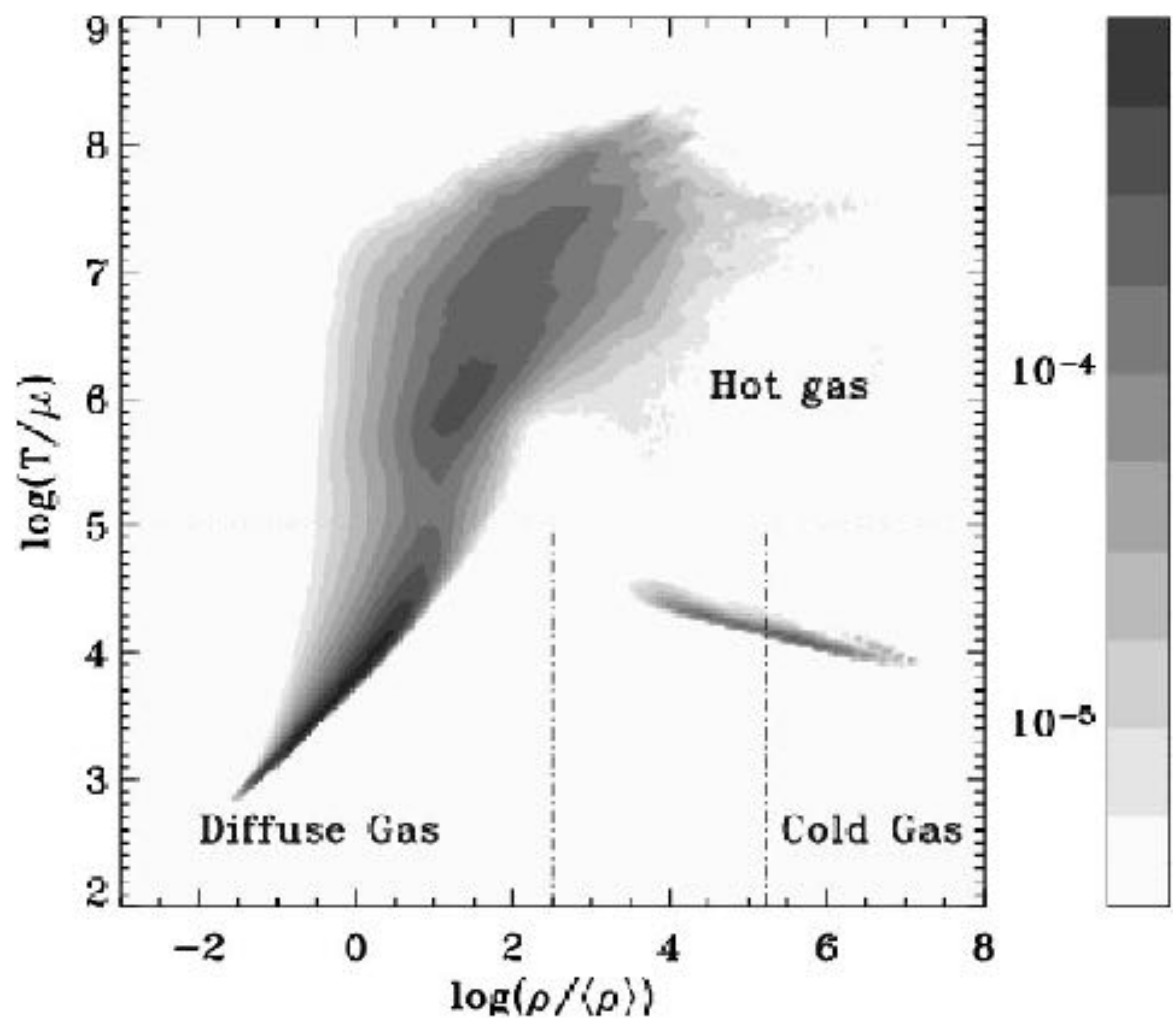
Robertson et al. 2015

The IGM Temperature Evolution

Most of the absorption is caused by quasilinear densities that follow a simple equation of state:

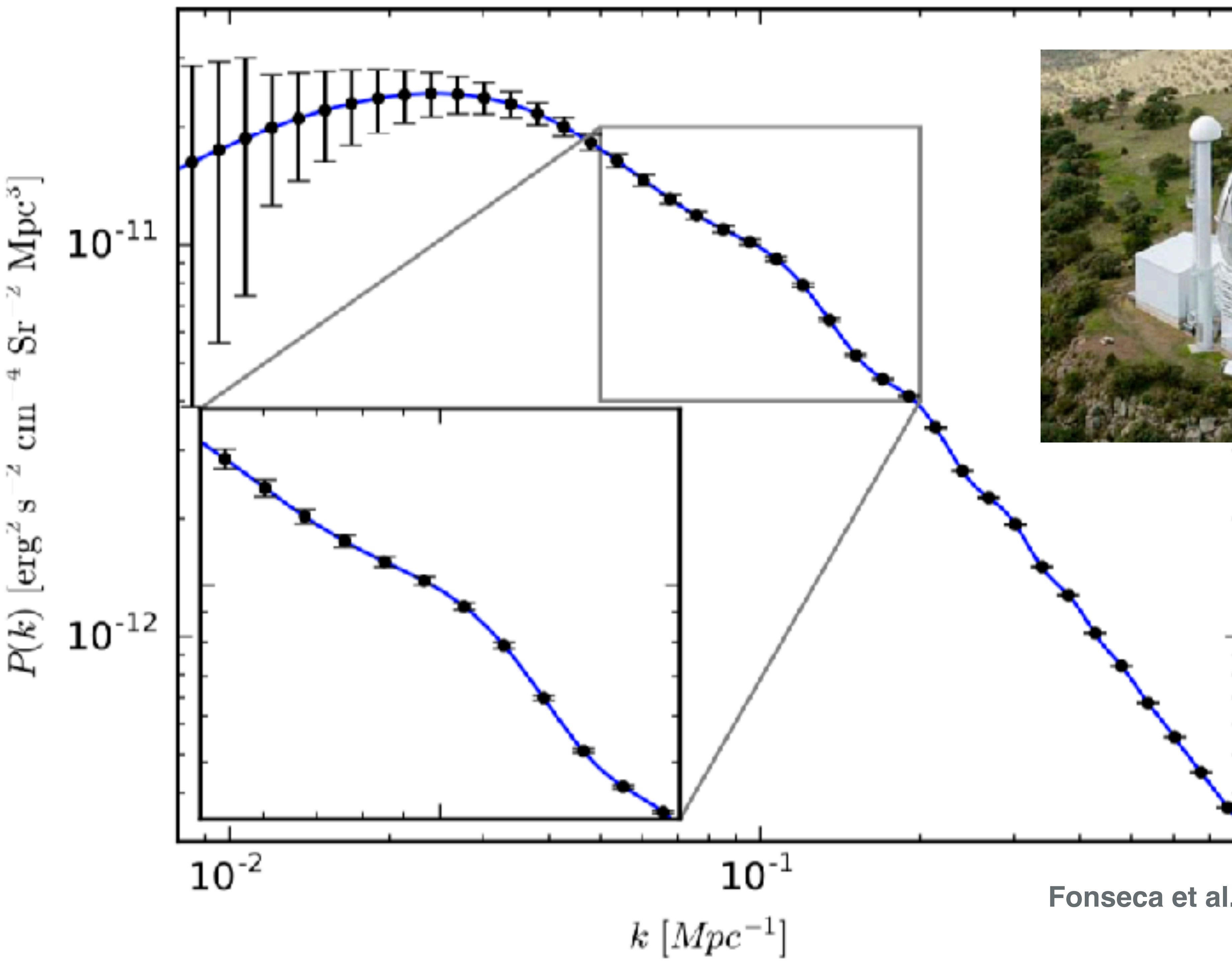
$$T = T_0 \left(\frac{\rho}{\bar{\rho}}\right)^{\gamma-1}$$

Since cooling time is long these absorption lines retain information about the thermal history of the IGM



Heating is made during the gas ionisations

Cosmology with Intensity Mapping of the Lyα line

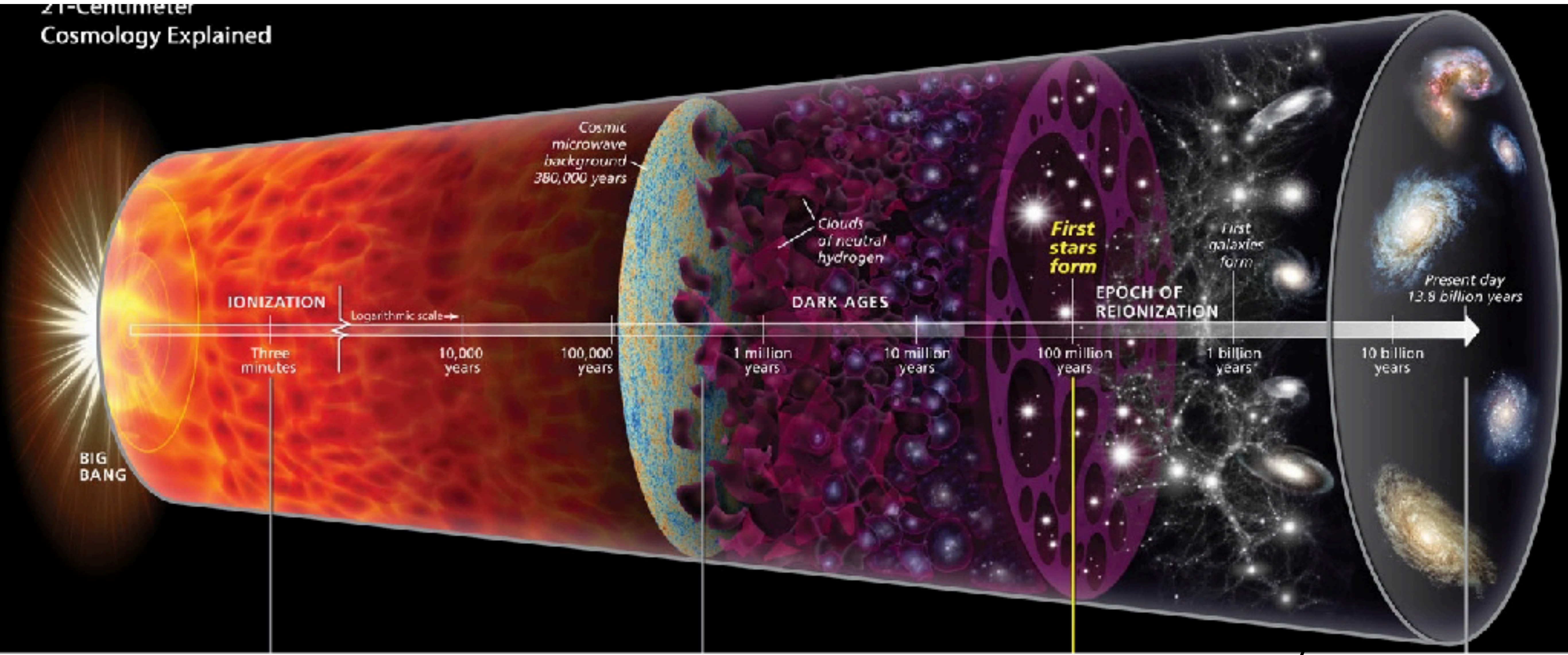


Hobby-Eberly Telescope

Fonseca et al. 2017

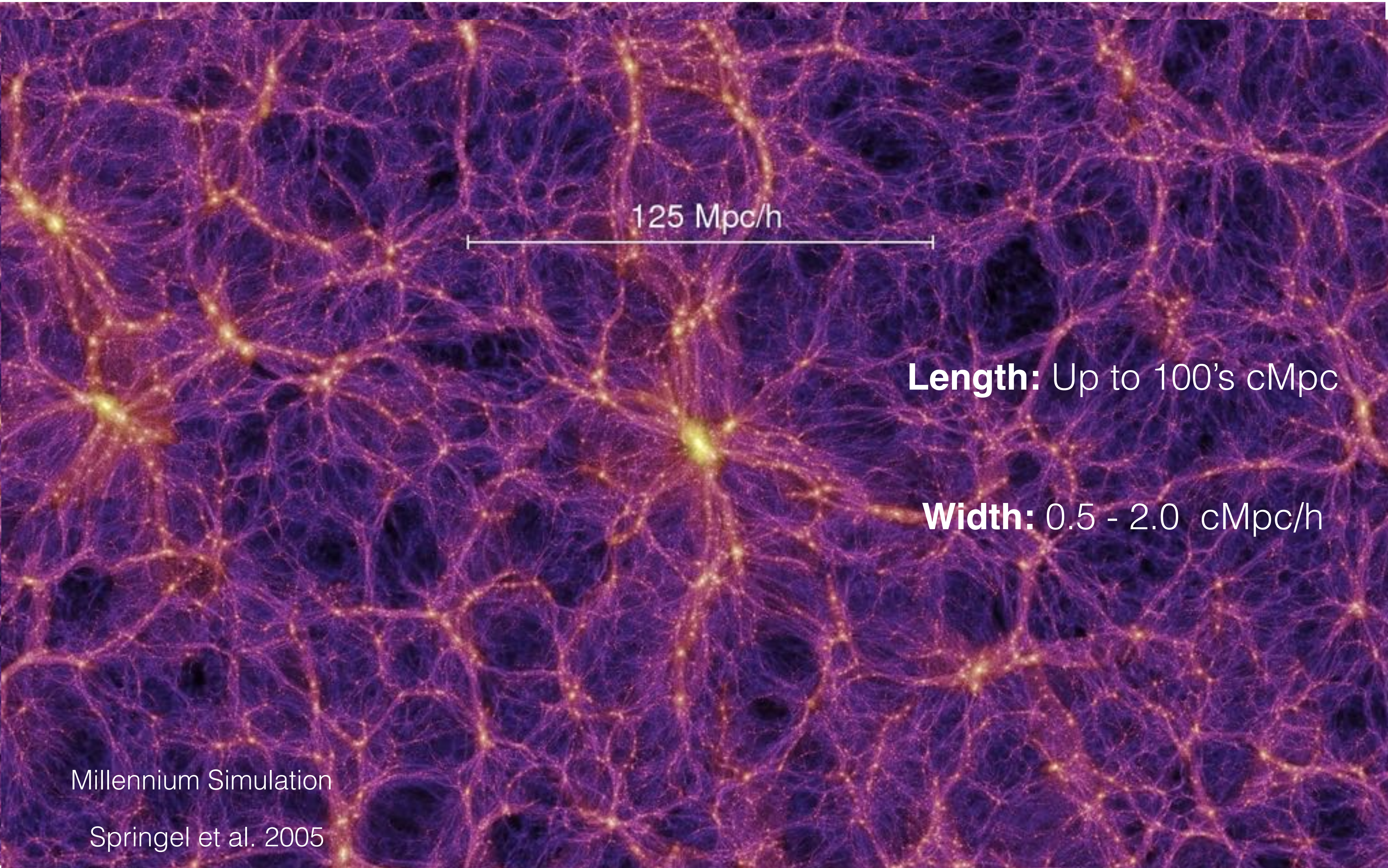
Lyα IM Power Spectrum at $z = 2.1$ with forecasted error bar for HETDEX.

HI Intensity Mapping in the post-EOR



HI in Galaxies plus
residual HI in IGM filaments

HI IM in the post-EOR: the cosmic web

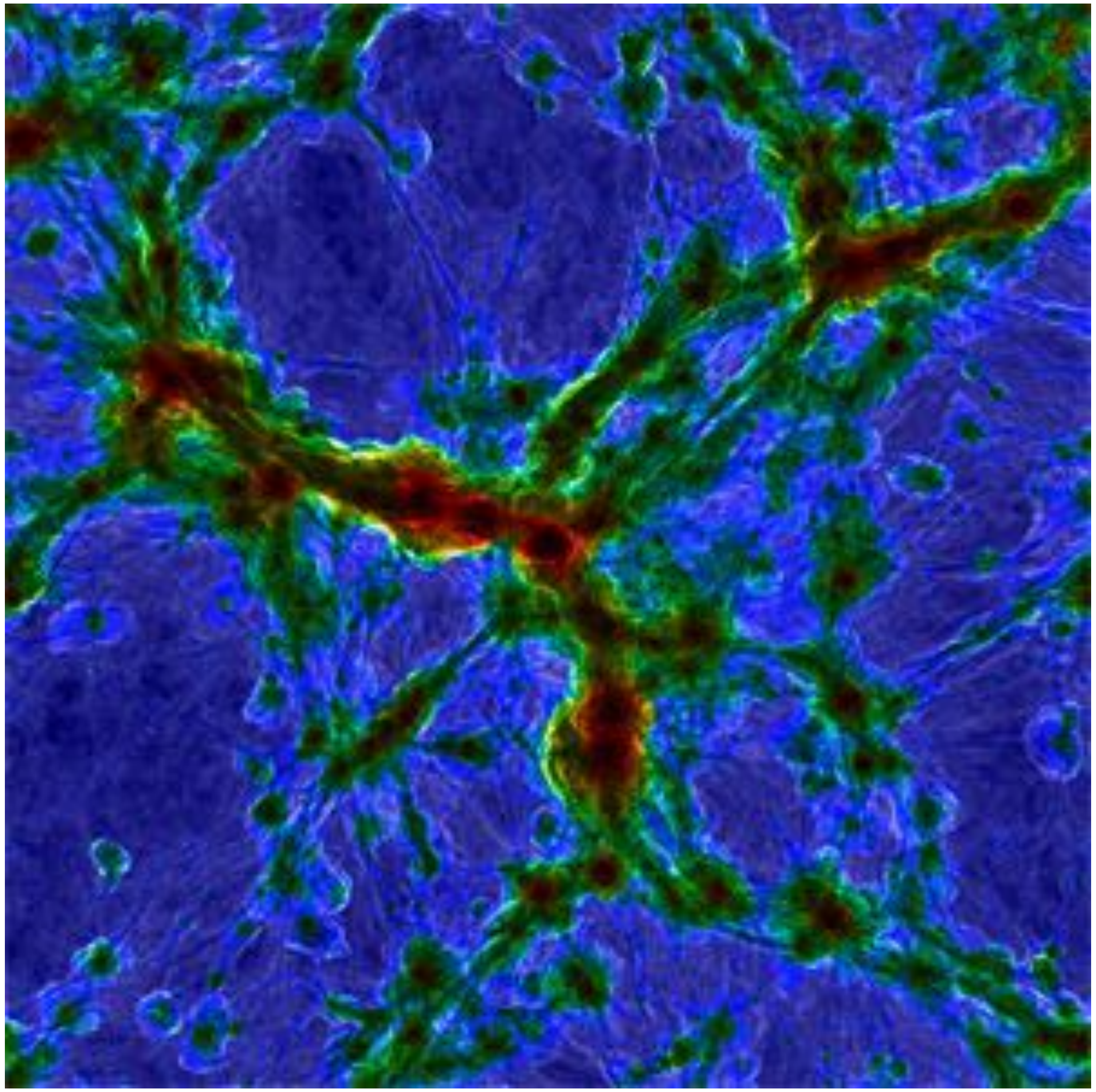


Properties of gas in Large-Scale filaments

Hydrogen + Helium
Hydrogen highly ionized
Helium single ionized (at $z \gtrsim 2$-3)
and double ionized later

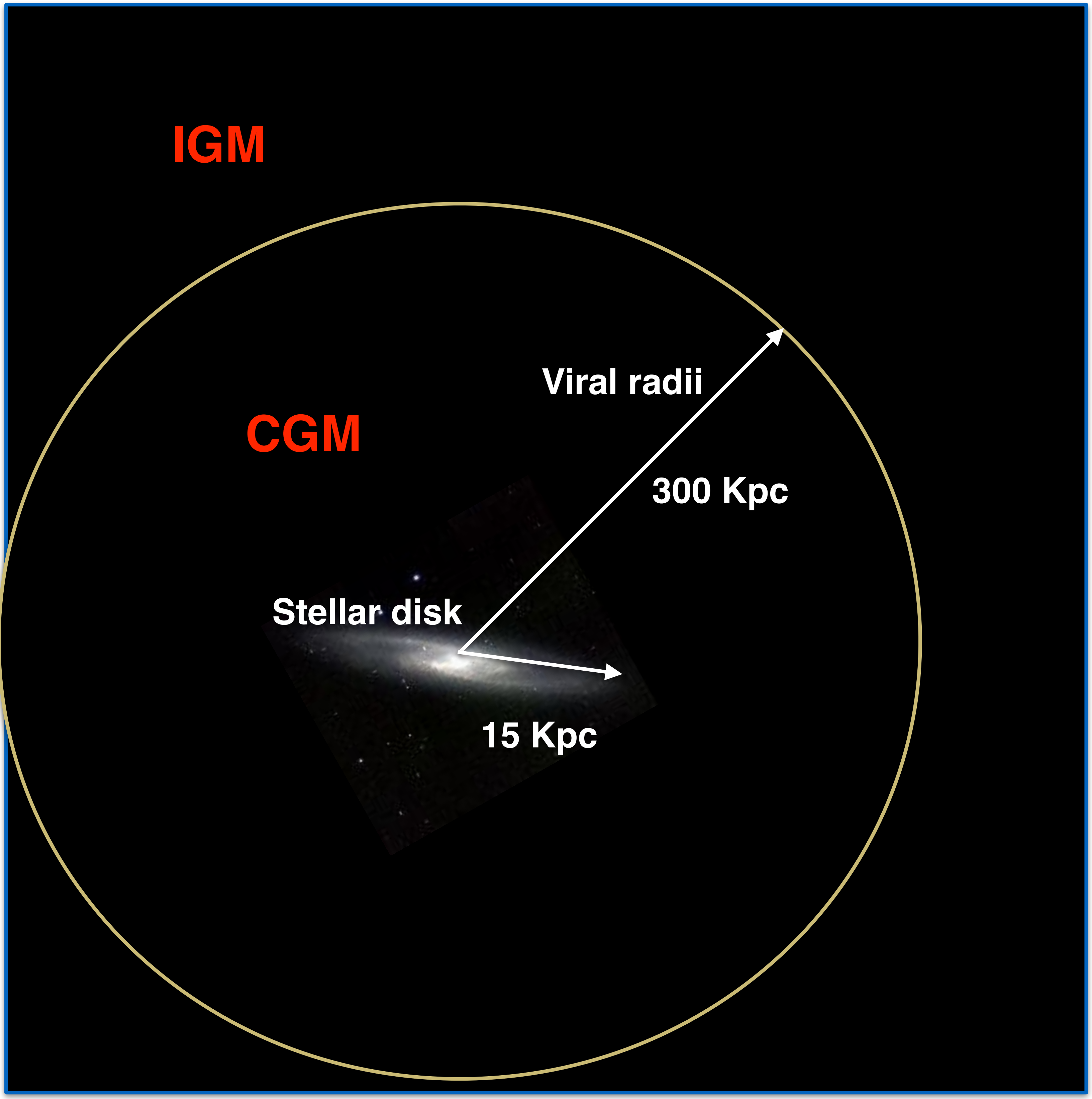
Warm hot gas ($T_K \sim 10^5 - 10^7$)
shock heated + rad. local sources

Cold gas ($T_K \sim 10^4 - 10^5$)
Tk and x_i set by the UVB

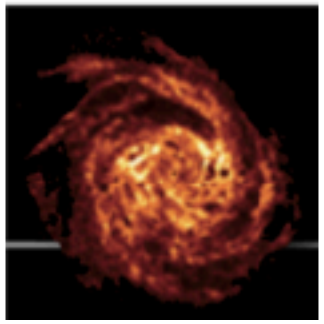


Illustris TNG

Scales of filaments



CGM extends from the stellar disk to the viral radius



HI at low-z Clouds of neutral gas

For $N_{HI} = 2 \times 10^{20}$ [cm^{-2}] :

CNM : $T_{spin} \approx 100$ K $\rightarrow$ $\tau_0 \approx 1$ optically thick

WNM : $T_{spin} \approx 10.000$ K $\rightarrow$ $\tau_0 \ll 1$ optically thin

- Writing τ_ν and $\varphi(\nu)$ in terms of velocity, and integrating over the line profile yields:

$$\int_{line} \tau_\nu \, dV = \frac{N_{HI} \; / \; T_{spin}}{1.83 \times 10^{18} \; [cm^{-2} \, K^{-1}]} \; [km/s]$$

or

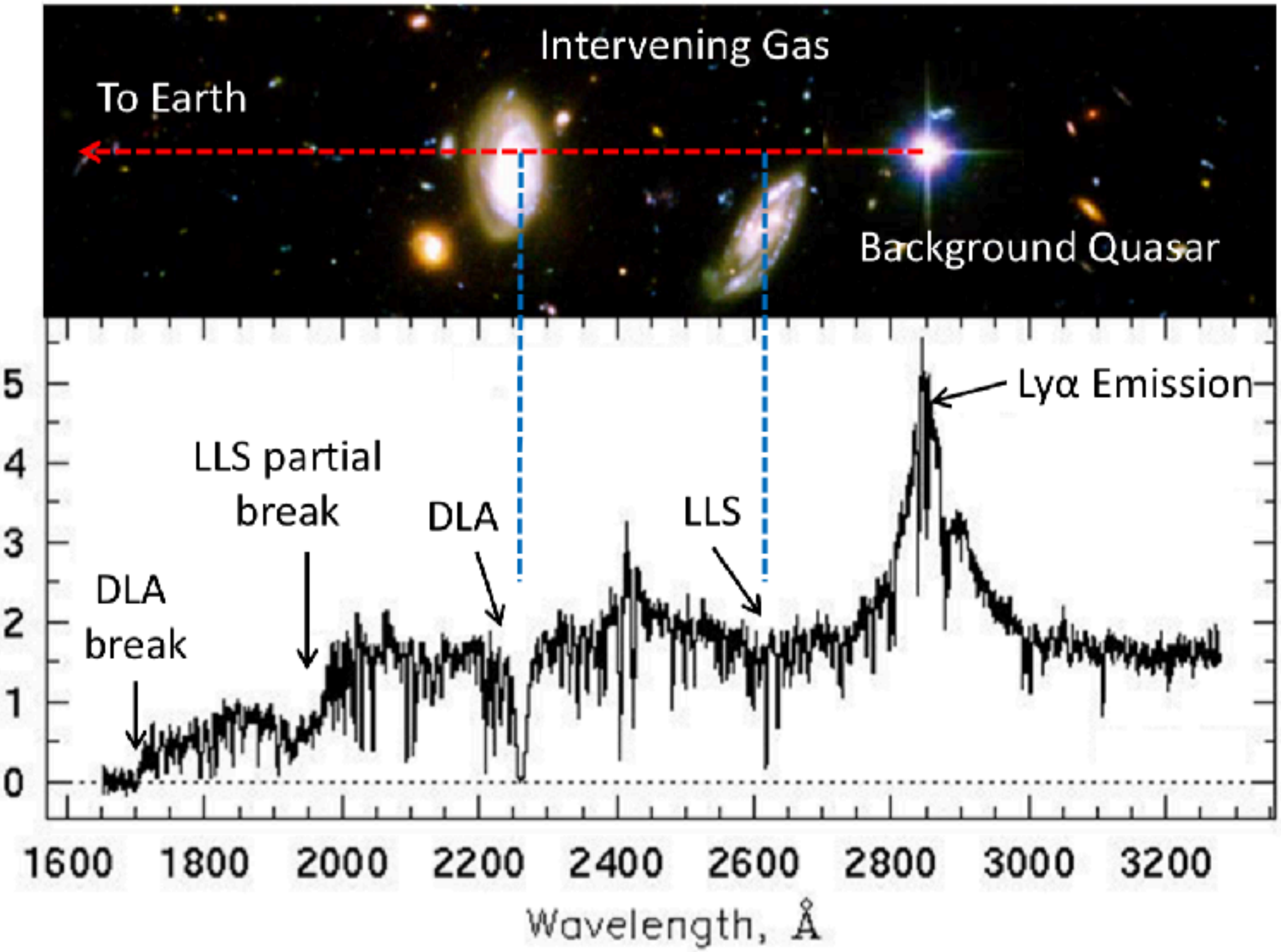
$$N_{HI} \, [cm^{-2}] = 1.83 \times 10^{18} \int_{line} T_{spin}[K] \; \tau_\nu \; dV[km/s]$$

HI at low-z: Absorption by clouds of neutral gas

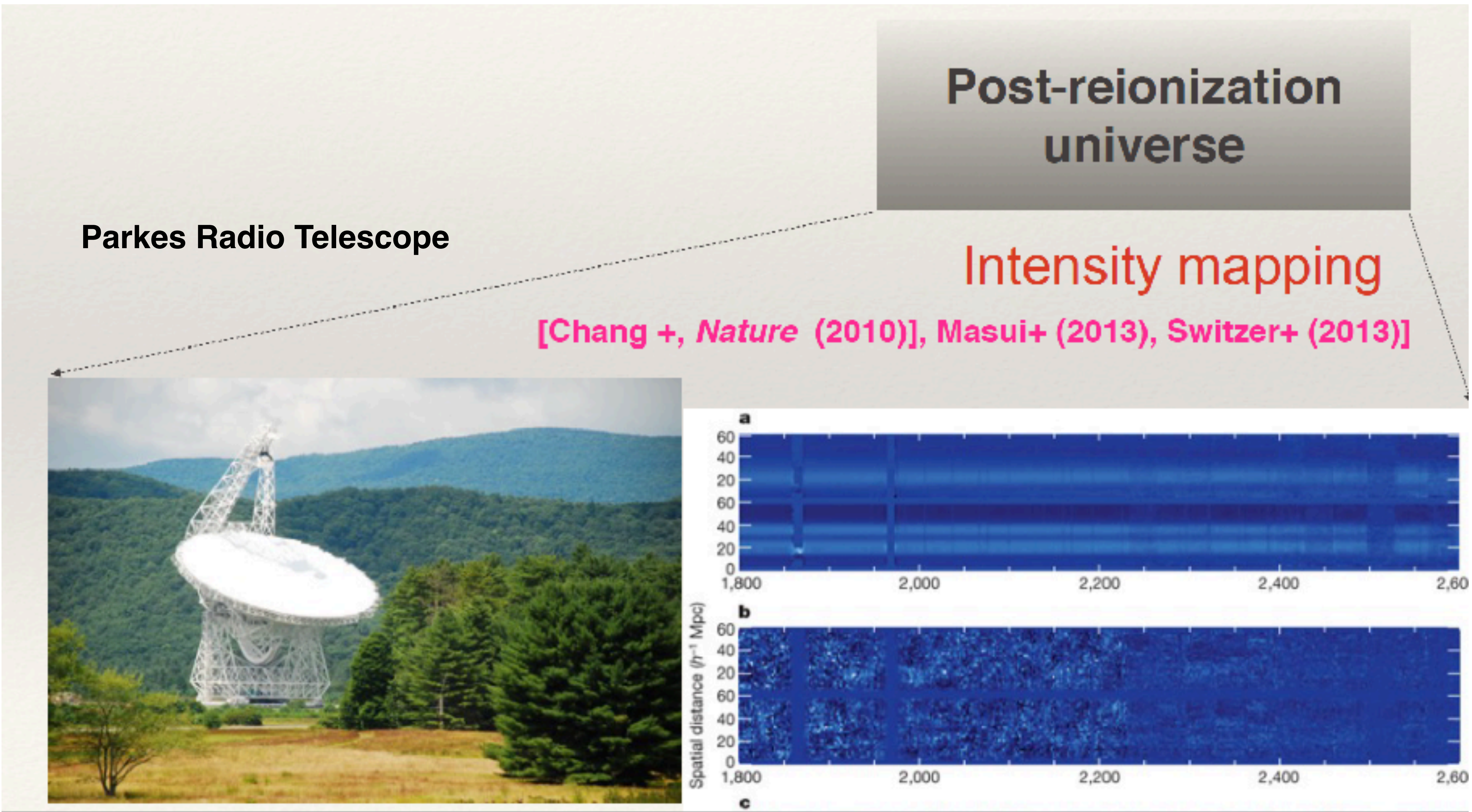
Lyman α Forest
$N_{HI} < 10^{17.2}$ cm^{-2},
($\sigma_{HI,912Å} N_{HI} < 1$)

Lyman limit system
$N_{HI} > 10^{17.2}$ cm^{-2}
($\sigma_{HI,912Å} N_{HI} > 1$)

Damped Lyα system
$N_{HI} > 10^{20.3}$ cm^{-2}



HI Intensity Mapping at z~0.8



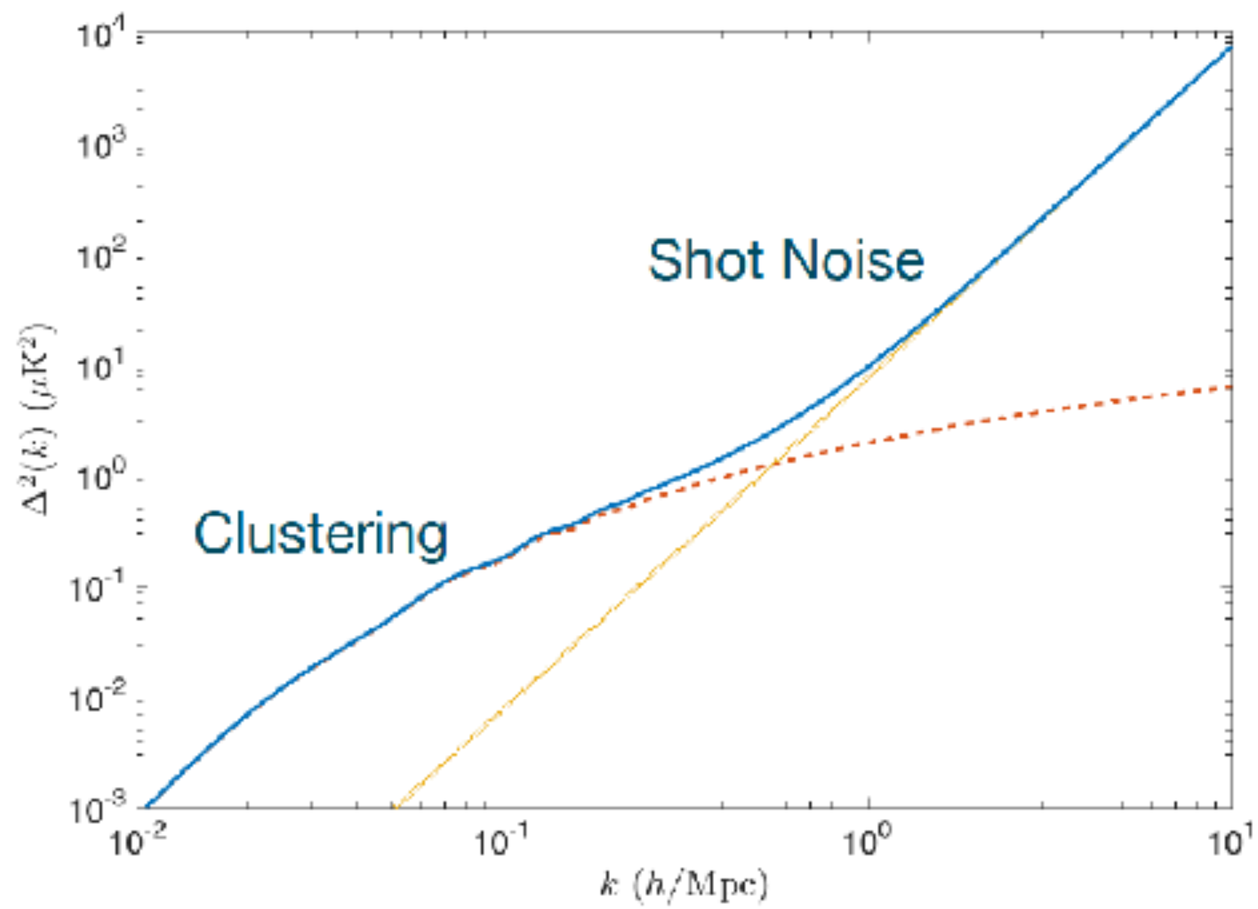
HI Power spectra in the Post EoR

$$P_{\rm line}(k,z) = \langle I_{\rm line}(z)\rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}(z)$$

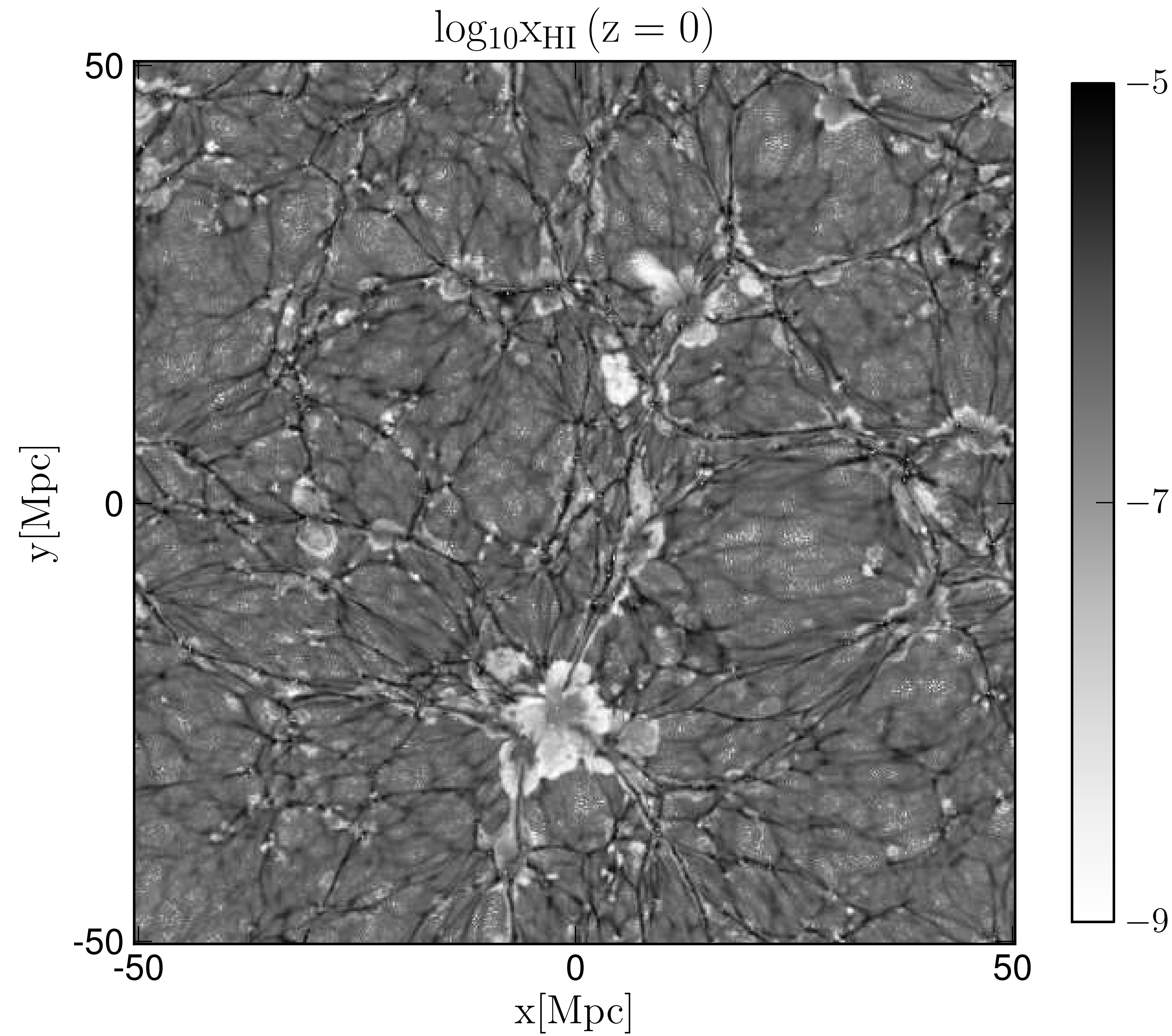
$P_{HI}= P_{HI,GAL}+P_{HI,IGM}$

Luminosity function

$$\langle I_{\rm line}(z)\rangle \propto \int L \frac{dn(z)}{dL} dL$$



HI in the IGM at z=0

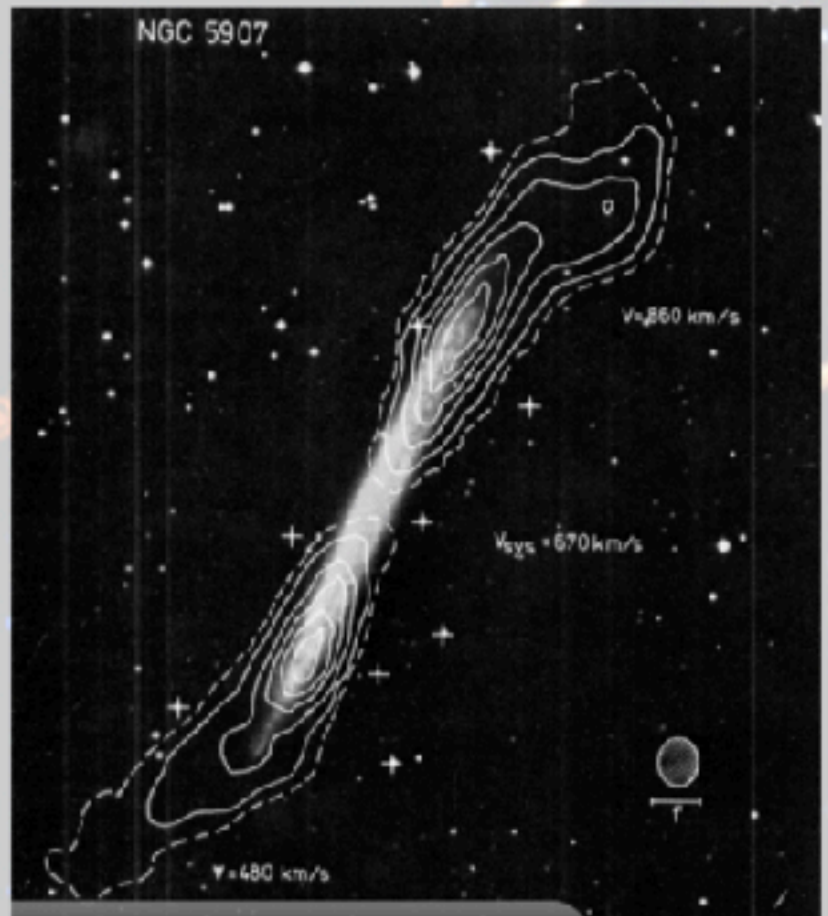


HI in Galaxies: Radio observations

HI shows spiral structure

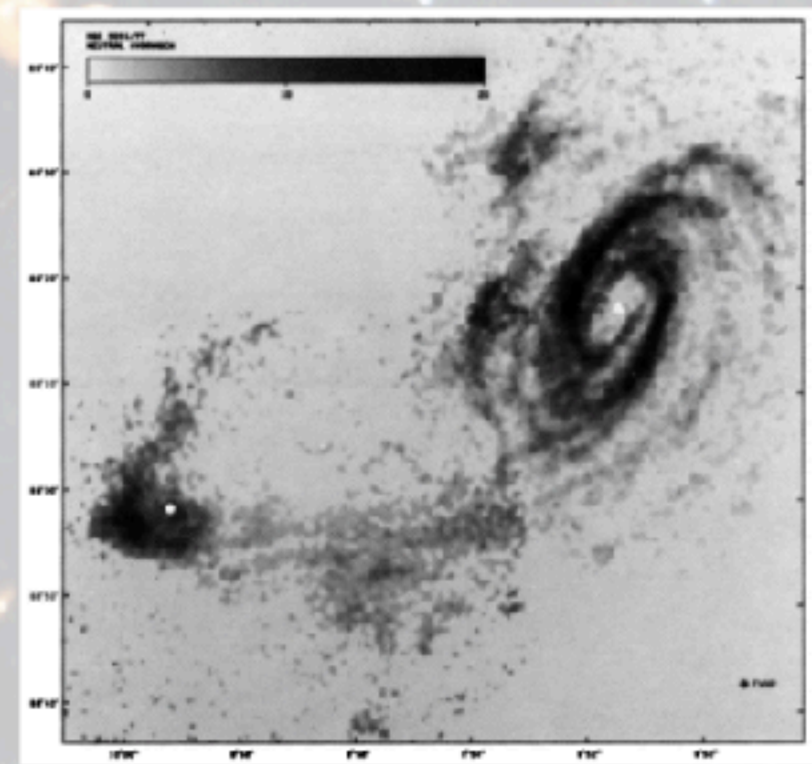
Allen et al. A&A 29, 447, 1973: HI in M 101

HI disks are warped



Sancisi A&A 53, 159, 1976: HI in NGC5907

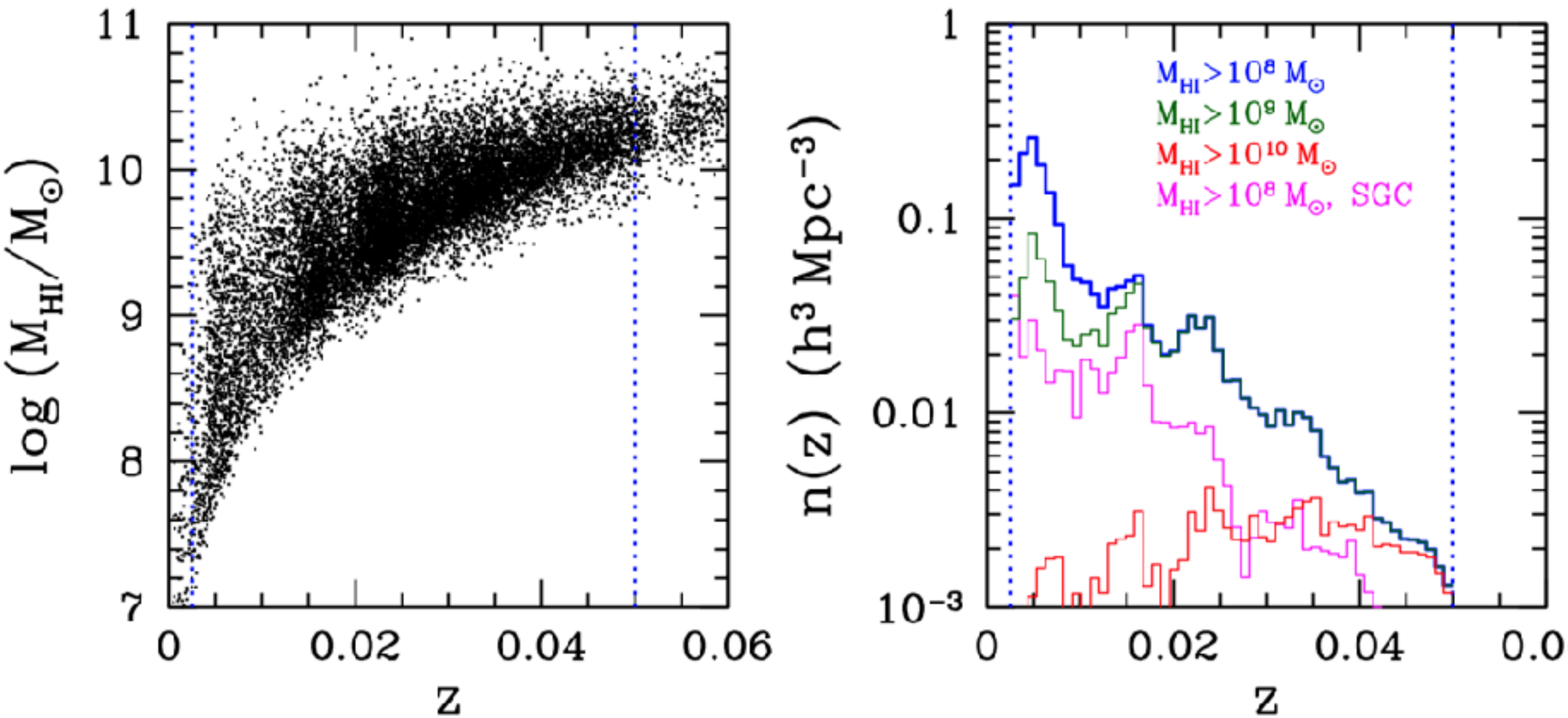
HI traces interactions



van der Hulst A&A 75, 97, 1979: HI in M81/NGC3077

HI in Galaxies: Radio observations

Data from the ALFALFA survey



Guo et al. 2017

HI Intensity Mapping in the Post EoR

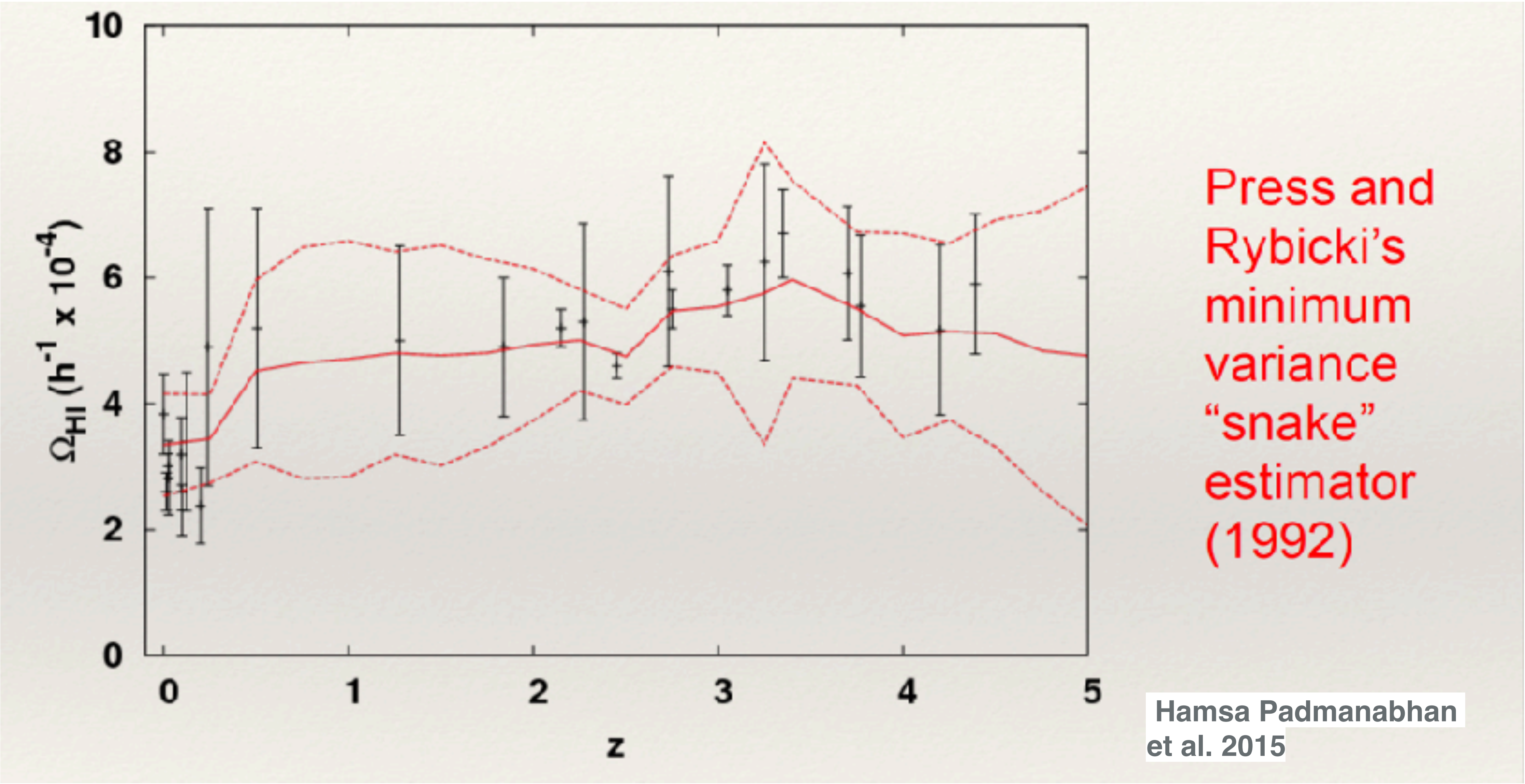
$$P_{\rm HI} \equiv [\delta T_{\rm HI}(k,z)]^2 = \bar{T}(z)^2 [b_{\rm HI}(k,z)]^2 \frac{k^3 P_{\rm cdm}(k,z)}{2\pi^2}$$

$$\bar{T}(z) = 44\ \mu{\rm K} \left(\frac{\Omega_{\rm HI}(z) h}{2.45 \times 10^{-4}} \right) \frac{(1+z)^2}{E(z)}$$

COSMOLOGY

HI Intensity Mapping in the Post EoR can be used as a cosmology probe

$$\bar{T}(z) = 44\ \mu\mathrm{K}\left(\frac{\Omega_{\mathrm{HI}}(z)h}{2.45\times10^{-4}}\right)\frac{(1+z)^2}{E(z)}$$



The HI halo Mass relation and the total HI density

$$M_{\rm HI}(M) = \alpha f_{H,c} M \left(\frac{M}{10^{11} h^{-1} M_\odot} \right)^{\beta} \exp\left[- \left(\frac{v_{c0}}{v_c(M)} \right)^3 \right]$$

Overall normalization; fraction of hydrogen relative to cosmic

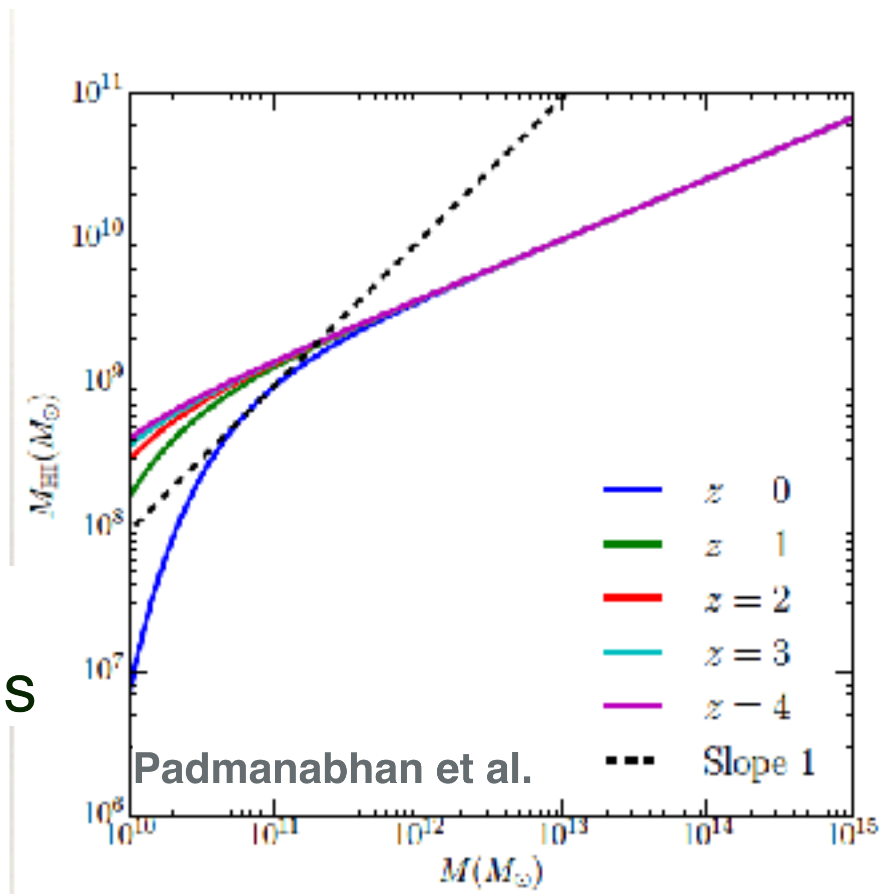
Slope

Lower cutoff

HP, Refregier, Amara, MNRAS (2017)

[cf. Barnes & Haehnelt (2010, 2014),

simulated but also compatible with observations



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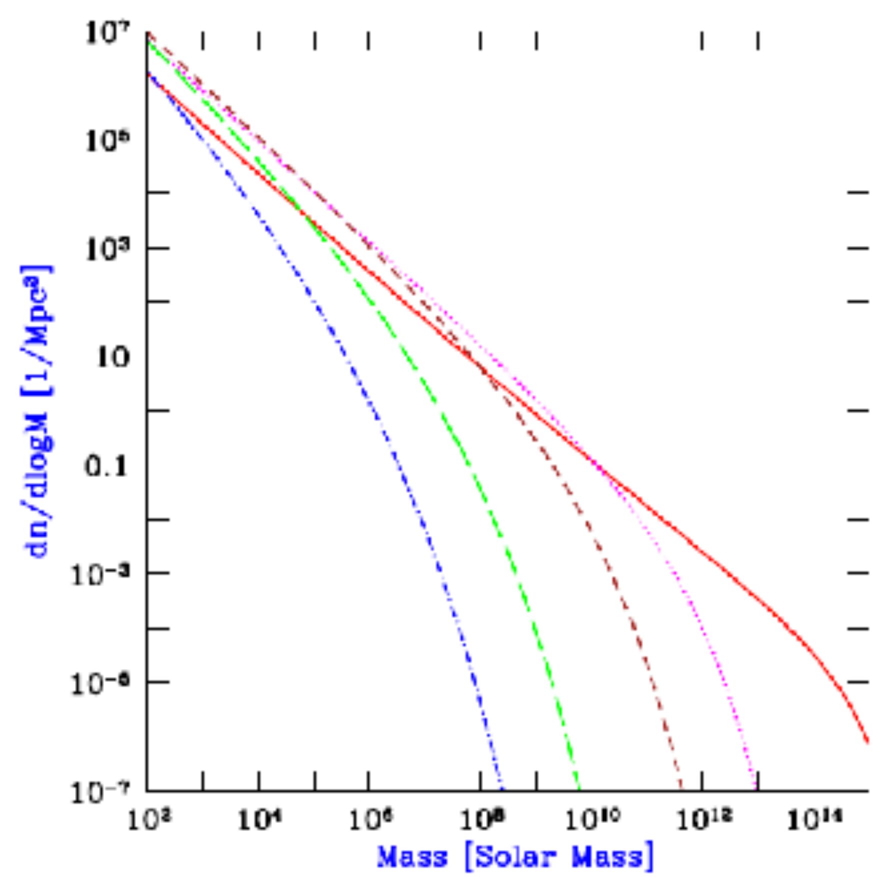
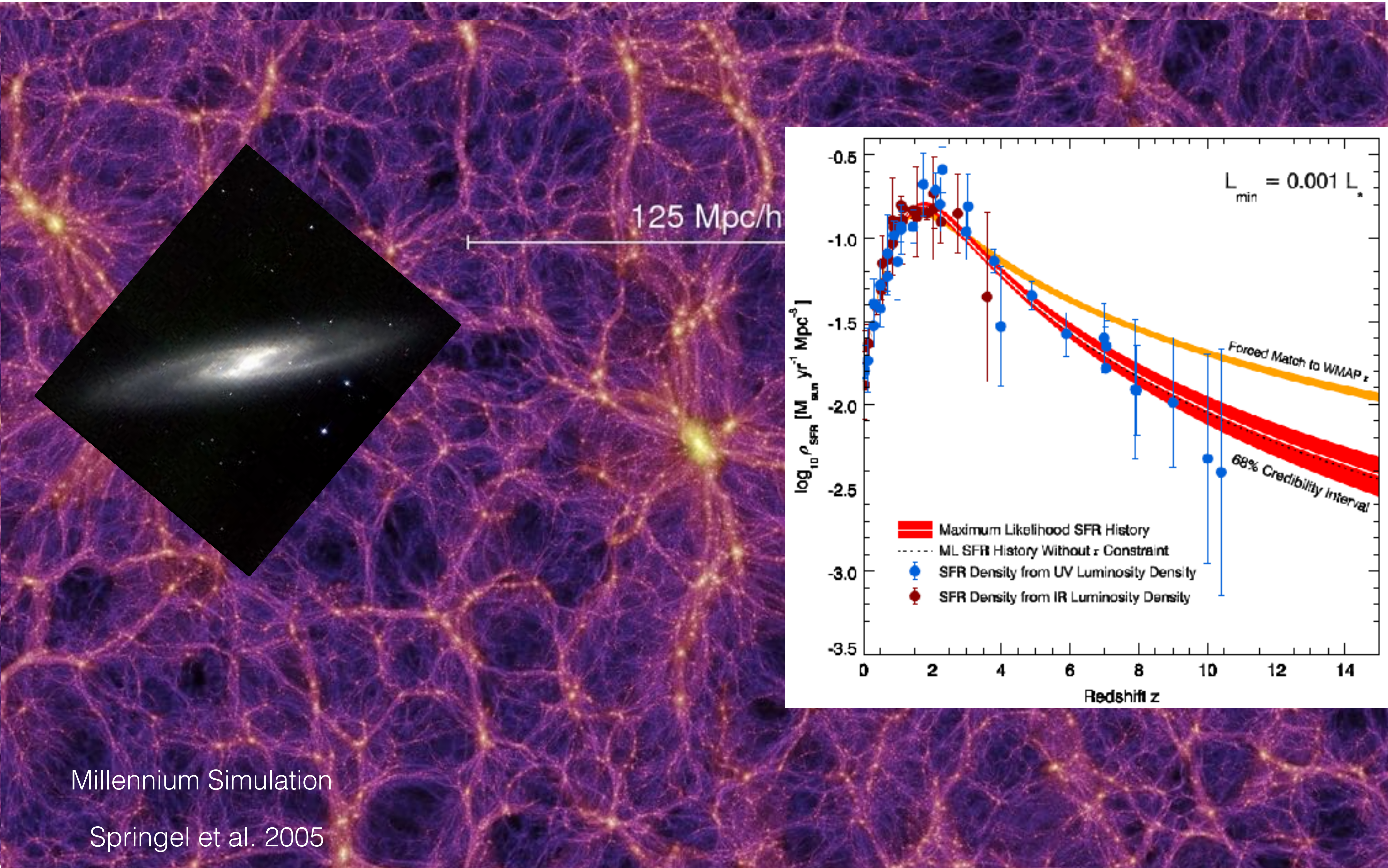


HI in Galaxies: Fuel for Star Formation



DM halos positions are correlated with the underlying matter density

Hypothesis: The HI mass in a halo scales on average with the halo mass.

Then the HI distribution will follow the matter distribution averaged over relatively large scales

HI intensity maps in the post-EoR are highly dominated by galaxies emission

Therefore, at large scales HI IM should follow Pdf

Conclusion: Conclusion: HI IM can be used for cosmology

There are still many peaces missing in the puzzle of our Universe

Thanks for your attention