The first stars in the Universe

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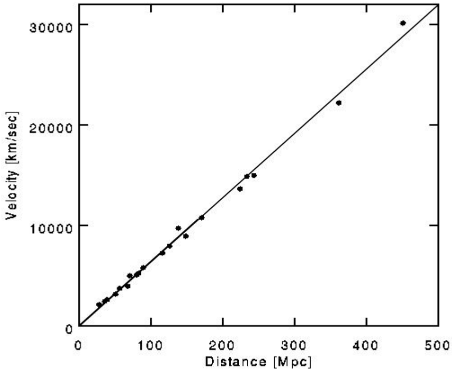
Cosmology

- The universe is homogeneous and isotropic at large scales.
- Hubble's law:



$$\mathbf{v} = H_0 \mathbf{r}$$

Recent measurements: $H_0 \sim 70$ km s^{-1} Mpc^{-1}.
Leads to the concept of an expanding universe.

Cosmology: basics

- The large-scale nature of the universe must be described by general theory of relativity.
- Assume the Universe to be homogeneous and isotropic, then it is described by the FRW metric

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left[\frac{\mathrm{d}r^2}{1-\kappa r^2} + r^2\mathrm{d}\Omega^2\right]$$

- Friedmann equations

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum_i \rho_i(a) - \frac{\kappa}{a^2}$$

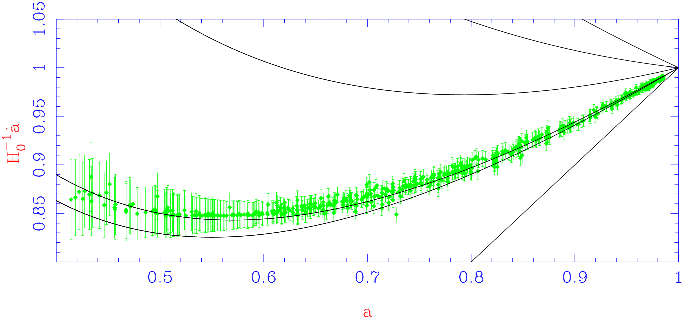
  and

$$\frac{\ddot{a}}{a} = -4\pi G \sum_i [\rho_i(a) + 3p_i(a)]$$

  Current observational data supports $\kappa = 0$.
- Note that for normal matter $\rho_i > 0, p_i \geq 0$, so $\ddot{a} < 0$. The Universe should be decelerating.

Accelerating universe

SN-Ia data from various experimental probes



Padmanabhan & **TRC** (2003); updated 2013

Data shows that the Universe is accelerating from $a \approx 0.6$ onwards.

Requires $\rho + 3p < 0 \Longrightarrow p < 0$. Dark Energy!

Dark matter

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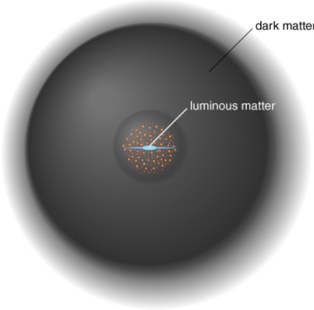
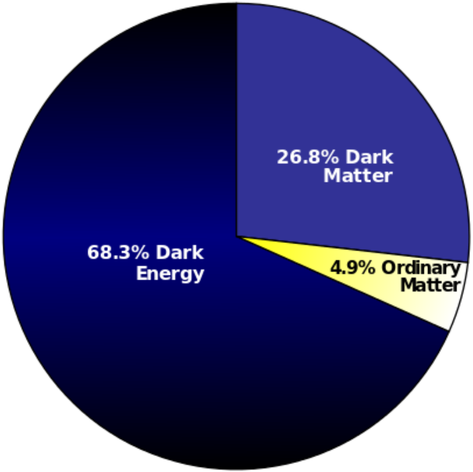
- However, only $\sim 4-5\%$ seen in stars, galaxies, intergalactic gas.
- So, $\sim 25\%$ is Dark Matter!
- Does not emit or interact with light, but otherwise like normal matter.



Yet to be detected in the laboratory experiments.

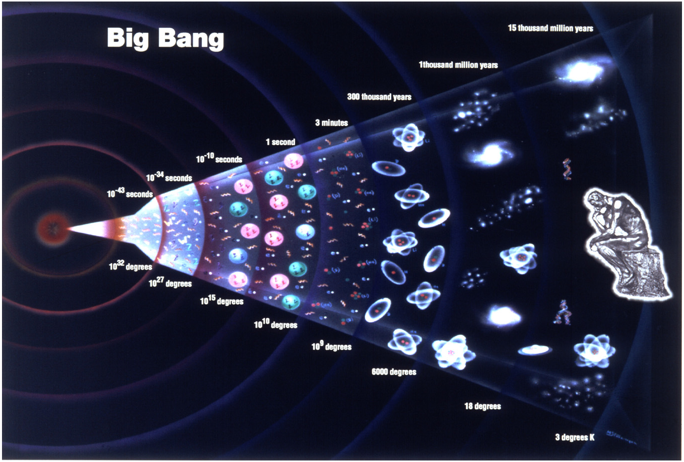
Constituents of the Universe



Mostly hydrogen (75%) and helium (25%)

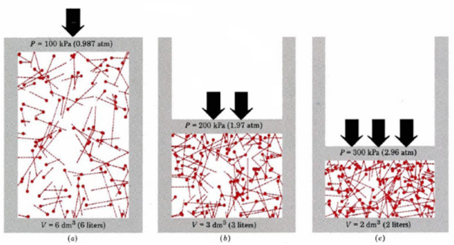
Big bang cosmology

If the Universe is expanding now, its size must be smaller in the past. If we go back enough in time, the Universe must be contained within a point. This paradigm is called the Hot Big Bang model of the Universe.



Hot universe

- Imagine a set of particles (gas) in a box, whose volume is compressed



- The (kinetic) energy of the particles would increase $\Longrightarrow$ rise in temperature

$$T = \frac{1}{3k_B} m \langle v^2 \rangle$$

- Universe was hotter at earlier times

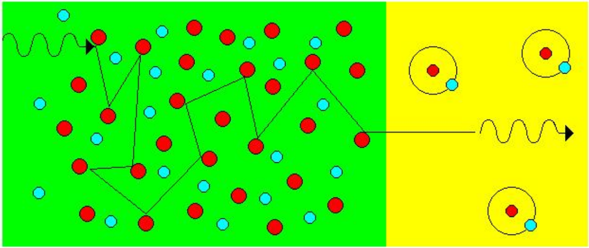
$$T \approx 2 \times 10^6 \text{ K} \left(\frac{t}{\text{year}} \right)^{-1/2} \approx 10^{10} \text{ K} \left(\frac{t}{\text{sec}} \right)^{-1/2}$$

Big bang timeline

- $t < 10^{-43}$ secs: Physics not understood, realm of quantum gravity
- $t \approx 0.0001$ secs: Baryogenesis. Small difference between the number of anti-particles and particles $\Longrightarrow$ Antiparticles annihilate with particles leaving only matter. Poorly understood.
- $t \approx 3$ mins: **Big Bang Nucleosynthesis**
- $t \approx 400,000$ years: **Formation of neutral atoms**
- $t > 10^8$ years: **Stars/Galaxies form**
- Present age of the Universe: $t \approx 10^{10}$ years

Formation of atoms

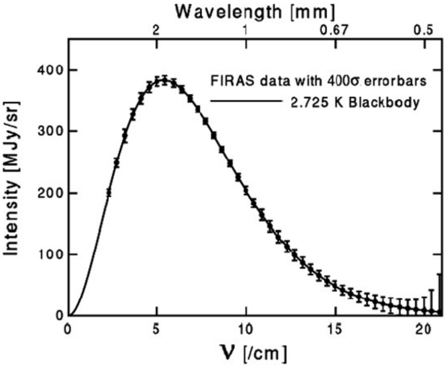
- At $t \approx 400,000$ years, energies are small enough so that electrons and protons can bind with each other.



- Photons (radiation) scattered off free electrons before atom formation. They travel freely afterwards.
- We detect this radiation as Cosmic Microwave Background.

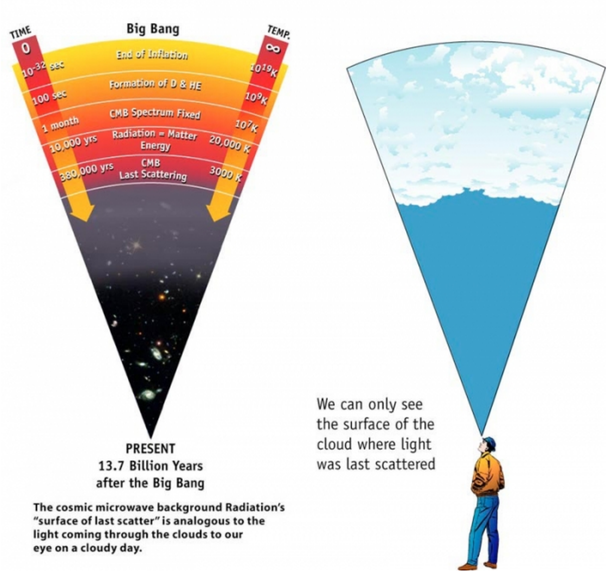
Spectrum of the CMBR

Before formation of neutral atoms, photons were getting scattered by electrons, thus coming to a local thermodynamic equilibrium $\Longrightarrow$ Black-body spectrum. Once atoms form, photons simply free-stream to us.



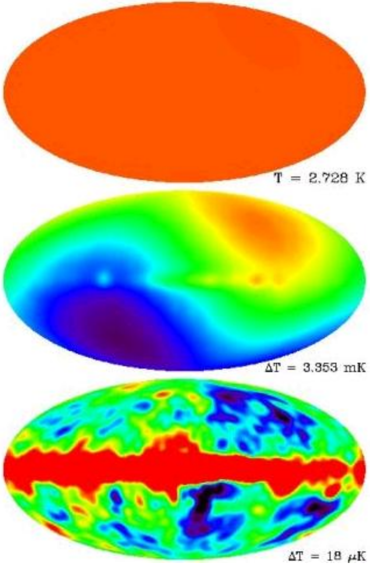
Spectrum measured by COBE (1992).
Competing theories of big bang fail to explain this spectrum

Last scattering surface

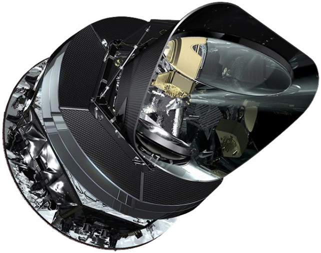


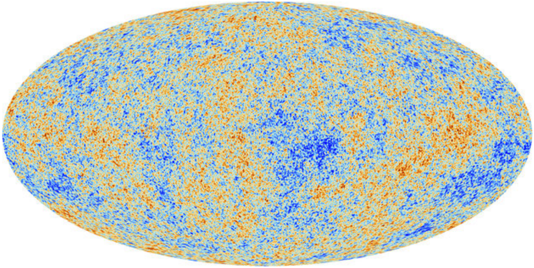
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

Inhomogeneities in the CMBR



Planck satellite

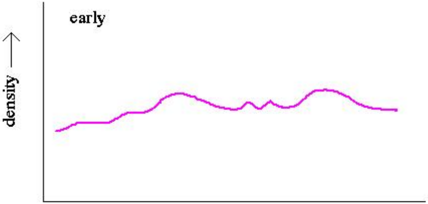




Inhomogeneities $\sim 10^{-5}$.
Seeds of Galaxies and all the structures we see today.

Gravitational instability

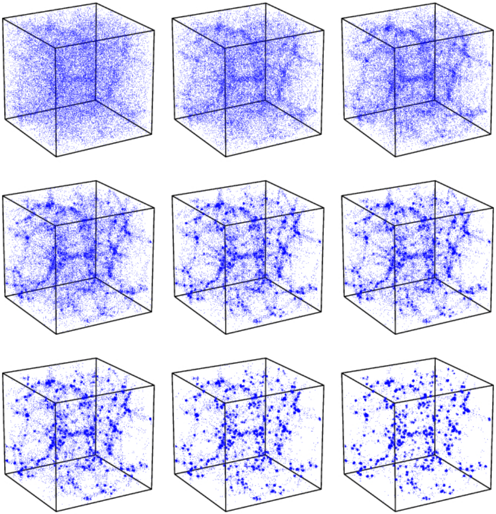
large scale fluctuations become gravitationally unstable and grow in amplitude



small scale fluctuations damp out with time

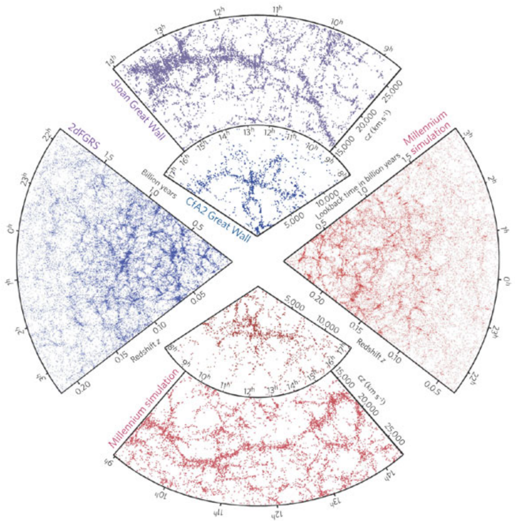
Growth of structures

Inhomogeneities grow via gravitational instability, probed by computer simulations



Galaxy distribution

Galaxy surveys vs Millennium simulations



Standard model of cosmology

Precision cosmology!

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71

Unsolved issues include: nature of dark matter and dark energy and H_0-tension.

Structures: theory and observations

Theoretical understanding

time	redshift	
?		Origin (?)
4×10^5 y	~ 1100	Small fluctuations (initial conditions)
		↓ Gravitational instability
$\sim 10^{10}$ y	0	Large-scale structure

Structures: theory and observations

Theoretical understanding			Observational probes
time	redshift		
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4×10^5 y	~ 1100	Small fluctuations (initial conditions)	CMBR
		Gravitational instability	
$\sim 10^9$ y	~ 6		
			Redshift surveys
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Observational probes

CMBR

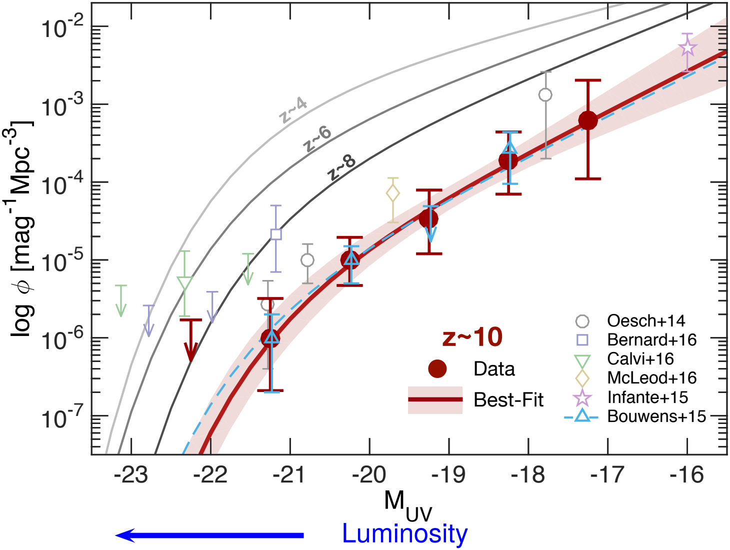
Redshift surveys

Structures: theory and observations

Theoretical understanding

time	redshift		Observational probes
?		Origin (?)	
4×10^5 y	~ 1100	Small fluctuations (initial conditions)	CMBR
		Gravitational instability	
$\sim 10^8$ y	~ 15		First stars/galaxies
$\sim 10^9$ y	~ 6		Redshift surveys
$\sim 10^{10}$ y	0	Large-scale structure	

Search for the first stars

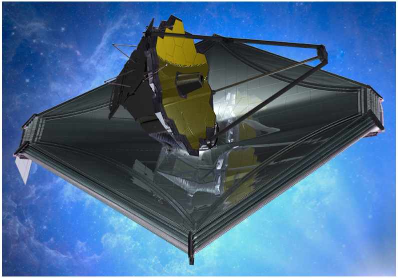


Oesch et al (2018)

push to fainter luminosities and higher redshifts with JWST (2021) and the ELTs

Probing the "final frontier"

Probes planned for detecting the first stars (cosmic dawn)



JWST

TMT

Brief history of neutral hydrogen

Big Bang — Universe expanding and cooling → — Present day

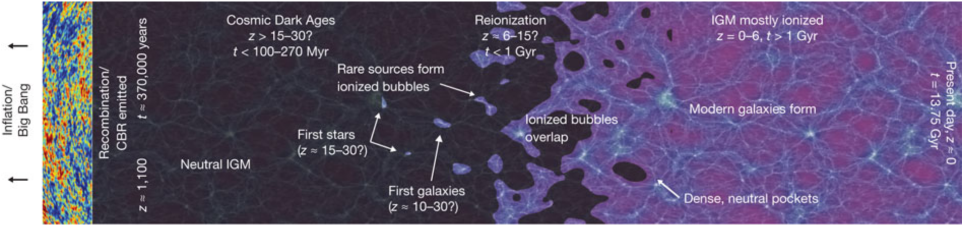


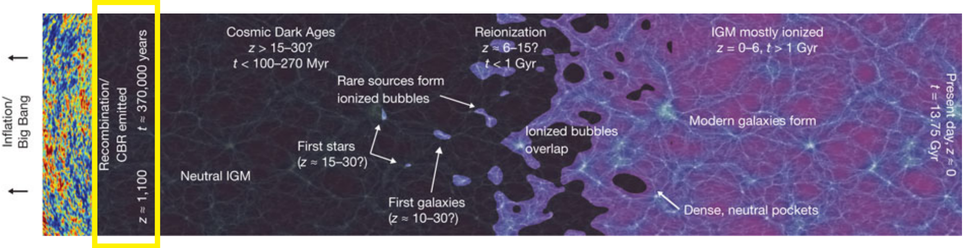
Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Brief history of neutral hydrogen

Big Bang

Universe expanding and cooling

Present day



Last scattering epoch

First hydrogen atoms form

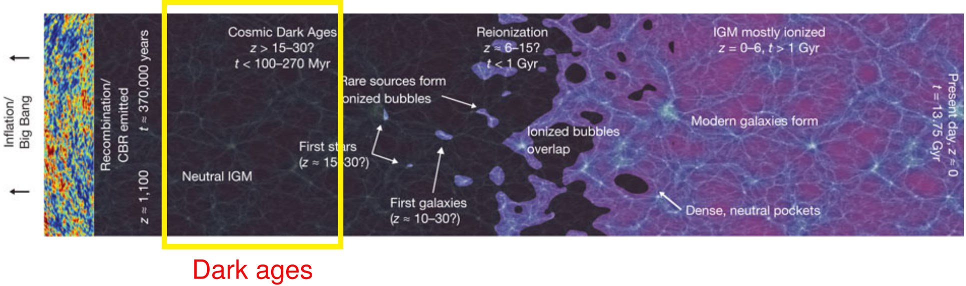
Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Brief history of neutral hydrogen

Big Bang

Universe expanding and cooling

Present day



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Brief history of neutral hydrogen

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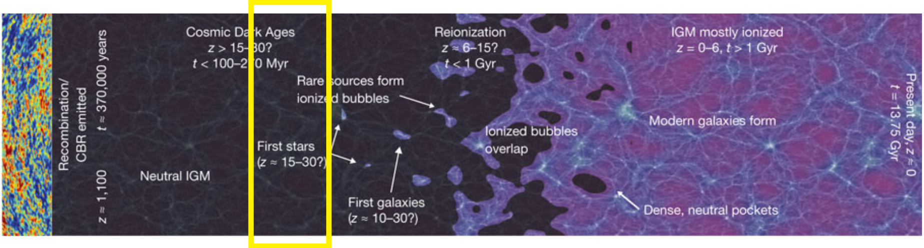
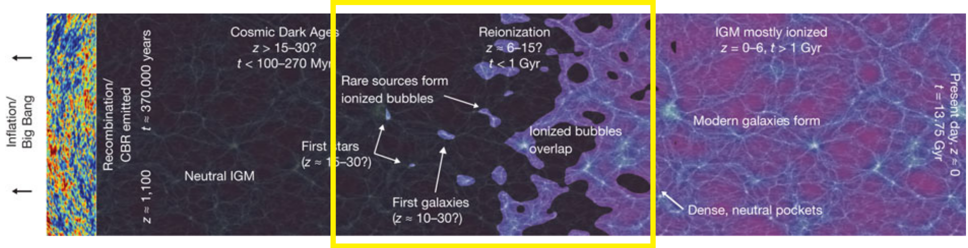


First stars form

Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Brief history of neutral hydrogen

Big Bang Universe expanding and cooling Present day



Reionization

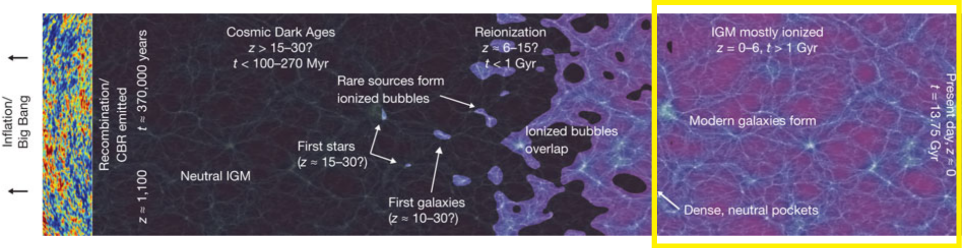
Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Brief history of neutral hydrogen

Big Bang

Universe expanding and cooling

Present day

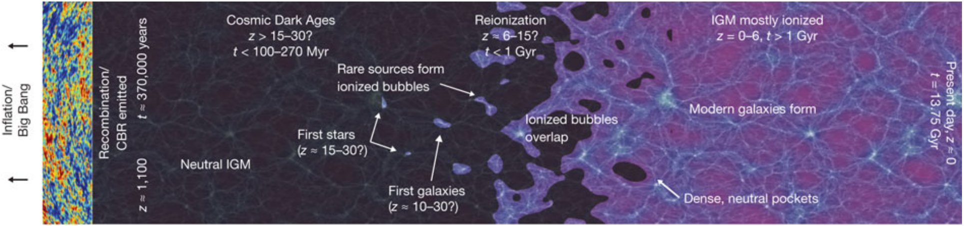


Post-reionization

Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Brief history of neutral hydrogen

Big Bang | Universe expanding and cooling → | Present day



Dark ages

Strong probe of cosmology

Reionization

1. First stars
2. Cosmology

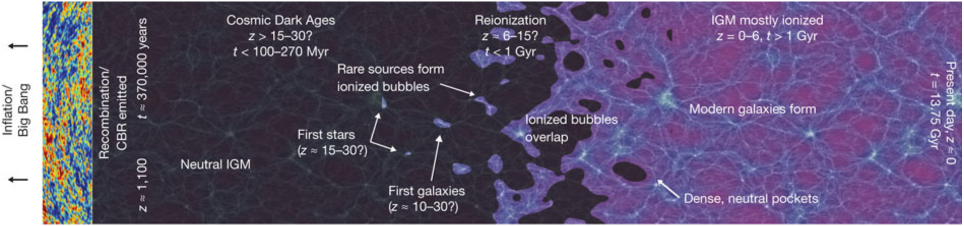
Post-reionization

1. Galaxy formation
2. Cosmology

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Brief history of neutral hydrogen

Big Bang | Universe expanding and cooling | Present day



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Strong probe of cosmology

Reionization

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Post-reionization

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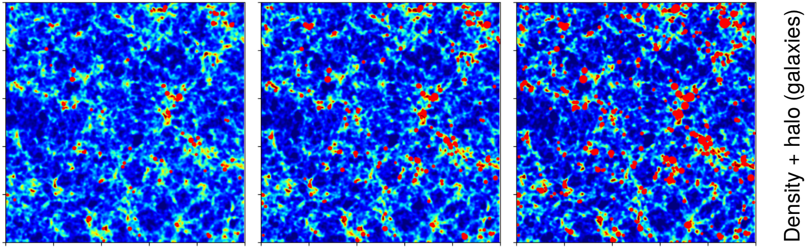
Phase transition

"Final frontier" of observational cosmology

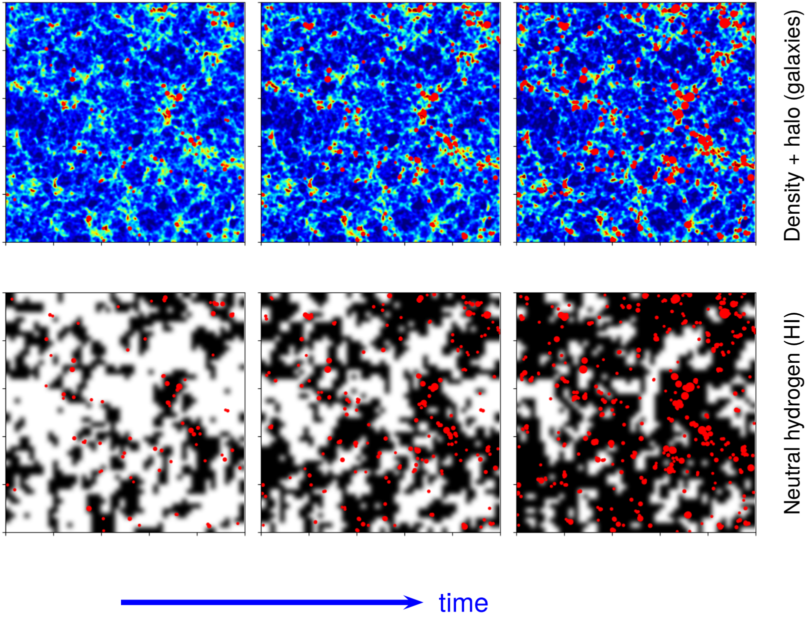
Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Galaxies and neutral hydrogen

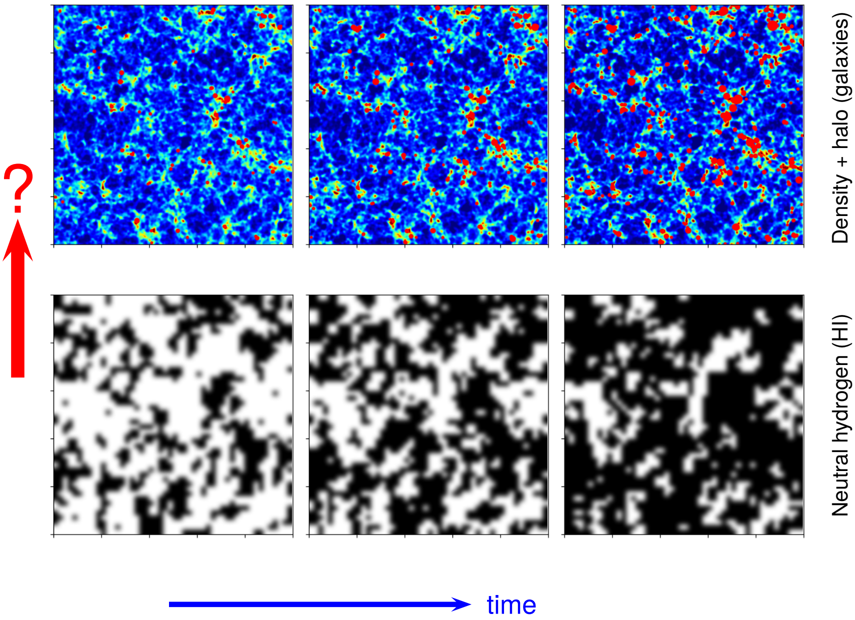


time

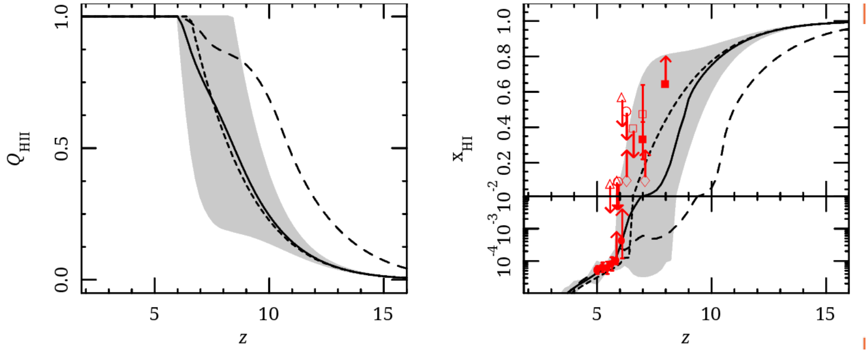
Galaxies and neutral hydrogen



Galaxies and neutral hydrogen



Data constrained models



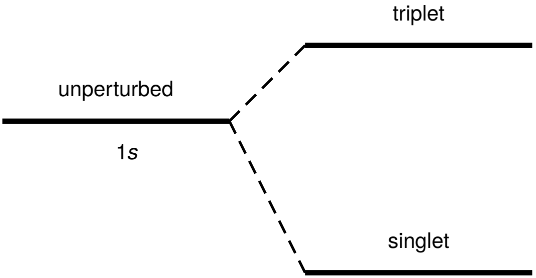
Constraints based on Planck data + quasar absorption line measurements at $z \sim 6$

reionization starts at $z \sim 12$

Mitra, **TRC** & Ferrara (2015)

21 cm observations

- Hydrogen 1s ground state split by the interaction between the electron spin and the nuclear spin.



$$|\uparrow\uparrow\rangle$$
$$\frac{1}{\sqrt{2}}\left[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right]$$
$$|\downarrow\downarrow\rangle$$

$\nu = 1420$ MHz, $\lambda = 21$ cm

$$\frac{1}{\sqrt{2}}\left[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right]$$

Line transition $\Longrightarrow$ a transition originating at z will be observed at a frequency $\nu_{\rm obs} = 1420/(1+z)$ MHz.

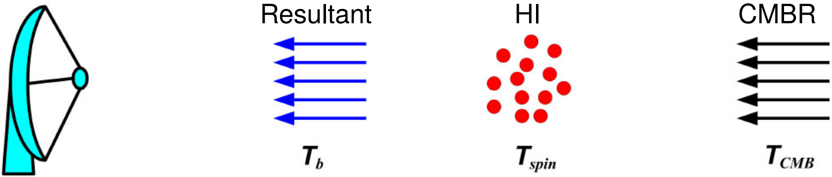
- It is a magnetic dipole transition, with transition probability $A_{21} = 2.85 \times 10^{-15}$ s^{-1} $\Longrightarrow$ an atom in the upper level is expected to make a downward transition once in 10^7 yr.

  For Lyα transition, the corresponding coefficient is $A_{21} \approx 6 \times 10^8$ s^{-1}.

How to observe the 21 cm signal?

$$\frac{n_2}{n_1} = 3\, \mathrm{e}^{-T_{\rm spin}/T_{21}}$$

Figure from Zaroubi (2013)



z

$$\nu = \frac{1420}{1+z}\ \text{MHz}$$

$$\nu = 1420\ \text{MHz}$$

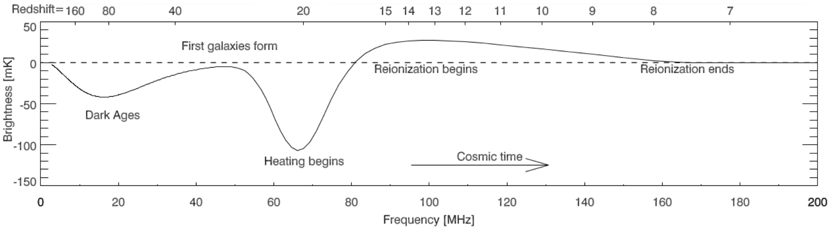
The signal: $$\delta I_\nu \propto \rho_{\rm HI} \left(1 - \frac{T_{\rm CMB}}{T_{\rm spin}}\right)$$

$$\propto \rho_{\rm HI} \text{ if } T_{\rm spin} \sim T_{\rm gas} \gg T_{\rm CMB}$$

Global 21 cm signature

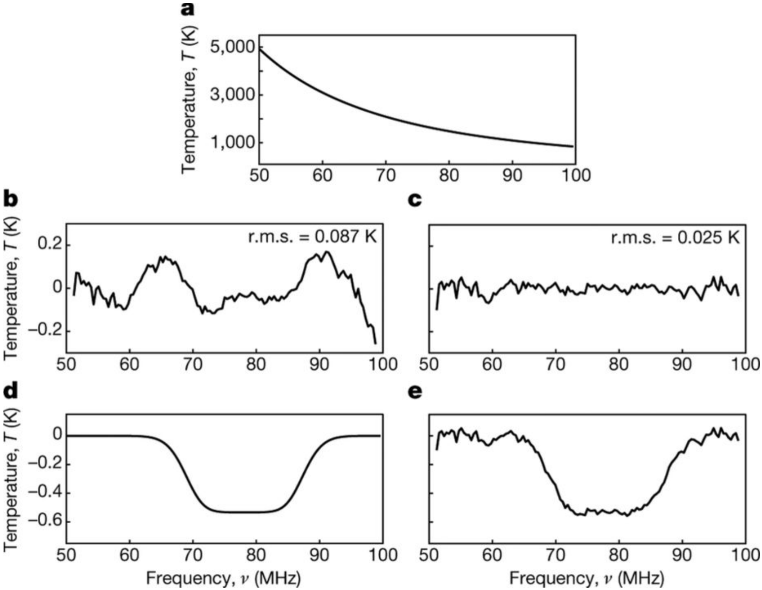
$$\delta T_b \propto \frac{T_s - T_{\rm CMB}(z)}{T_s}\rho_{\rm HI}$$

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$



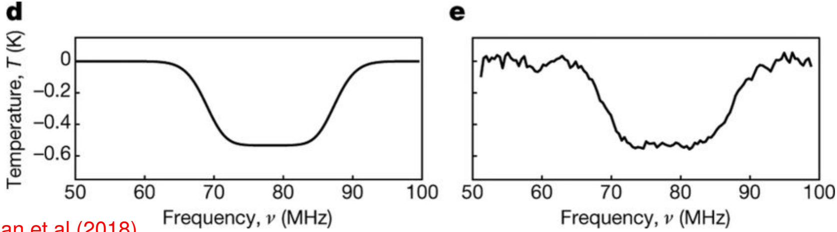
Pritchard & Loeb (2012)

Recent detection of the global 21 cm signal



Bowman et al (2018)

Consistent with standard calculations?



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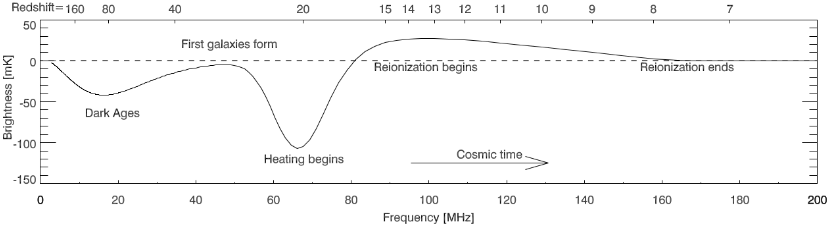
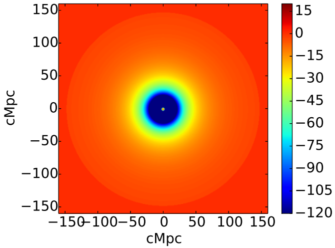


Pritchard & Loeb (2012)

$$\delta T_b = 0.023 \text{ K } x_{\mathrm{HI}} \left(\frac{T_s - T_{\mathrm{CMB}}(z)}{T_s} \right)$$

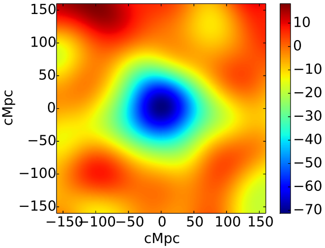
21 cm maps

HI density field



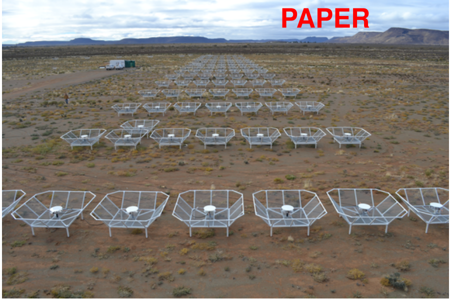
Possible to observe using
radio-interferometric array

21 cm map



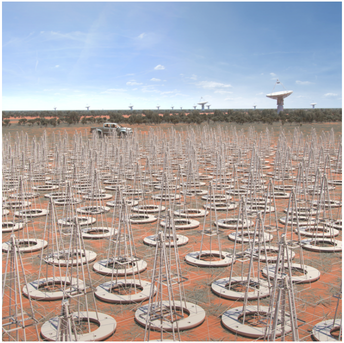
Ghara, **TRC** & Datta (2016)

“Final frontier” using radio telescopes

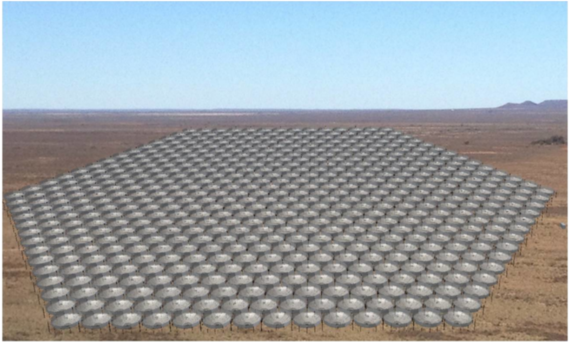


Future telescopes

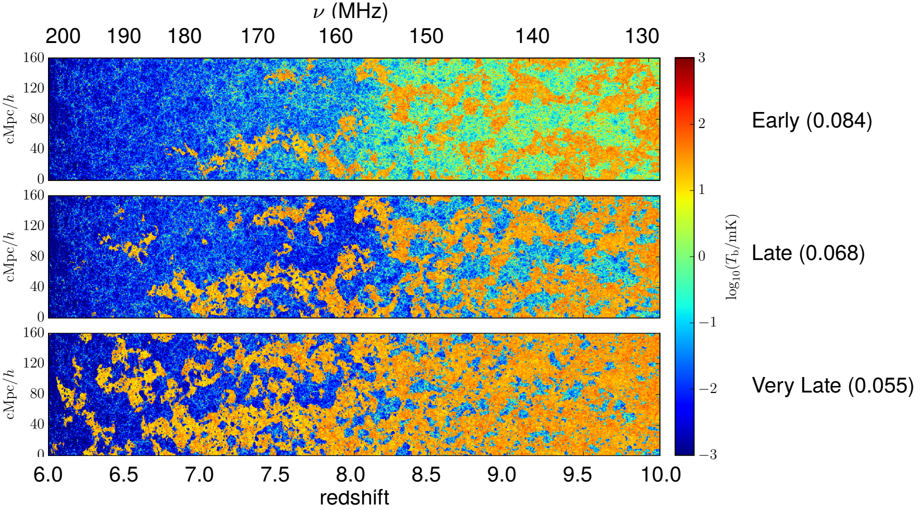
SKA-LOW



HERA

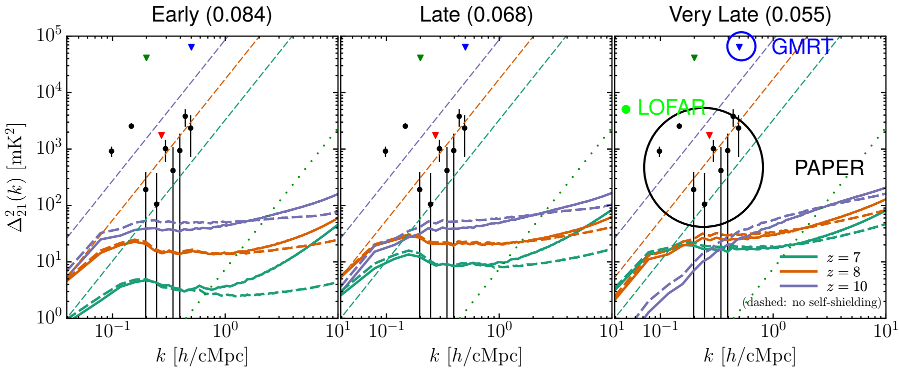


21 cm maps



Kulkarni, **TRC**, Puchwein & Haehnelt (2016)

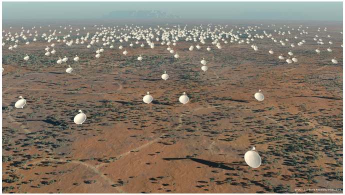
EoR 21 cm power spectra



$z = 7$
$z = 8$
$z = 10$

Kulkarni, **TRC**, Puchwein & Haehnelt (2016)

The SKA



- Square Kilometre Array: most ambitious radio astronomy project ever attempted
- To be built in Australia and South Africa
- Phase I: target 2022. Main science goals include EoR
- India is a member of the SKA international collaboration (lead by NCRA-TIFR). GMRT often provides useful test-bed for SKA

Summary

- Studying the formation of the first stars is the "Final frontier" of observational cosmology.
- Good progress in theoretical modelling, possible to construct models consistent with all available data.
- Field driven by observational data – various observations will soon (?) settle the long-standing question on when and how the first stars formed.
- Important to develop detailed analytical and numerical models to extract the maximum information about the physical processes relevant for galaxy/star formation and evolution out of the expected **large and complex data sets**.