Cosmology with the Square Kilometre Array

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Part One

What is SKA Cosmology?

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Acknowledgments & References

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I would like to thank for letting me steal here and there:

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SKA specific material can be found at: `https://www.skatelescope.org` or `https://www.skaobservatory.org/`.

See also: Advancing Astrophysics with the Square Kilometre Array,

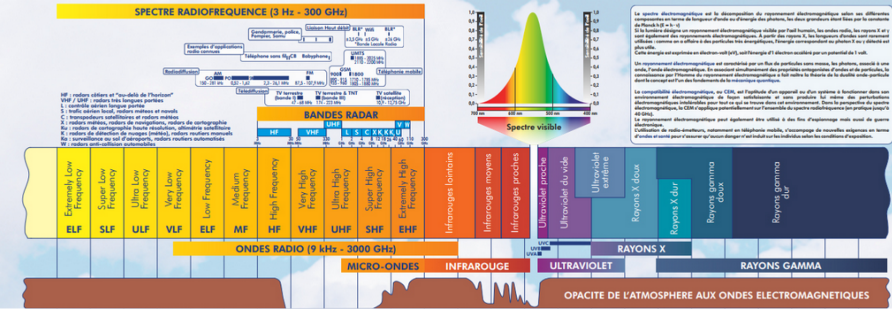
`https://pos.sissa.it/215/`

What is SKA Cosmology?

A *never seen before anything like this* Radio Facility will be available for doing science soon, the Square Kilometre Array.

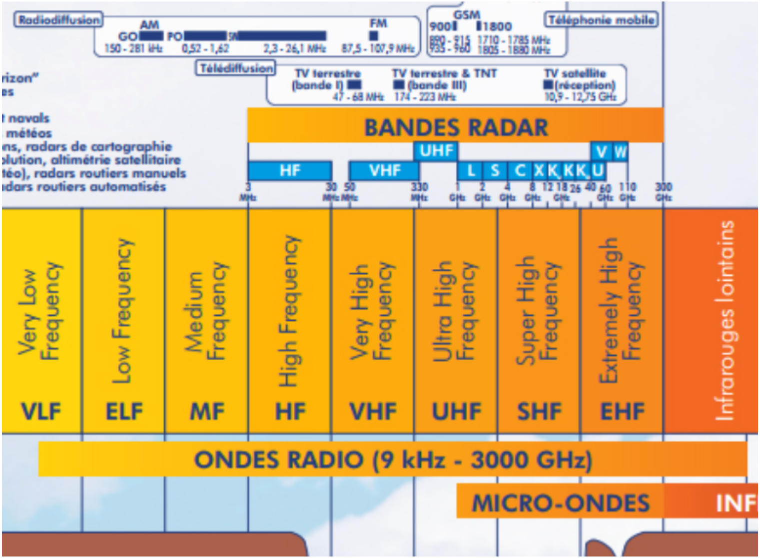
- What is Radio Astronomy and what is the SKA?
- What are SKA pathfinders and precursors?
- How Radio Astronomy can be interesting for Cosmology?
- Why cosmologists talk more and more about Intensity Mapping?

Light Spectrum



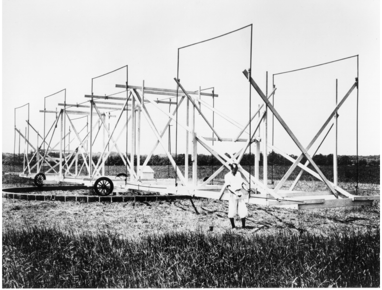
www.emitech.fr

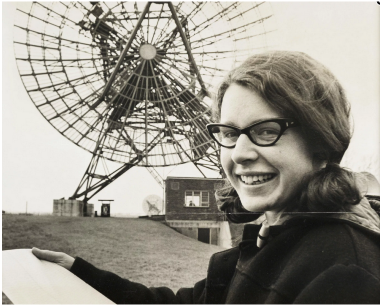
Radio Waves


Radiodiffusion
AM
GO
PO
FM
150 - 281 kHz
0,52 - 1,62
2,3 - 26,1 MHz
87,5 - 107,9 MHz
GSM
900
1800
890 - 915
935 - 960
1710 - 1785 MHz
1805 - 1880 MHz
Téléphonie mobile
Télédiffusion
TV terrestre (bande I)
47 - 68 MHz
TV terrestre & TNT (bande III)
174 - 223 MHz
TV satellite (réception)
10,9 - 12,75 GHz
BANDES RADAR
HF
VHF
UHF
L
S
C
X
V
W
U
Very Low Frequency
VLF
Low Frequency
ELF
Medium Frequency
MF
High Frequency
HF
Very High Frequency
VHF
Ultra High Frequency
UHF
Super High Frequency
SHF
Extremely High Frequency
EHF
Infrarouges lointains
ONDES RADIO (9 kHz - 3000 GHz)
MICRO-ONDES
INF

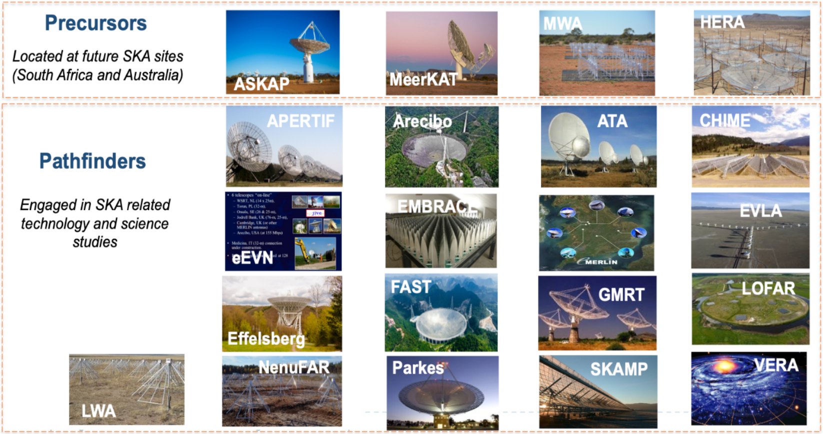
A little bit of history

- In the early 30s, at Bell Laboratories Karl Jansky built an antenna to receive radio waves at about 20 MHz.
- 1942: Radio waves from the Sun discovered during the World War II.
- Radio astronomy progressed with many great discoveries, such as the discovery of pulsars by Jocelyn Bell in 1967.
- Today radio-telescopes all over the world (VLA,ALMA,LOFAR,HERA,..)





Today (in SKA perspective)



[Courtesy of A. Bonaldi]

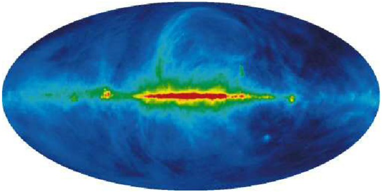
Why radio signal from the Universe?

- Any charged particle when accelerated or de-accelerated gives rise to electromagnetic radiation.
- Synchrotron radiation due to electrons with relativistic velocities gyrate and radiate in the presence of magnetic fields.
- Brehmstrahlung (Free-Free) radiation produced by the deceleration of (typically) an electron when deflected by the presence of hot gas
- coherent radio emission from pulsars (and other sources?)
- atomic and molecular transitions from various celestial objects

We will focus on the 21cm (1420 MHz) line of Neutral Hydrogen (HI)

Diffuse synchrotron radiation

- Depends on $B_\perp$ to the LOS modulated by the density of *cosmic electrons*
- CR power law energy density: $n(E) \sim E^{-p}$



Haslam Map @ 408 MHz

Diffuse polarised emission:

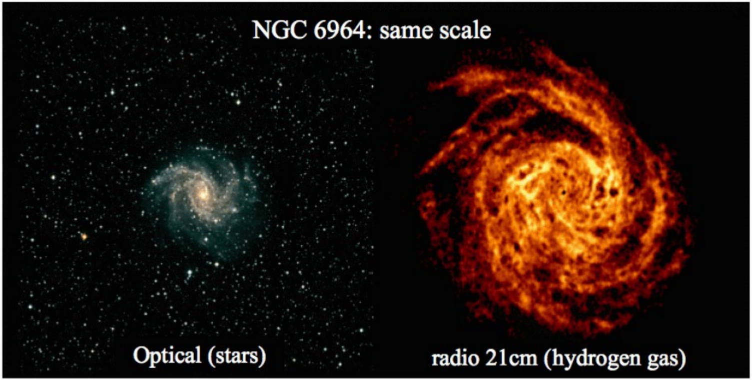
$P = Q + iU = \Pi_0(p) I e^{2i\phi}$ with
$\phi = \phi_0 + \psi\lambda^2$ faraday rotation
given by $B_\parallel$ and the presence of
thermal electrons

$$\psi \propto \int_{\mathrm{LOS}} n_e B_\parallel dr$$

ψ important for studying magnetic fields

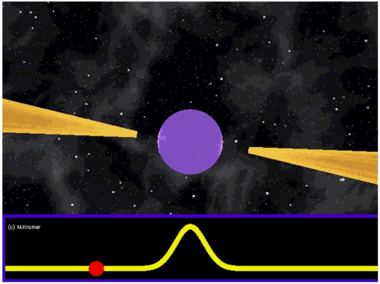
HI galaxies

- HI in galaxies more extended than the stellar content
- HI velocity fields can be used to calculate rotation curves and trace the total mass distribution to very large radii



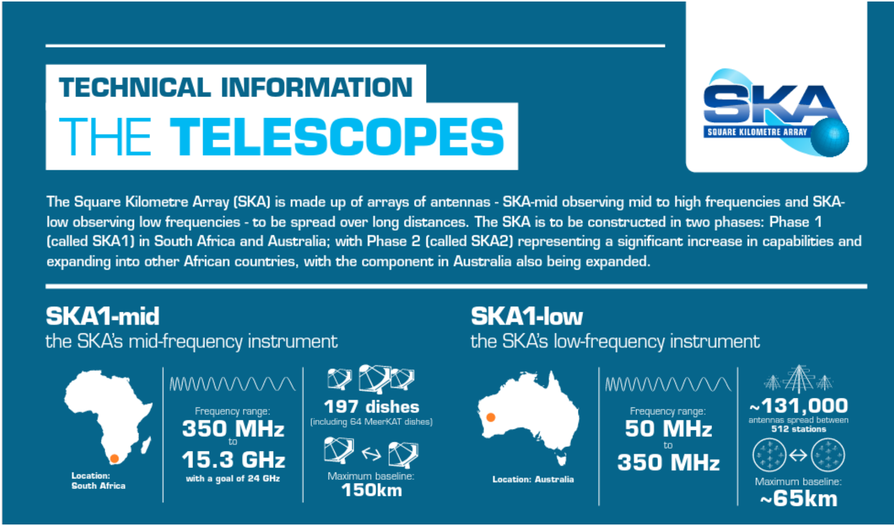
Pulsars

- highly magnetized rotating compact star (neutron stars/white dwarfs)
- almost Black Holes: mass of ~1.4 Solar Mass within 20km
- emits beams of electromagnetic radiation out of its magnetic poles
- cosmic lighthouses
- ranges from milliseconds to seconds
- precision GR tests



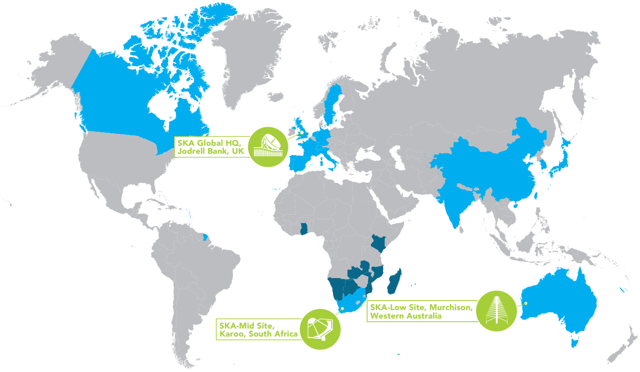
up to now more than 2.300 pulsars (nearly 300 ms ones)

SKAO project overview



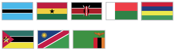
SKAO project overview

SKA Partners *(June 2021)*

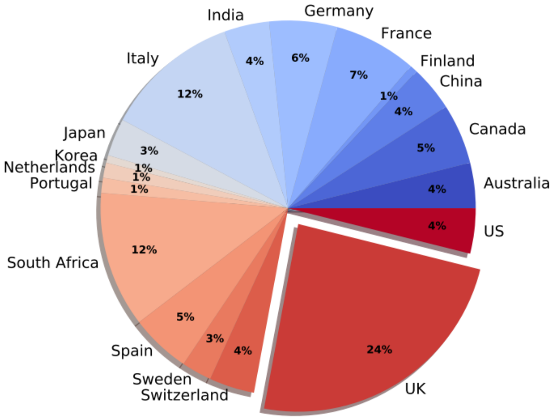


SKA Partners – includes Members of the SKA Organisation – precursor to the SKAO –, current SKAO Member States*, and SKAO Observers (as of June 2021)

African Partner Countries



In proportion



Science goals

www.skatelescope.org

Cradle of Life

SKA will be able to detect extremely weak extraterrestrial radio signals (if they were to exist).

Cosmic Magnetism

Magnetic fields are invisible. Measure polarized synchrotron, Faraday rotation, Zeeman splitting

Tests of gravity

Pulsars to test general relativity in extreme conditions, for example, close to black holes.

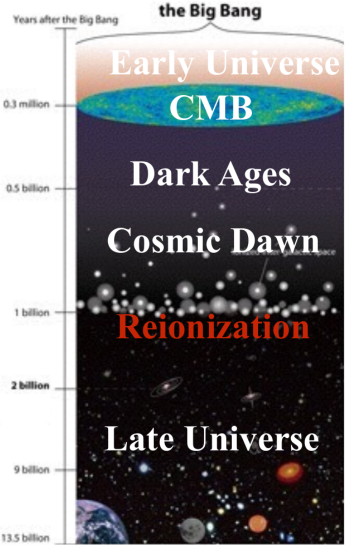
Cosmic Dawn and Reionization

Through the redshifted 21cm line of Neutral Hydrogen we can probe the evolution of the universe down up to the Cosmic Dawn

Cosmology

study Dark Matter and Dark Energy both using the 21cm line, radio weak lensing and radio continuum survey

Brief history of Hydrogen



universe filled of ionized gas

recombination:
hydrogen become neutral

thermal decoupling:
hydrogen cools

structures form:
hydrogen heated

hydrogen ionised again

neutral hydrogen only in dense clumps

Recombination

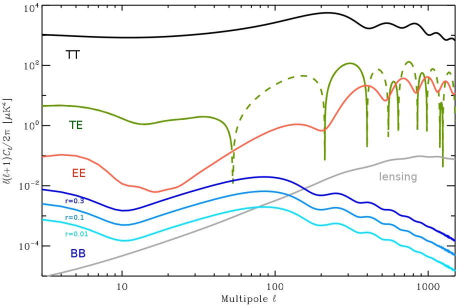
Generalities on CMB:

- A black body radiation at 2.7 K
- Temperature anisotropies of the order of 10^{-5}
- Power spectrum:

$$\Delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$a_{\ell m} \sim N(0, \sigma^2)$
with $\sigma^2 = C_\ell^{TT}$

- Linear polarisation generated by Thompson scattering in presence of a quadrupolar structure



Stokes I,Q,U $\rightarrow$ T,E,B

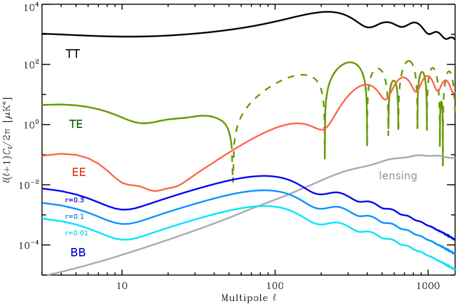
Recombination and Reionization

e.g Kosowsky (1996),Zaldarriaga & Seljak (1997)

Reionization effects on CMB:

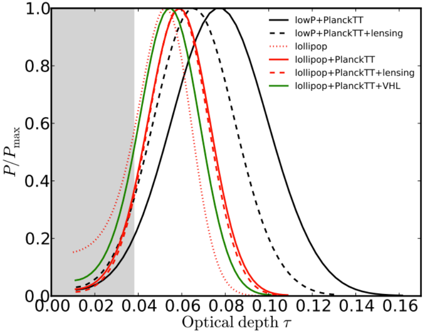
- CMB photons diffuse on "newly" free electrons and anisotropies are suppressed on small scales
- quadrupolar structure (originating polarisation at recombination) reprocessed at reionization

$\ell_{obs}^{reio} \sim \sqrt{z_{reio}}$

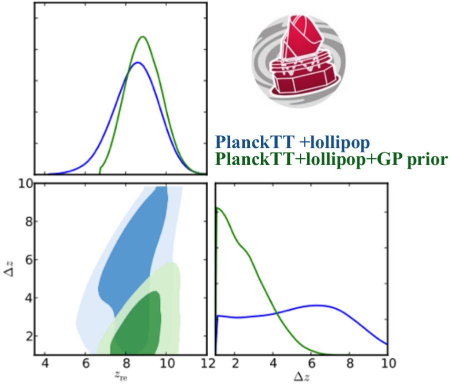


CMB constraints

- characterise reionization via Thompson scattering optical depth $\tau = \int_{t(z)}^{t_0} n_e \sigma_T c dt'$
- use low-ℓ polarization and high-ℓ temperature spectra



Planck 2016 int.res. XLVII

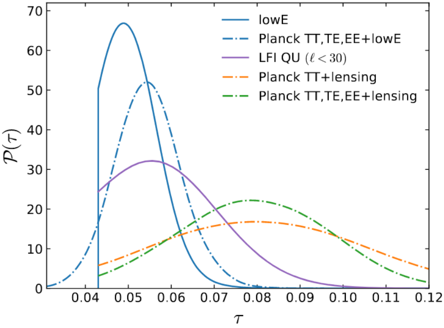


Assuming a reionization history recover z_{reio} and Δz

CMB not sensitive to reio details

Planck 2018 constraints

- TT,TE,EE and $lowEE$
  $\tau = 0.0544^{+0.0070}_{-0.0081}$
- reionization *late and fast*
- Universe is substantially neutral at redshift $z \gtrsim 7.5$
- low τ value makes constraints (almost) model independent

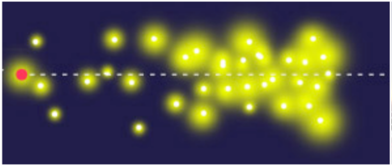


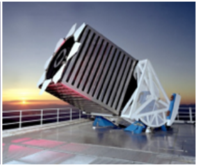
Planck 2018

Observational evidences of Reionization

e.g. Zarubi (2013)

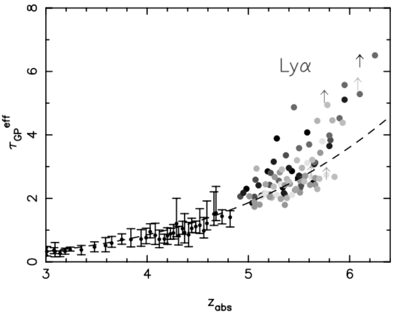
Quasar





SDSS (e.g)

- emission from distant Quasars absorbed by neutral hydrogen clouds (Gunn–Peterson effect)
- Lyman Alpha absorption prop to x_{HI}: *hydrogen highly ionised in the late universe*
- Precise quasar spectra show that after $z \sim 6$ the neutral fraction is higher

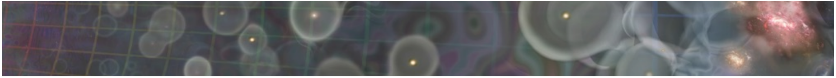


Fan et al. (2006)

Still a long way to go...

Observational evidences:

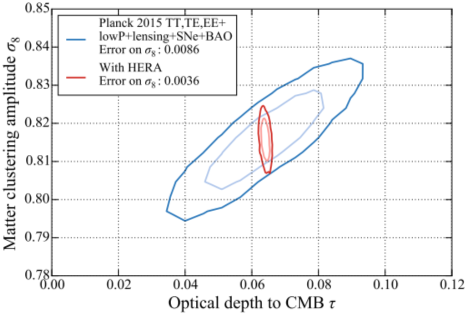
- CMB optical depth $\rightarrow \tau \sim 0.05$ ($z_{\text{reio}} \sim 8$)
- Lyα forest absorbtion + Lyα emitters $\rightarrow$ end around $z \sim 6$



Open questions:

- When did the sources produce enough photons to ionise the Universe? $z \sim 20$ or $z \sim 6$?
- Nature of reionization? Sudden or gradual? homogeneous or inhomogeneous?
- What are the sources responsible? Stars, quasars, exotic particles?

Synergies (just an example)



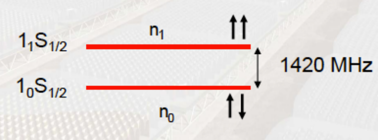
De Boer et al. (2017)

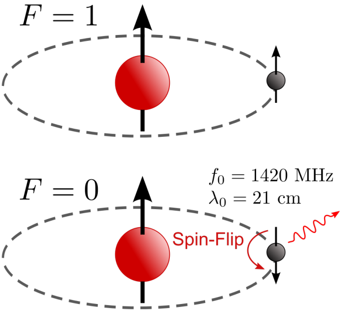
- the constraints from Reio break the CMB degeneracy between the amplitude of density fluctuations σ_8 and the optical depth τ, improving constraints on both
- an external constraint on τ will help CMB constraints on lensing, neutrinos, and new physics

The 21cm line of Neutral Hydrogen

- ground state hyperfine transition
- lowest energy state: spins of the electron and the proton are antiparallel
- parallel spins: the atom has a tiny amount of extra energy
- if the level gets excited: atoms radiate photons with $\lambda = 21\text{cm}$

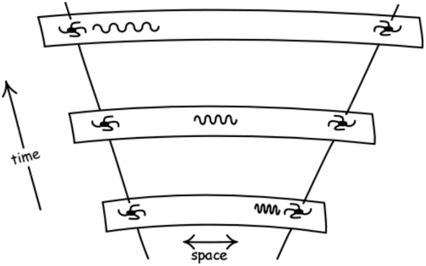
it occurs roughly every 10^6y
but there is a lot of HI!





Frequency and redshift for the 21cm line

$$z = \frac{(\nu_{\text{emitted}} - \nu_{\text{observed}})}{\nu_{\text{observed}}} \text{ with } \nu_{\text{emitted}} = 1420 \text{ MHz}$$

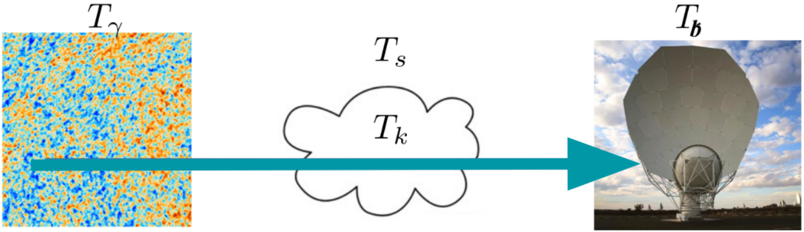


https://www.pitt.edu/~jdnorton/teaching/

Examples:

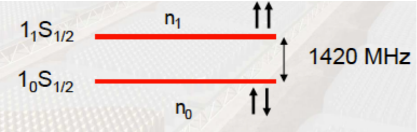
- $\nu_{\text{observed}} \sim 900$ MHz corresponds to $z \sim 0.6$ (late Universe)
- $\nu_{\text{observed}} \sim 170$ MHz corresponds to $z \sim 7$ (EoR)
- $\nu_{\text{observed}} \sim 70$ MHz corresponds to $z \sim 20$ (Cosmic Dawn)

The 21cm probe



3 fundamental temperatures:

- T_γ the CMB temperature
- T_k the gas (IGM) temperature
- T_s the spin temperature: sets the population of the hyperfine level with respect to the ground state

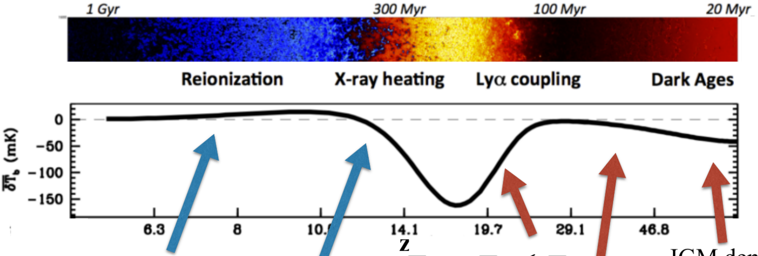


$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-h\nu_{21}/kT_s}$$

21cm signal

Mesinger, Greig & Sobacchi (2016)

$$\delta T_b \propto x_{HI}(1+\delta)(1-\frac{T_\gamma}{T_s})\ \mathrm{mK}$$



Ionising sources fluctuation dominated by x_HI

$T_k = T_s \gtrsim T_\gamma$

IGM hotter than CMB: emission ->absorption

$T_k \sim T_s \lesssim T_\gamma$

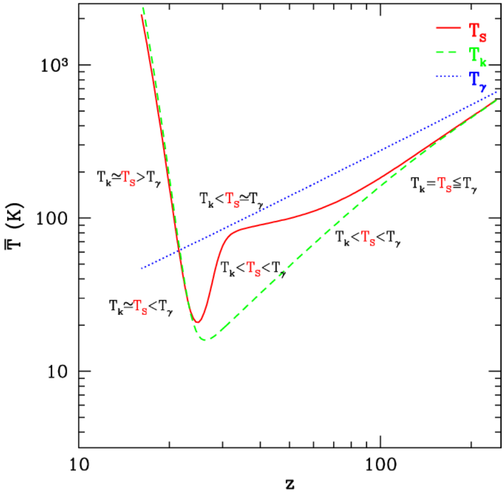
Universe expands, IGM less dense collisional decoupling

$T_k < T_s \lesssim T_\gamma$

IGM dense: collisional coupling

$T_k = T_s \lesssim T_\gamma$

21cm signal



Mesinger et al. (2011)

And after Reionization?

- Reionization process is complete, but there is neutral hydrogen left in dense clumps that protected it from UV radiation
- the presence of cold gas traces the distribution of dark matter, i.e. a bias tracers
- observing at different frequencies, we observe at different redshift ⇒ tomography ⇒ evolution of structures ⇒ dark energy