Cosmic Neutral Hydrogen as a probe of the first stars in the Universe

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NCRA • TIFR

Colloquium
International Centre for Theoretical Sciences
Tata Institute of Fundamental Research, Bangalore
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Plan of the talk

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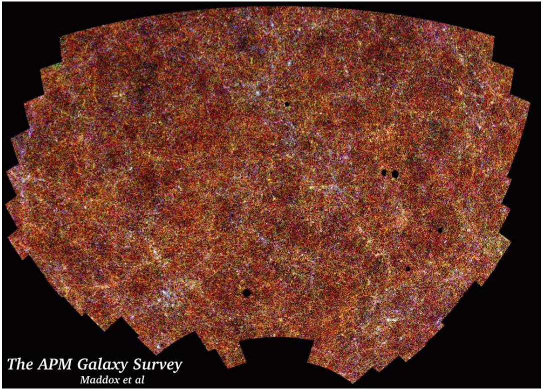
- First stars in the context of modern cosmology
- Connection between the first stars and neutral hydrogen (HI)
- Current constraints on early star formation
- Future: 21 cm probes

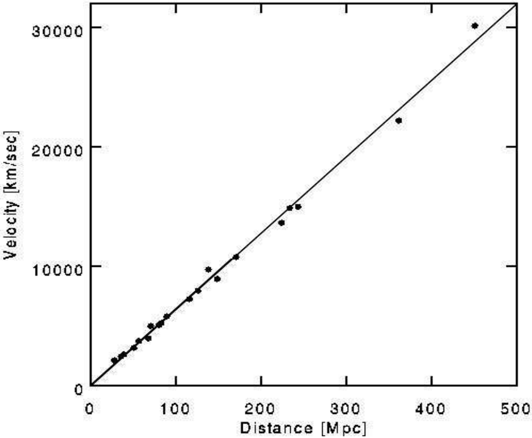
Large-scale properties of the Universe

- Universe is homogeneous and isotropic



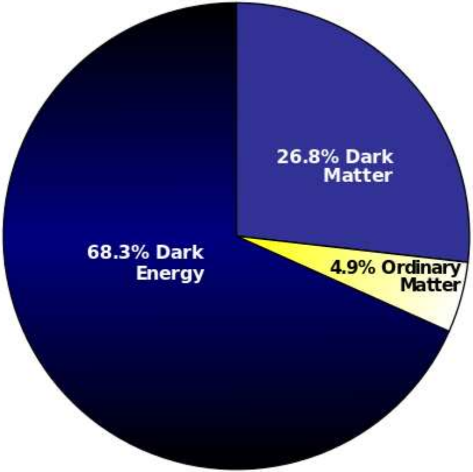
Large-scale properties of the Universe

- Universe is homogeneous and isotropic
- Universe is expanding, scale factor $a(t)$



Constituents of the Universe

Expansion rate $\Longleftrightarrow$ Constituents



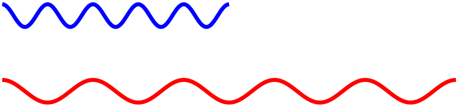
Mostly hydrogen (75%) and helium (25%)

Observational cosmology

- Redshift

$a < 1$

$a = 1$



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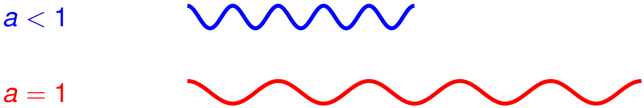

- $$1 + z(t) \equiv \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \frac{1}{a(t)}$$

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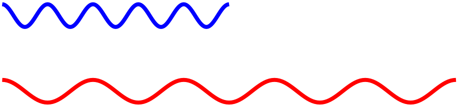

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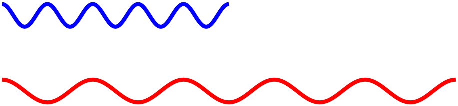

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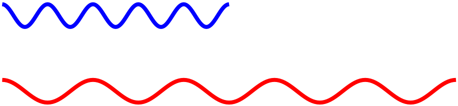

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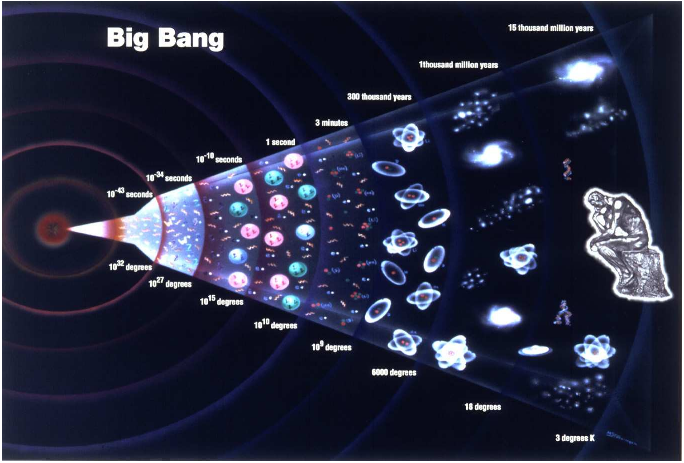
The hot big bang model

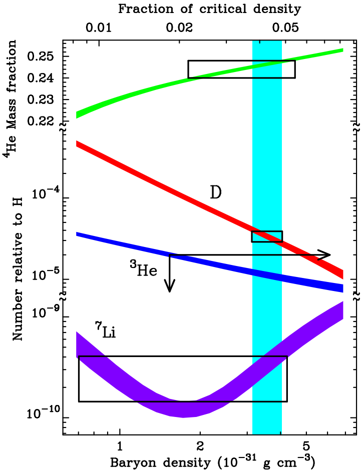
If the Universe is expanding now, its size must be smaller, and hence hotter, in the past. This paradigm is called the Hot Big Bang model of the Universe.



Important “milestones”

Present age of the Universe: $t \approx 10^{10}$ years

- $t \approx 3$ mins: **Big Bang Nucleosynthesis**



Tytler et al (2000)

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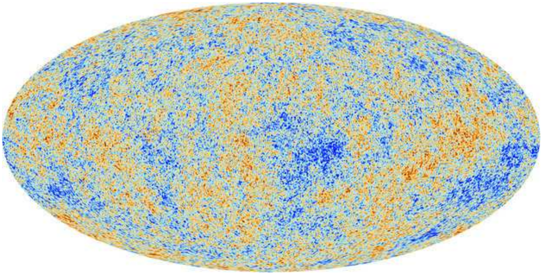

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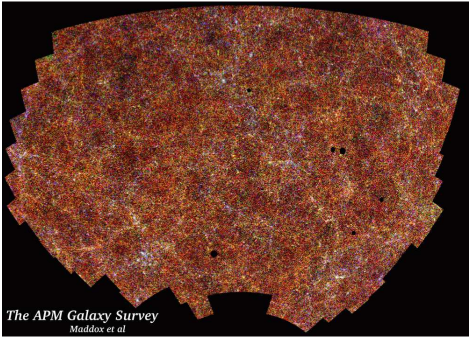
- $t > 10^{8}$ years: **Stars/Galaxies form**



Structure formation

Concept of gravitational instability

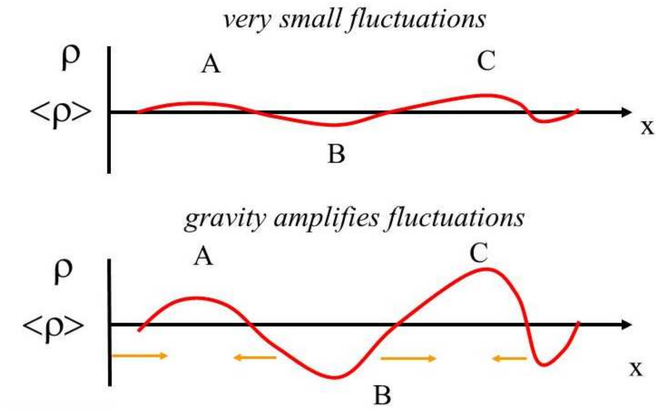


Figure taken from a talk by Michael Norman

Structure formation: formulation

- Origin of the “seed” fluctuations unknown, probably quantum-gravitational

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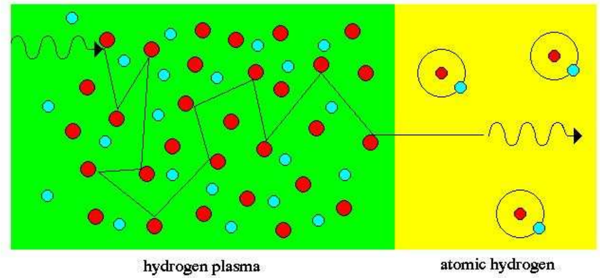
- Start with CMBR fluctuations!

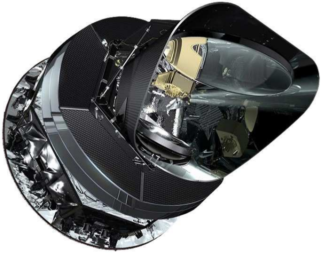
Formation of atoms

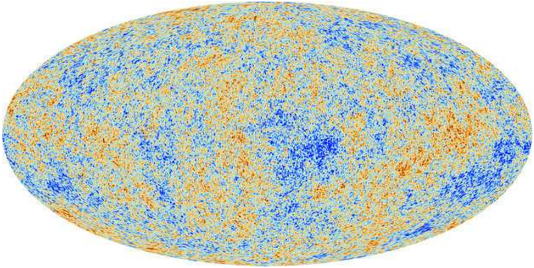
- At $t \approx 400,000$ years, energies are small enough so that electrons and protons can bind with each other.



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

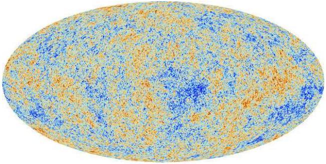
Inhomogeneities in the radiation background

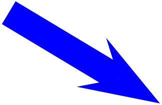


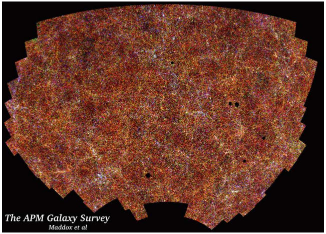


Inhomogeneities $\sim 10^{-5}$.
Seeds of Galaxies and all the structures we see today.

Cosmological structure formation

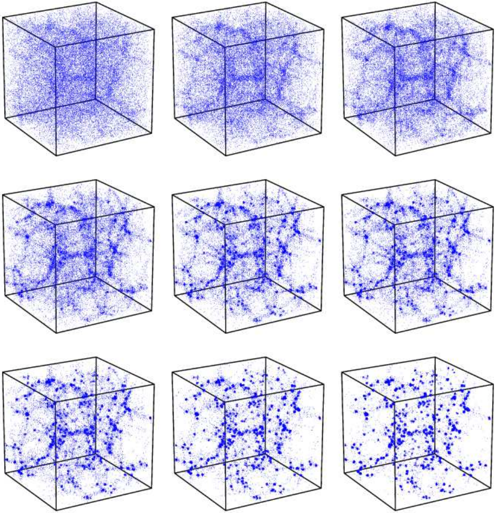






Growth of structures

Inhomogeneities grow via gravitational instability, probed by computer simulations



The predictions match with observations ....

Structures: theory and observations

Theory

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

Structures: theory and observations

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$\sim 10^9$ y — ~ 6

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Observations

CMBR

Galaxy surveys

Structures: theory and observations

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Structures: theory and observations

Theory: time	z		Observations
?		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		Galaxy surveys
$\sim 10^{10}$ y	0	Large-scale structure	

First / early stars

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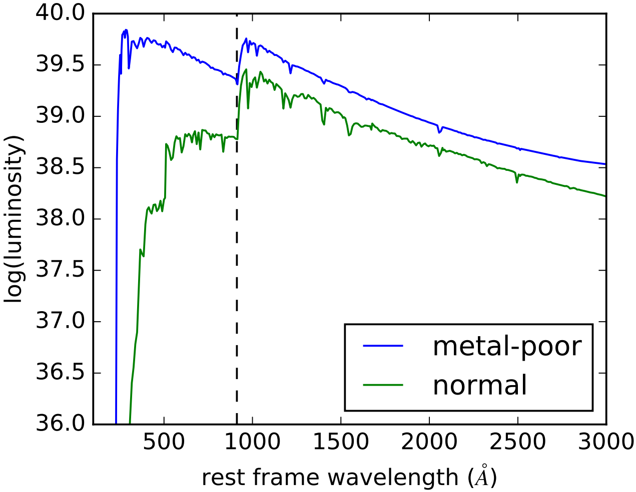
- Effective surface temperature $\sim 10^5$ K (for sun this is ~ 6000 K)

UV spectra



early stars produce more hydrogen ionizing photons $\Longrightarrow$ detect the early stars through their effect on hydrogen

Reionization of hydrogen

Big Bang | Universe expanding and cooling → | Present day

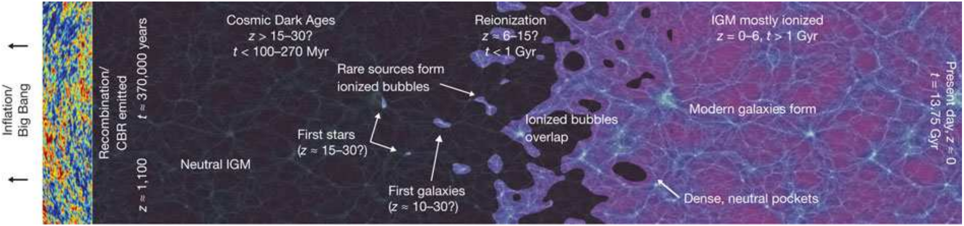


Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

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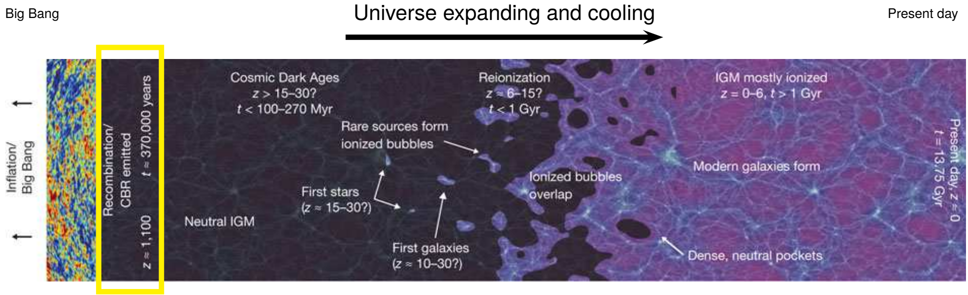

Last scattering epoch
First hydrogen atoms form
Origin of the CMBR

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

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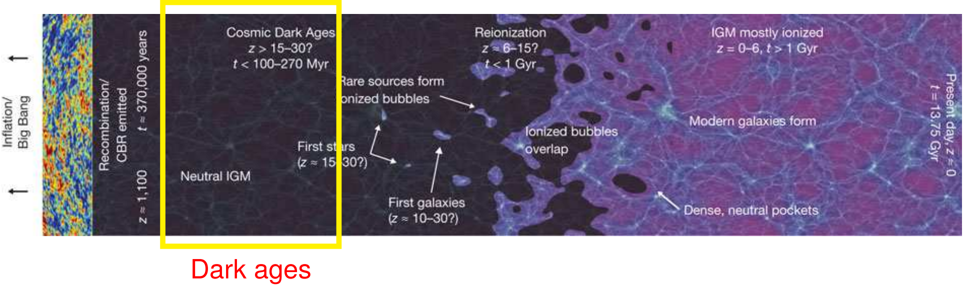

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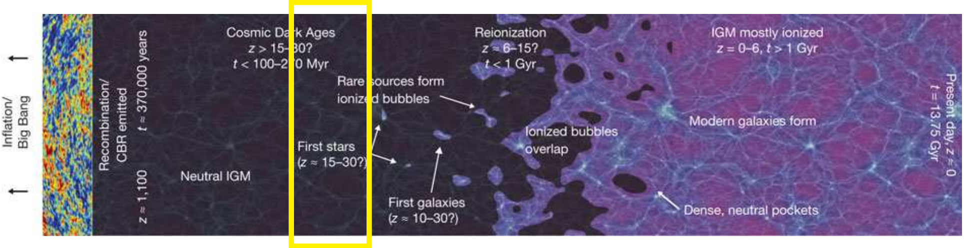


Cosmic dawn
First stars form

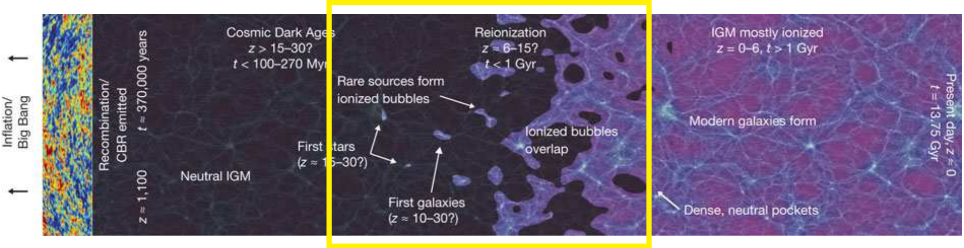
Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Reionization of hydrogen

Big Bang

Universe expanding and cooling

Present day



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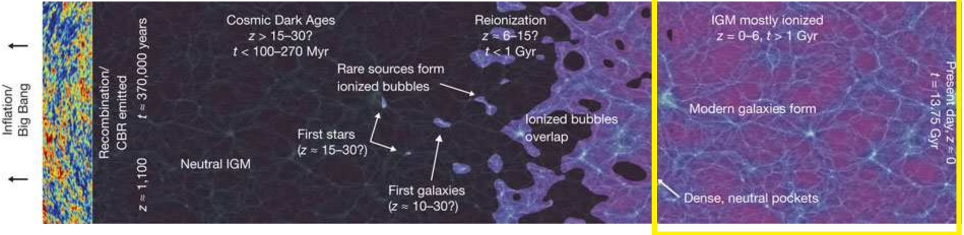

Post-reionization

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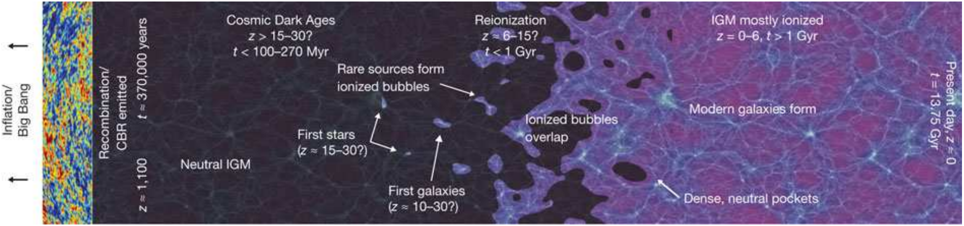
Reionization of hydrogen

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`

Reionization of hydrogen

Big Bang

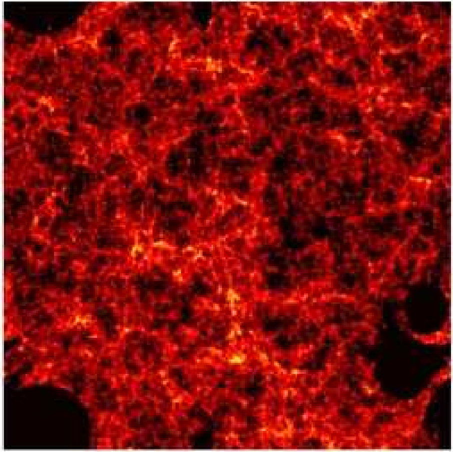
Universe expanding and cooling

Present day

“Final Frontier” of observational cosmology

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

Hydrogen reionization by stars (HI $\rightarrow$ HII)



N-body simulations (GADGET) + Semi-numerical radiative transfer

TRC, Haehnelt & Regan (2009)

Figure courtesy Aditya Chowdhury

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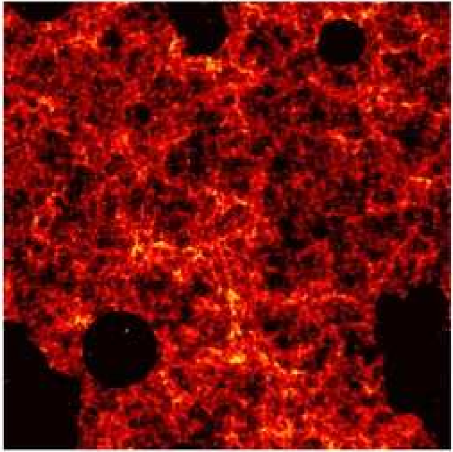

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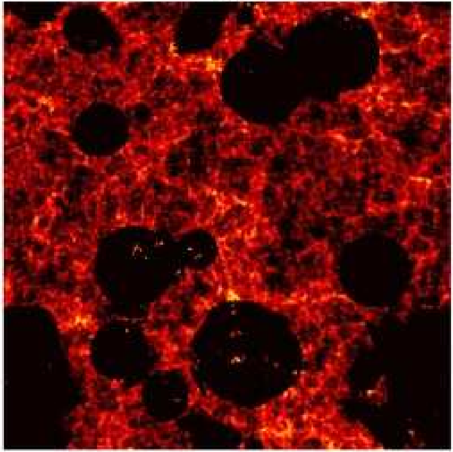

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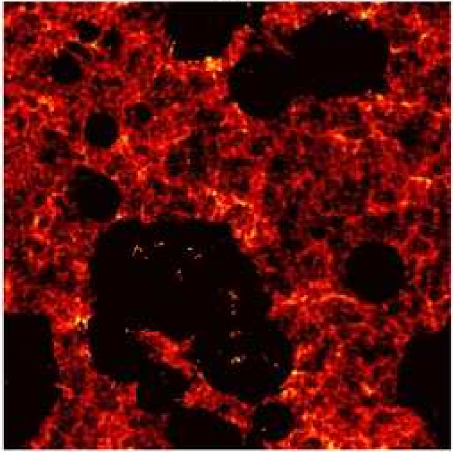

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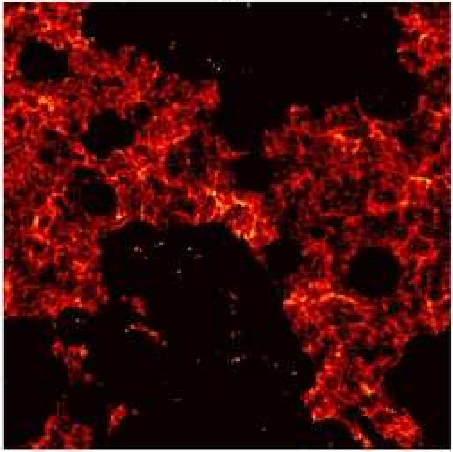

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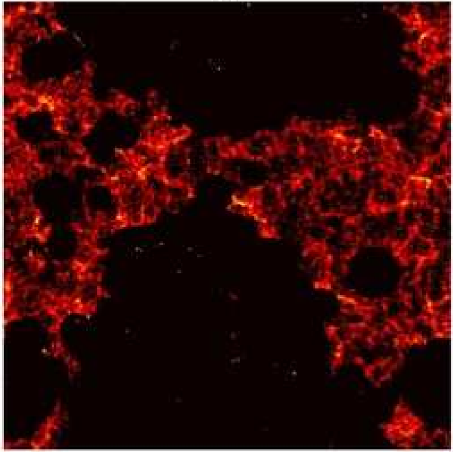

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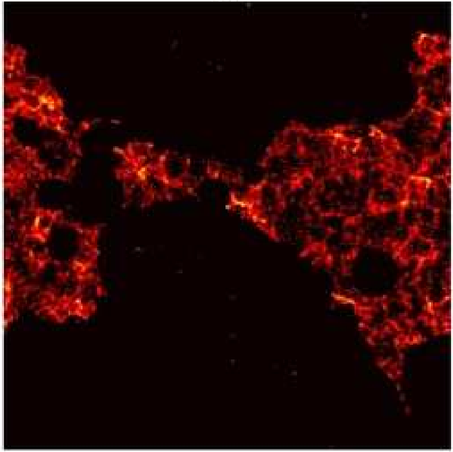

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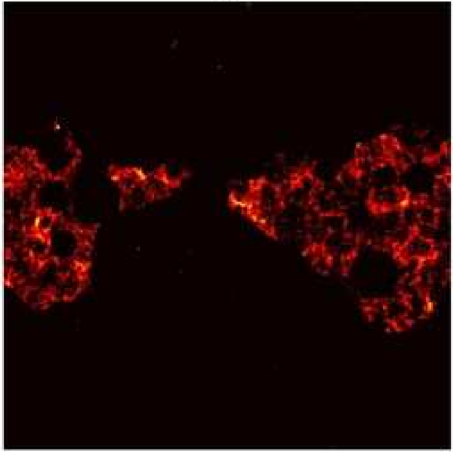

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Reionization models: ingredients

Dark matter haloes M

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Dark matter haloes M

↓ cooling, fragmentation, feedback, ...

Galaxy + star formation $M_* = f_* M$

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Stellar spectra / no of ionizing photons

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↓ clumpiness, outflows, ...

Escape of photons from the galaxy $f_{\rm esc}$

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Stellar spectra / no of ionizing photons ← galaxy observations

↓ clumpiness, outflows, . . .

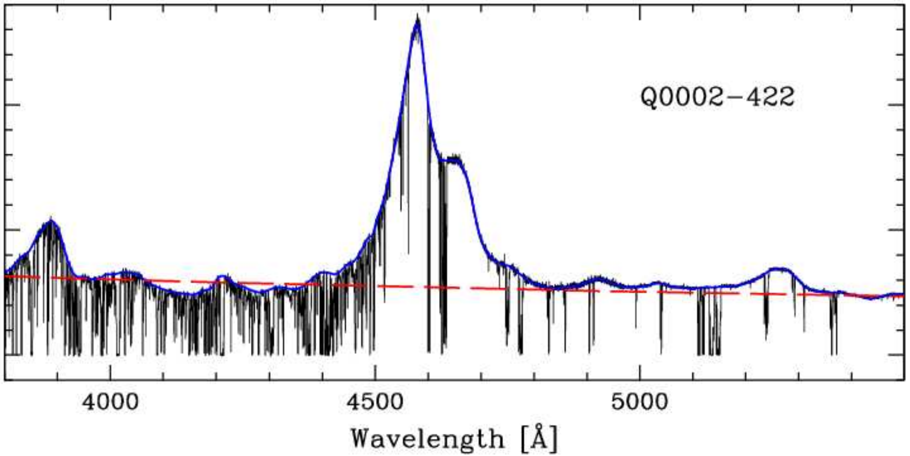
Escape of photons from the galaxy $f_{\rm esc}$

↓ propagation of ionization fronts

Radiative transfer through the intergalactic medium

Current observational probes

- Spectra of distant quasars: Lyman-α forest



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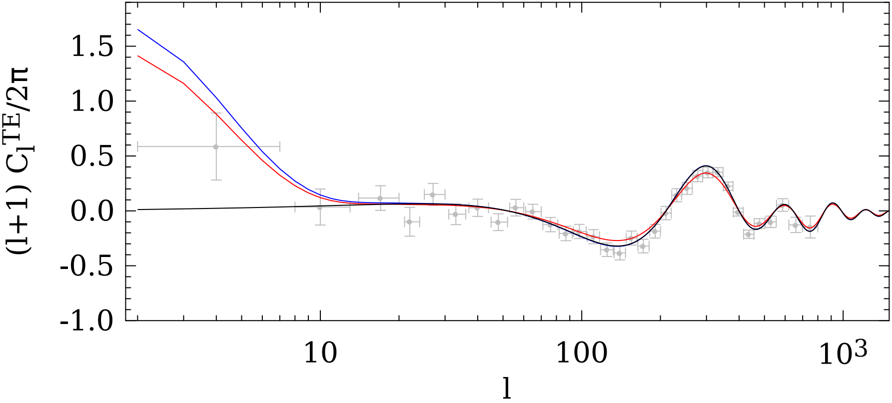
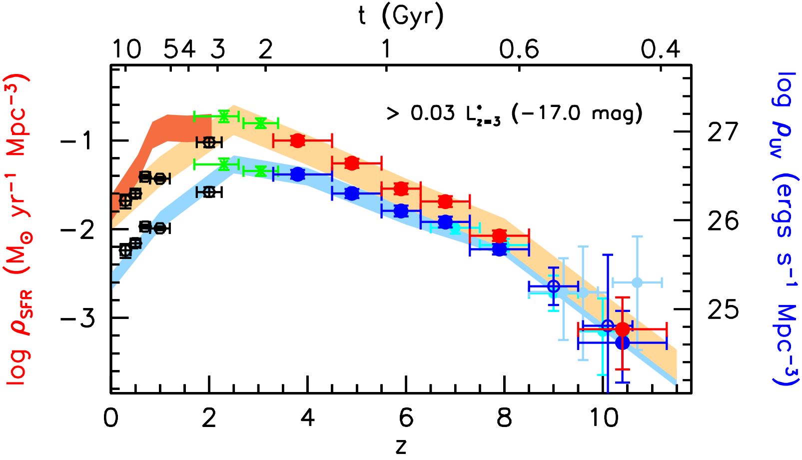


Current observational probes

- Spectra of distant quasars: Lyman-α forest
- CMBR polarization
- High redshift galaxies

Bouwens et al (2014)



Data constrained models

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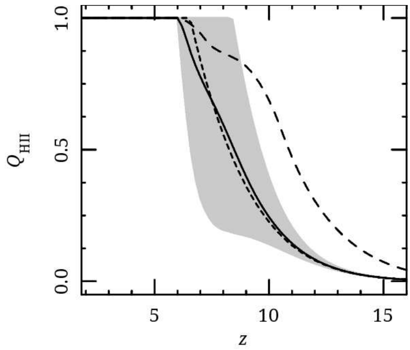
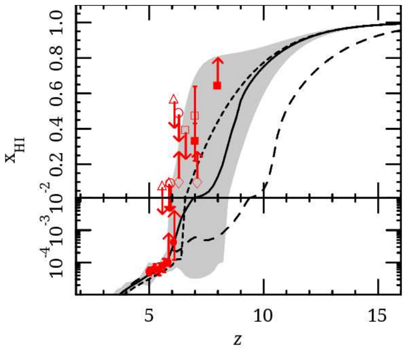


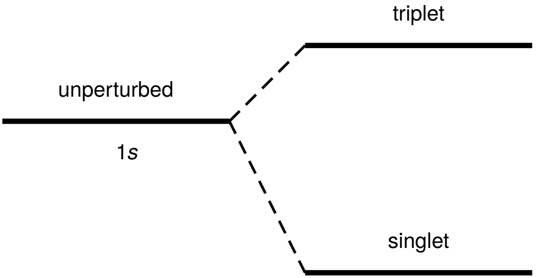


- Constraints obtained using Monte-Carlo Markov Chain (MCMC) techniques, based on Planck data + quasar absorption line measurements at $z \sim 6$
- data sets imply that reionization starts at $z \sim 12$, and completes between $z \sim 6 - 8$

TRC & Ferrara (2005), **TRC** & Ferrara (2007), **TRC**, Ferrara & Gallerani (2008), Mitra, **TRC** & Ferrara (2012), Mitra, **TRC** & Ferrara (2013), Mitra, **TRC** & Ferrara (2015)

Future: 21 cm line

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



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

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

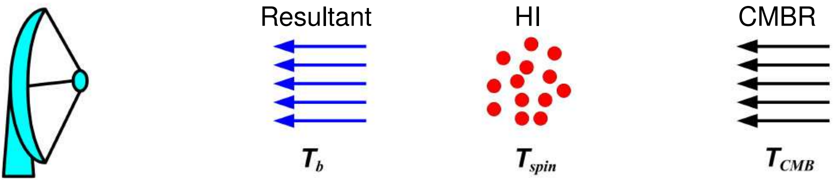
Singlet: $\frac{1}{\sqrt{2}}\left[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right]$

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 $A_{21} = 2.85 \times 10^{-15}\ \mathrm{s}^{-1} \Longrightarrow$ 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 $A_{21} \approx 6 \times 10^8\ \mathrm{s}^{-1}$.

How to observe the 21 cm signal?

Figure from Zaroubi (2013)



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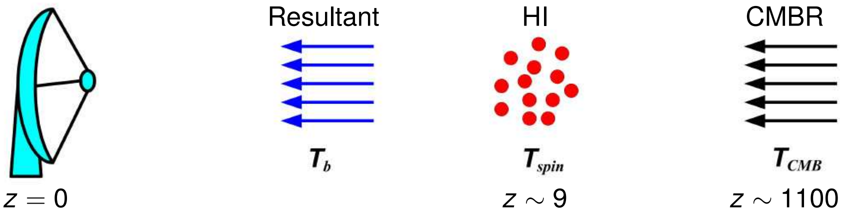

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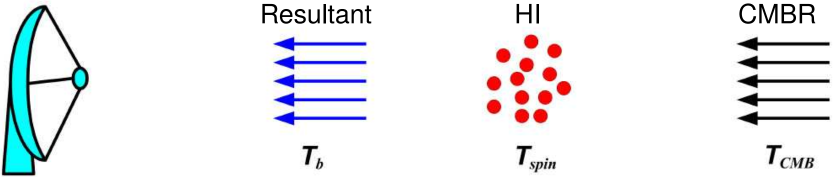
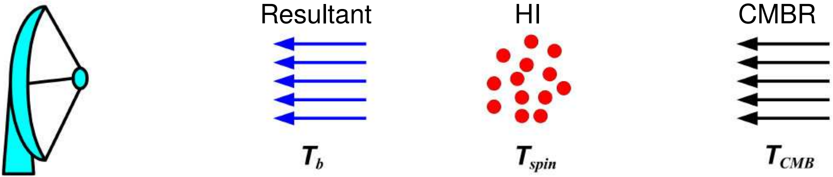


$z = 0$ | $z \sim 9$ | $z \sim 1100$

$\nu = 142$ MHz | $\nu \sim 156$ GHz

How to observe the 21 cm signal?

Figure from Zaroubi (2013)



$z = 0$, $\nu = 142$ MHz

$z \sim 9$, $\nu = 1420$ MHz

$z \sim 1100$, $\nu \sim 156$ GHz

How to observe the 21 cm signal?

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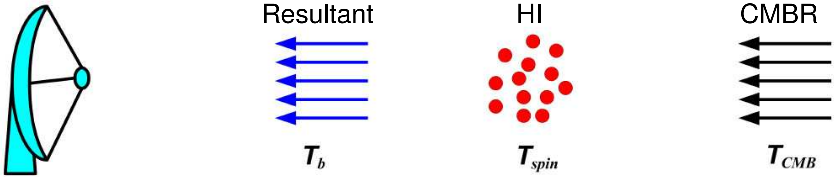

$z = 0$ — $\nu = 142$ MHz

$z \sim 9$ — $\nu = 1420$ MHz

$z \sim 1100$ — $\nu \sim 156$ GHz

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

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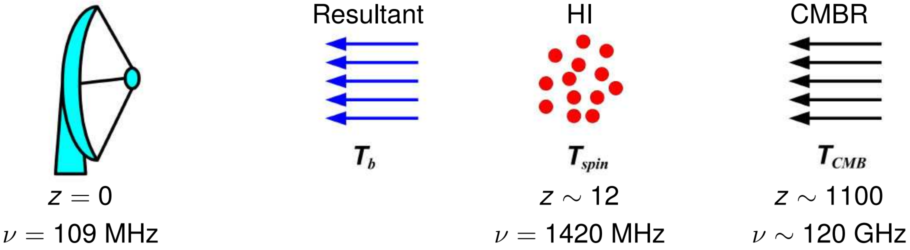
Figure from Zaroubi (2013)



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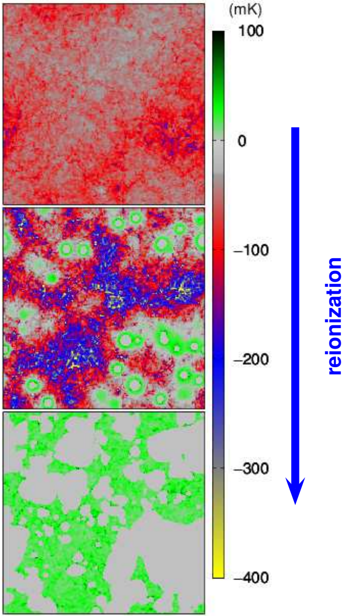
21 cm intensity maps

Ghara, **TRC** & Datta (2014)



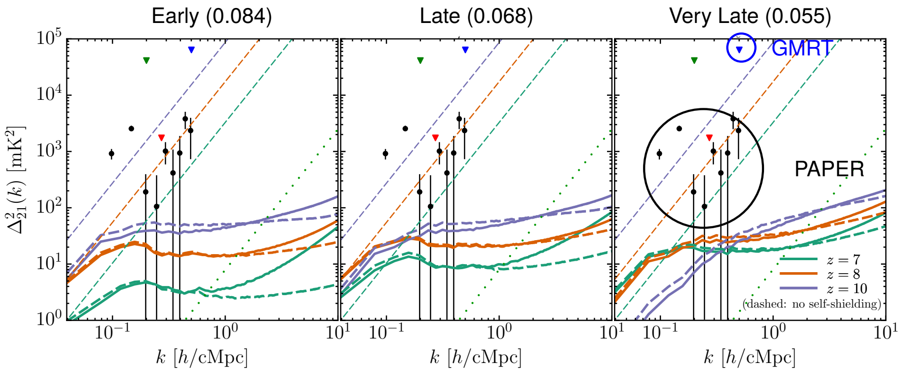
$z \sim 15$ ($\nu \sim 90$ MHz), $x_{\rm HII} \sim 10^{-3}$

$z \sim 12$ ($\nu \sim 110$ MHz), $x_{\rm HII} \sim 0.02$

$z \sim 8$ ($\nu \sim 160$ MHz), $x_{\rm HII} \sim 0.56$

Low frequency instruments

21 cm power spectra



$z = 7$

$z = 8$

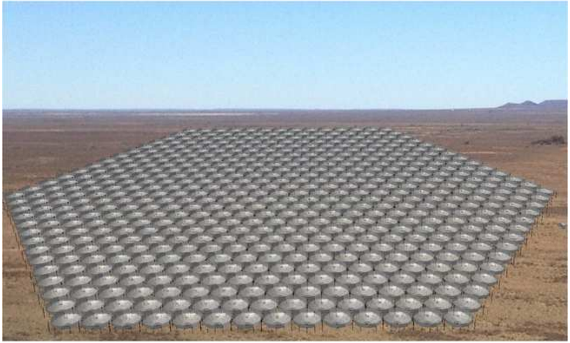
$z = 10$

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

Future telescopes

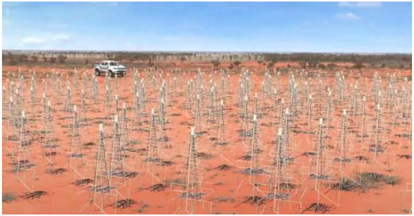
SKA-LOW

HERA

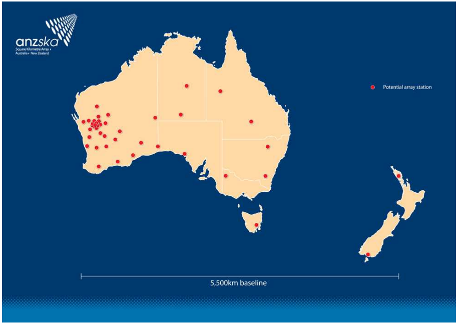


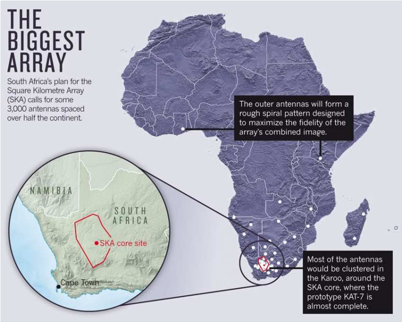
Square Kilometre Array Phase 1

- will be built in two phases: SKA1 should be completed by 2022
- dishes in South Africa, called **SKA1-MID**
- dipoles in Australia, called **SKA1-LOW**
- largest distance between antenna elements: $\sim$ 80 km
- effective collecting area $\sim$ km^2 $= 10^6$ m^2 $\sim 5 - 10$ times more collecting area than any existing telescope!



SKA: sites

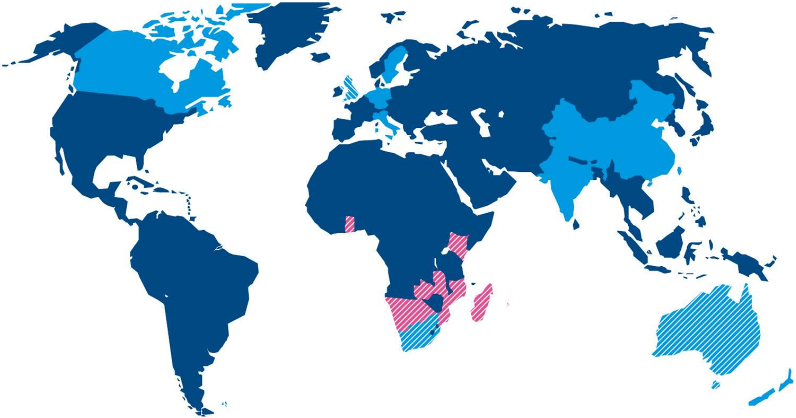




- Very low population density
- Large amount of empty space
- Western Australia, Karoo desert (South Africa)

Countries participating in the SKA

NCRA • TIFR



Full members

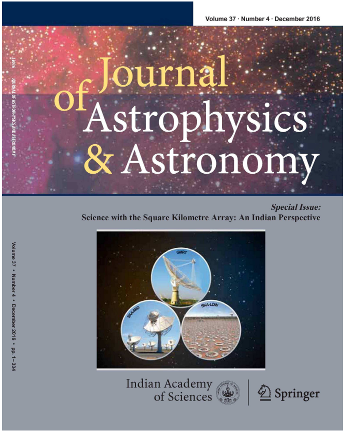
SKA Headquarters host country

SKA Phase 1 and Phase 2 host countries

African partner countries
(non-member SKA Phase 2 host countries)

This map is intended for reference only and is not meant to represent legal borders

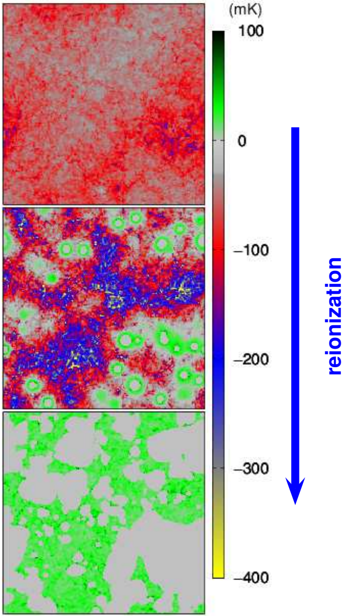
SKA: Indian involvement



- India has been associated with the SKA from the beginning
- India formally joined the SKA on **Oct 5, 2015**
- The activities within India are coordinated by the SKA-India Consortium
- $\sim$ 20 organisations are members of the Consortium
- India involved in all the key science projects in the SKA

Possibility of detecting individual sources

Ghara, **TRC** & Datta (2014)



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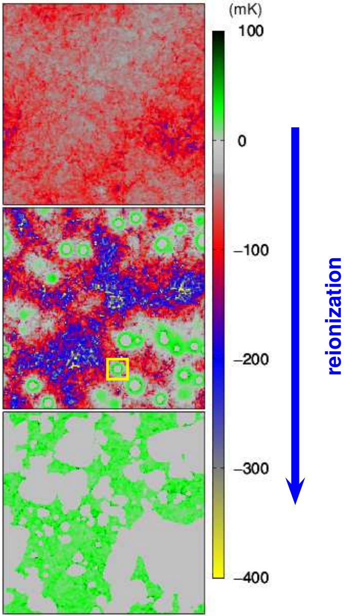

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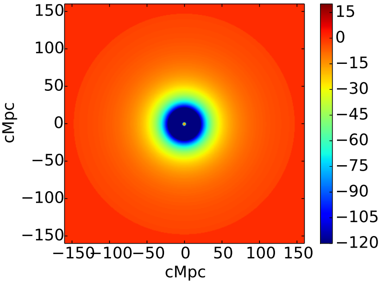
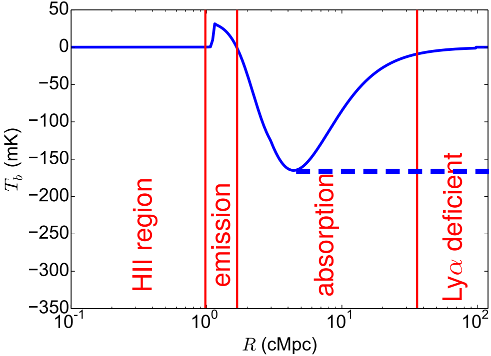
Image of the 21cm pattern

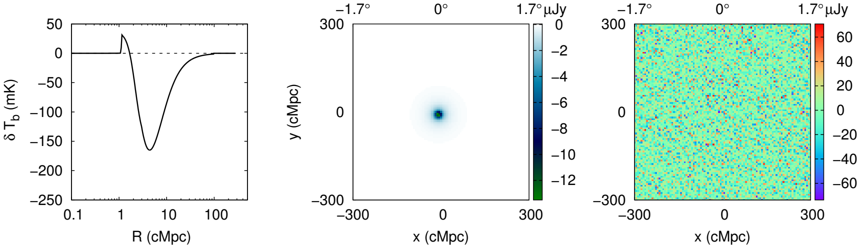
Galaxy + power-law X-ray source ($M_\star \sim 10^7 M_\odot, f_{\rm esc} \sim 0.1, t_{\rm age} \sim 10^7$ yr)





Alvarez, Pen & Chang (2010)
Yajima & Li (2014)
Ghara, **TRC** & Datta (2015)

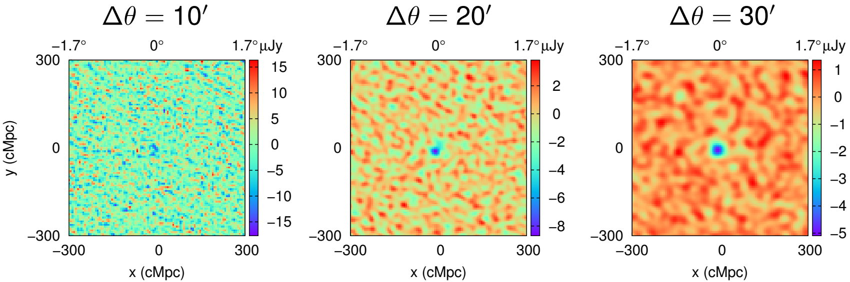
Possibility of imaging



resolution: 2’, integration time: 2000h

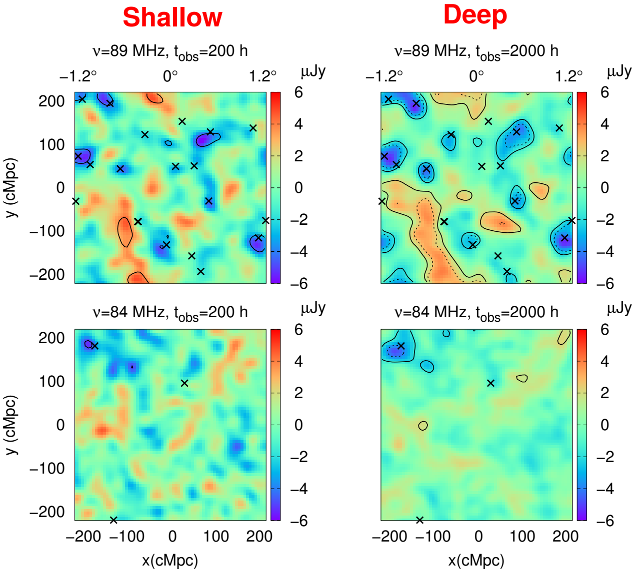
Ghara, **TRC**, Datta & Choudhuri (2016)

Smoothing the image



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

Survey planning



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

Summary

- Evolution of HI is crucially linked to the first stars. "Final frontier" of observational cosmology.
- Good progress in theoretical modelling, possible to construct models consistent with available data.
- Field driven by observational data:
  - QSO absorption lines + GRBs
  - high-redshift galaxies,
  - CMBR polarization + SZ signal,
  - Lyα emitters
- 21 cm experiments would open a new window in studying the first stars, looking forward to the SKA!
- Important to develop detailed analytical and numerical models to extract the maximum information about the physical processes relevant for reionization out of the expected **large and complex data sets**.

Analytical models

NCRA • TIFR

- Reionization mainly by galaxies
- Photon production rate:

$$\dot{n}_\gamma = N_{\rm ion} \left(\frac{\Omega_b}{\Omega_m}\right) \frac{{\rm d}f_{\rm coll}}{{\rm d}t}$$

Number of ionizing photons in the IGM per baryons

Collapse rate of dark matter haloes

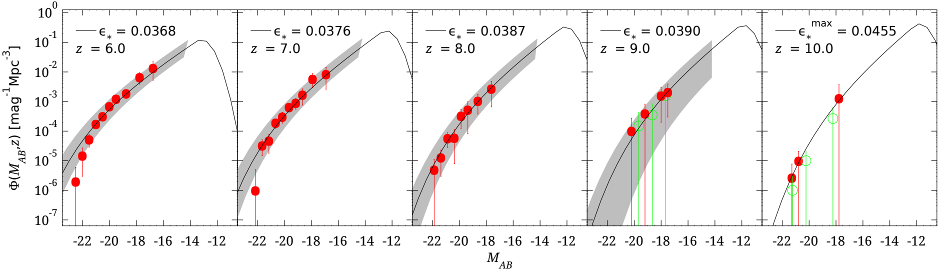
$$N_{\rm ion} = f_{\rm esc}\ \epsilon_* \ \times \ \text{number of photons per baryons in stars}$$

- Study the evolution of globally-averaged ionized mass fraction.
- Supplemented by temperature and species evolution equations
- Predict observables, e.g., $\tau_{\rm el}$ (or C_ℓ), photoionization rate (or mean transmitted flux), ...

TRC & Ferrara (2005, 2006)

Galaxy luminosity function

$N_{\rm ion} = f_{\rm esc} \, \epsilon_* \times$ number of photons per baryons in stars



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

Detecting the 21 cm signal

- The intensity is determined by the ratio of level populations, which is characterised by the spin temperature T_S:

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} \mathrm{e}^{-h_P \nu_{21}/k_B T_S}$$

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- The spin temperature couples to either the CMBR temperature T_γ or the gas temperature T_K:

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_K^{-1}}{1 + x_c + x_\alpha}$$

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- Collisional coupling x_c
- Lyα coupling x_α

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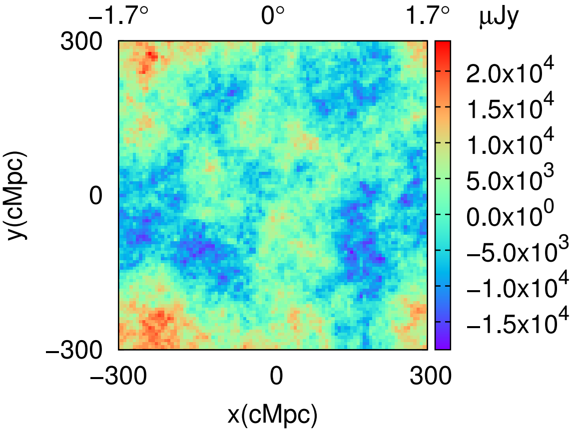
- Collisional coupling x_c
- Lyα coupling x_α
- The signal will be observable only if $T_S \neq T_\gamma$. The differential brightness temperature

$$\delta T_b = \bar{T}_b \, x_{\mathrm{HI}} \, \frac{\rho_b}{\bar{\rho}_b} \left(1 - \frac{T_\gamma}{T_S}\right)$$

if $T_S < T_\gamma$, then the signal will be observed in absorption,
if $T_S > T_\gamma$, then the signal will be observed in emission,
if $T_S = T_\gamma$, then there is no observable signal.

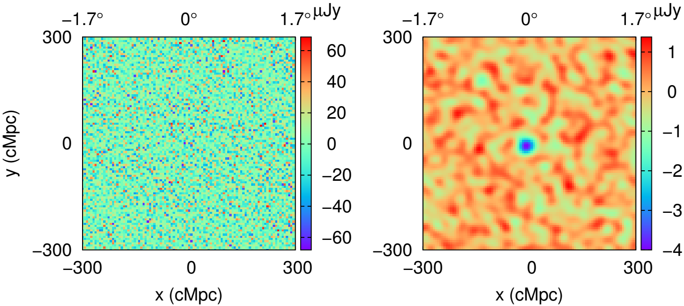
What about the foregrounds?



mainly Galactic synchrotron

Ghara, **TRC**, Datta & Choudhuri (in prep)

After foreground removal



Ghara, **TRC**, Datta & Choudhuri (in prep)