Cosmic Reionization and Cosmology

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APCTP Focus Program

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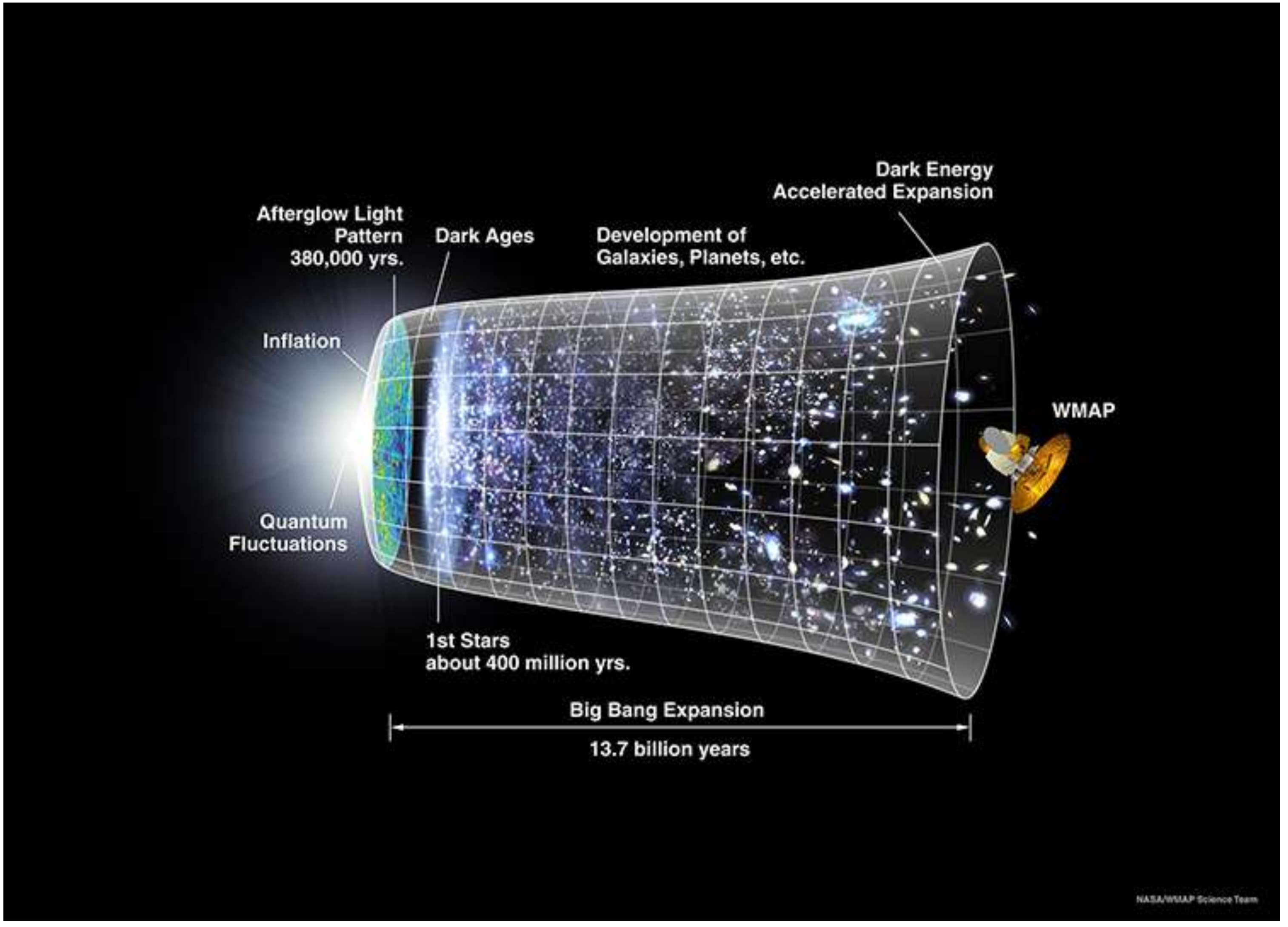
Why study of cosmic reionization is booming

- Precision Cosmology achieved; will get better
  - WMAP, Planck, .. → cosmological initial condition provided in huge dynamic range
- Huge span of redshift, but never been directly observed; Only indirect observations exist
- Frontier both in theory and observation
- Dark Ages: z =~ 1100 to ~30
  - Structure is mostly linear
  - Stars and quasars are very rare
- Epoch of Reionization: z =~ 30 to ~6
  - Radiation sources emit hydrogen-ionizing radiation
  - Global ionized fraction <x> increases in time, to reach ~1 at z~6
  - Universe stays ionized afterwards

Evolution of Universe in a nutshell



Cosmic Dark Ages

Cosmic Dark Ages

- Recombination epoch (z~1100) to start of reionization (z~20-30)
- No appreciable radiation sources
  - Almost no stars or quasars; Only a handful, if any
- No direct observation made yet
- May be probed directly by 21cm observation
  - Scott, Rees (1990): Probing large scale structure (LSS) by redshifted 21cm
  - Madau, Meiksin, Rees (1997): IGM preheating by early QSOs and galaxies, probing LSS by 21cm
  - Tozzi, Madau, Meiksin, Rees (2000): Lyα coupling and 21cm fluctuation
  - Carilli, Gnedin, Owen (2002): numerical, 21cm absorption by IGM
  - Furlanetto, Loeb (2002): 21cm forest (absorption) by minihalos, disks, IGM
  - Iliev, Shapiro, Ferrara, Martel (2002): semi-numerical, 21cm emission from minihalos
  - Shapiro, Ahn, Alvarez, Iliev, Martel, Ryu (2006): numerical, 21cm emission from both minihalos and IGM

21cm Radiation

- Theoretically calculated by Van de Hulst (1944)
- From hyperfine splitting of 1S state of neutral hydrogen
- First detected by Ewen & Purcell, published in Nature (1951)
- Prospects in cosmology (from Wikipedia): The line is of great interest in big bang cosmology because it is the only known way to probe the "dark ages" from recombination to reionization. Including the redshift, this line will be observed at frequencies from 200 MHz to about 9 MHz on Earth. It potentially has two applications. First, by mapping redshifted 21 centimeter radiation it can, in principle, provide a very precise picture of the matter power spectrum in the period after recombination. Second, it can provide a picture of how the universe was reionized, as neutral hydrogen which has been ionized by radiation from stars or quasars will appear as holes in the 21 centimeter background.

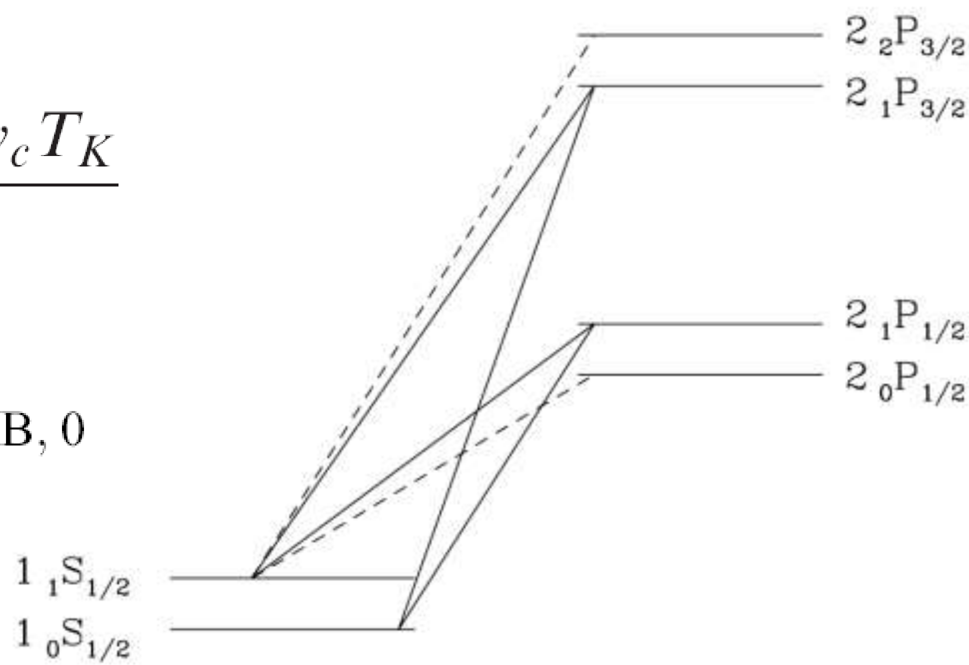
  However, 21 centimeter experiments are very difficult. Ground based experiments to observe the faint signal are plagued by interference from television transmitters and the ionosphere, so they must be very secluded and careful about eliminating interference if they are to succeed. Space based experiments, even on the far side of the moon (which should not receive interference from terrestrial radio signals), have been proposed to compensate for this. Little is known about other effects, such as synchrotron emission and free-free emission on the galaxy. Despite these problems, 21 centimeter observations, along with space-based gravity wave observations, are generally viewed as the next great frontier in observational cosmology, after the cosmic microwave background polarization.

21cm pumping

- Lyα pumping (Wouthysen-Field effect) of T_s (spin temperature) toward T_α (Lyα color temperature)
- Collisional coupling toward T_k (kinetic temperature)
- Absorption against continuum of high-z radio source or CMB continuum
- Emission against continuum of high-z radio source or CMB blackbody continuum

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

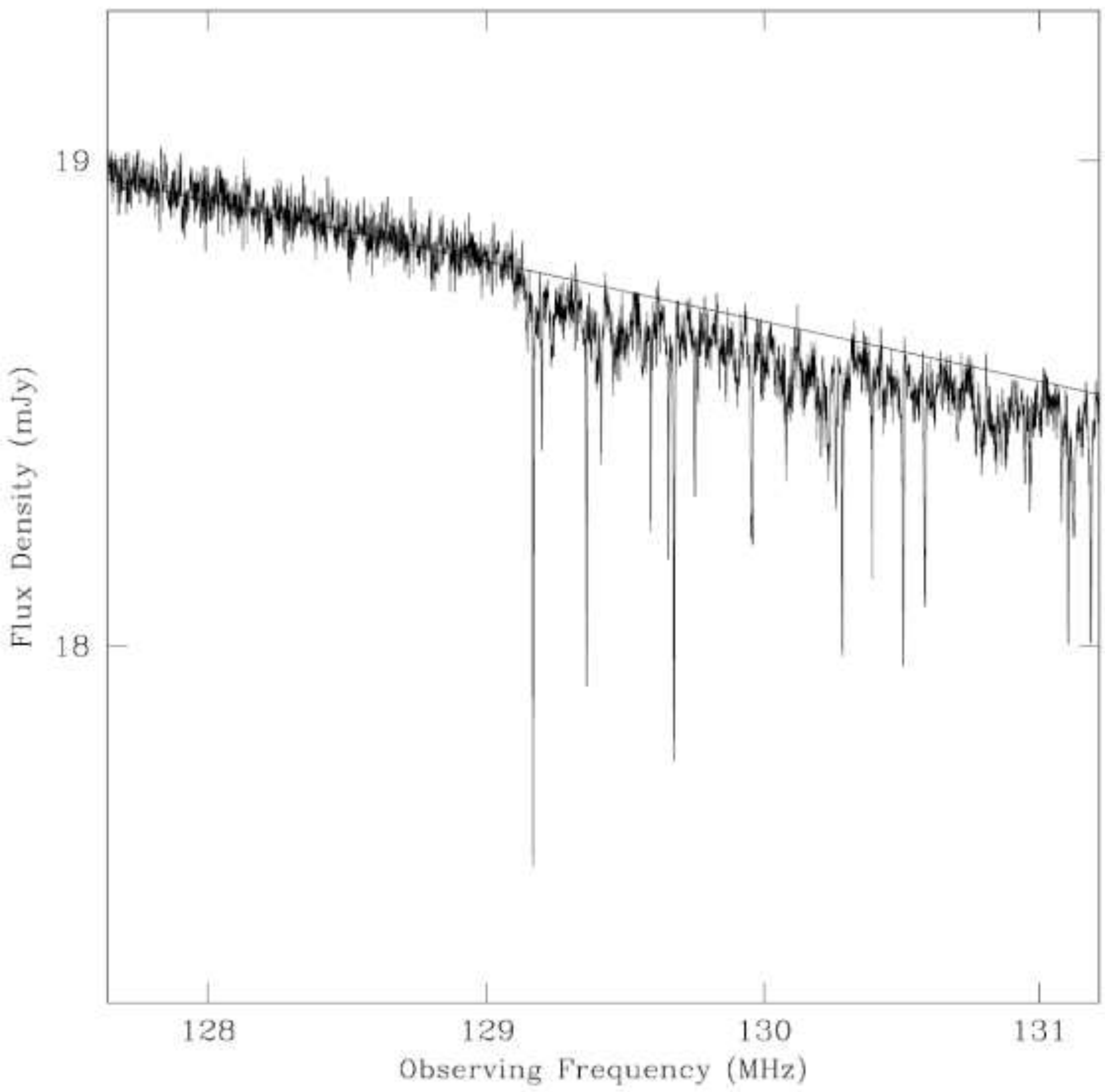
$$\delta T_b(\nu) \equiv T_b(\nu) - T_{\rm CMB,\,0}$$



21cm forest (absorption spectra of high-z radio source)

- Mechanism is identical to that for Lyα forest

21cm forest by IGM(Carilli, Gnedin, Owen 2002)



21cm forest (Furlanetto, Loeb)

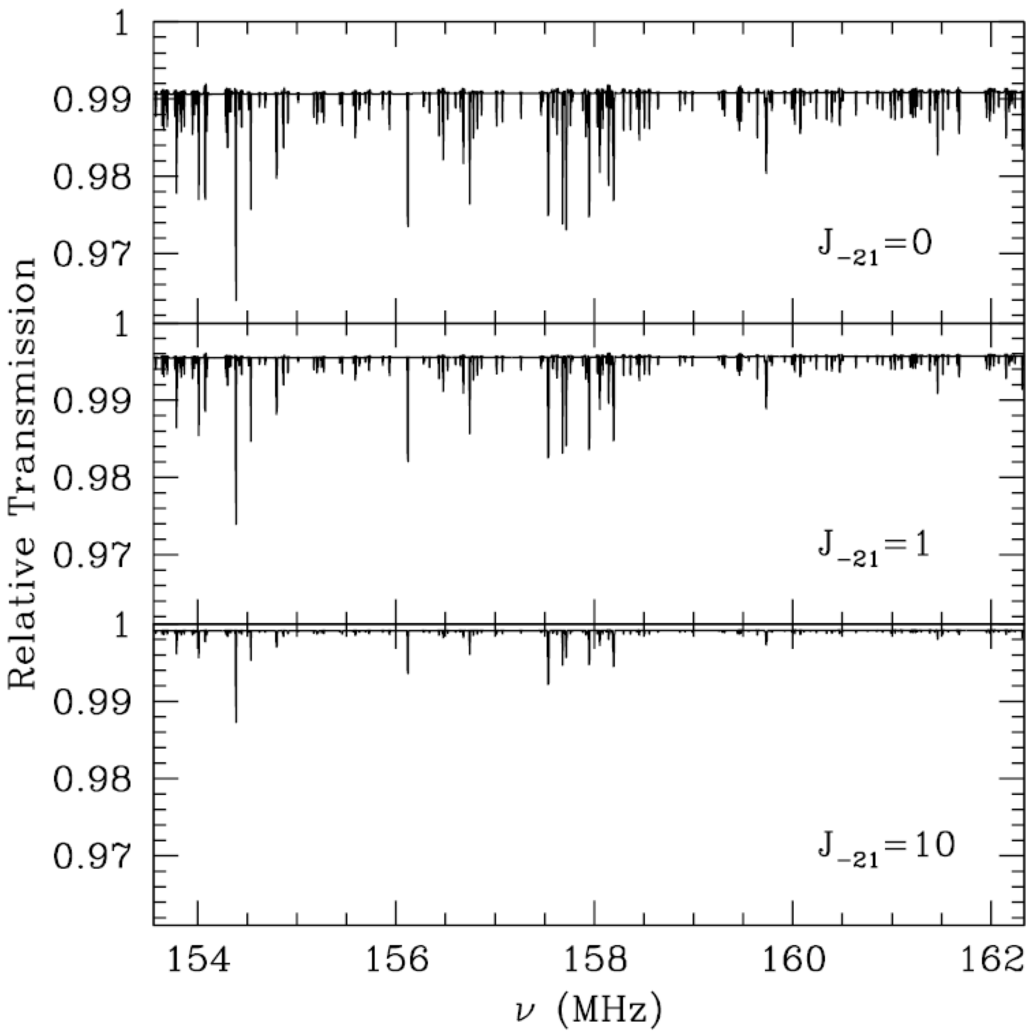
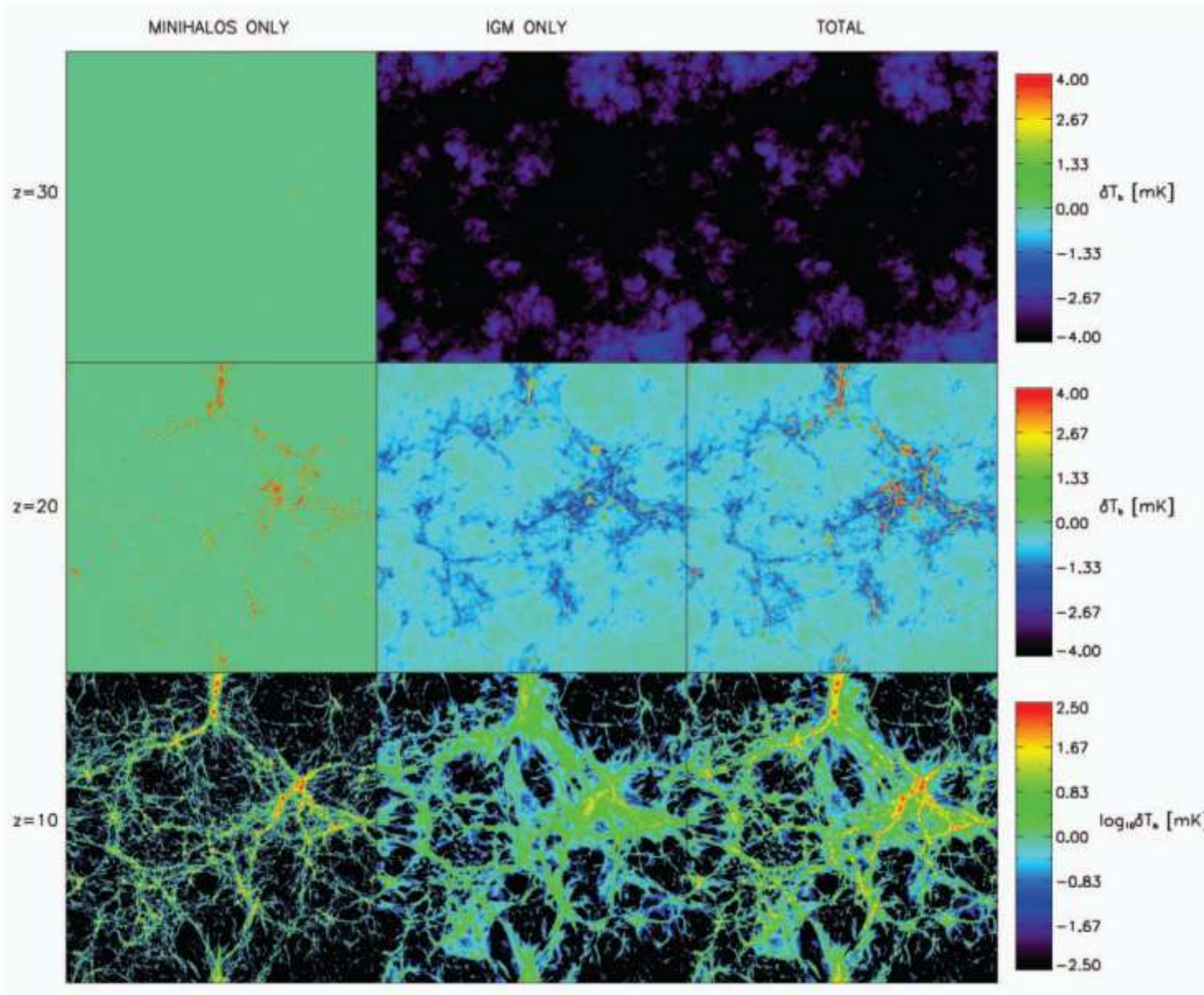


FIG. 6.—Simulated transmission along a line of sight to a distant radio source assuming absorption by intervening minihalos. All panels are generated using the same realization of the minihalo mass field and assume a heated IGM. *From top to bottom*: $J_{-21} = 0,\ 1$, and 10.

21cm emission from minihalos and IGM (Shapiro, Ahn, Alvarez, Iliev, Ryu)



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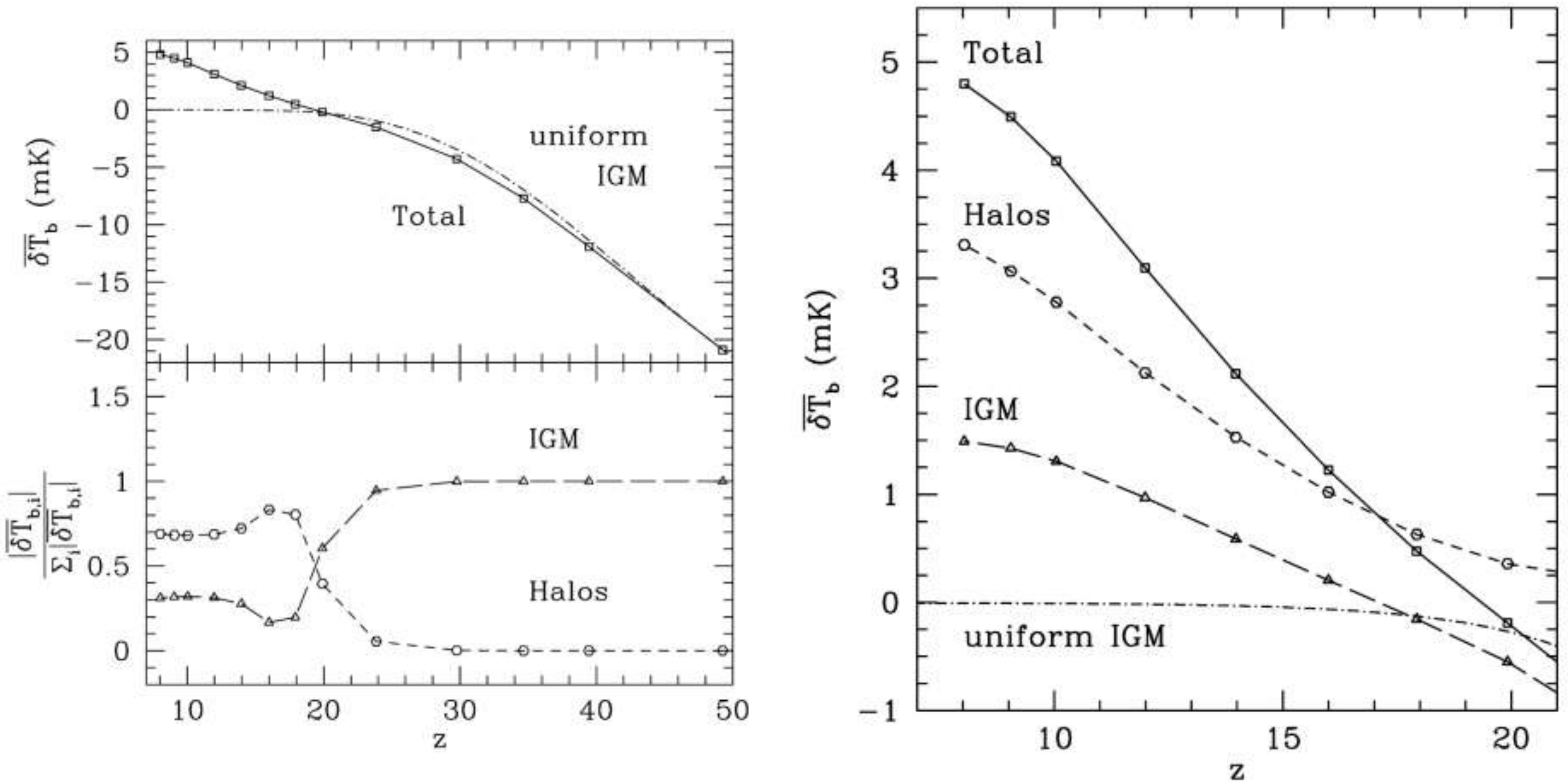
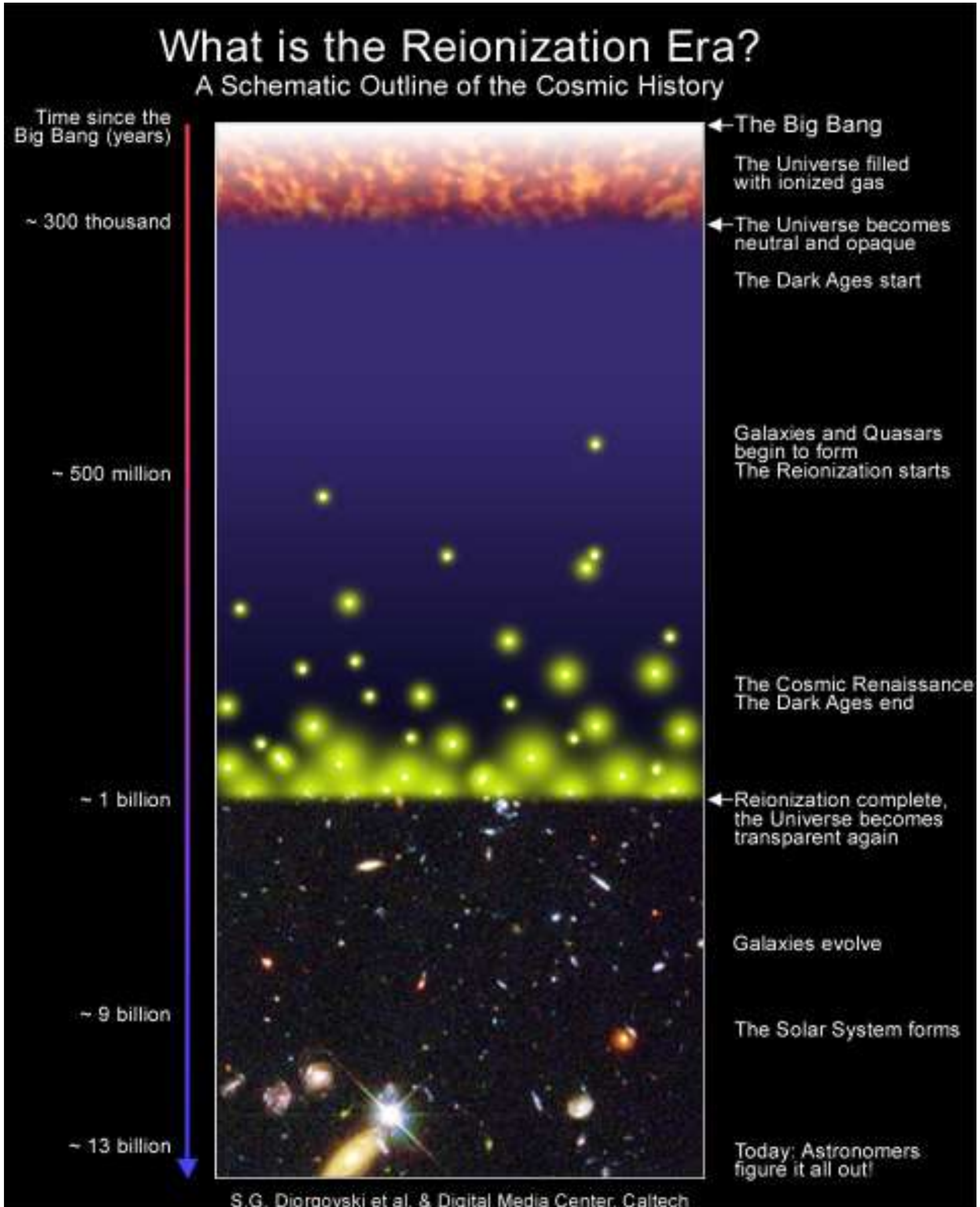


FIG. 4.—Evolution of mean differential brightness temperature, $\overline{\delta T}_b$, of 21 cm background. *Left:* Evolution of the total 21 cm signal vs. redshift. All data points are directly calculated from our highest resolution (C4) simulation box, with the assumption that optical depth is negligible throughout the box. *Right:* $\overline{\delta T}_b$ vs. redshift below $z = 20$. The contributions from minihalos (*circles*), the IGM (*triangles*), and the total (*squares*) are plotted, as labeled. For comparison, the result for the unperturbed IGM is also plotted (*dash-dotted curves*).

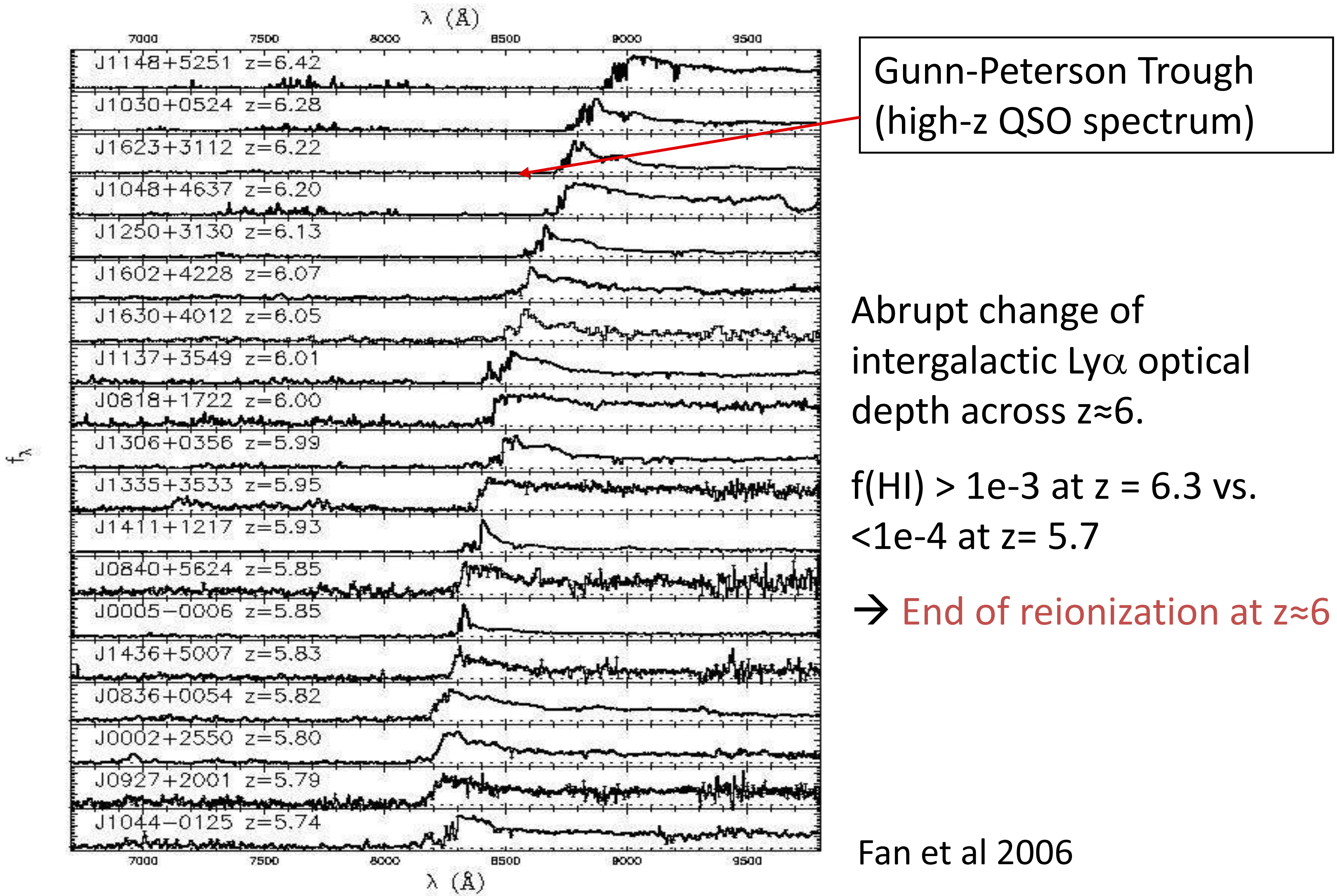
Epoch of Cosmic Reionization

Epoch of Reionization

- Start of reionization (z~20-30) to end of reionization (z~6)
- # of radiation sources increase in time
  - Consistent with hierarchical build-up scenario
  - Warning: Star formation rate is not simply proportional to halo formation rate (star formation rate starts to decrease since z~1)
- Globally, process is gradual and inhomogeneous. Ends when H II bubbles completely overlap with one another. Then ionized state is maintained by continuous star formation (Madau condition).
- No direct observation made yet; Indirect, observational hints do exist
  - WMAP TE correlation, SDSS high-z quasars, Lyα temperature
- Inhomogeneous distribution of still neutral gas may be probed by 21cm observation, kinetic Sunayev-Zeldovich effect on CMB temperature, polarization of CMB
  - 21cm tomography by …………………………….SKA, LOFAR, MWA, GMRT
  - kinetic Sunyaev-Zeldovich on CMB by …….ACT, SPT
  - polarization on CMB by ………………………….ACT, SPT (?)
- Theory usually involves numerical simulations


What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

Observational Hints for Cosmic Reionization



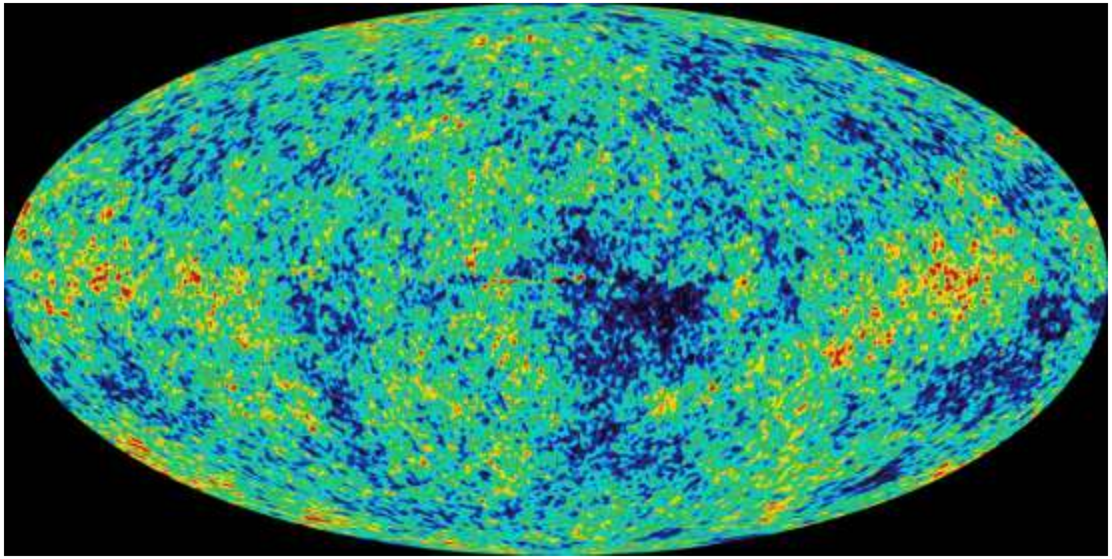
Abrupt change of intergalactic Lyα optical depth across z≈6.

f(HI) > 1e-3 at z = 6.3 vs. <1e-4 at z= 5.7

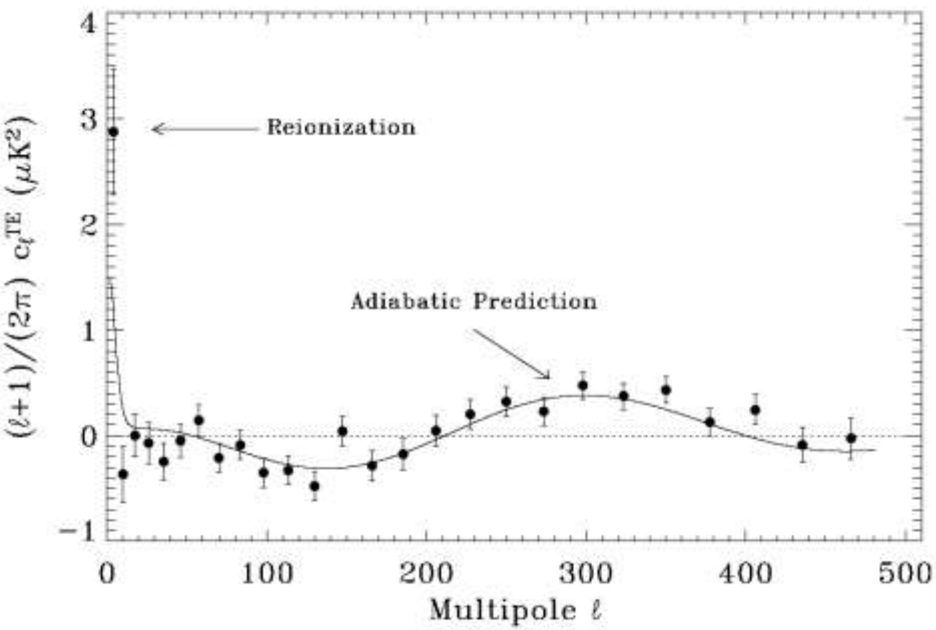
→ End of reionization at z≈6

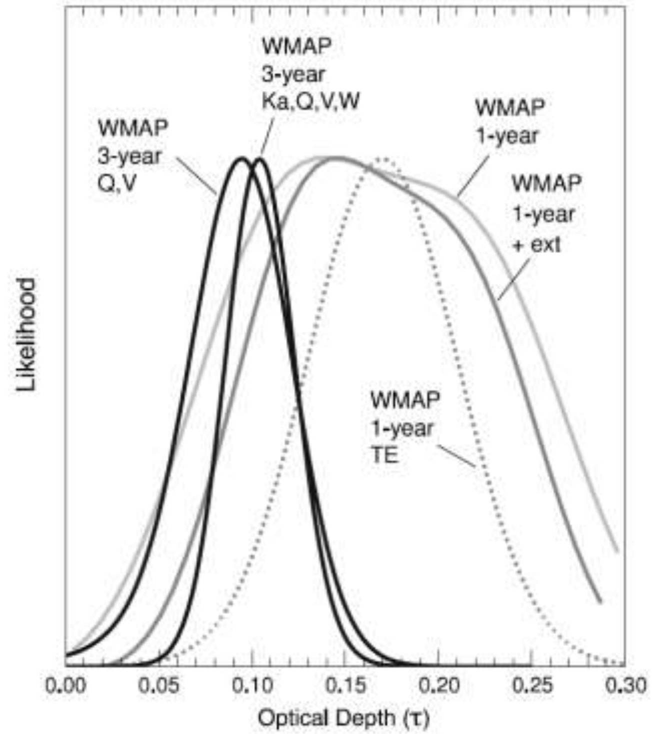
Fan et al 2006

Observational Hints for Cosmic Reionization



WMAP: High Tompson Scattering Optical Depth to CMB photons → Early start ($z \approx 11$), and long duration of cosmic reionization



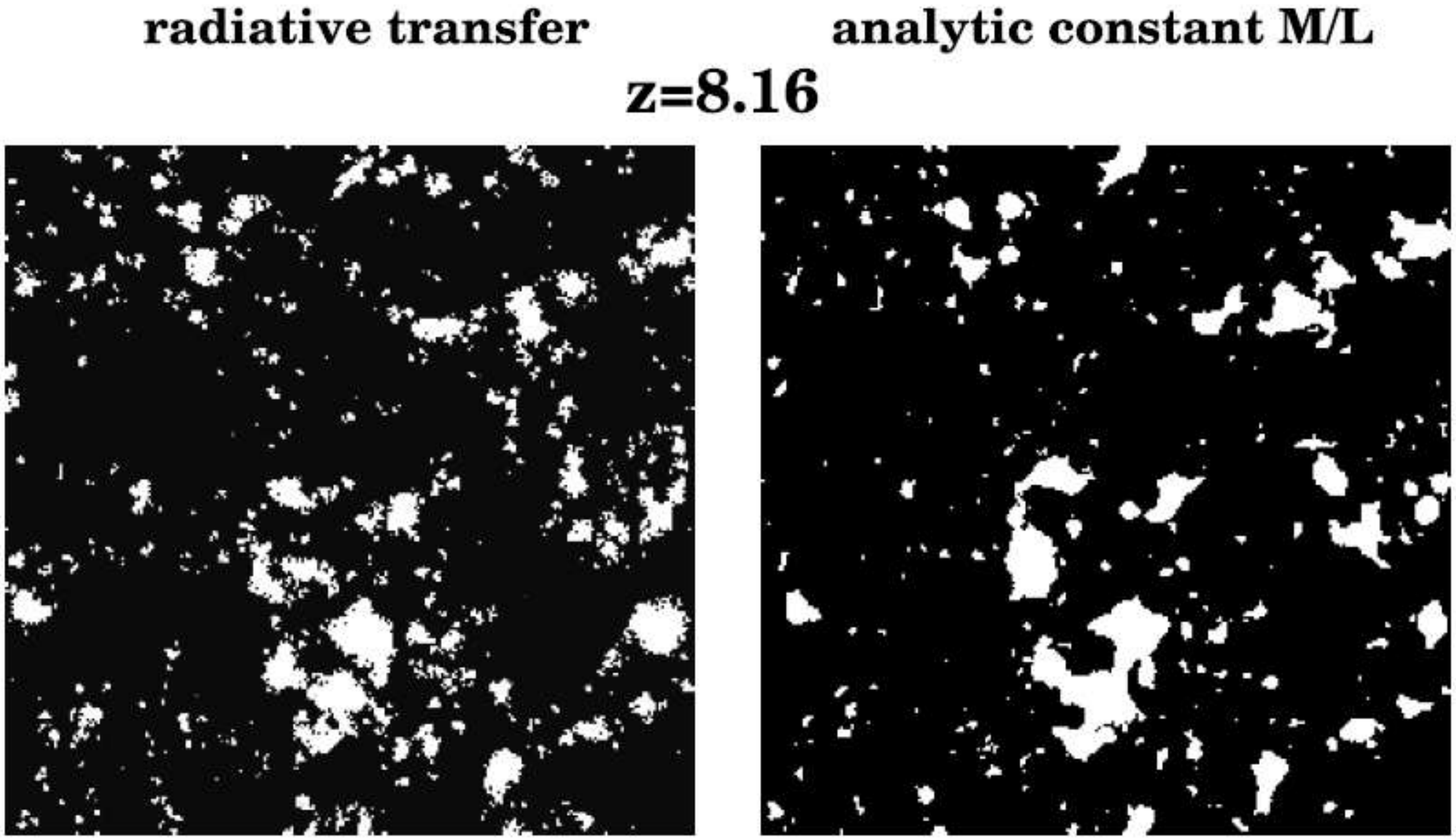


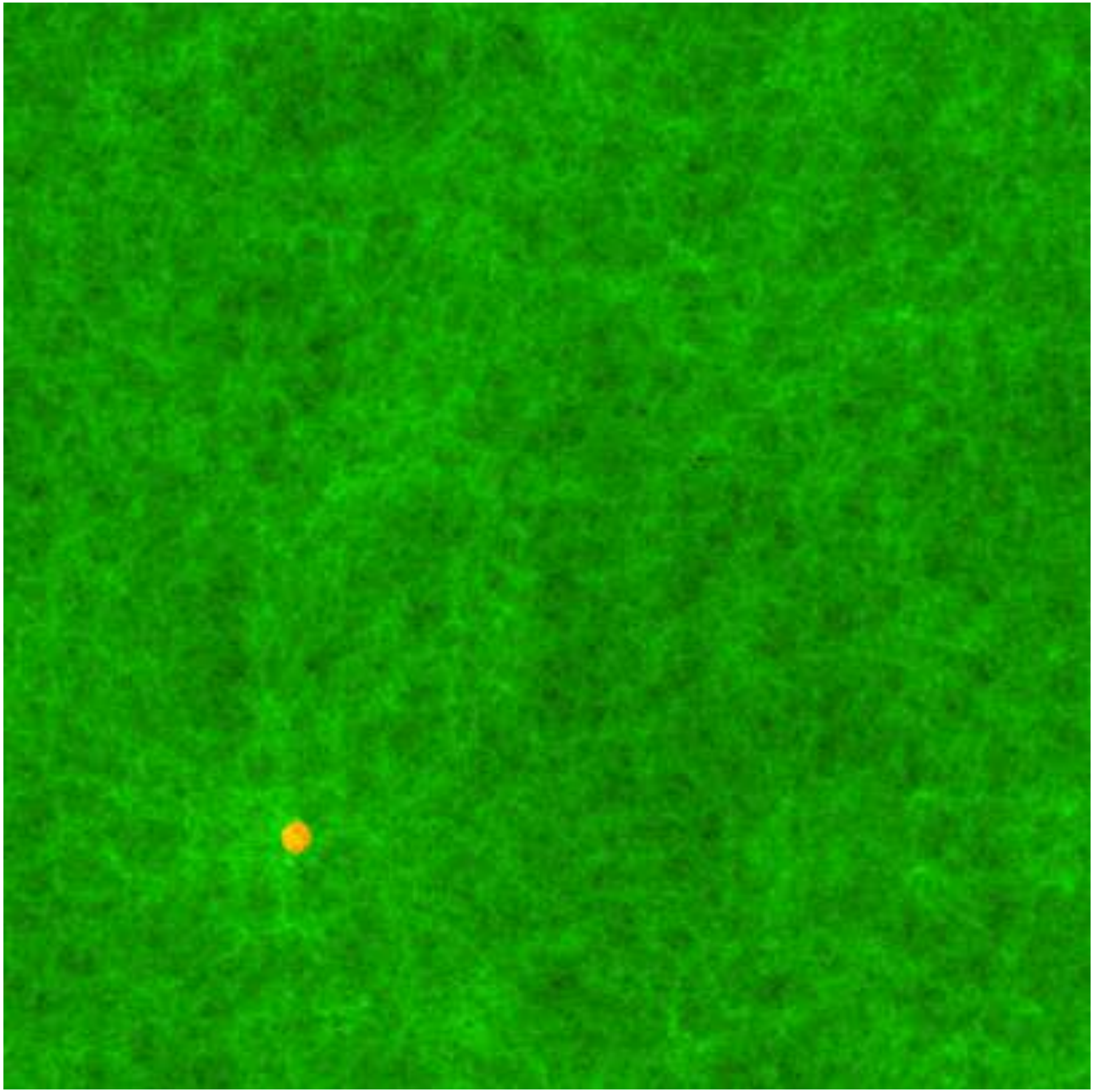
How to transfer ionizing radiation?

Theoretical Study of Reionization

- Analytical Methods
  - Global reionization history
  - Useful to understand basic physics
  - Limited - Hard to study anisotropic evolution
- Numerical Methods
  - Structure Formation → Source specification → Ray-tracing → Rate Equation solving
  - Usually requires parallel computing (expensive)
  - Several groups with their own codes and methods (e.g. C2-Ray group)
  - Semi-analytic, semi-numerical method – Excursion set formalism (Furlanetto)

Excursion Set Formalism (Furlanetto, Zaldarriaga, Hernquist; Zahn et al.)





Simulation of Cosmic Reionization – 1. N-body simulation

- Iliev et al. (2005 – current)
- Perform a pure N-body simulation in a big box (> ~ 50 comoving Mpc)
- Create a density field
- Paint hydrogen(HI) with cosmic abundace

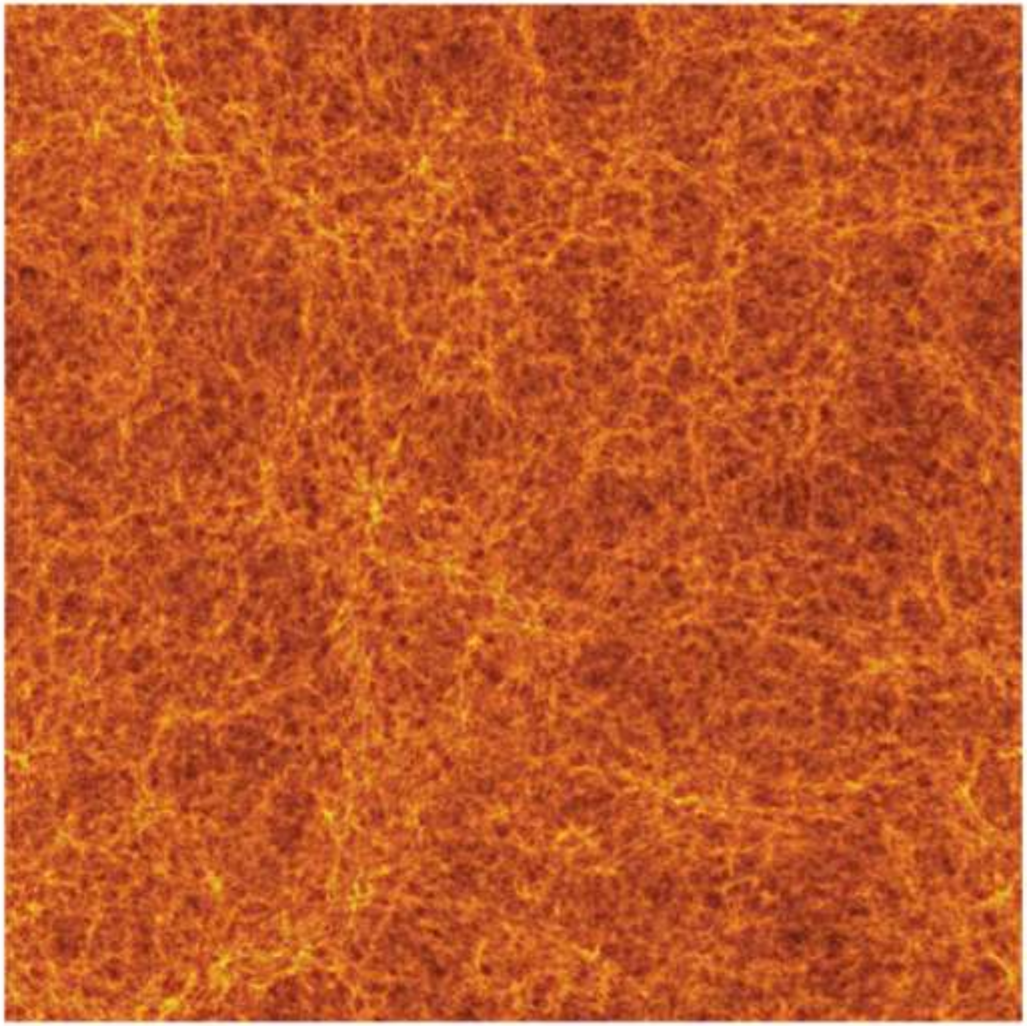
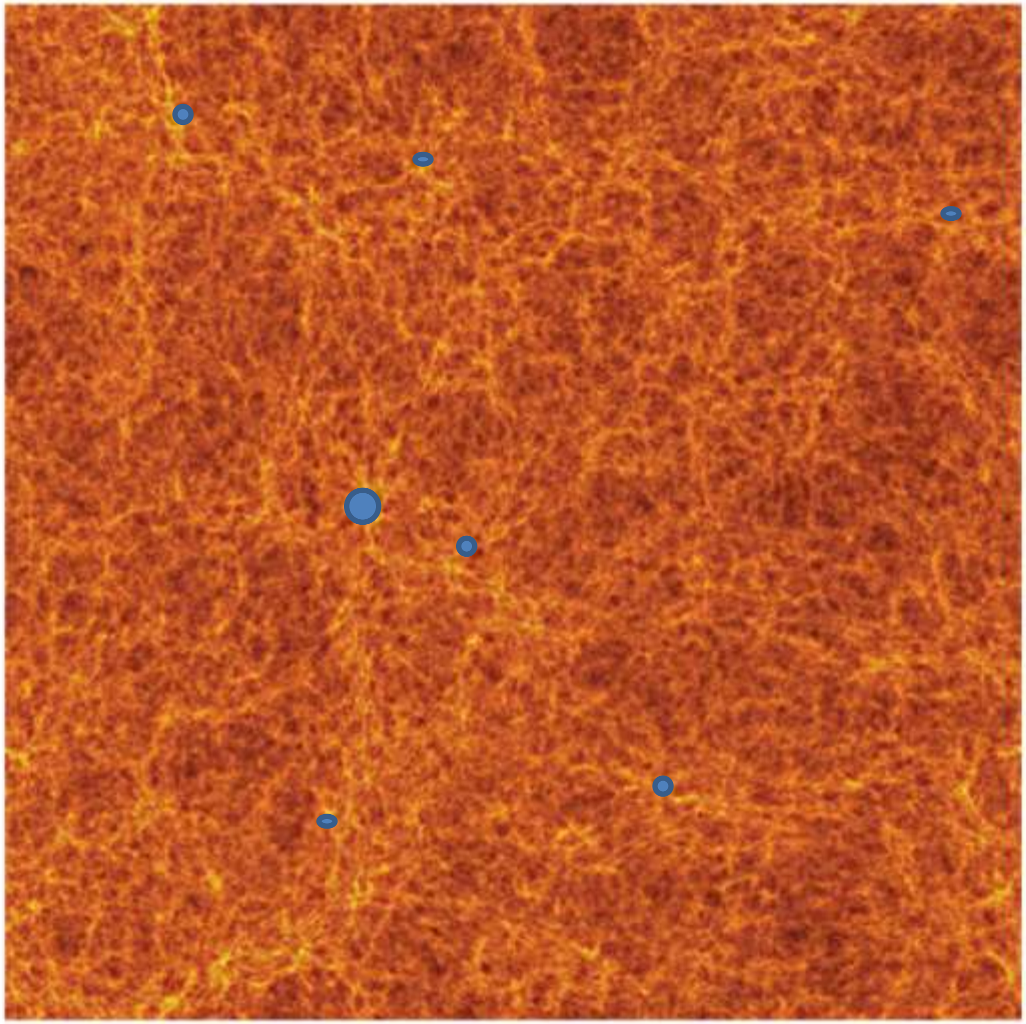


Figure 1. Early structure formation in ΛCDM, at $z = 10$, from our N-body simulation: projection of the cloud-in-cell densities on the fine simulation grid (3248 × 3248 pixel) in a 20 comoving Mpc slice ($\sim 6 \times 10^8$ particles in the slice) of the $(100\,h^{-1})^3$ Mpc^3 simulation volume. (See http://www.cita.utoronto.ca/~iliev/research.html for the full-resolution images and some movies of our simulations.)

Simulation of Cosmic Reionization – 2. Halo Identification

- Identify halos
- halo mass → stellar mass → ionizing photon luminosity
- "Parametrizing our ignorance" –quote by A. Loeb



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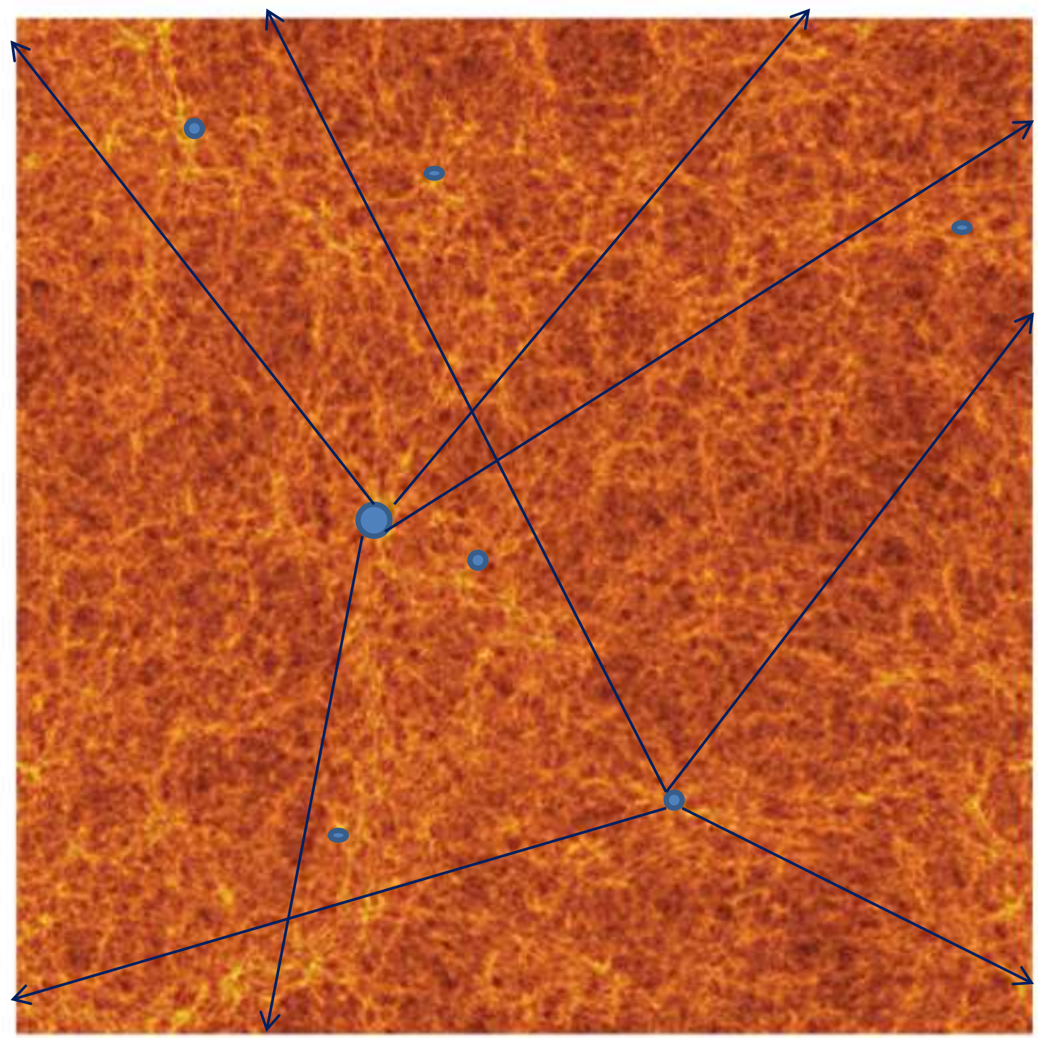
Simulation of Cosmic Reionization – 3. Ray tracing

- Draw rays into all directions from each source
- Along each ray, perform radiative transfer calculation



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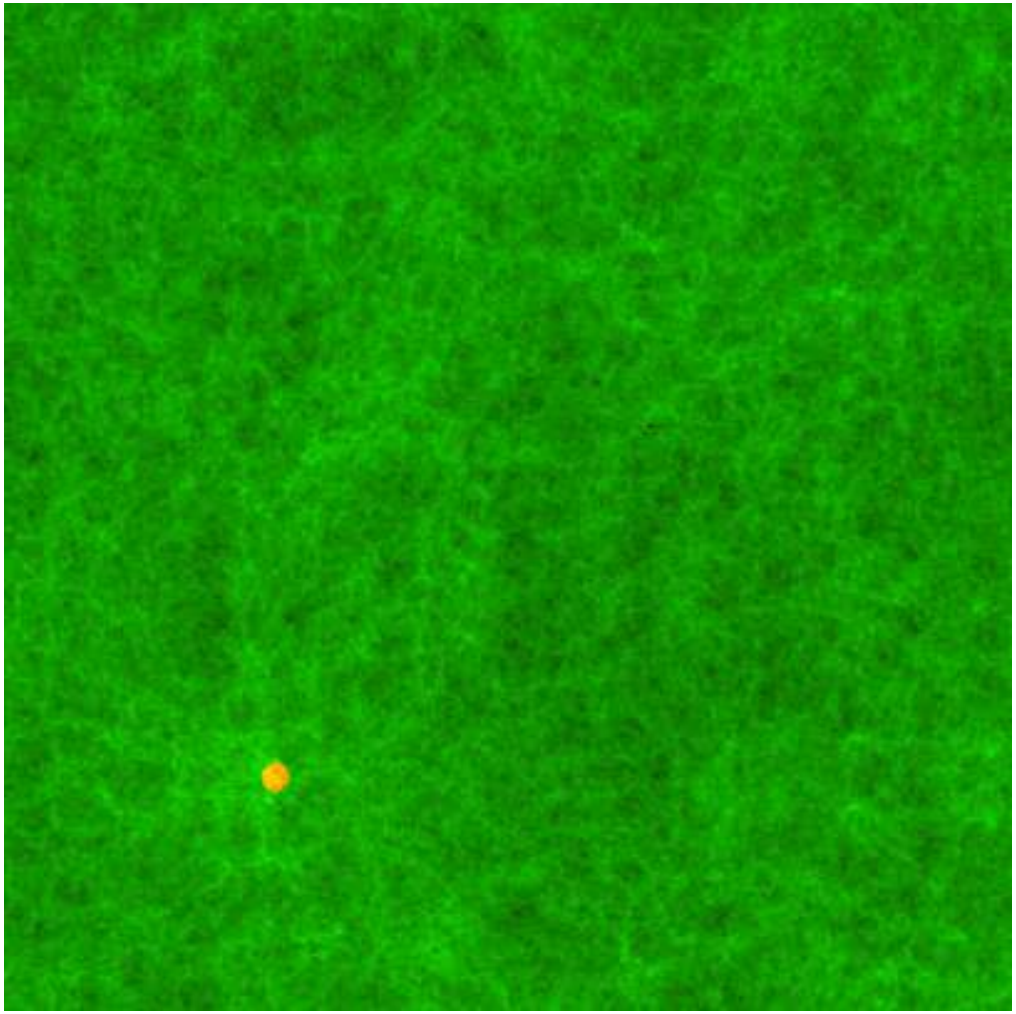
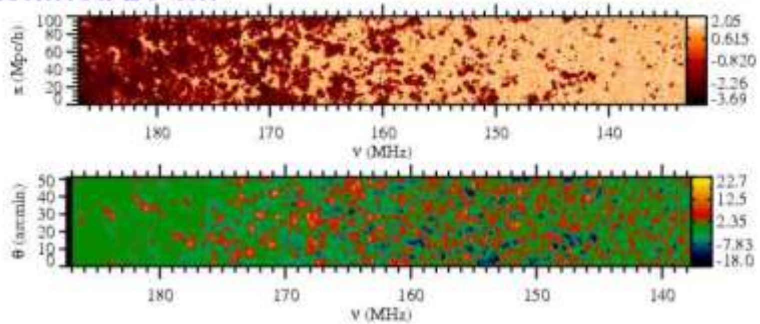
Simulation of Cosmic Reionization – 4. Evolve in time

- Get ionized fraction on each grid, solving rate equations for ~ 20 million year
- Update source population
- Iterate

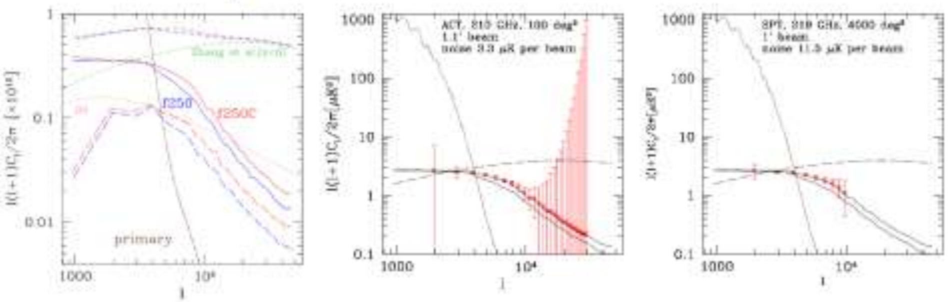


Direct observation of cosmic reionization

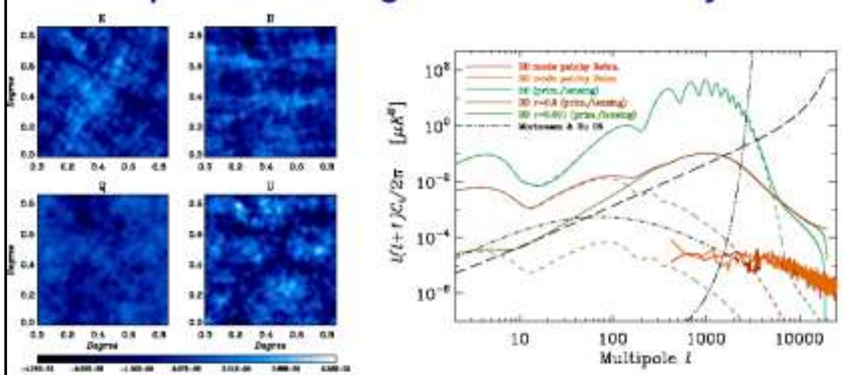
1 Redshifted 21-cm



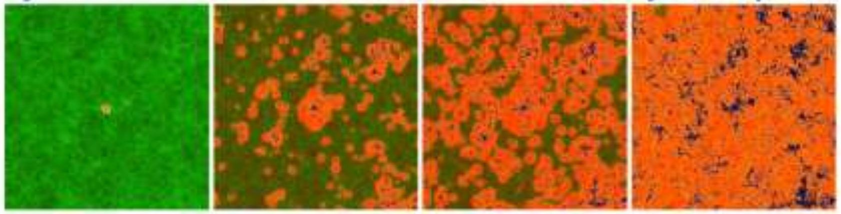
2 Kinetic Sunyaev-Zel'dovich Effect from Reionization



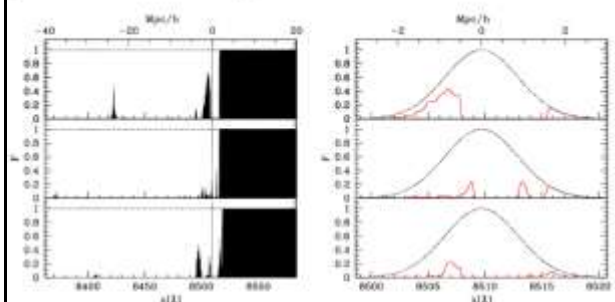
3 CMB polarization Signatures from Patchy Reionization

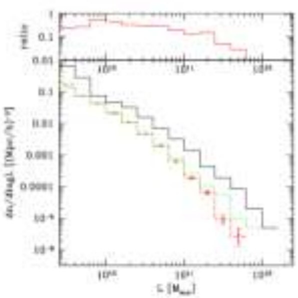


4 Ly-α observations: local reionization history and spectra



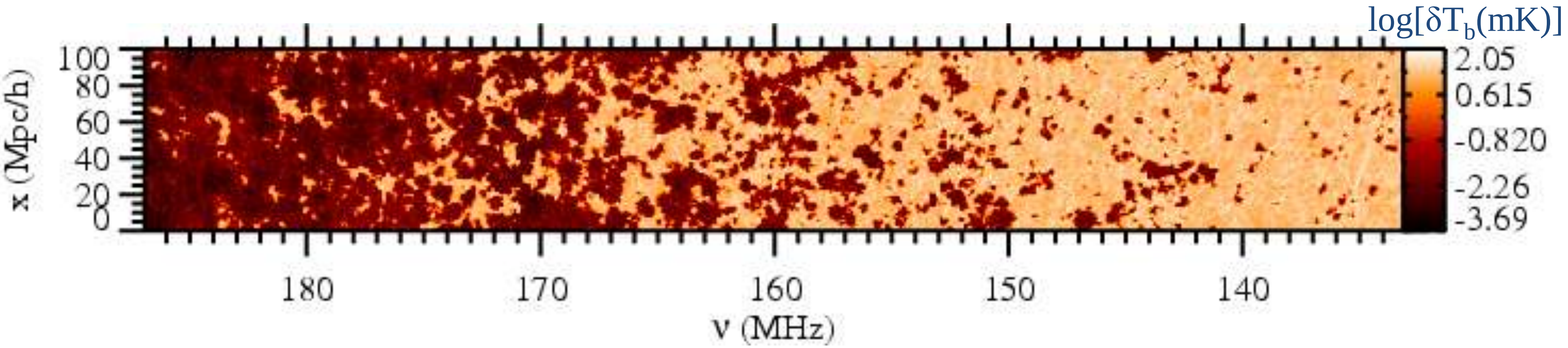
g. 7: The reionization history of a high density peak. The images are centered on the most massive (at $z = 6$) halo in
nputational volume and are of size $100\,h^{-1}$Mpc to the side. The snapshots are at: $z = 12.9$, $z = 9.0$, $z = 8.0$,and $z =$
underlying cosmological density field (dark,green) is superimposed with the ionized fraction (light, orange) and the c
taining ionizing sources (dark, blue dots). Quasi-spherical H II regions exist only during the early evolution. Generall
e number of sources is driving each ionization front.



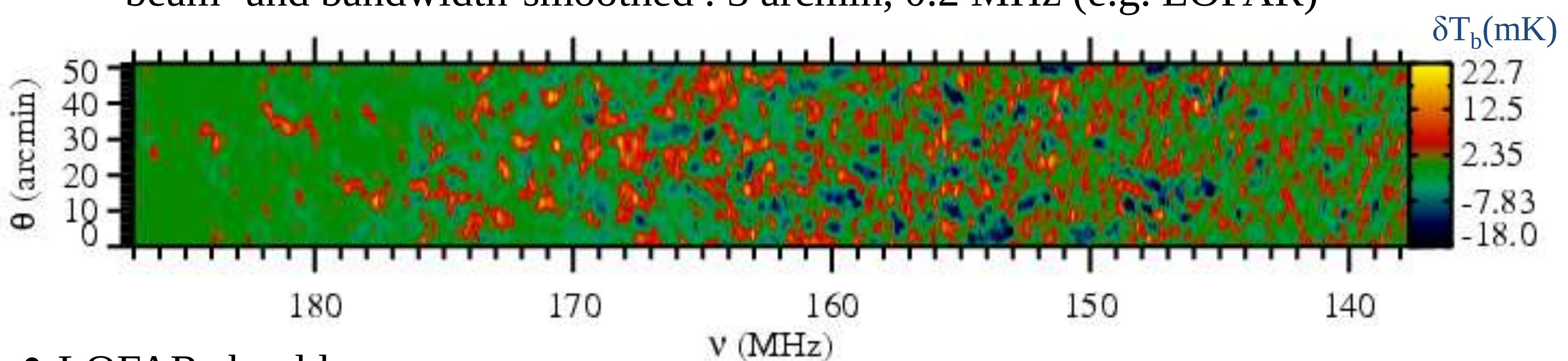


21cm tomography (Mellema et al. 2007)

- mapping the sky along the LOS: high-resolution cuts in position-redshift space



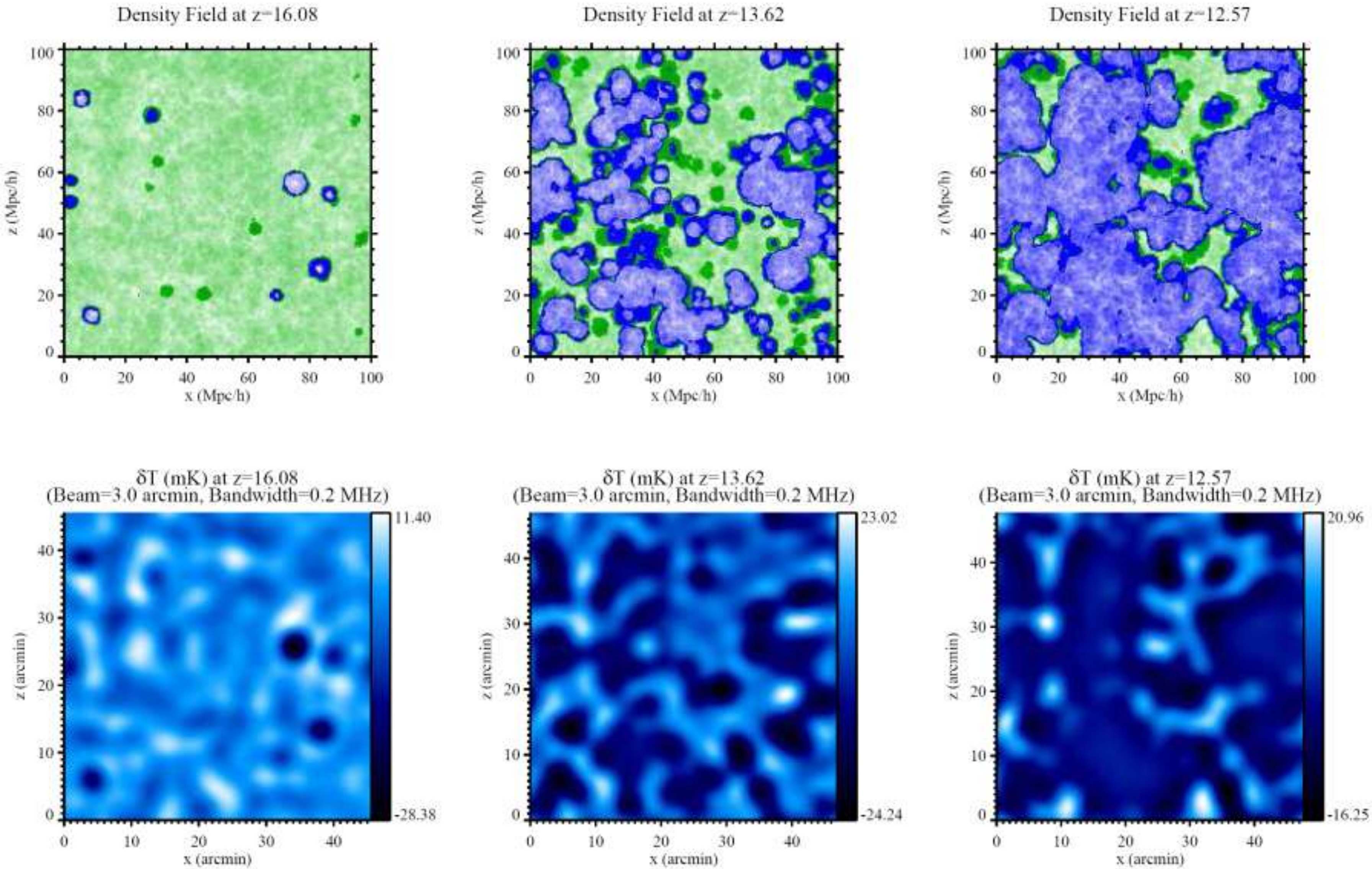
- beam- and bandwidth-smoothed : 3 arcmin, 0.2 MHz (e.g. LOFAR)



- LOFAR should see large ionized bubbles!

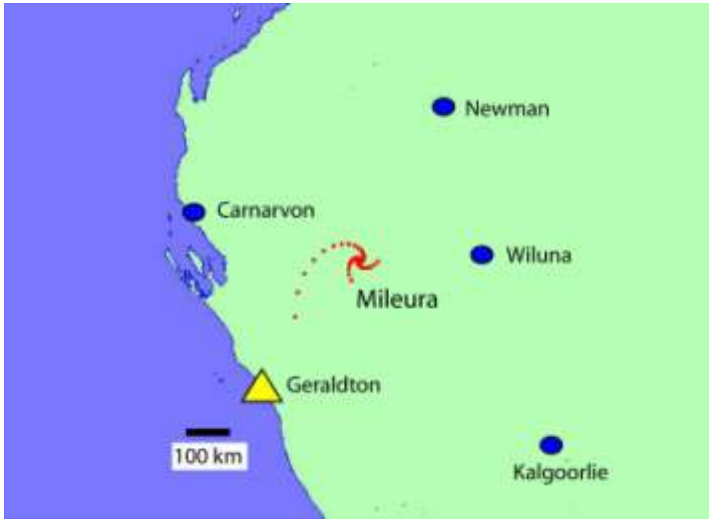
Case: $f_\gamma = 250$, subgrid clumping factor C(z), WMAP3

21cm tomography (Mellema et al. 2007)



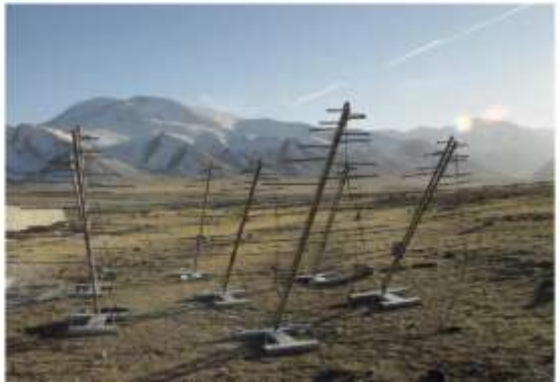
Low Frequency Array (LOFAR)

Mileura Wide-field Array (MWA)



PrimevAl Structure Telescope (PAST)

Prototype Tests, Ulastai, Xin Jiang, China

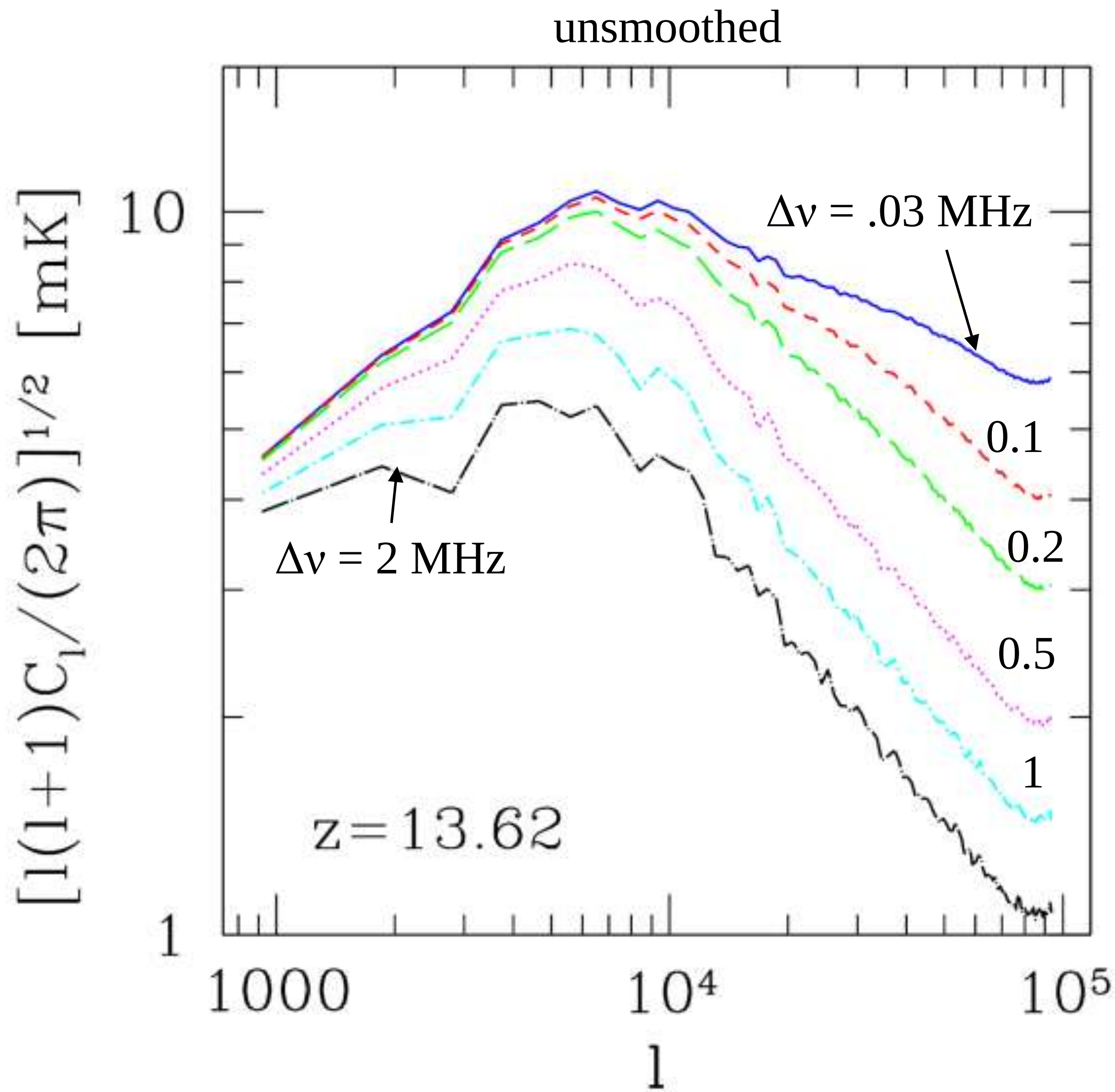


Giant Meterwave Radio Telescope (GMRT)

Square Kilometer Array (SKA)

21cm 2-D angular power spectrum

- May distinguish source properties
  - f2000: max ~10mK at ℓ_{max} ~ 4000 (~ 5') at z = 13.6, when <x> ~ 50% .
  - f250: max ~10mK at ℓ_{max} ~ 5000 (~ 4') at z = 11.8.
- Finite bandwidth → ℓ_{max} ↓ as Δν ↑
- Non-gaussianity?? Stay tuned (/w Park)



Summary

- Theory and observation of dark ages and the epoch of cosmic reionization are VERY promising
- Density fluctuation grows linearly during dark ages!
- 21cm observation is a powerful probe
- Theory needs heavy numerical simulations
- Indirect and direct observational probes