The intergalactic medium
and
the epoch of reionization

Cristiano Porciani
AIfA, Uni-Bonn

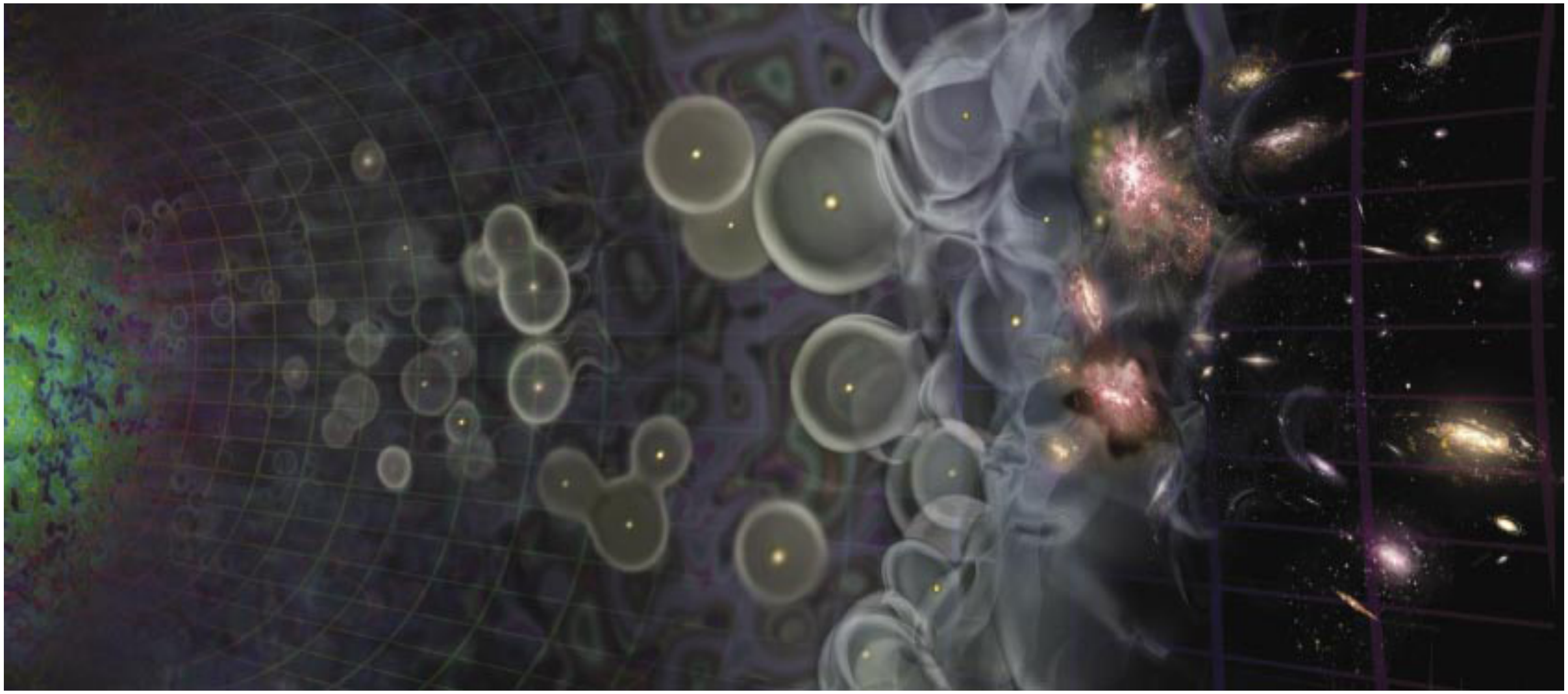
Questions?

Warning

- So far we explored rather standard physics which is well-established.
- With the class of today we enter uncharted territory at the forefront of current research.
- This means that the “unknowns” are more numerous than the “knowns”. Hope you will find this exciting!
- Bachelor, Diploma and PhD theses can be started right-away on this subject

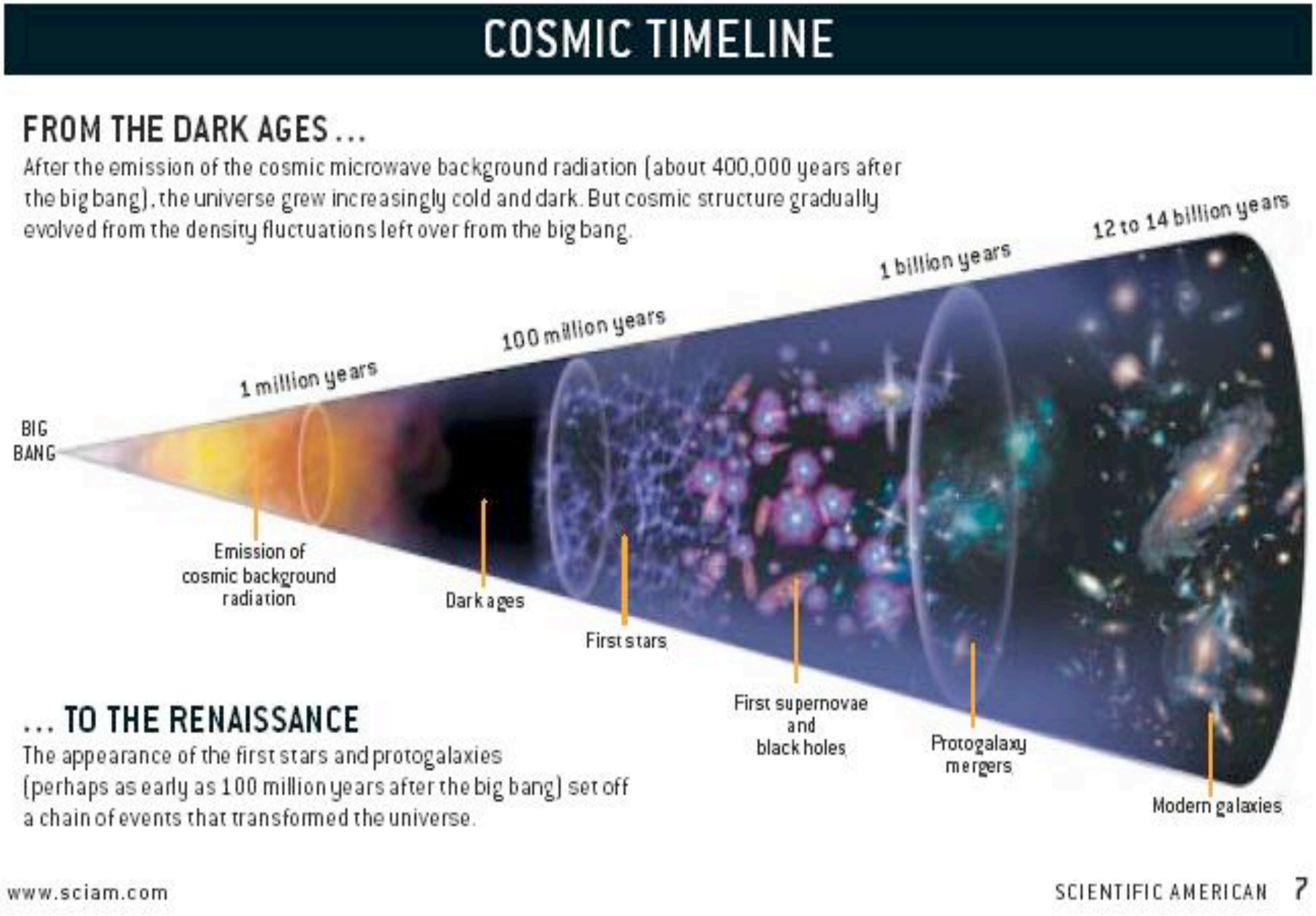
Cosmic reionization

also known as the
Epoch of Reionization (EoR)



Introduction

- The existence of the CMB and its blackbody spectrum suggest that the pre-galactic medium (PGM) was hot, fully ionized and tightly coupled with radiation via Thomson scattering off free electrons at redshift $z>1100$
- At $z\sim1100$, when the PGM temperature dropped below 10^4 K due to cosmic expansion, protons and electrons combined to form neutral-hydrogen atoms. Photons could then free stream across the universe and form the CMB.
- The absence of Gunn-Peterson troughs in quasar spectra at $z<5$ indicates that the intergalactic medium (IGM) is highly ionized at low redshift
- Can the last two statements be easily conciliated?



COSMIC TIMELINE

FROM THE DARK AGES ...

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

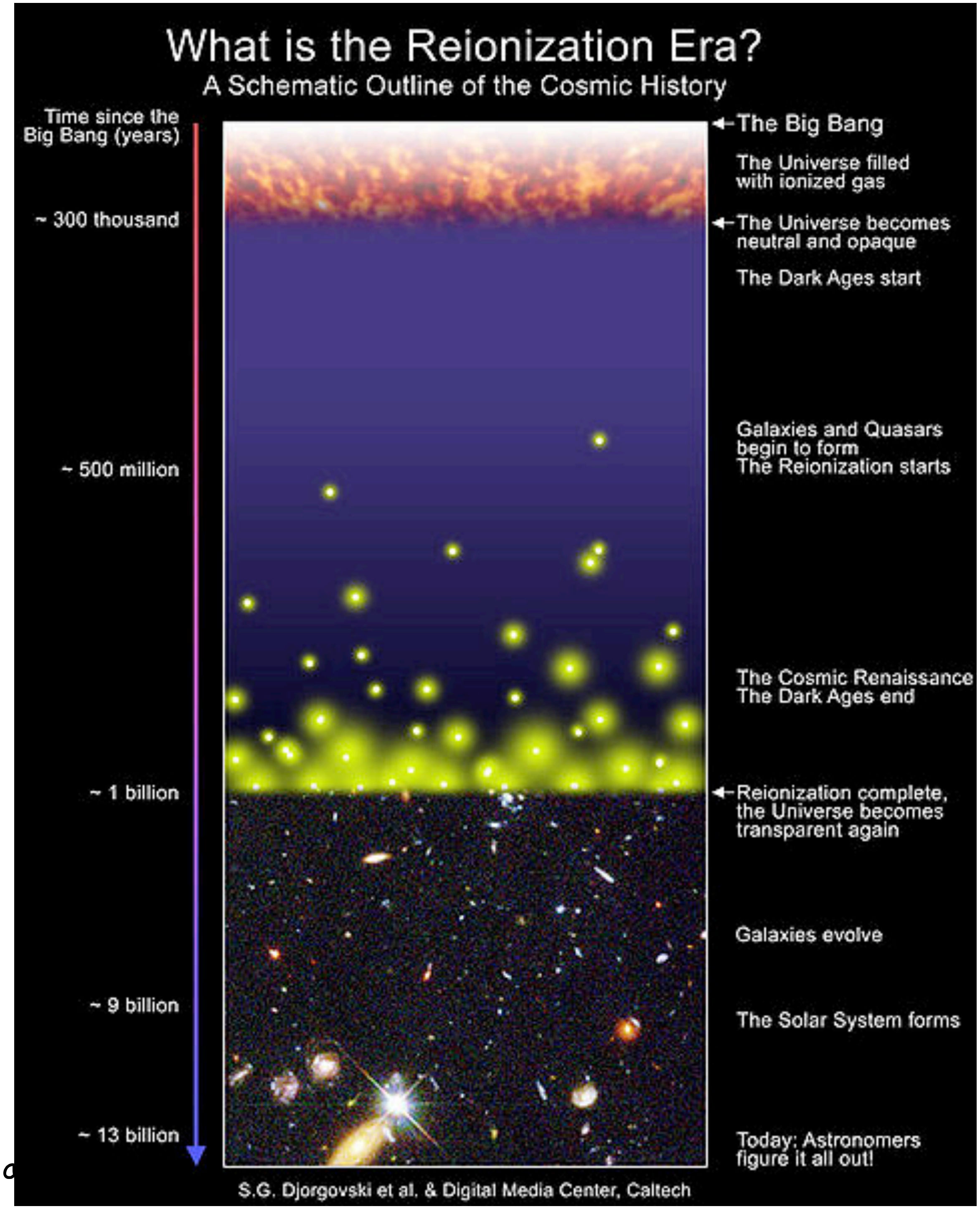
... TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

www.sciam.com

SCIENTIFIC AMERICAN 7

With time souces become more and more abundant. Random points in the IGM start receiving UV photons by more than one source.



S.G. Djorgovski et al. & Digital Media Center, Caltech

The first UV sources start ionizing gas in their neighbourhood

Finally, the bubbles cover the whole volume. This is known as percolation (or bubble-overlap) phase.

Currently pressing questions

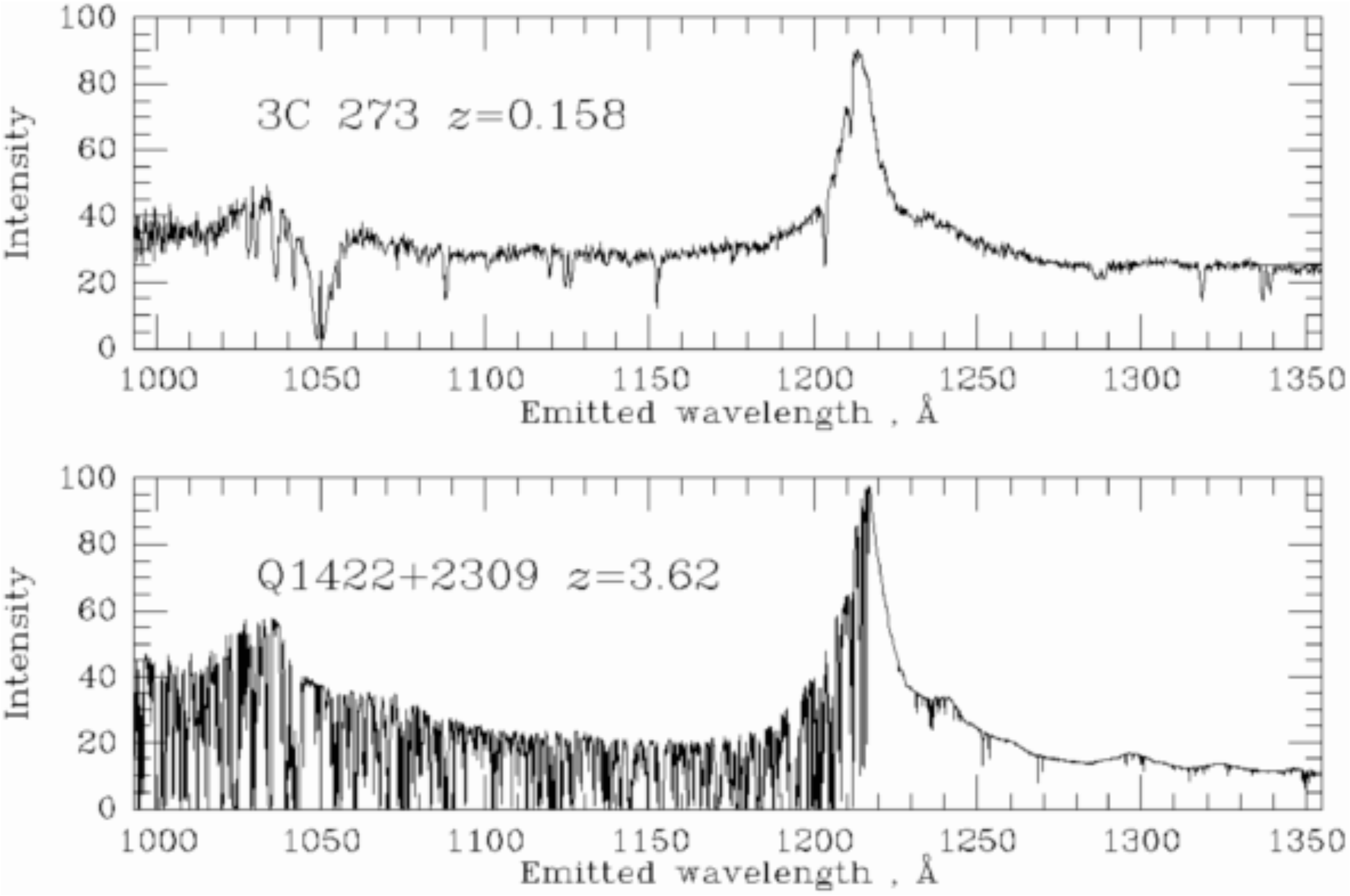
- WHEN: When did it happen? How long did it last?
- WHO: What were the sources responsible?
- HOW: How did it proceed? Was it gradual or sudden? What was its topology? (inside-out vs. outside-in) Was it homogeneous or patchy?

When did reionization take place?

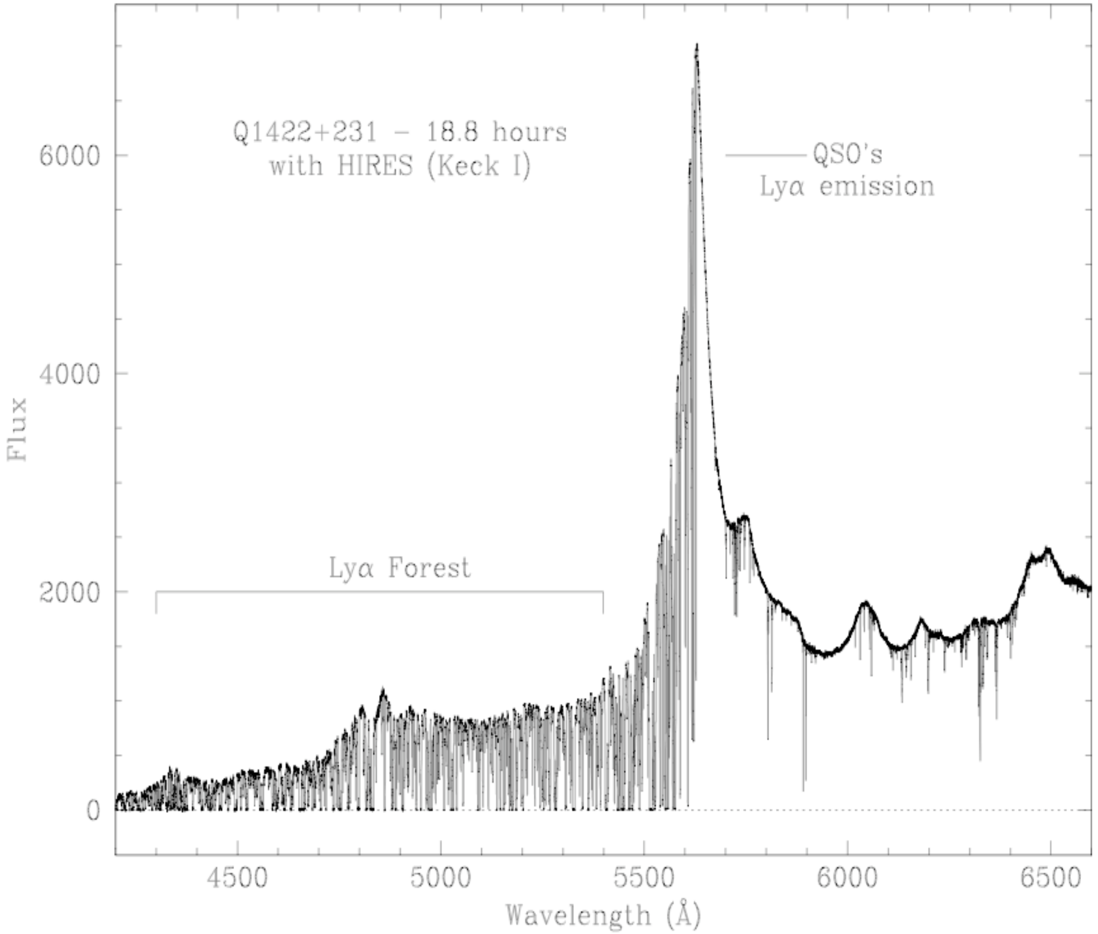
Constraints from quasar absorption lines and CMB

Quasar spectra and absorption lines

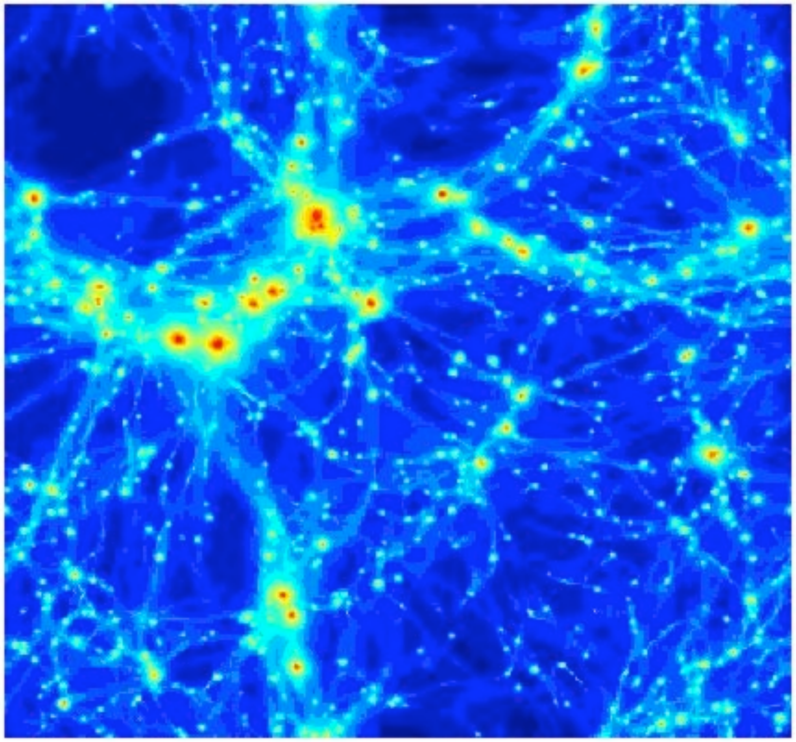
Courtesy B. Keel



Spectrum of a z~3 quasar



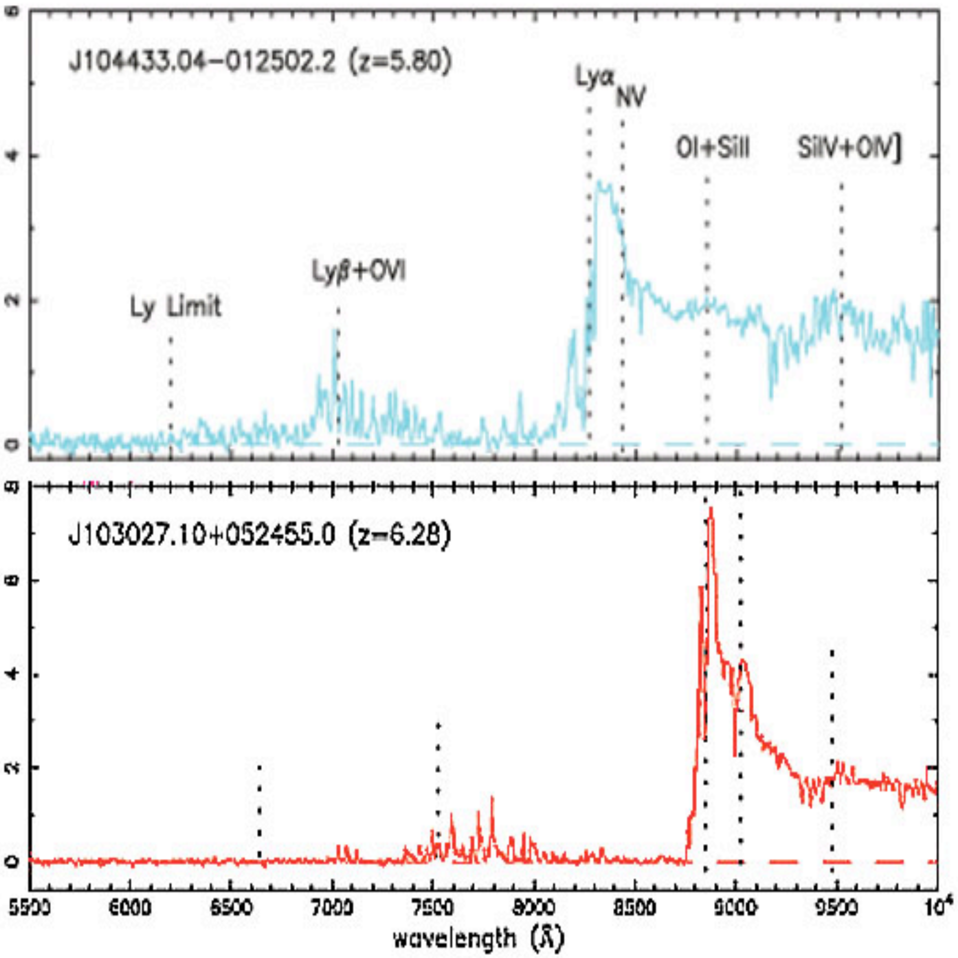
The intergalactic medium

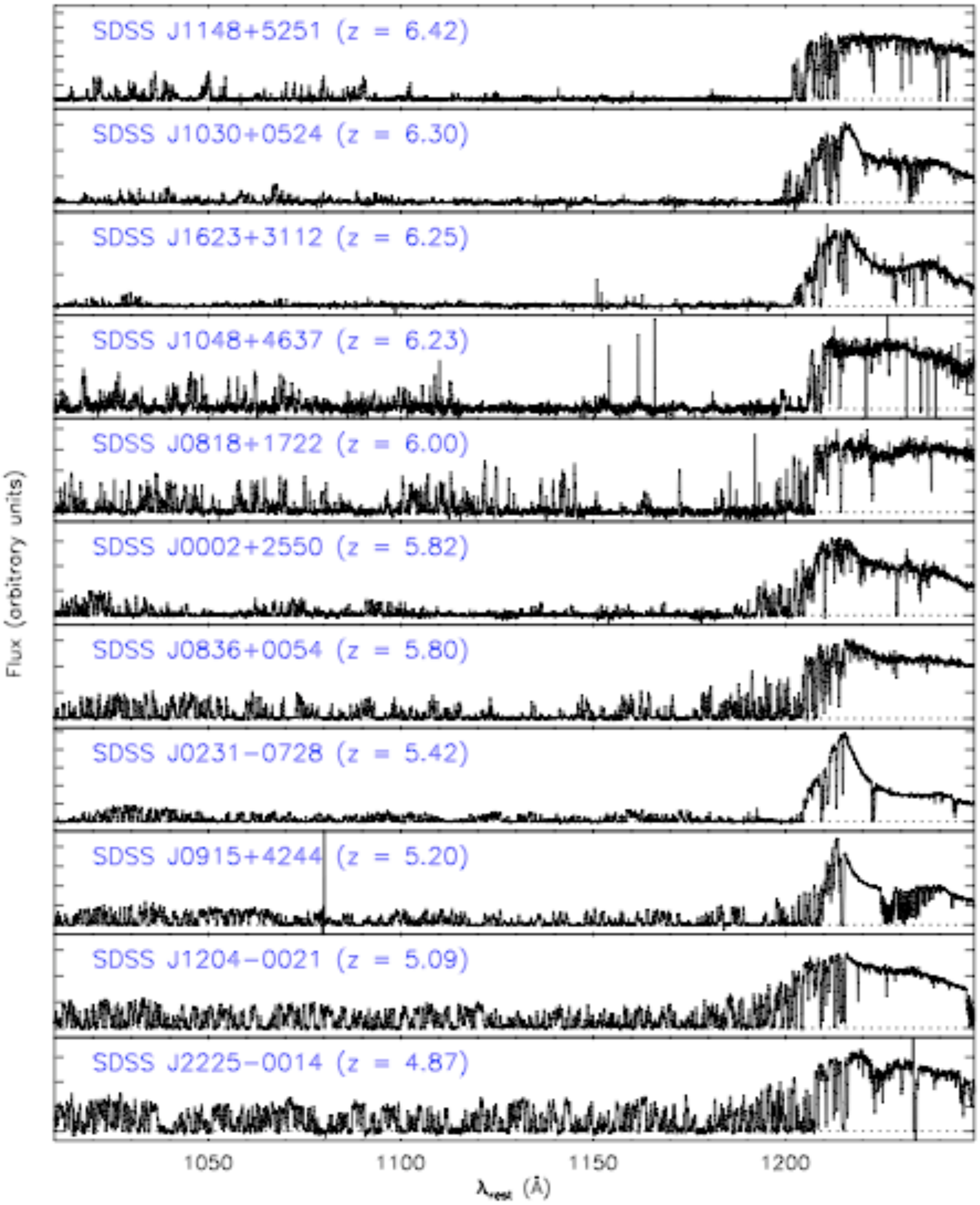


- Lyman-alpha absorption against background quasars can be successfully modeled within CDM models for structure formation
- The IGM at z<6 is highly photoionized by an ultraviolet cosmic background generated by the combined action of young stars and quasars
- Intergalactic gas appears to have a rather tight temperature-density relation

Quasar spectra at z=6

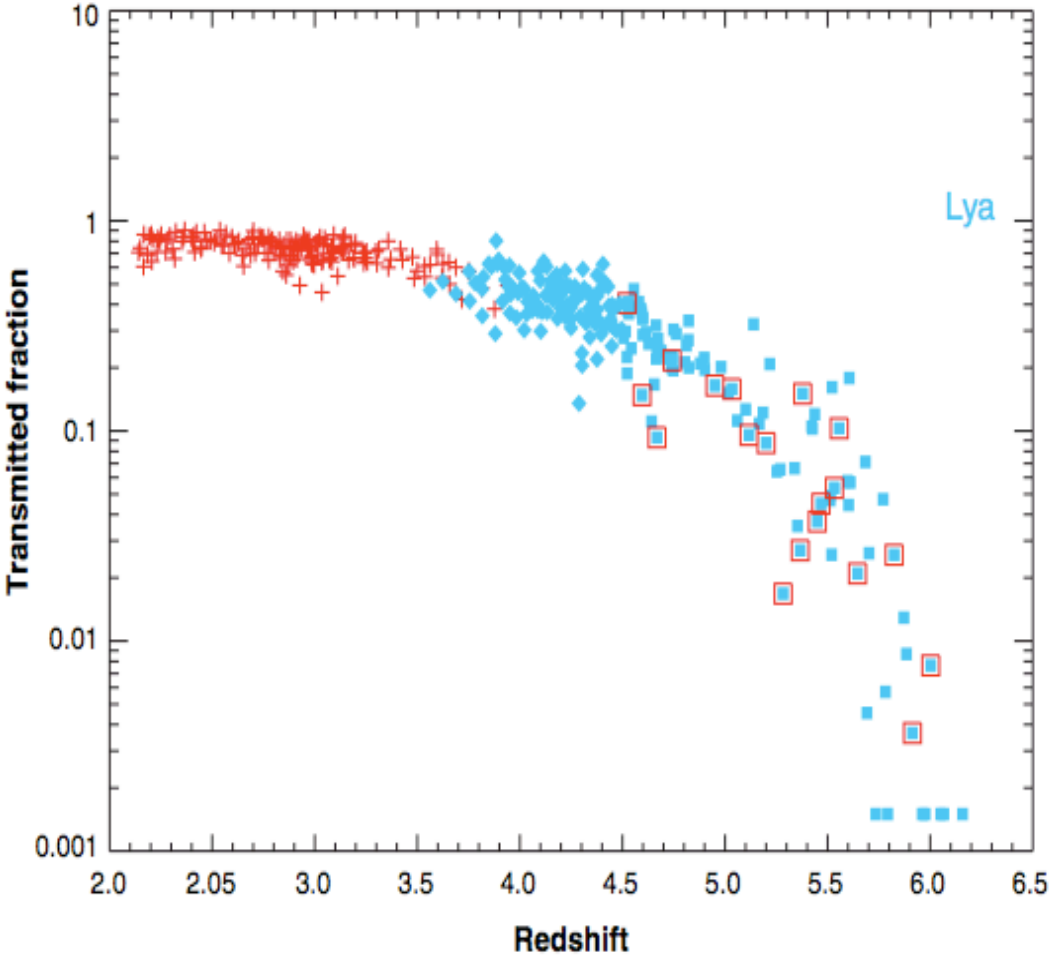
Becker et al. 2001





Evidence for evolution!

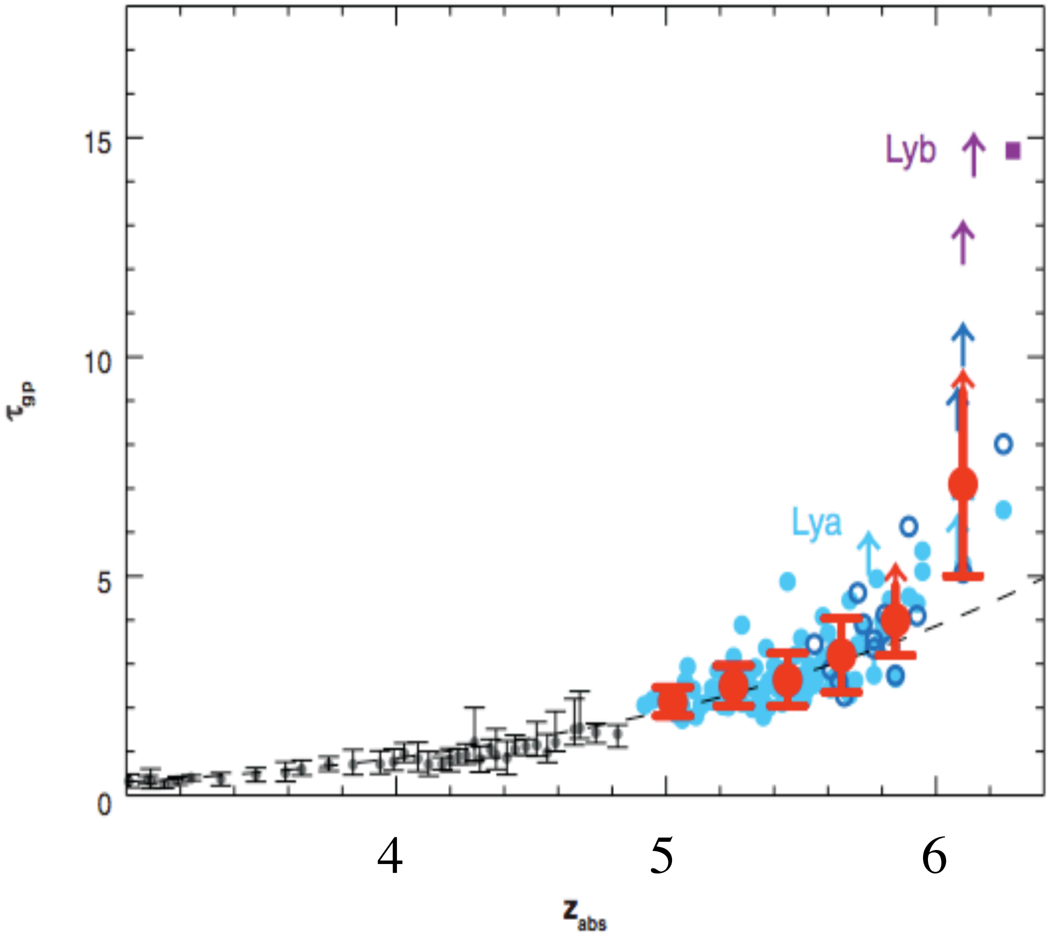
Transmitted flux



Optical depth

Best-fit at z<5.5

$\tau_{gp} \propto (1+z)^{4.3}$

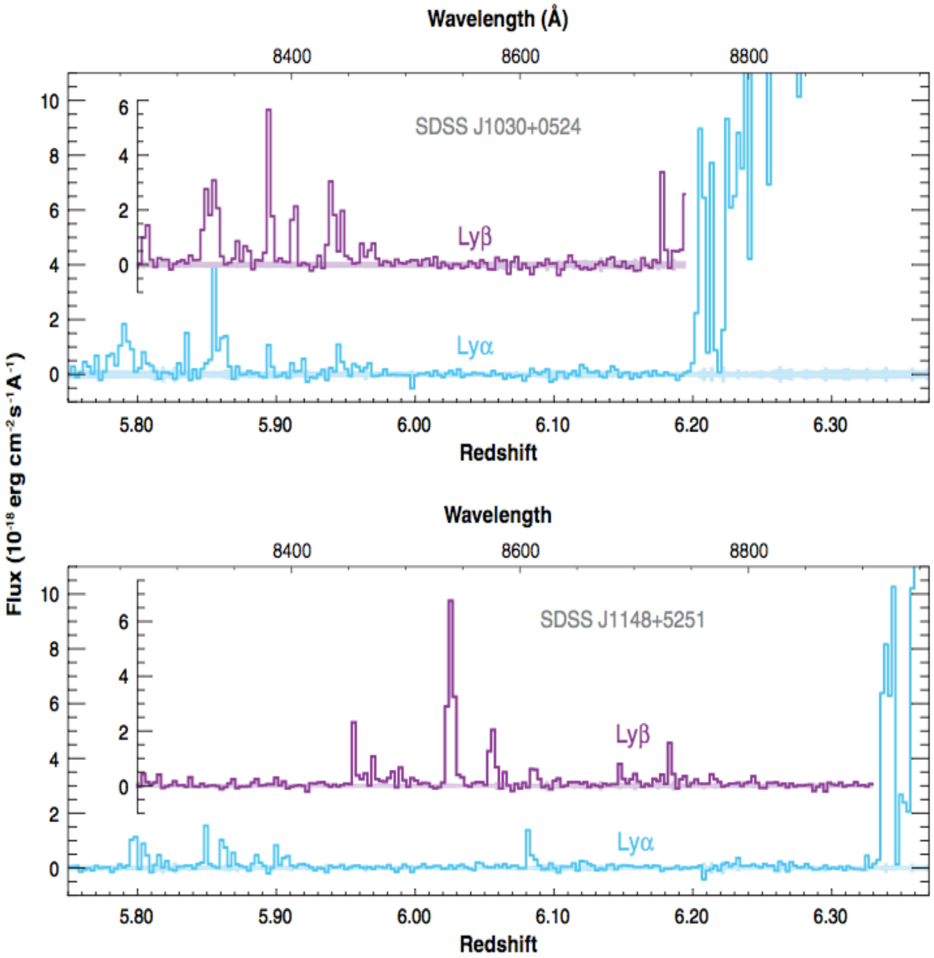


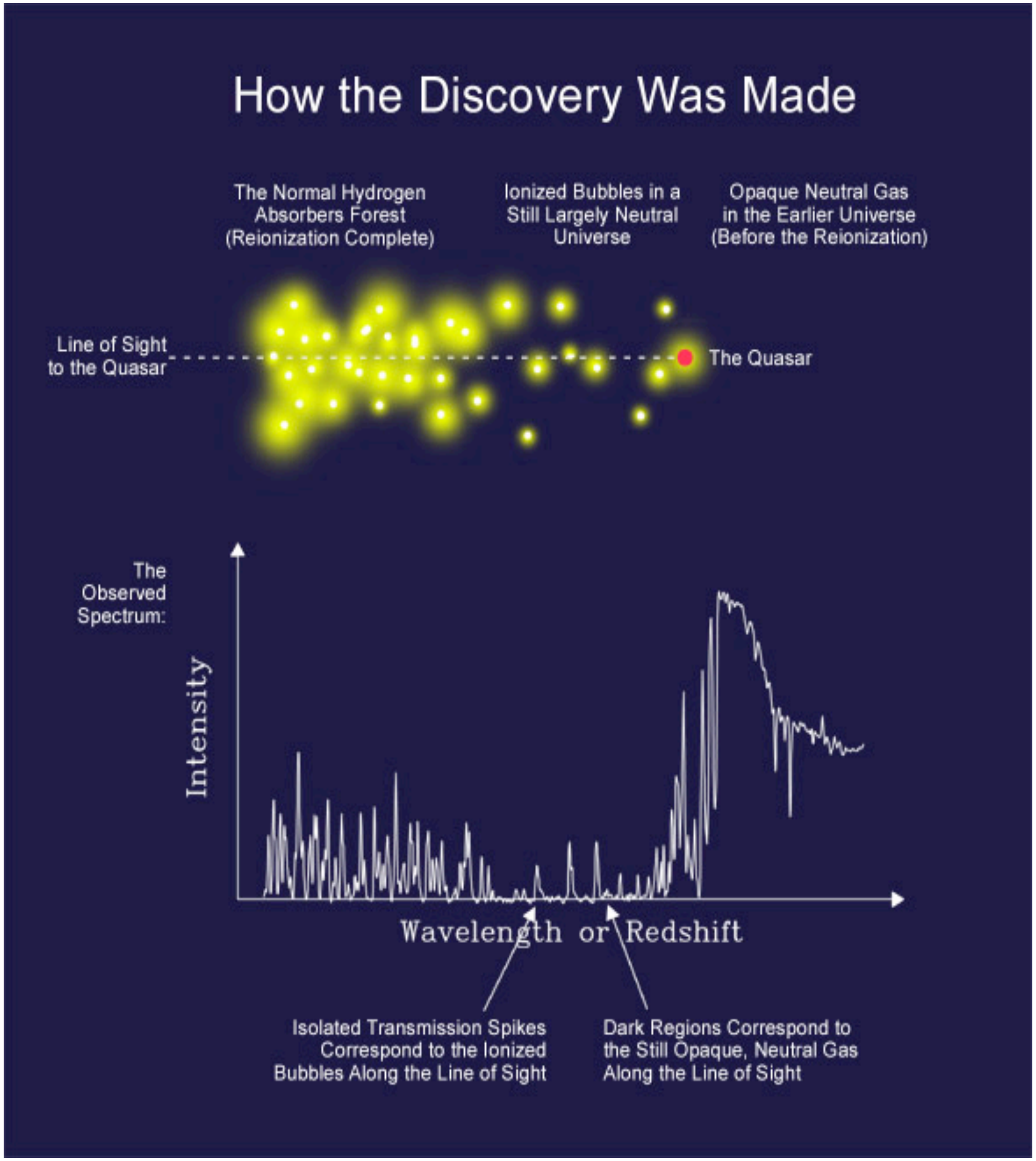
Best-fit at z>5.5

$\tau_{gp} \propto (1+z)^{10.9}$

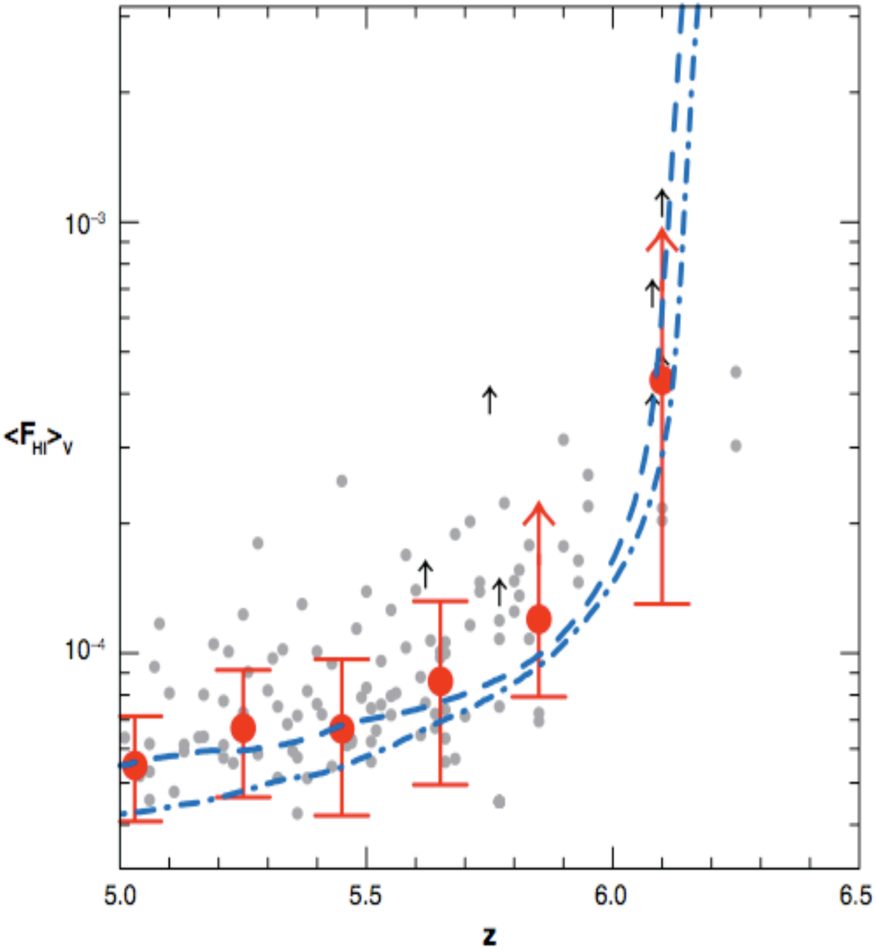
Note that also the scatter grows, as expected near bubble overlap

GP trough finally seen!




How the Discovery Was Made
The Normal Hydrogen Absorbers Forest (Reionization Complete)
Ionized Bubbles in a Still Largely Neutral Universe
Opaque Neutral Gas in the Earlier Universe (Before the Reionization)
Line of Sight to the Quasar
The Quasar
The Observed Spectrum:
Intensity
Wavelength or Redshift
Isolated Transmission Spikes Correspond to the Ionized Bubbles Along the Line of Sight
Dark Regions Correspond to the Still Opaque, Neutral Gas Along the Line of Sight

Volume-averaged neutral fraction



The dashed lines show the outcome of two different numerical simulations

Remarks

- Because of the large optical depth it is hard to push the GP-trough analysis to higher redshifts ($e^{-\tau}$ is basically zero if τ is 5 or 5,000 and with the current signal-to-noise of the spectra it is not possible to distinguish the two cases)

- Therefore it is really hard to infer the corresponding neutral fraction (realistically, you can only get a lower limit)!

- The GP results indicate that cosmic hydrogen is likely between $10^{-3.5}$ to $10^{-0.5}$ neutral at z=6.

- One expects that transmission is mainly due to rare voids while most HI lies at higher overdensities. In consequence, estimates of the neutral fraction depend on a number of assumptions regarding the density distribution of the baryons, quasar physics, etc.

- Need other methods: e.g. statistics of dark gaps, OI and SiII forest

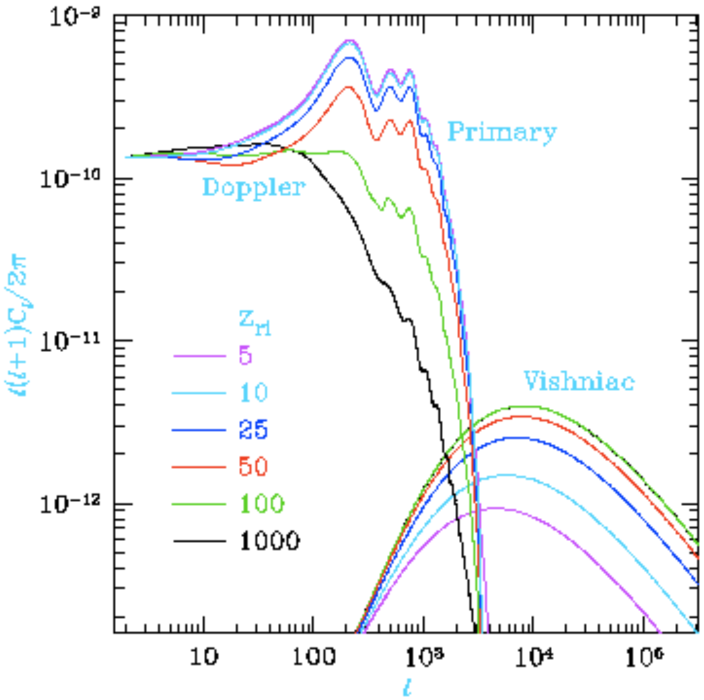
So, quasar absorption lines suggest that reionization started before z=6 and might have reached the percolation phase around z=6.

What about CMB studies?

The EoR and the CMB: Temperature anisotropies

- Reionization produces free electrons that can scatter off CMB photons at late times.
- Therefore, CMB probes of the EoR are sensitive to ionized hydrogen and are therefore complementary to the GP effect which is sensitive to neutral hydrogen.
- On scales smaller than the causal horizon at the EoR primordial temperature perturbations are then reduced as $e^{-\tau}$ (with τ the optical depth to Thomson scattering).
- Patchy reionization, however, generates new temperature fluctuations on small angular scales ($l>2000$)

CMB and reionization



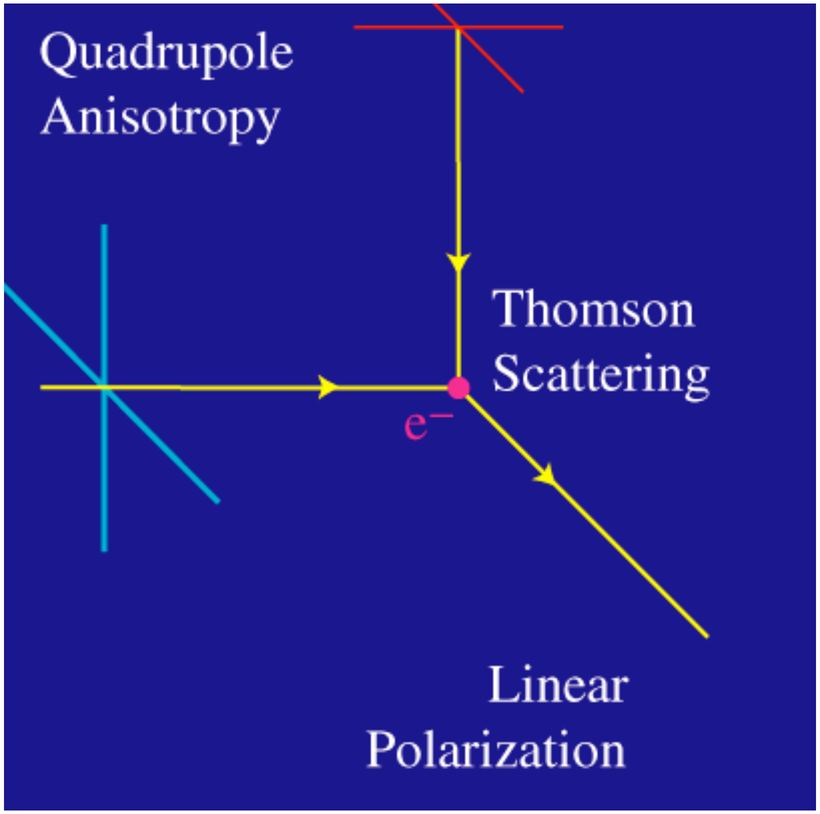
- Rescattering of CMB photons damps fluctuations as $e^{-\tau}$, with τ the optical depth to Thomson scattering

- New perturbations are generated on small scales due to the bulk motion of electrons in overdense regions (Ostriker-Vishniac effect)

The EoR and the CMB: Polarization

- In Thomson scattering: scattered radiation is polarized parallel to the incident polarization

- If, in the rest-frame of the electron, the radiation possesses a non-zero quadrupole anisotropy, then the scattering leads to linear polarization on a scale comparable to the horizon at time of scattering

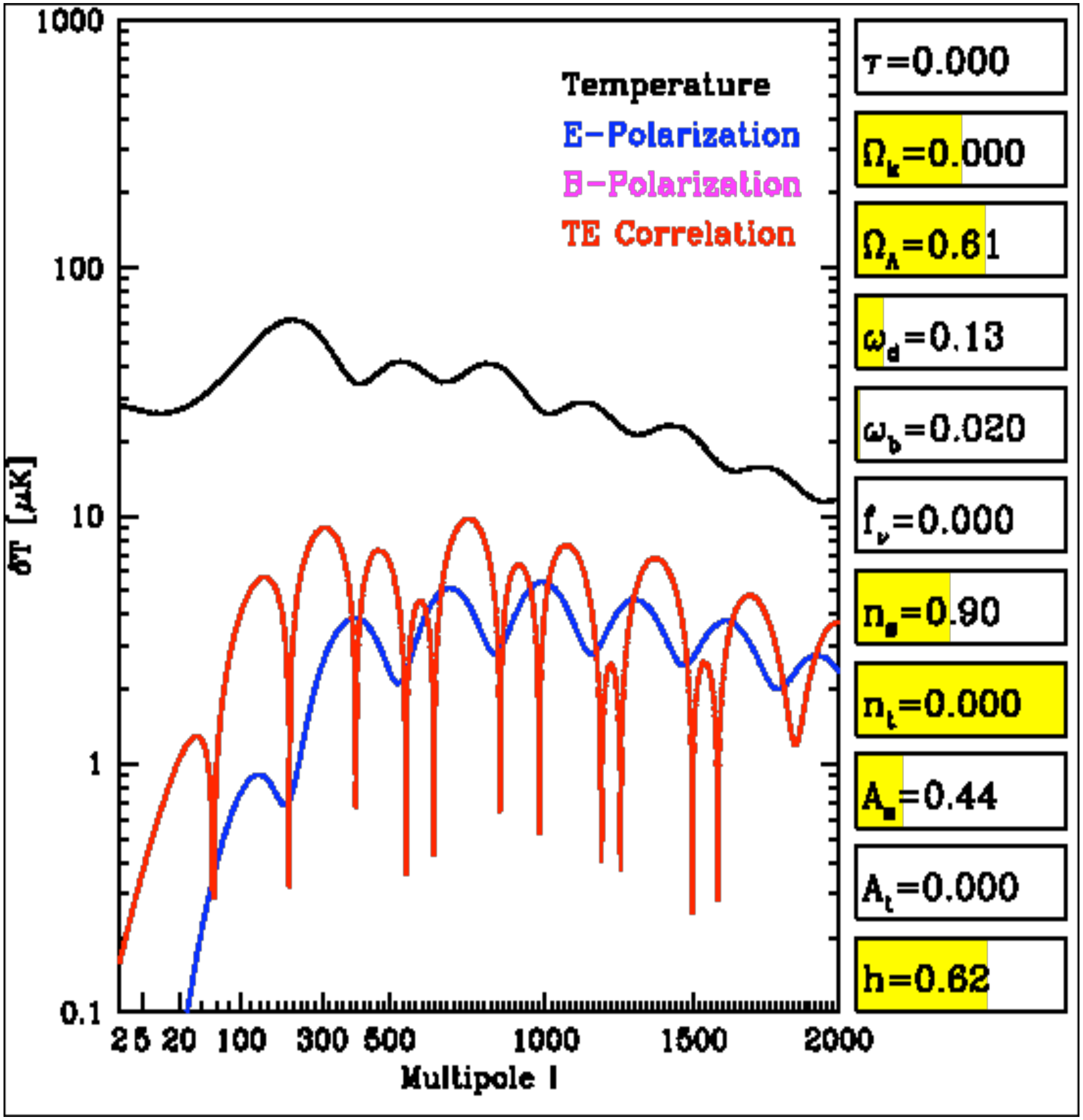


A technical issue

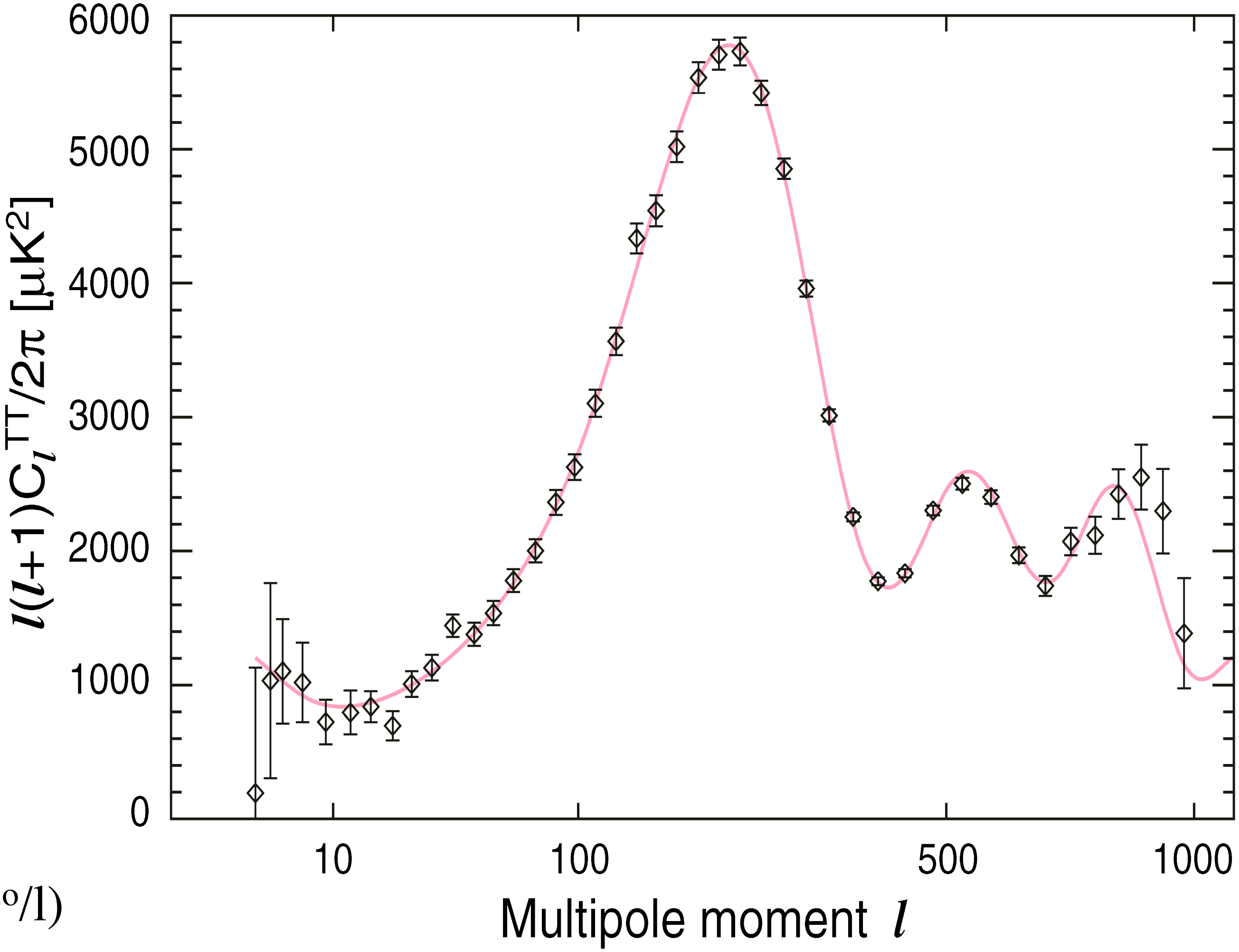
- The polarization pattern on the sky can be decomposed into two independent components.
- The E-mode (divergence-like with no-handedness) and the B-mode (curl-like with handedness).
- E-mode generated by reionization.
- B-mode can be generated by gravitational waves and gravitational lensing.

$$\mathbf{Y}^{(E)}_{\ell m,ab} = \frac{1}{\ell(\ell+1)}\left[\nabla_a \nabla_b - \frac{1}{2}\delta_{ab}\right] Y_{\ell m}(\hat{\Omega})$$

$$\mathbf{Y}^{(B)}_{\ell m,ab} = \frac{1}{\ell(\ell+1)}\frac{1}{2}\left[\epsilon_{ac}\nabla_c \nabla_b + \nabla_a \epsilon_{bc}\nabla_c\right] Y_{\ell m}(\hat{\Omega})$$

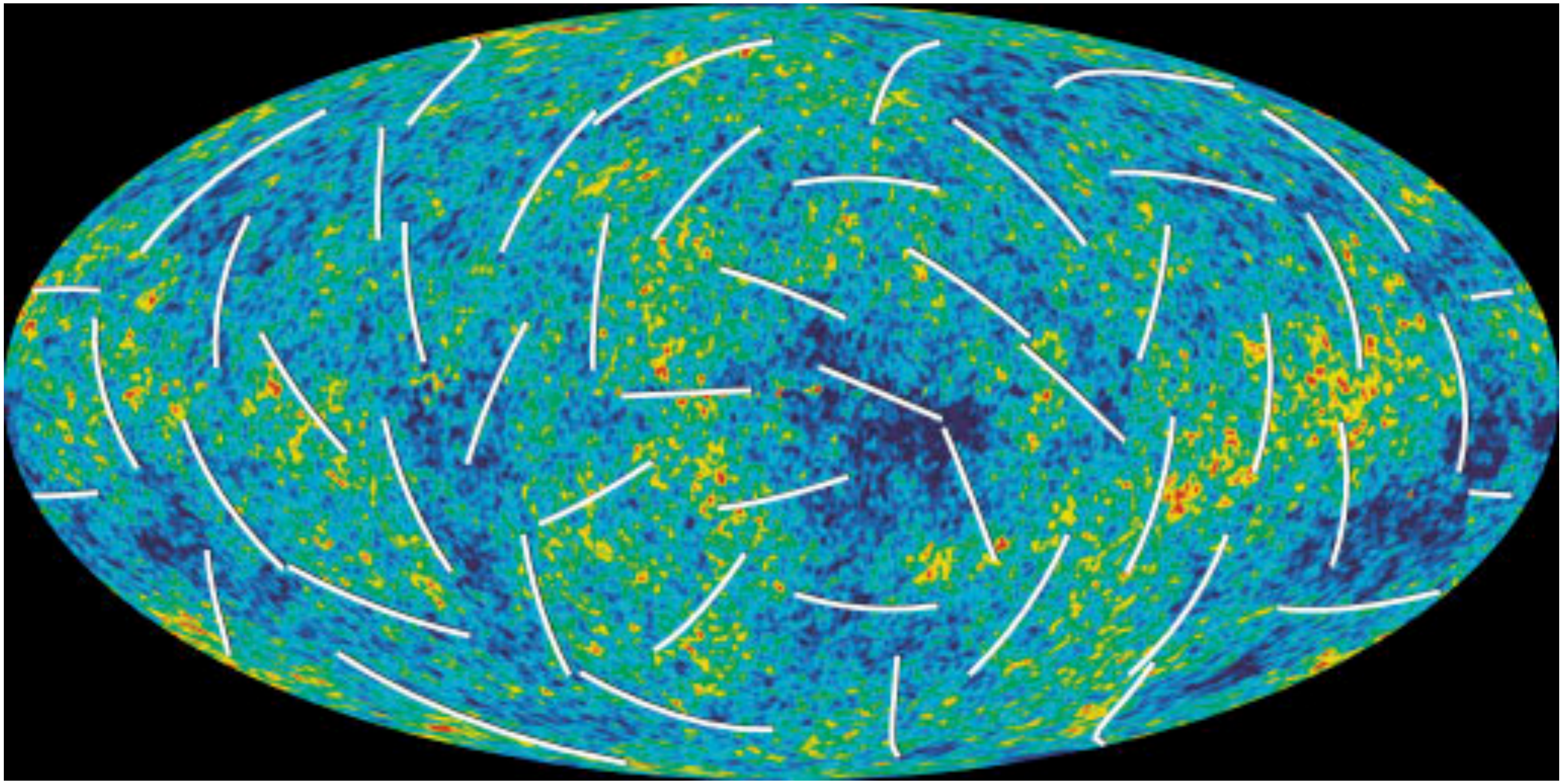

Temperature
E−Polarization
B−Polarization
TE Correlation
1000
100
10
1
0.1
δT [μK]
2 5 20 100 300 500 1000 1500 2000
Multipole l
τ=0.000
Ω_k=0.000
Ω_Λ=0.61
ω_d=0.13
ω_b=0.020
f_ν=0.000
n_s=0.90
n_t=0.000
A_s=0.44
A_t=0.000
h=0.62

Temperature fluctuations

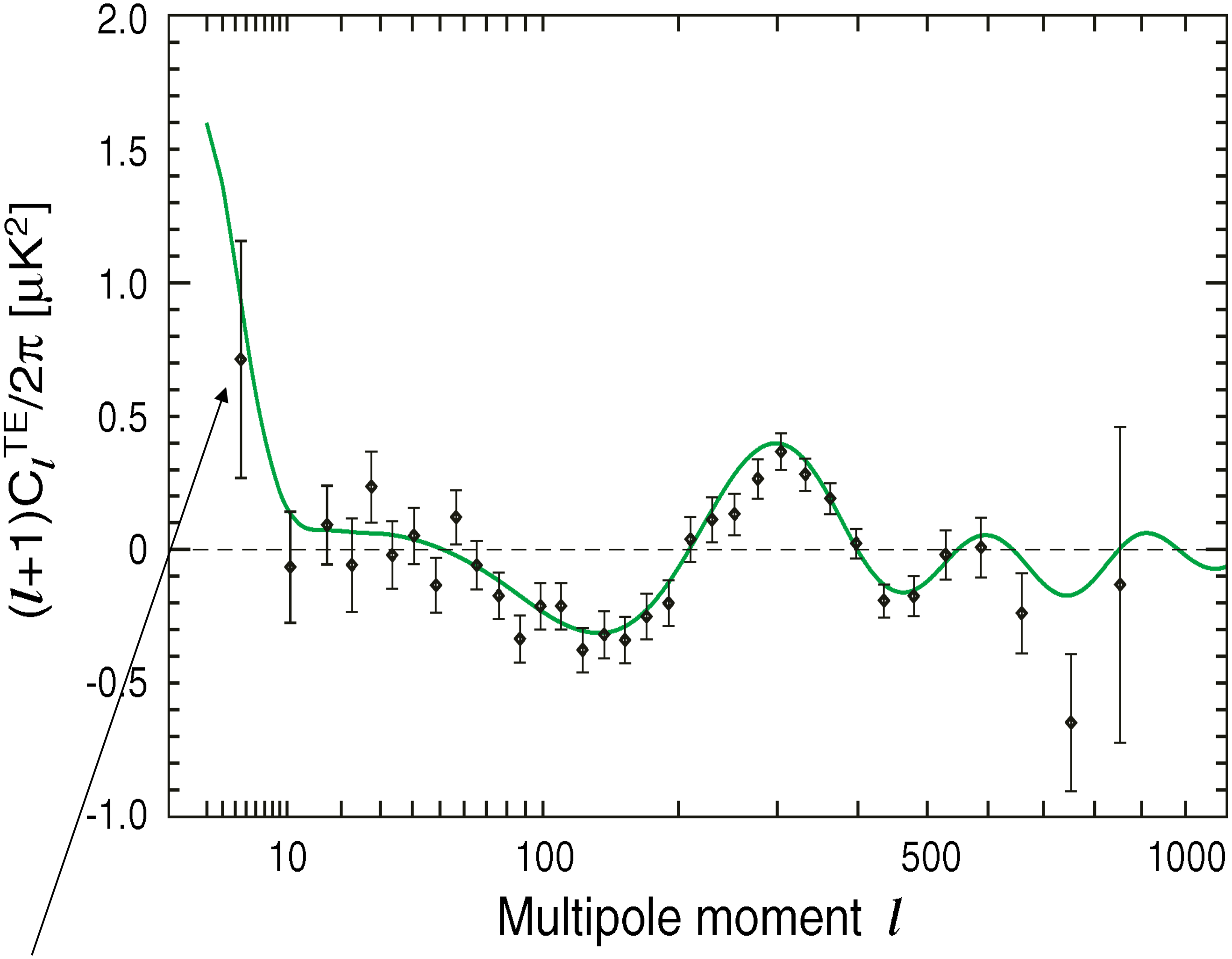


Variance at
multipole l
(angle ~180°/l)

The WMAP measurement

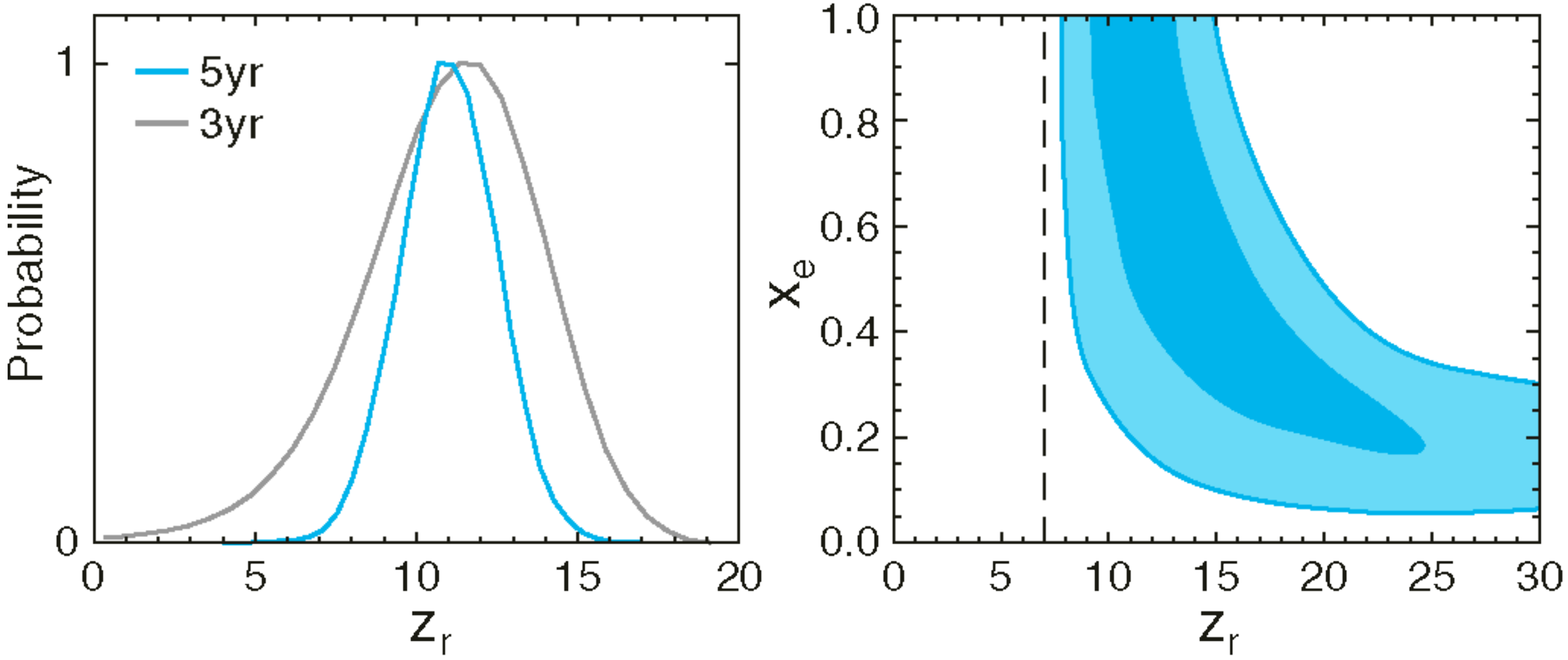


Nolta et al. 2009



Re-scattering of CMB photons during and after reionization added to the polarization spectrum at large angular scales.

Dunkley et al. 2009



Current results

- The combined analysis of the WMAP 5-yr data (temperature and polarization) gives $\tau = 0.087 \pm 0.017$ (Dunkley et al. 2009)

- This means that nearly 9% of the CMB photons have been re-scattered by free electrons produced by the reionization process.

- Assuming that the universe was reionized instantaneously, this gives $z_{reion} = 11.0 \pm 1.4$

- This is only an indicative result as reionization is likely to have been extended in time.

How did reionization take place and what were the UV sources?

Still an open question

- It can be easily shown (see for instance the past classes on the intergalactic medium) that at $z<4$ observed stars and quasars produce enough UV photons to explain the high level of ionization in the IGM

- However, the nature of the sources responsible for converting most of the IGM from neutral to ionized remains uncertain, as does the epoch of reionization

Energetically: easy task!

- Nuclear fusion releases 7 x 10^6 eV per proton.
- Black-hole accretion even 10 times more!
- It only takes 13.6 eV to ionize an hydrogen atom.
- Therefore, converting a fraction $\approx 10^{-5}$ of baryonic mass into stars or black holes would be more than enough to ionize the rest of the universe.

Caveats

- Not all the UV photons leak out from galaxies! (This is genereally described by the f_{esc} parameter)
- Ionizing all atoms is not enough, one has also to keep all atoms ionized thus preventing hydrogen to recombine!
- The presence of dense mini-halos can slow down the propagation of ionization fronts.
- Exact estimates depend on many details but, basically, a few ionizing photons per baryon (let's say from 2 to 10) should be enough to do the job.

Looking for the culprit

- We know that there are not that many bright quasars at $z>4$. What about galaxies?
- Massive stars in known high-redshift galaxies should produce from 2 to 20 ionizing photons per proton by $z=6$. This might or not be enough.
- Nuclear fusion also produces metals and one has to pay attention that reionization models do not overproduce the metallicity of the IGM. Many subtle details play a role here, for instance the physical mechanisms with which metals are spread out in the IGM by galaxies.
- The most recent studies indicate that, if galaxies provide a substantial contribution to reionization, then galaxies below current detection limits must play a significant role.
- In other words, steep luminosity functions at the faint end are required.
- Alternatives: mini-quasars, Pop III (metal free) stars, decay of exotic particles (all somewhat unlikely)

Patchy or homogeneous?

- In principle, from the degree of patchiness and the size of the ionizing bubbles before overlap it should be possible to infer the origin of the sources.

- Quasars should produce a very patchy reionization, galaxies a more uniform transition and decaying particles like light neutrinos a very uniform one.

- Current data do not allow this kind of analysis yet but there are ideas about how to do it in the future.

Pop III stars

- Very massive, metal free stars with harder UV spectra

- Boost in ionizing photon rate by a factor of ≈20

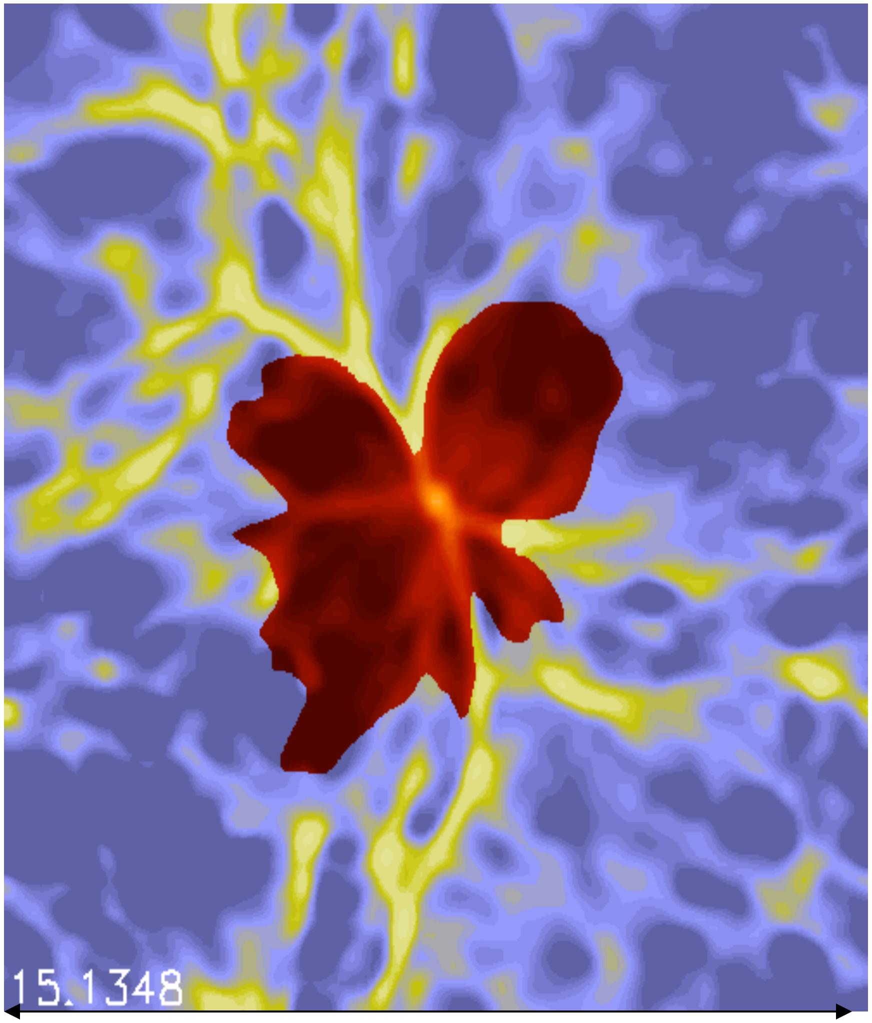
- Return to “normal” stellar pops at $Z>10^{-4}\ Z_{\odot}$

- But too few if only one per halo can be formed (remember that molecular hydrogen is destroyed by UV photons)

Numerical simulations

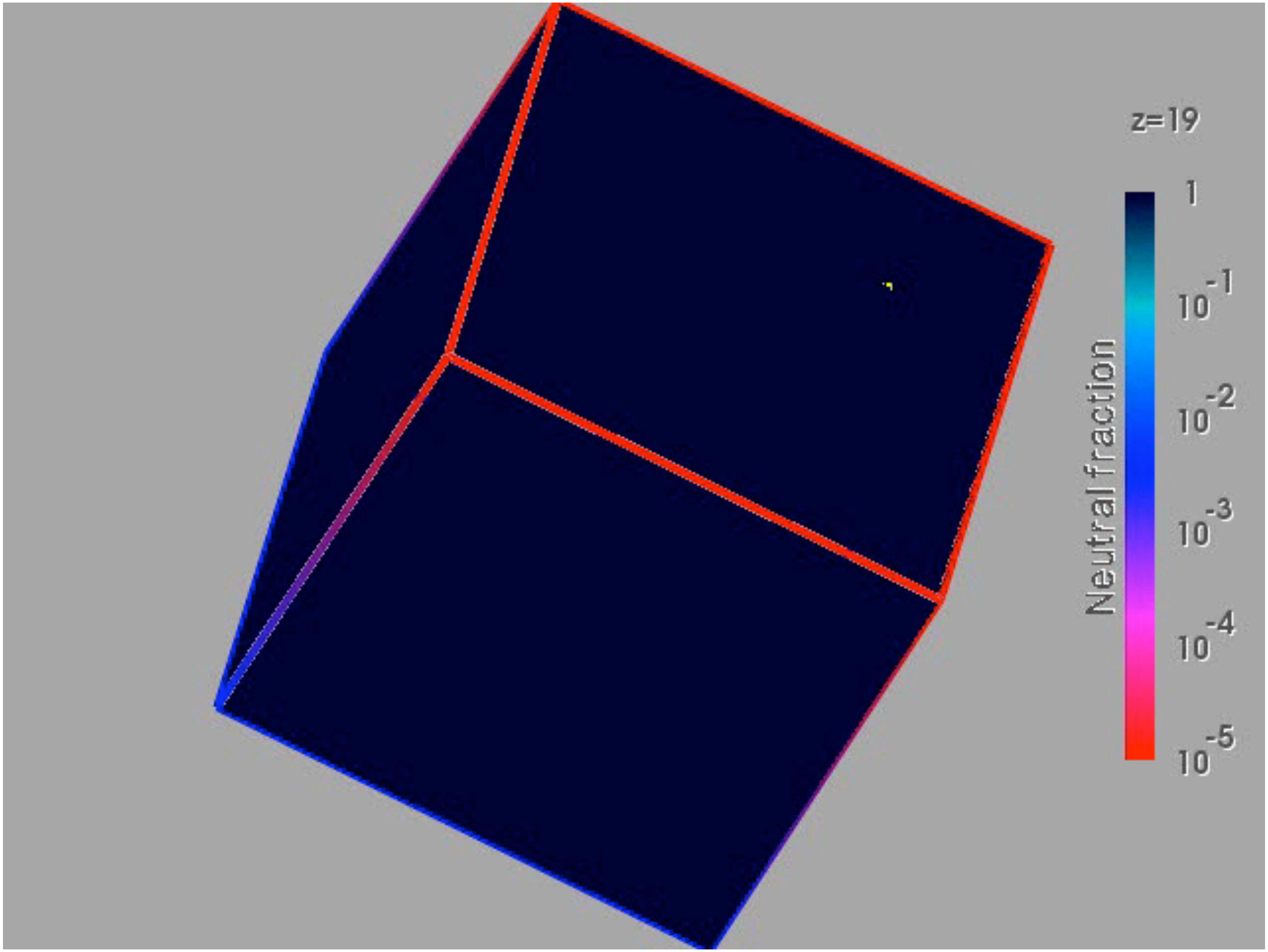
- Numerical simulations including radiative transfer helped shading new light on the reionization process.
- Note that numerical radiative transfer requires working in 7 dimensions and is very computationally demanding!
- This is much more complex than simulations of the IGM at $z<5$ where the UV background is assumed to be uniform and the optically-thin approximation is used.

Ionization fronts are not spherical



300 kpc proper

Galaxy at z=7


z=19
Neutral fraction
1
10^-1
10^-2
10^-3
10^-4
10^-5

Reionization history and the thermal state of the IGM

- During reionization, the IGM is heated up by the photoionization process

- For gas around mean density, the dominant cooling process is the adiabatic expansion of the universe, except at $z>7$ when inverse Compton cooling off the CMB is more efficient

- Because its cooling time is relatively long, the low-density IGM retains some memory of when and how it was ionized

Constraints from the thermal history of the IGM

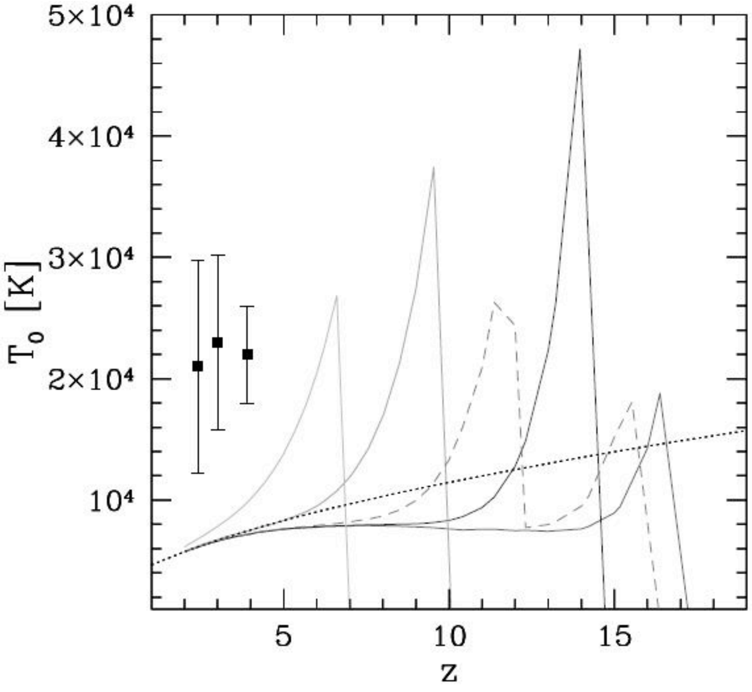


FIG. 1.—Thermal asymptote (*dotted line*; eq. [4]), illustrating the fact that a wide range of ionization histories results in the same IGM temperature by redshift $z = 4$, unless reionization occurs late. Each solid line describes the evolution of the temperature (T_0) for a fluid element at mean density, according to a different reionization history (and a different initial reheating temperature). The dashed line illustrates the thermal evolution for a complex reionization history—such complexities do not stop the temperature from reaching the late-time asymptote, as long as they take place early, before $z \sim 10$. The points with ($2\,\sigma$) error bars on the left are measurements of T_0 from the Lyα forest (ZHT01). [*See the electronic edition of the Journal for a color version of this figure.*]

- Thermal state at z<4 does not remember ionization history at z>10

- However, it has short-term memory of z<10 events

- An higher reionization redshift implies a lower temperature

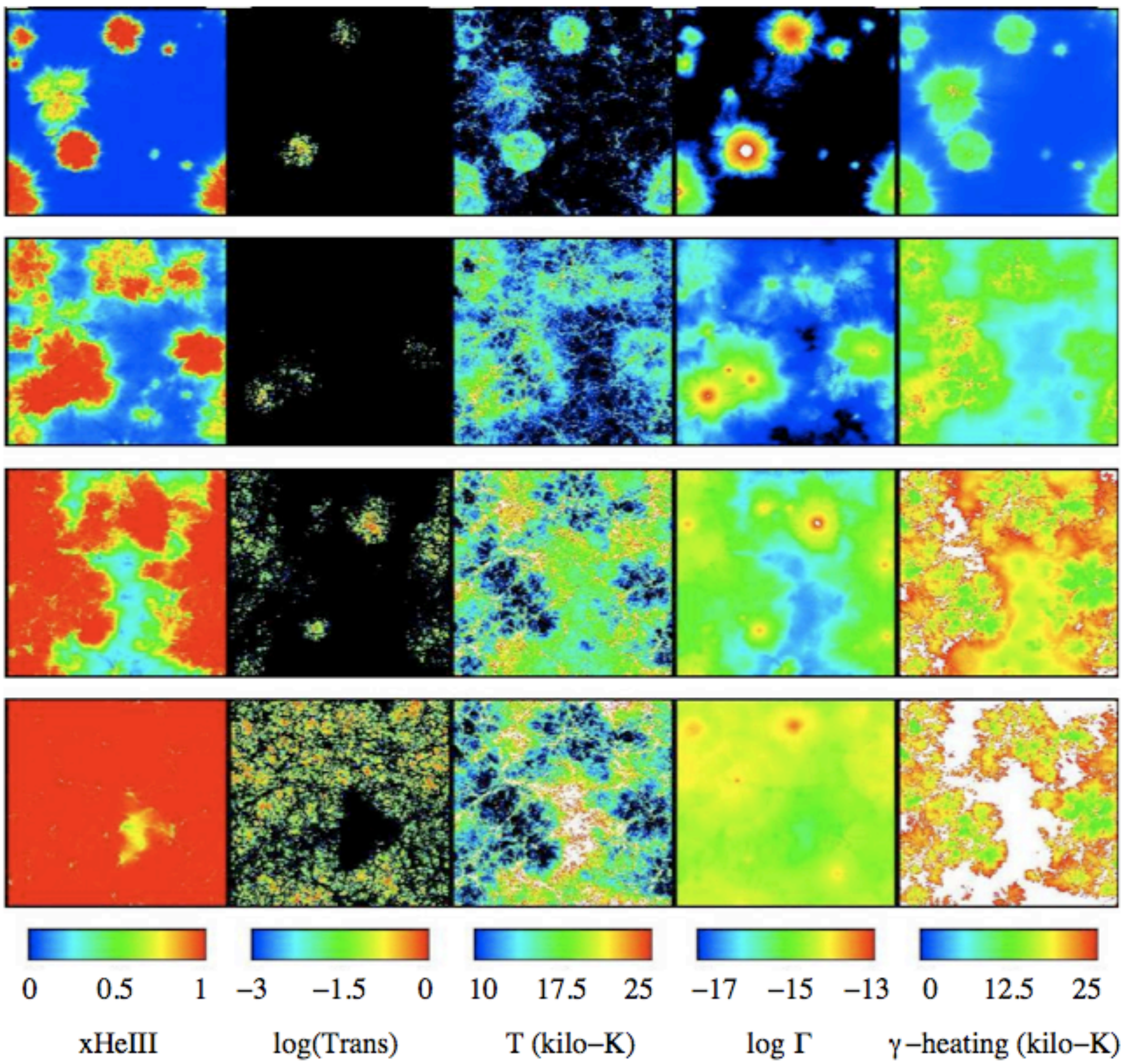
- Models cannot match observations?

Helium II reionization

HeII reionization in a nutshell

- The ionization threshold of HeI (24.6 eV) is quite close to that of HI (13.6 eV).
- There is nearly 1 helium atom every 10 hydrogen atoms.
- In the standard picture of reionization, therefore, population II stars ionized the intergalactic HI at $z>6$ as well as the HeI, converting the vast majority of intergalactic helium to HeII.
- However, these stars cannot ionize HeII.
- It is therefore expected that quasars, with their harder UV spectrum, doubly ionize helium at late times ($z \approx 3$).

Simulating HeII reionization



HeIII
Fraction

0.1

0.5

0.8

0.99

(cumulative
HeII heating)

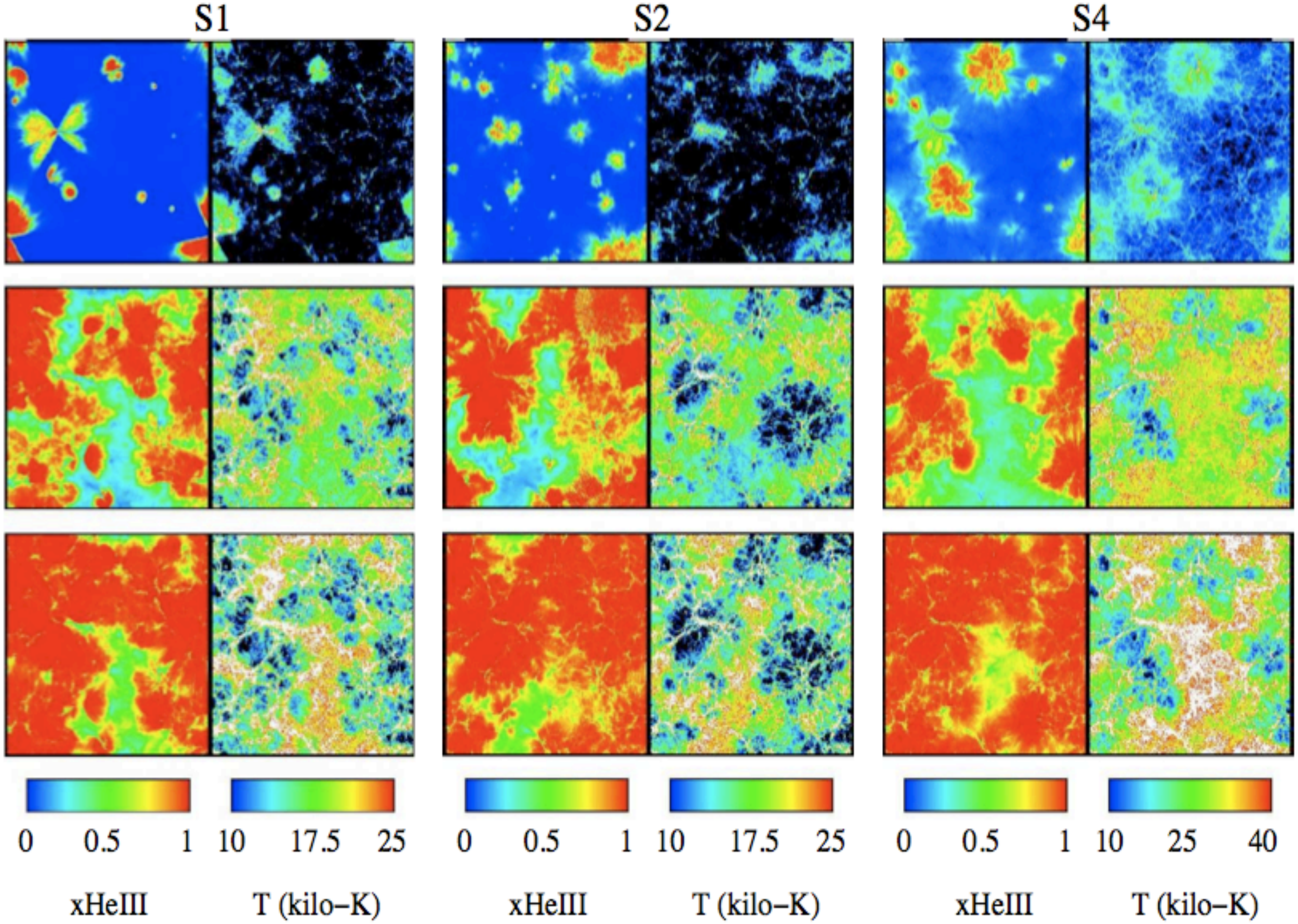
C. Porcia

HeIII fraction

0.1

0.75

0.90



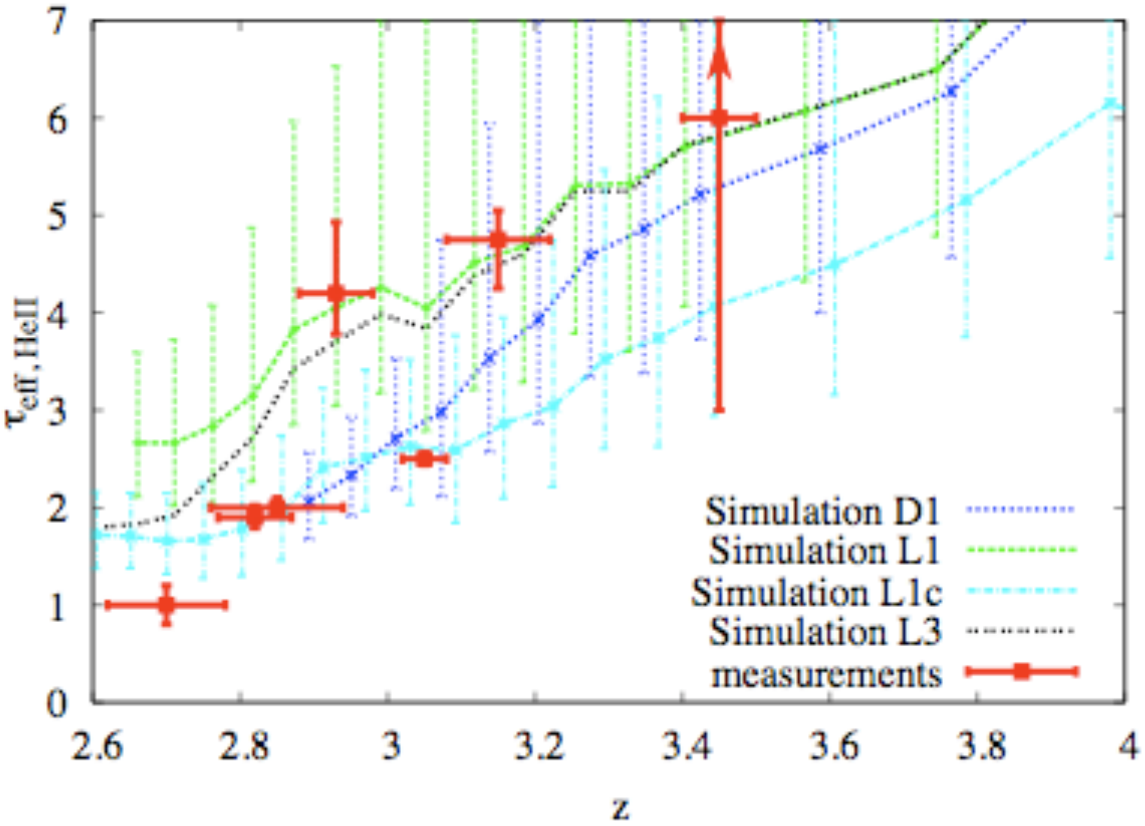
Beamed quasars

Light-bulbs

Very hard spectrum

t_{qso}=10 Myr

HeII Gunn-Peterson effect

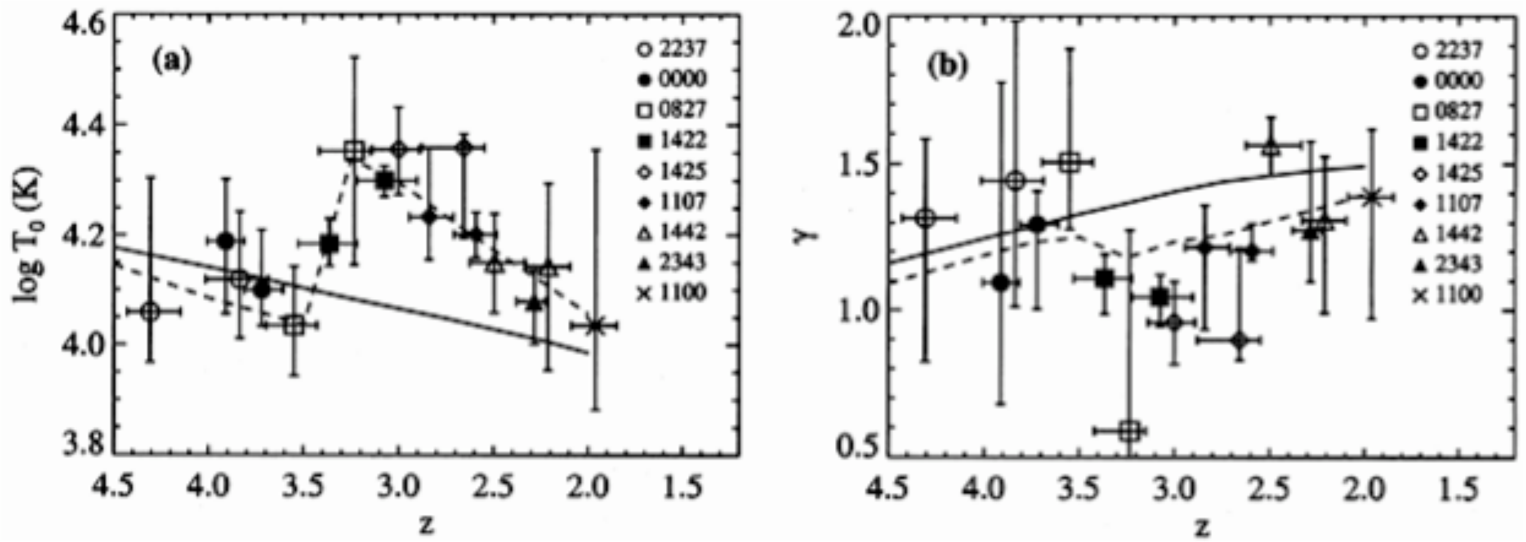


There are currently only a handful of HeII Lyα forest sightlines!

Data suggest that second reionization of He has happened around redshift 3 at the peak of quasar activity.

The situation will improve dramatically with the advent of the Cosmic Origins Spectrograph (COS) on HST (installed during the fourth servicing mission in May 2009).

Thermal history at z~3



Temperature at mean density and slope of the effective equation of state as a function of redshift. Horizontal errorbars indicate the redshift interval spanned by the absorption lines. Vertical errorbars are 1σ errors. The continuous line correspond to a simulation with an Haardt-Madau UV background dominated by quasars. The dashed line to a model where quasar provide a much smaller contribution at high redshift. This provides (weak) evidence that HeII reionization happens at z ~ 3.2.

The current state of the art

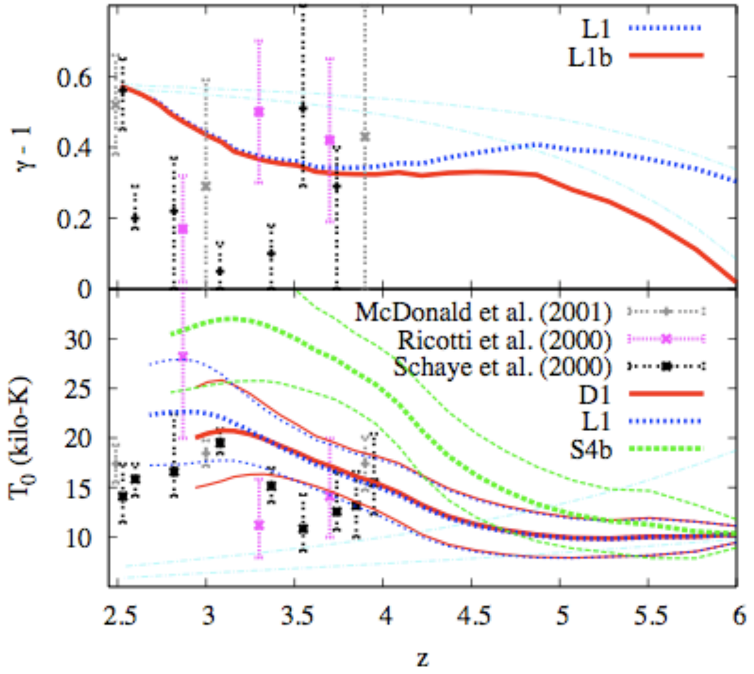


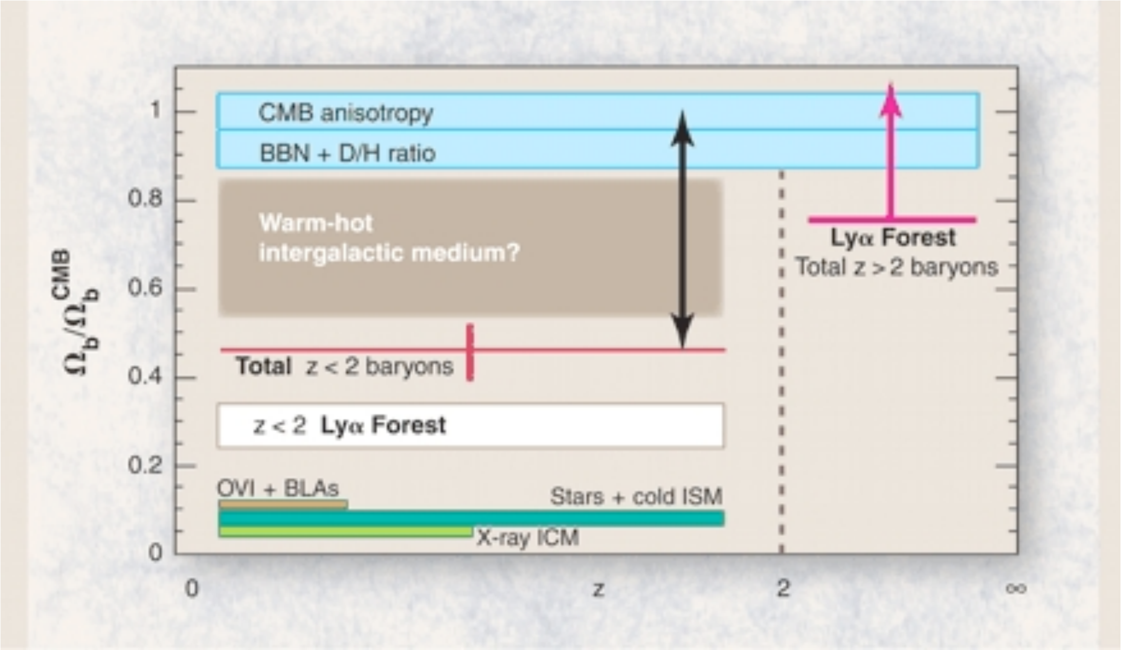
FIG. 12.— Top Panel: Best-fit power-law index of the T-Δ_b relation in two simulations (thick curves), as well as its evolution in simulations without a $z \sim 3$ HeII reionization (thin curves). The markers with error bars are measurements of this quantity in the literature, and the references for these measurements are given in the key in the bottom panel. Bottom Panel: Evolution of best-fit T_0 in three simulations (thick curves) as well as ±1 s.d. in this quantity (the thinner curves with the same line style). The thin cyan dot-dashed curves that are increasing with z represent simulations in which HeII reionization occurs at $z > 6$. Also shown are measurements of T_0.

Conclusions

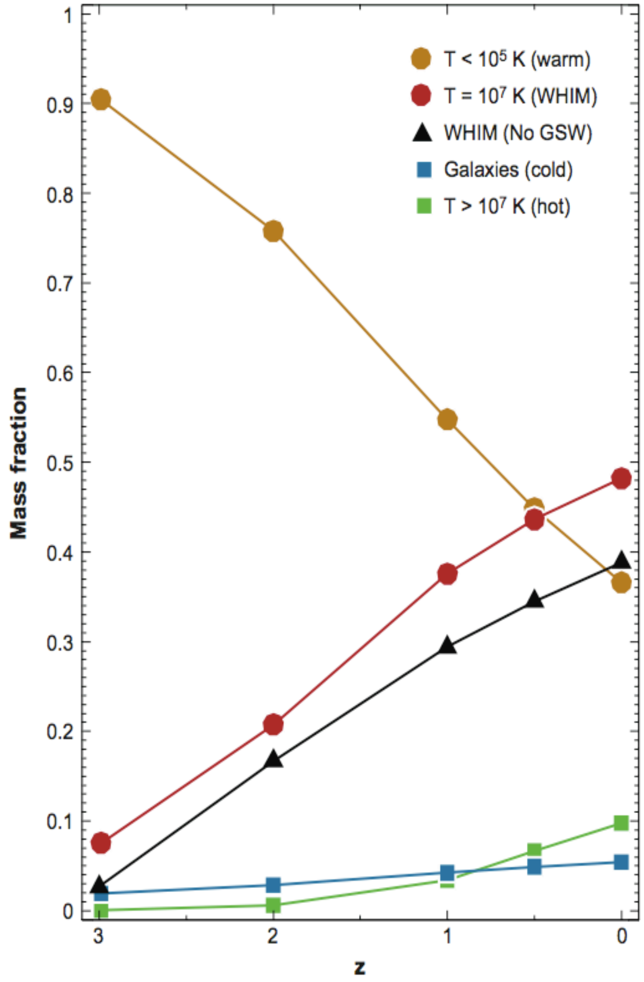
- Understanding hydrogen and helium reionizations is crucial to gain a complete understanding of the IGM and of its evolution.
- Data are still scarce and their interpretation is challenging.
- Uncertainties in the cosmic evolution of UV sources and the need to model radiative transfer makes theoretical models complicated.
- Anyway, the GP effect and CMB data constrain the EoR between $6<z_{reion}<14$.
- The current standard model uses Pop II stars to reionize HI and HeI at $z>6$ and quasars to reionize HeII at $z\sim3$

The missing baryons and the WHIM

Nicastro et al. 2008

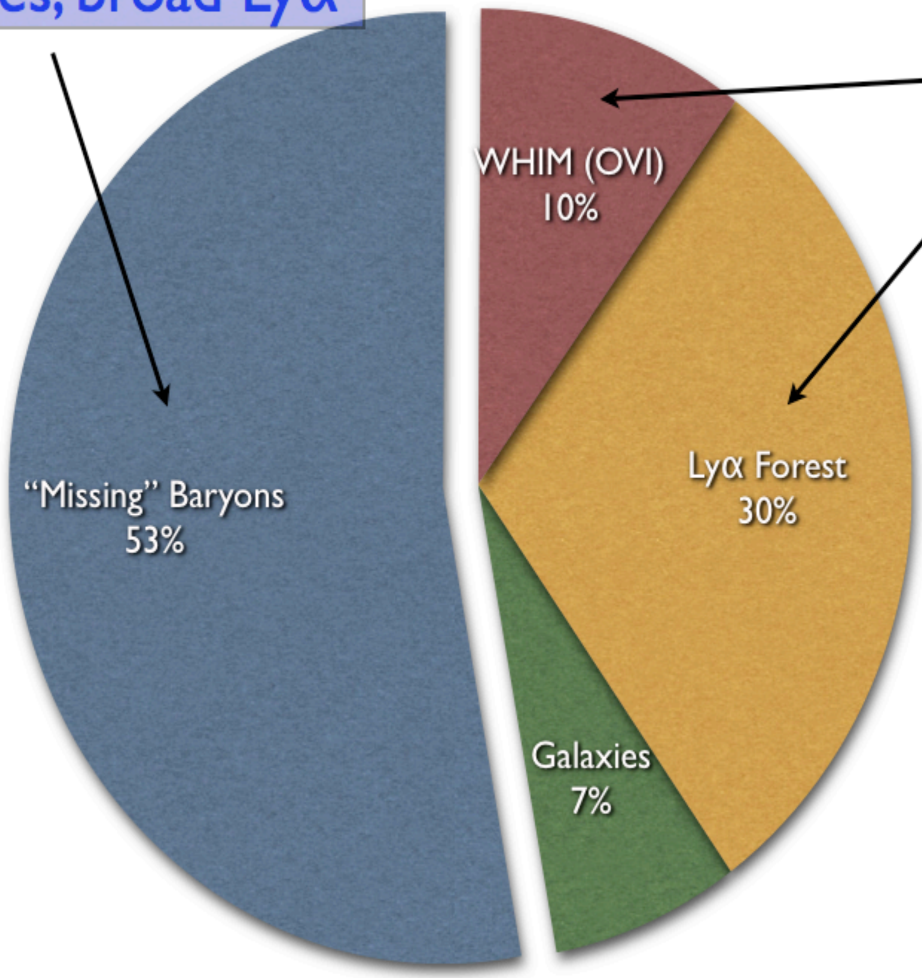


Cen & Ostriker 2006



Baryon Census (low-z)

Probed by X-ray lines, broad Lyα



Both of these are uncertain

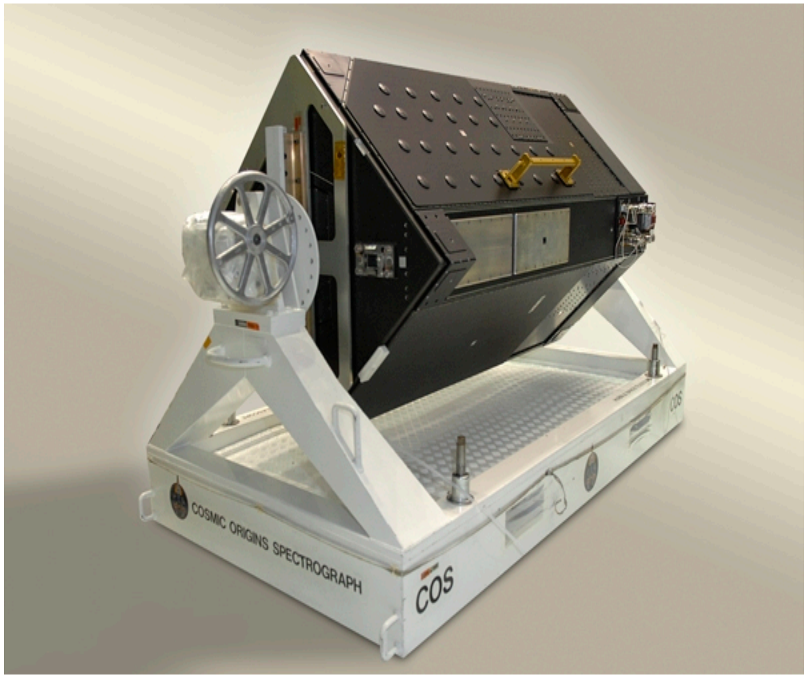
IGM Systematics:

- EUV radiation field
- Oxygen metallicity
- Ioniz corrections
- Cloud geometry

The introduction of metals into the IGM and subsequent mixing are not understood

Future perspectives

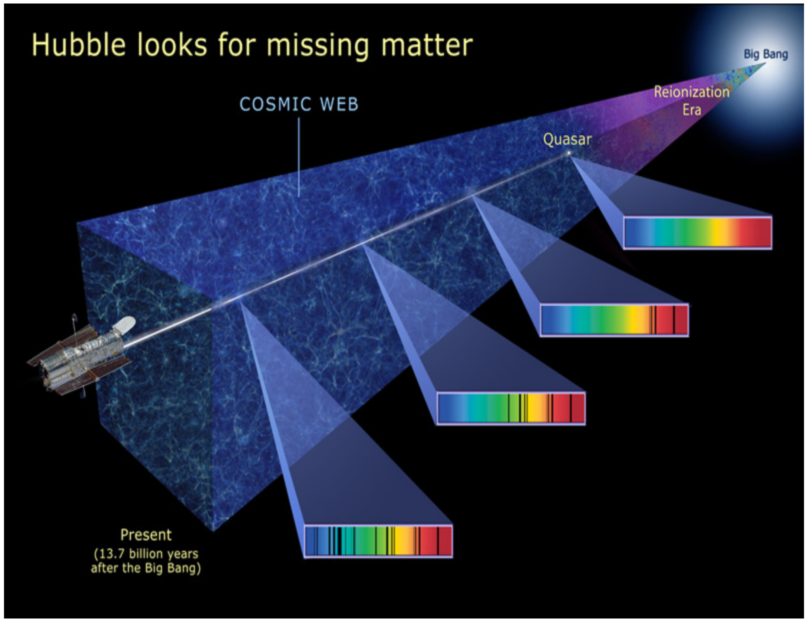
The Cosmic Origins Spectrograph



- The most sensitive ultraviolet spectrograph ever built for space (10 to 30 times better than STIS)
- Optimized to observe faint point sources
- Installed by spacewalking astronauts on Servicing Mission 4 (May 2009)
- FUV channel: $1150 < \lambda < 1775$ Å
  R=20,000-24,000
- NUV channel: $1700 < \lambda < 3200$ Å
  R=16,000
- Low-res grism: $1230 < \lambda < 2050$ Å
  R=2500-3500
- Cost: 70 M$

COS science

- Charting the cosmic web by studying absorption lines towards background quasars
- Detect the WHIM
- Measure the amount of heavy metals and the history of enrichment
- Constrain the thermal history of the IGM
- Study the HeII Gunn-Peterson trough and HeII reionization



Baryon Oscillation Spectroscopic Survey (BOSS)

- Fall 2009 - Spring 2014
- 1000-fiber spectrograph, R~2000, wavelengths: 360-1000 nm
- Spectra of 160,000 quasars at redshifts $2.2<z<3$ within 10,000 deg^2
- Measurement of the angular diameter distance at $z=2.5$ with a precision of 1.5%
- A large database of quasar absorption lines

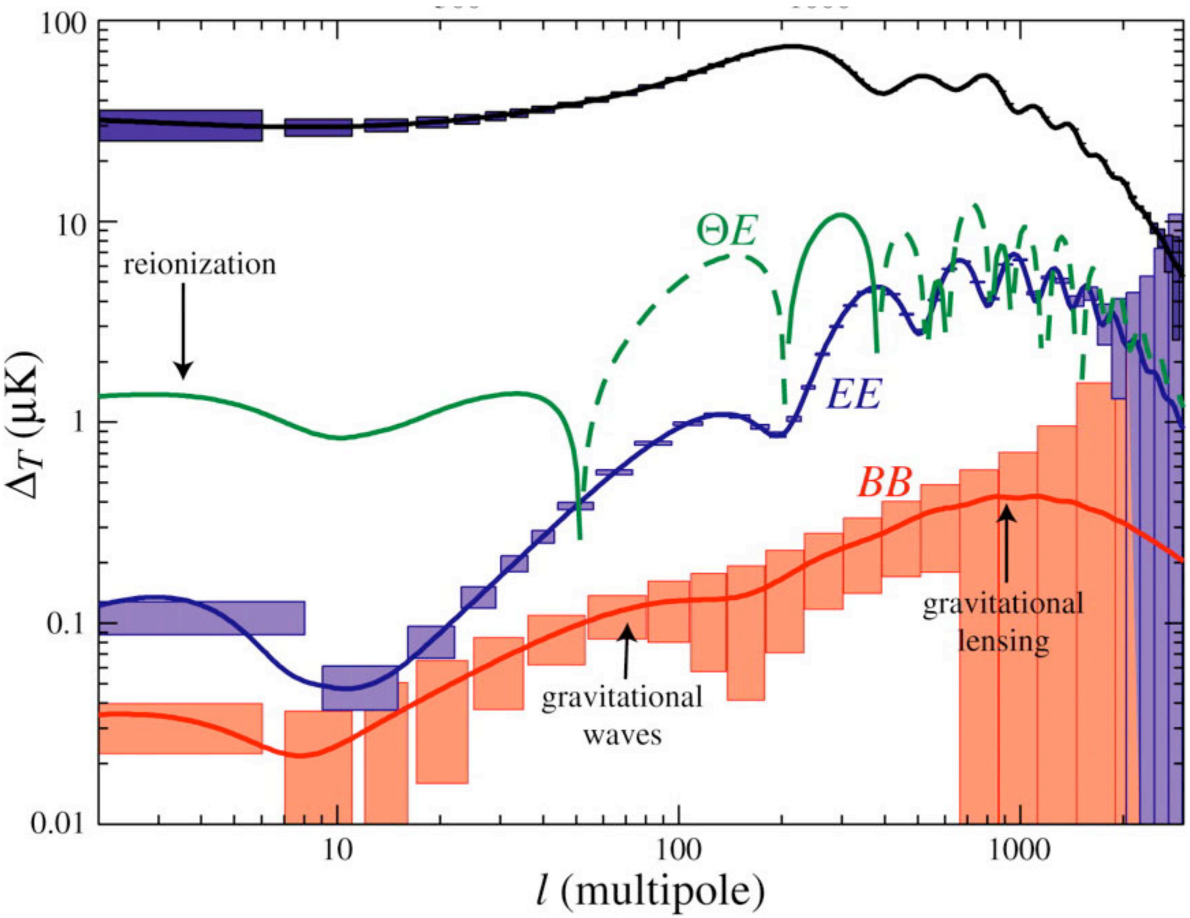
The Planck satellite

- Medium-Sized Mission (M3) part of ESA's Cosmic Vision Programme
- Launched on May 14 2009
- Much better sensitivity, angular resolution and frequency range than previous experiments
- The total cost of the Planck mission is about 700 MEUR

Forecast of Planck spectra

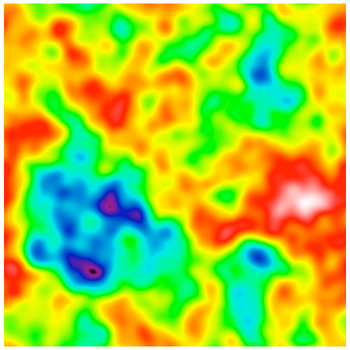
Planck will determine the optical depth to reionization with an accuracy of

$\Delta\tau = 0.005$

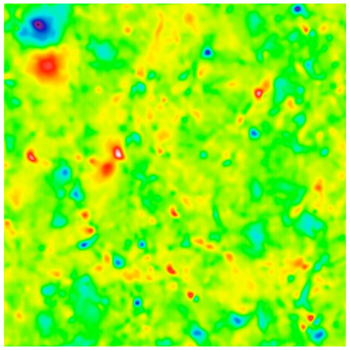


Prospects with ACT/SPT

1.4°x 1.4°

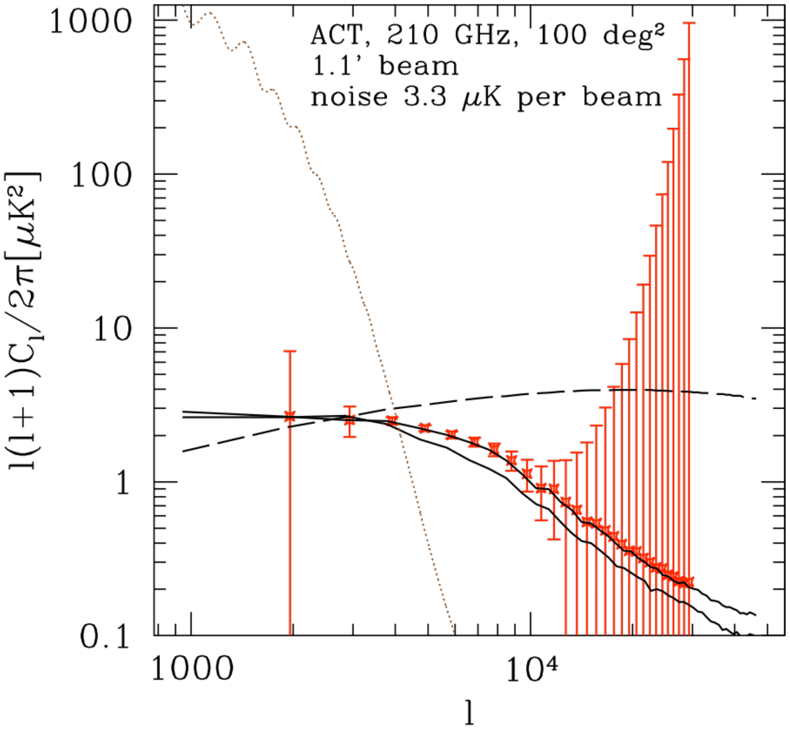


CMB



SZ + OV

Iliev et al. 2008

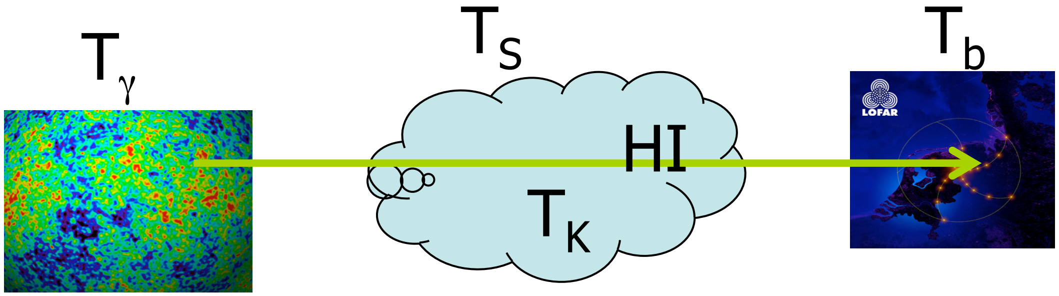


Hard to separate the patchy reionization signal from OV+SZ

If this is doable, we could learn about the size of the bubbles

The 21cm background

The key idea is to use CMB backlight to probe 21cm transitions

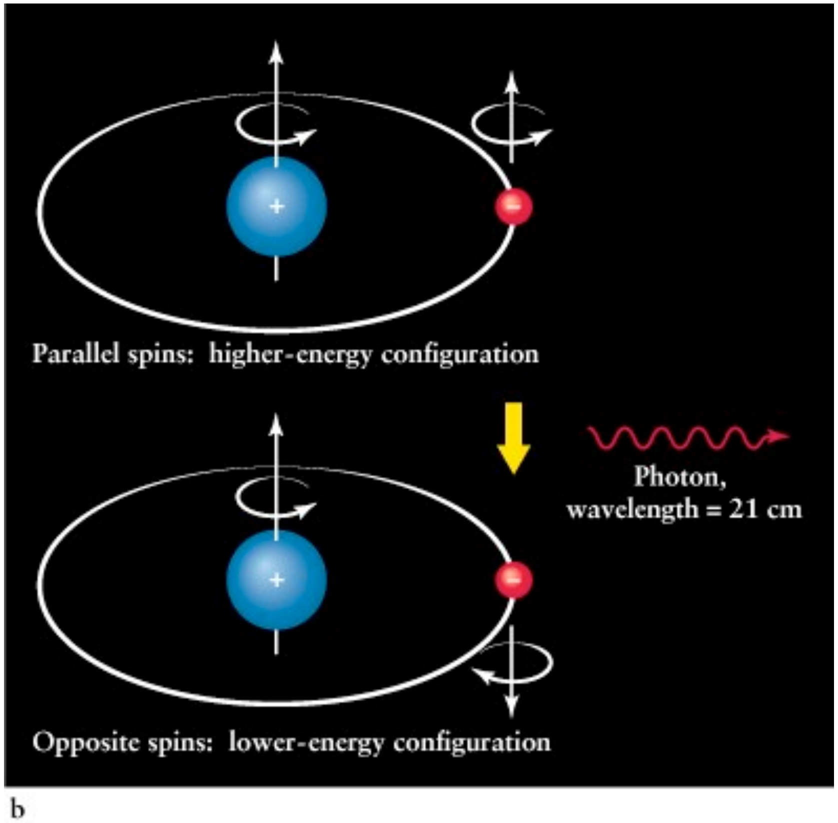


Brightness temperature at λ = (1+z) 21 cm:

$$\delta T_b \approx 23 x_{HI}(1+\delta)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{T_S-T_{cmb}}{T_S}\right)\left(\frac{H(z)/(1+z)}{\partial \mathrm{v}_\mathrm{r}/\partial r}\right)\ \mathrm{mK}$$

3-dimensional information: angle on the sky plus wavelength

Hydrogen 21cm radiation



- Spin-flip transition at 1420.4 MHz between hyperfine levels of the 1s state
- Magnetic dipole transition with a probability of 2.9×10^{-15} s^{-1} (1 transition every 10^7 yr)
- Predicted by van de Hulst 1944, First detected by Ewen and Purcell in 1951

Spin temperature

Ratio of level populations: $\frac{n_1}{n_0} = 3e^{-\Delta E/k_B T_S} = 3e^{-T_*/T_S}$

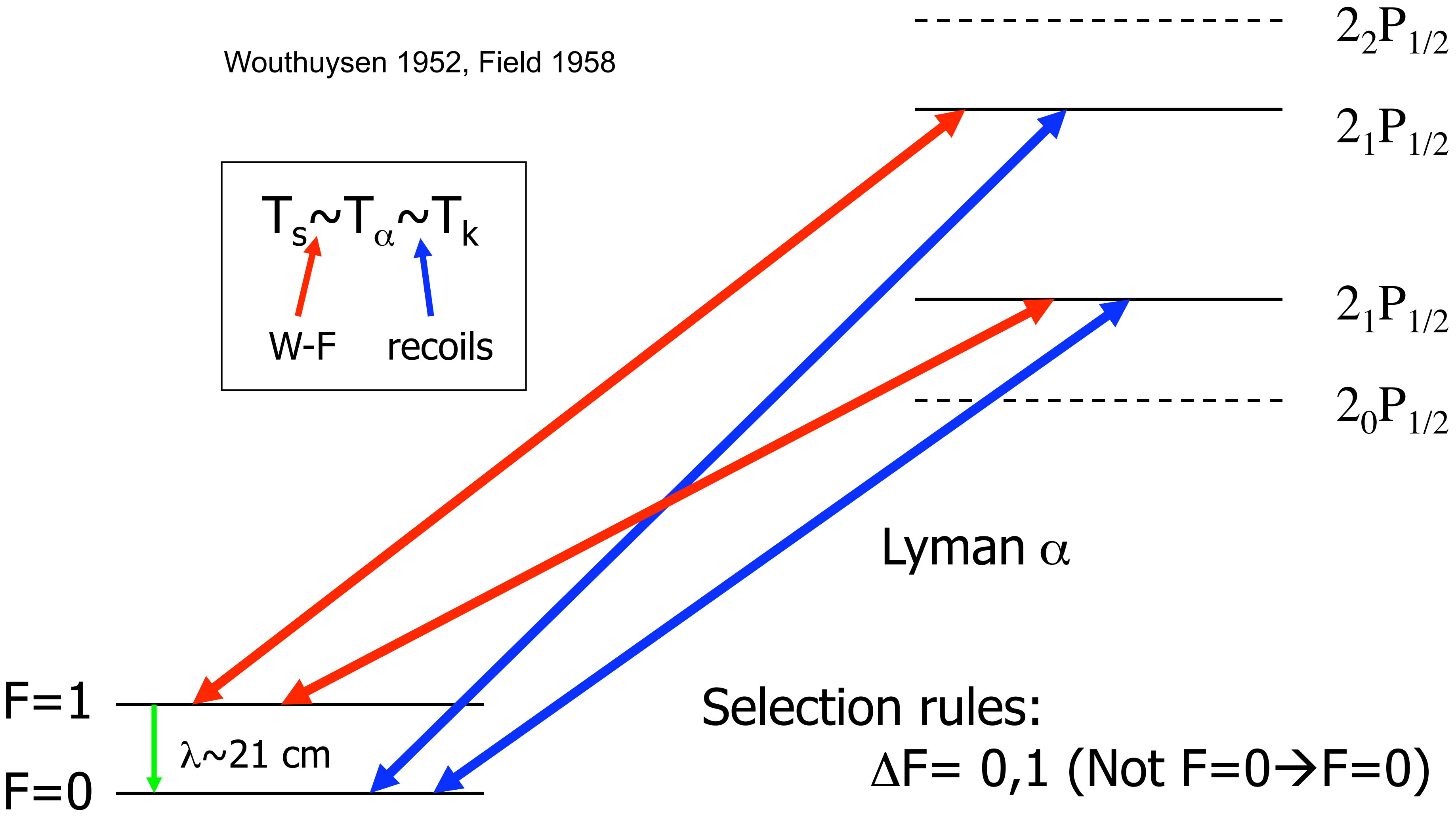
Coupling mechanisms:

- Radiative transitions (CMB)
- atomic collisions
- Lyman α pumping

$$T_S = \frac{T_{\rm CMB} + y_c T_K + y_{\rm Ly\alpha} T_{\rm Ly\alpha}}{1 + y_c + y_{\rm Ly\alpha}}$$

Wouthuysen - Field effect

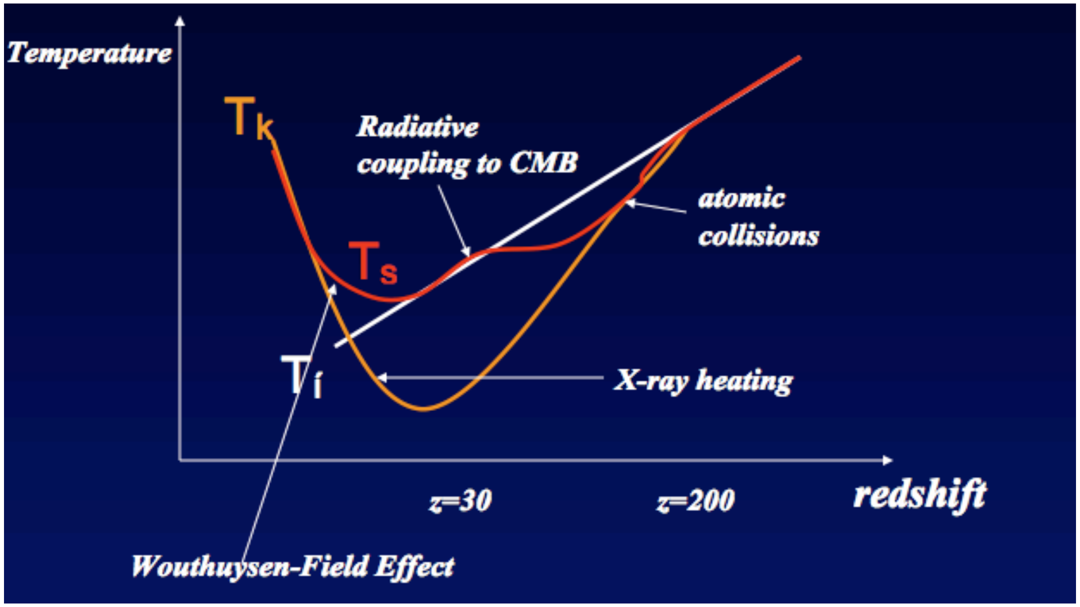
Wouthuysen 1952, Field 1958



Selection rules:

ΔF= 0,1 (Not F=0→F=0)

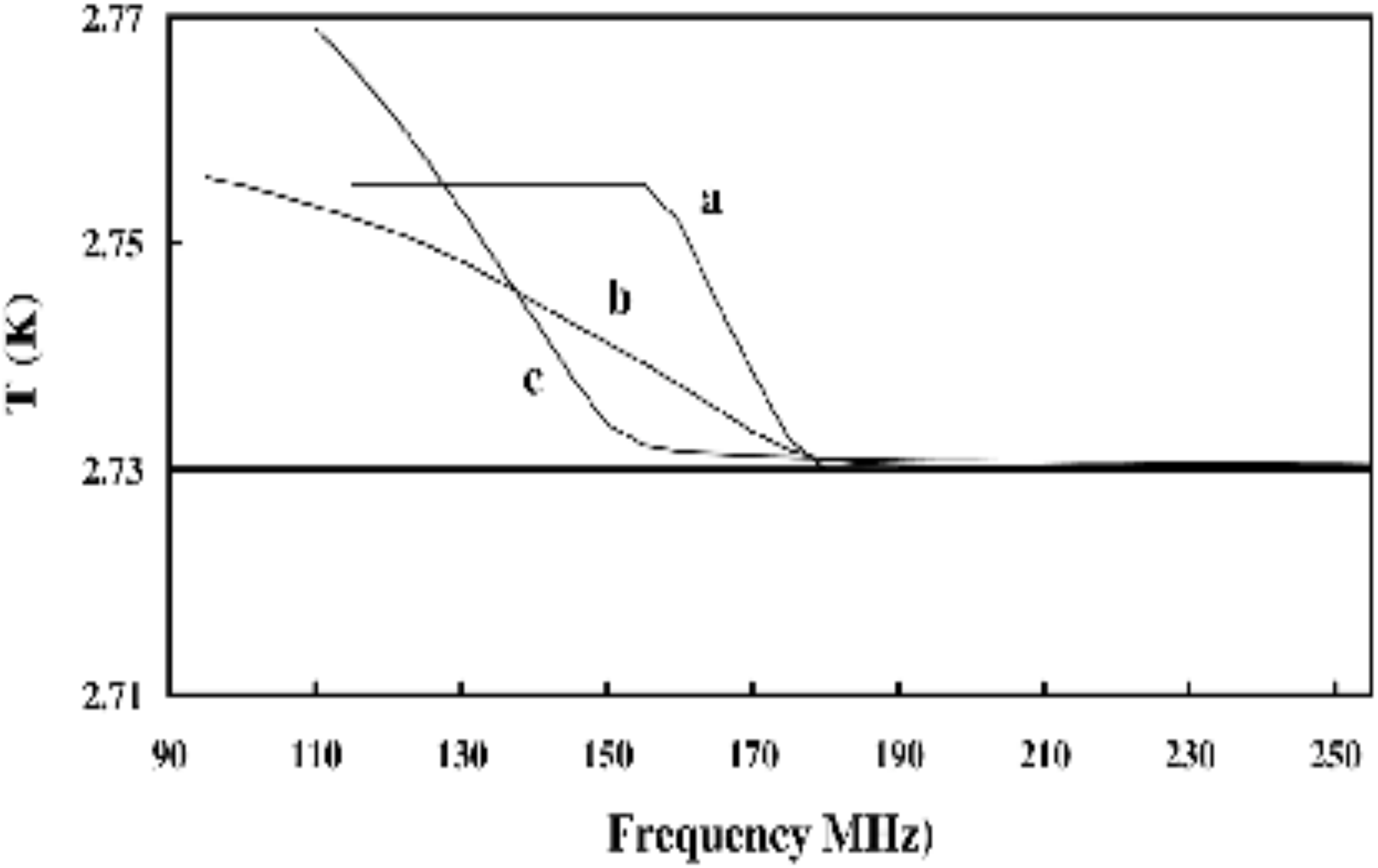
Thermal history and 21 cm background



- z > 200 no signal
- 30<z<200 21cm detected in absorption against CMB
- 20<z<30 no signal
- 6<z<20 21cm detected in emission against CMB

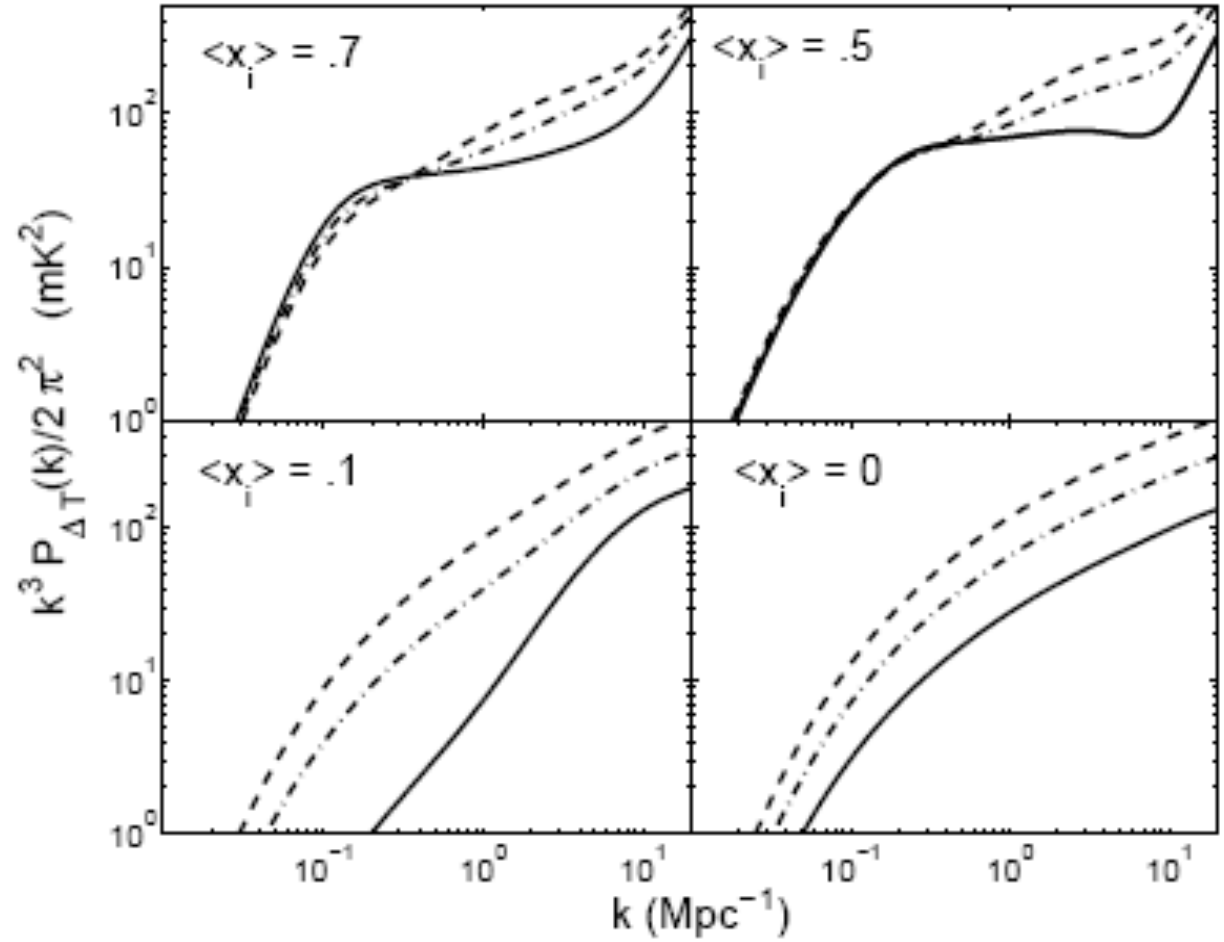
Global signal

Shaver 1999



Statistical approach

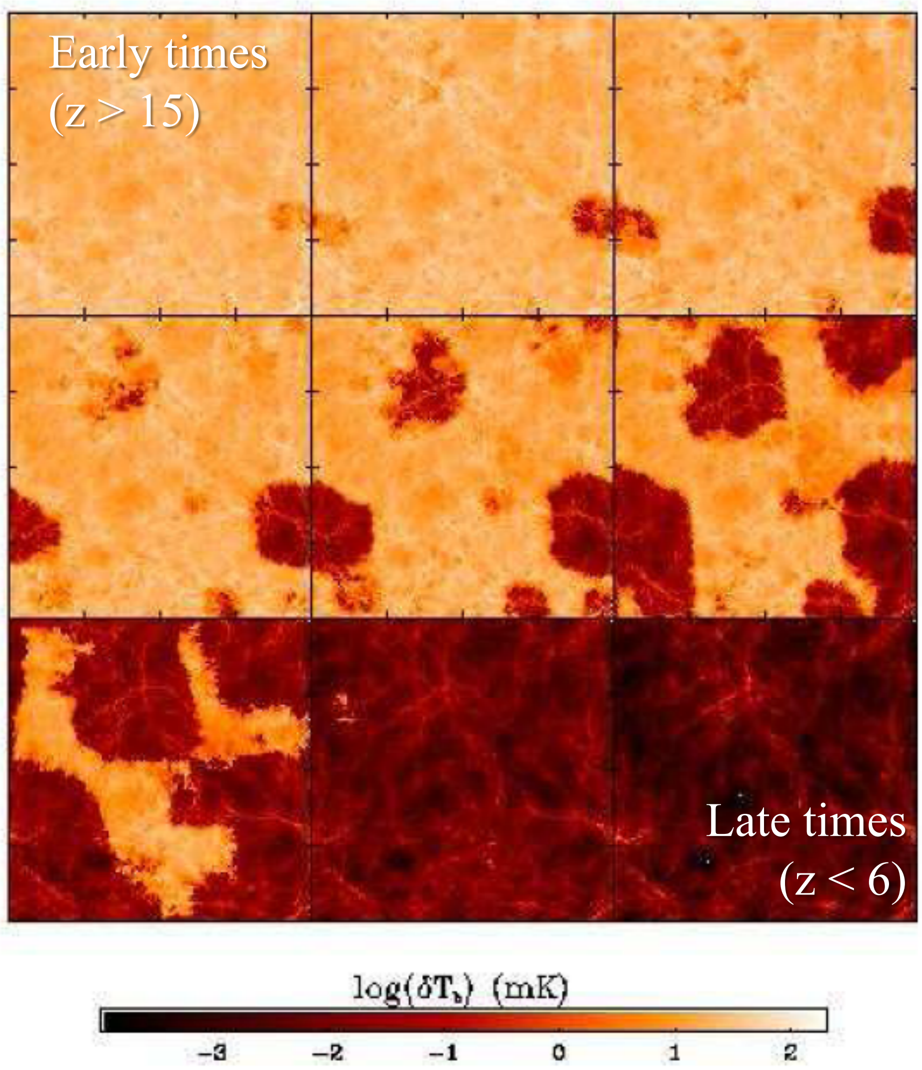
McQuinn et al. 2006



δT_b tomography

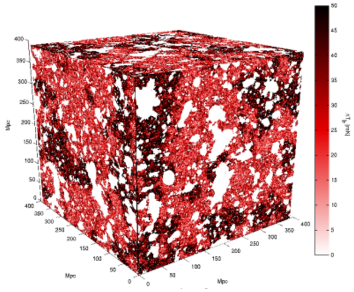
Furlanetto et al. 2004

Primarily density fluctuations →

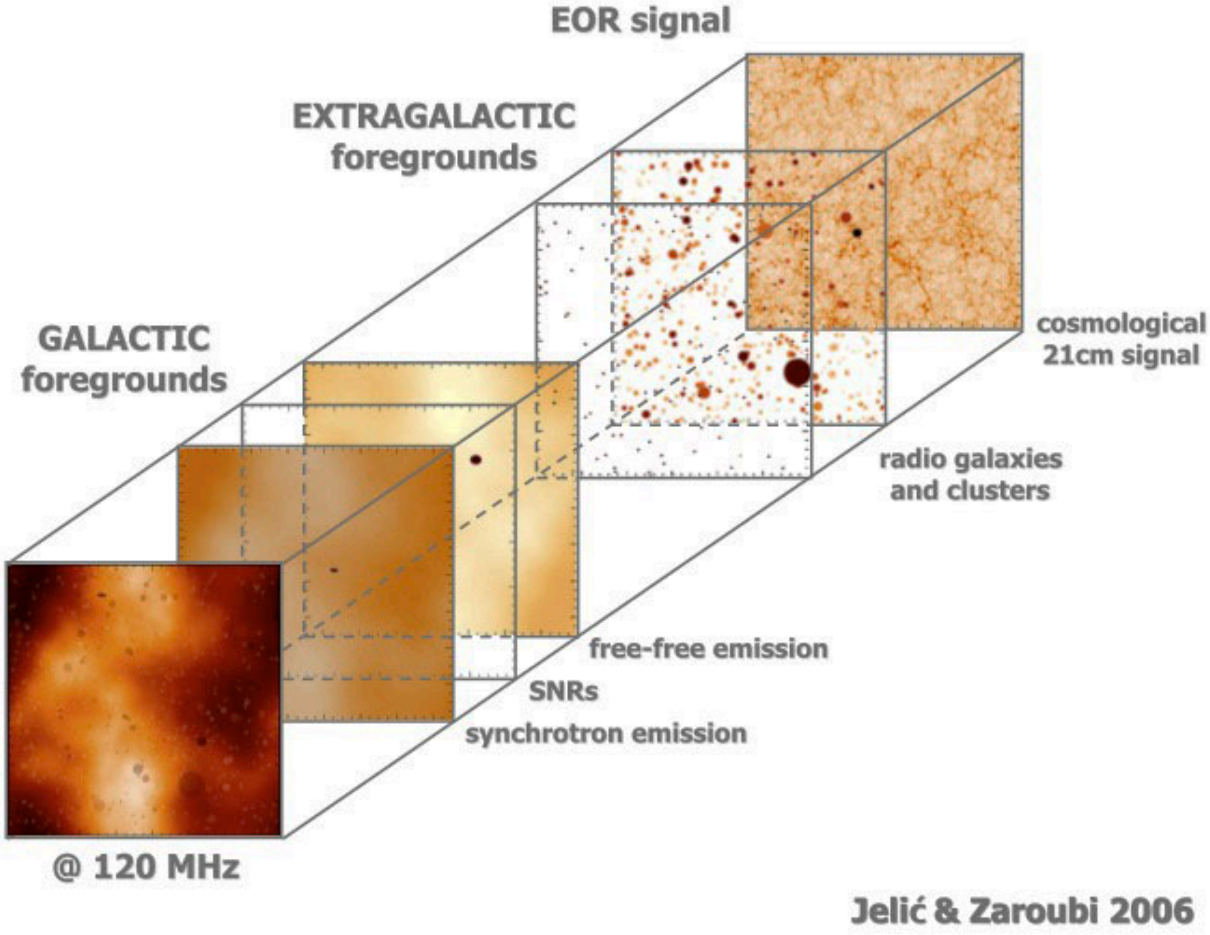


5 arcmin

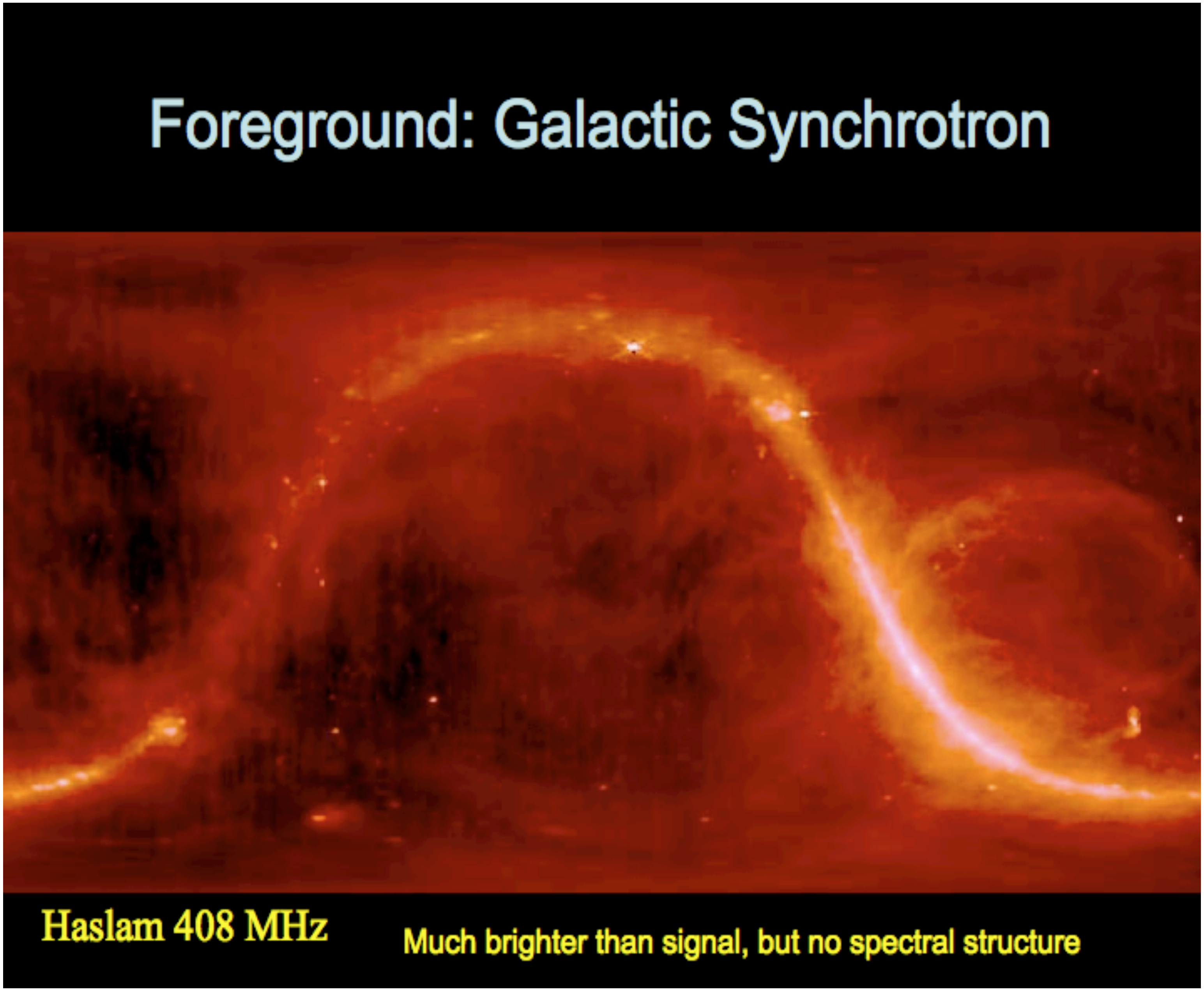
← Ionized regions



Foreground signal



Jelić & Zaroubi 2006



Foreground: Galactic Synchrotron

Haslam 408 MHz

Much brighter than signal, but no spectral structure

~250 K
at 150
MHz

LOFAR in Germany

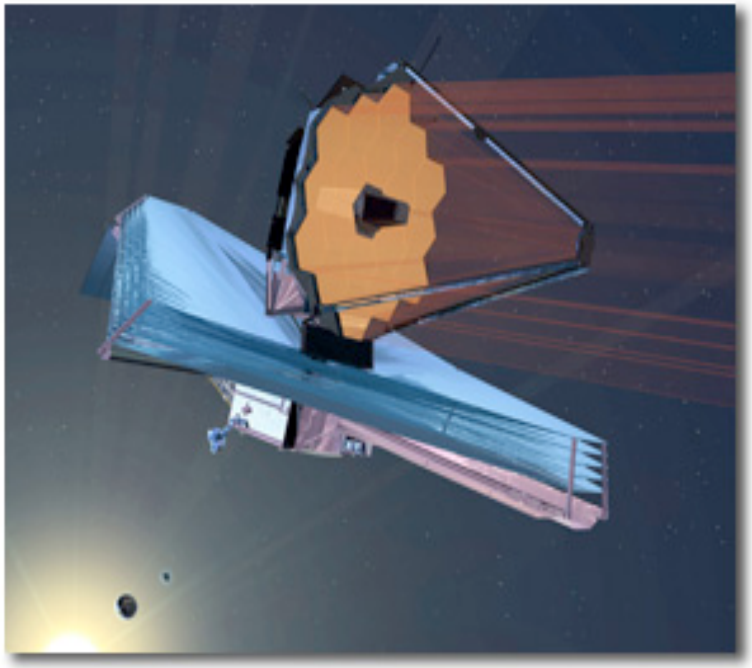
Pathfinder experiments

- Global signal:
  EDGES (Caltech/MIT),
  CORE (Australia)

- Fluctuations (power spectrum):
  LOFAR (Dutch + EU),
  21CMA (China, formerly called PAST),
  MWA (Australia/MIT),
  GMRT (India, operational),
  PAPER (UC Berkeley)

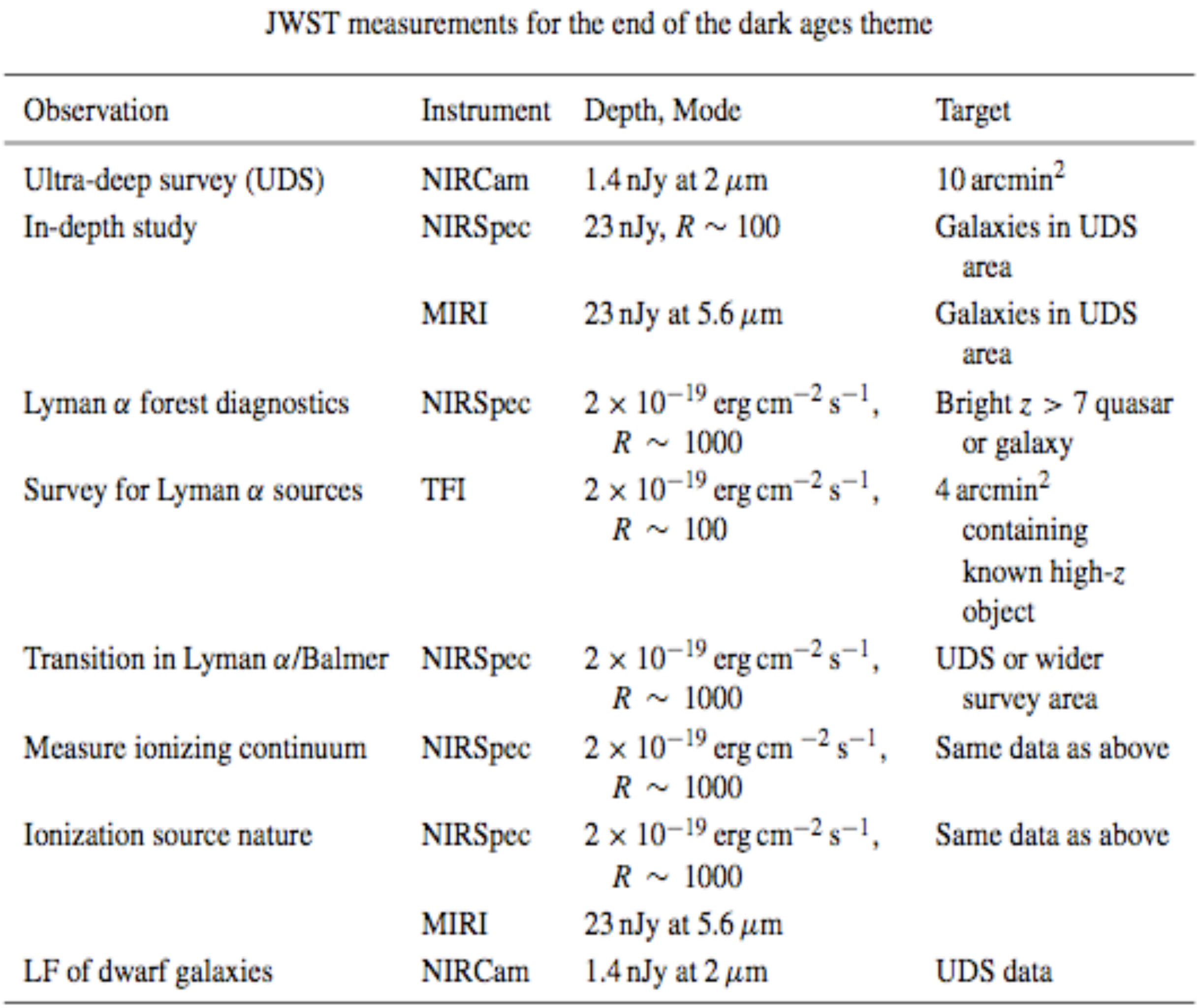
- Ultimate experiment (tomography):
  SKA (phase-1 2014, full 2020)

James Webb Space Telescope



- 6.6-meter diameter primary mirror, diffraction limited at 2 micron
- Launch planned for 2014, 5-10 years of scientific operations after 6 months of commissioning period
- 5B$ budget (plus European and Canadian contributions)
- The end of the dark ages: first light and reionization is one of the four main science themes of JWST

JWST will mainly tell us about the sources that reionized the universe



JWST measurements for the end of the dark ages theme

Observation	Instrument	Depth, Mode	Target
Ultra-deep survey (UDS)	NIRCam	1.4 nJy at 2 μm	10 arcmin^2
In-depth study	NIRSpec	23 nJy, $R \sim 100$	Galaxies in UDS area
	MIRI	23 nJy at 5.6 μm	Galaxies in UDS area
Lyman α forest diagnostics	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Bright $z > 7$ quasar or galaxy
Survey for Lyman α sources	TFI	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 100$	4 arcmin^2 containing known high-z object
Transition in Lyman α/Balmer	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	UDS or wider survey area
Measure ionizing continuum	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Same data as above
Ionization source nature	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Same data as above
	MIRI	23 nJy at 5.6 μm	
LF of dwarf galaxies	NIRCam	1.4 nJy at 2 μm	UDS data

Cosmic star formation history also from CO lines with ALMA (>2011)

German involvement

- COS: ESA
- BOSS: AIP, MPA, MPIA
- Planck: MPA, DLR
- ACT: MPA
- LOFAR: GLOW (Bochum, Bonn (MPIFR + Uni), Bremen, Garching, Hamburg, Jülich, Köln, Potsdam, Tautenburg)
- ALMA: ESO (regional centre: Bonn, Bochum, Cologne)
- JWST: ESA