Studying the First Stars using Neutral Hydrogen

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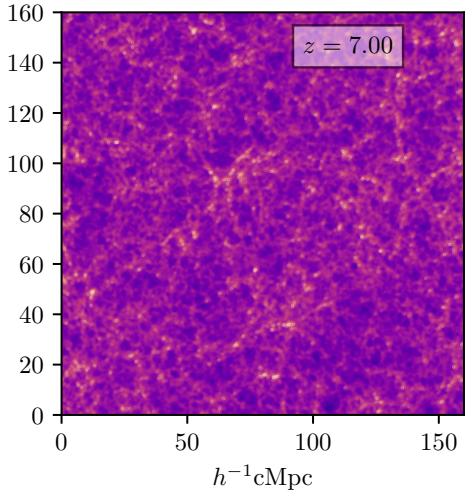
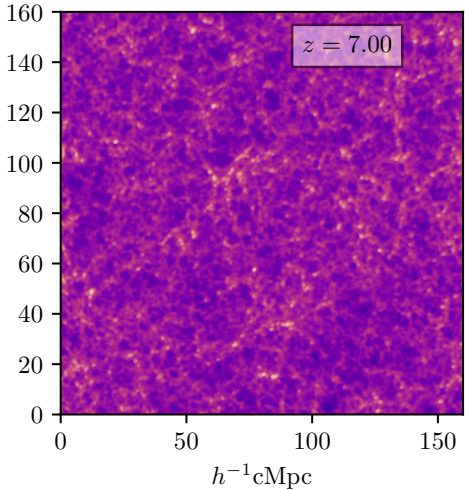
Second Chennai Symposium on Gravitation and Cosmology
Centre for Strings, Gravitation and Cosmology, IIT Madras
04 February 2022

Large-scale structure at high-redshifts



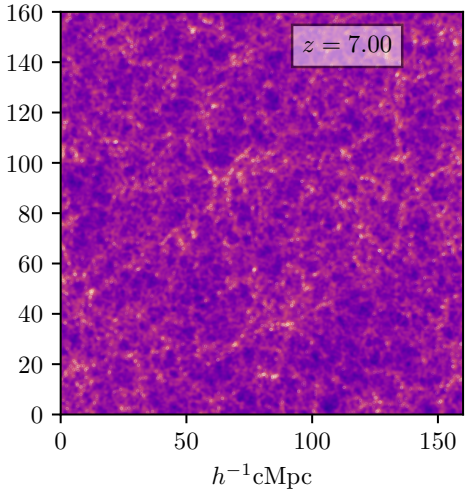
N-body simulations using *GADGET-2* (Springel et al 2005)

Detecting the first galaxies



- Search for the first galaxies using Optical/NIR telescopes (e.g., JWST and the Extremely Large Telescopes).

Detecting the first galaxies



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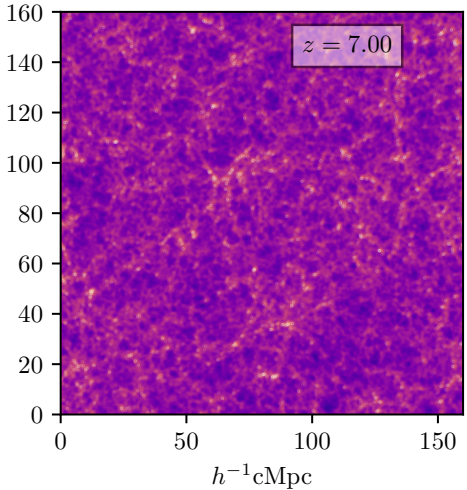


- Search for the first galaxies using Optical/NIR telescopes (e.g., JWST and the Extremely Large Telescopes).
- The direct detections would be biased towards intrinsically brighter galaxies.
- An alternate way to study the early galaxies is via their effect on the IGM (e.g., hydrogen reionization).

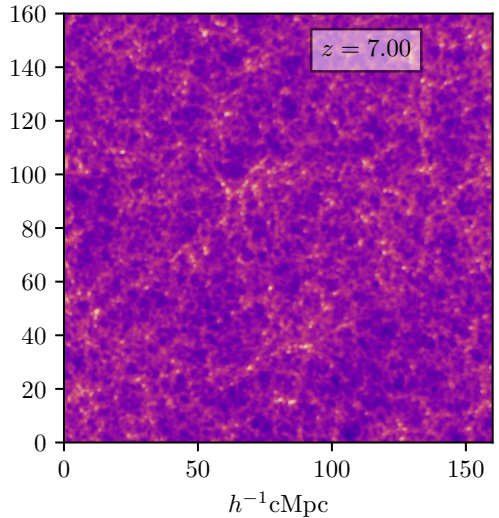
Galaxies and reionization

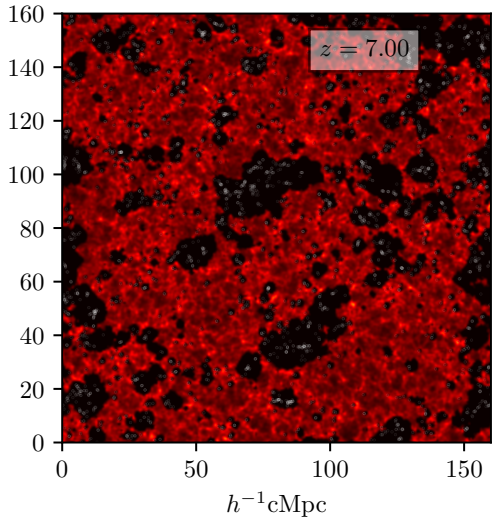
Density + halo (galaxies)

Neutral hydrogen (HI)

GADGET-2 N-Body

SCRIPT Semi-numerical





Main points of discussion

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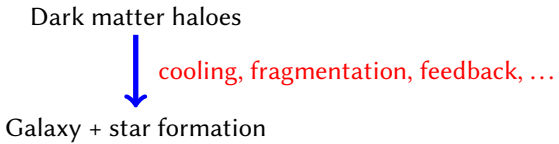
- Reionization physics and model ingredients, connection to cosmology
- Parameter estimation using reionization models (highlight work done by our group).
- Future prospects.

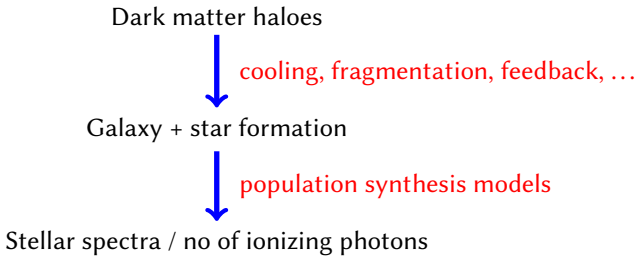
Reionization physics

Dark matter haloes

Reionization physics



Reionization physics



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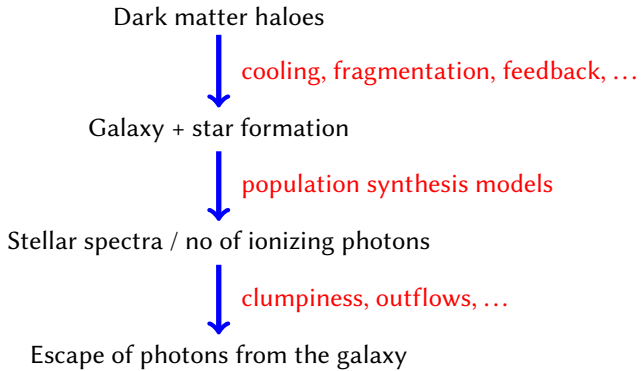

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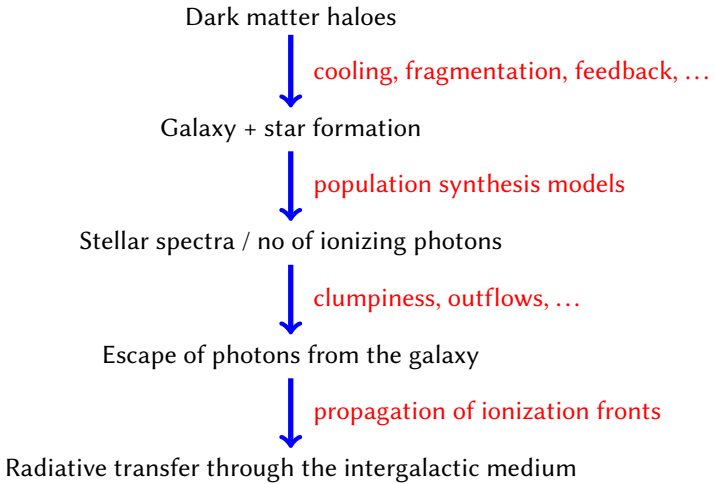

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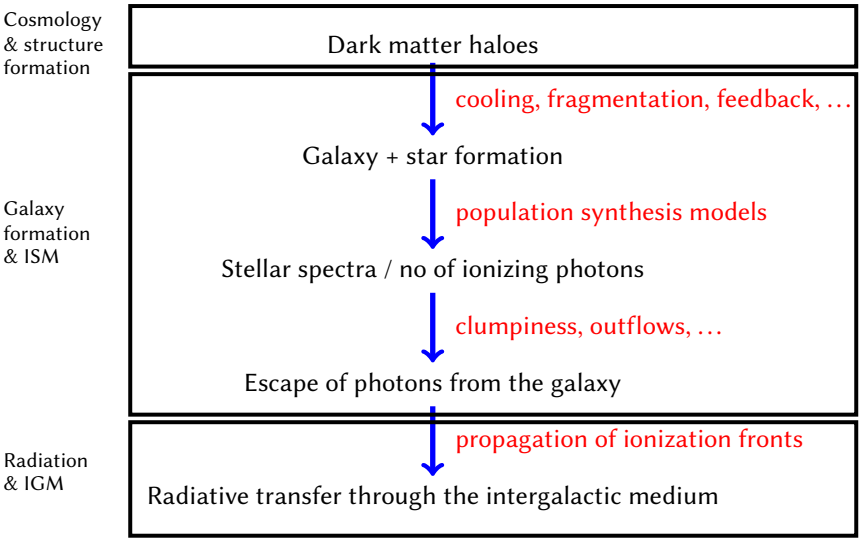

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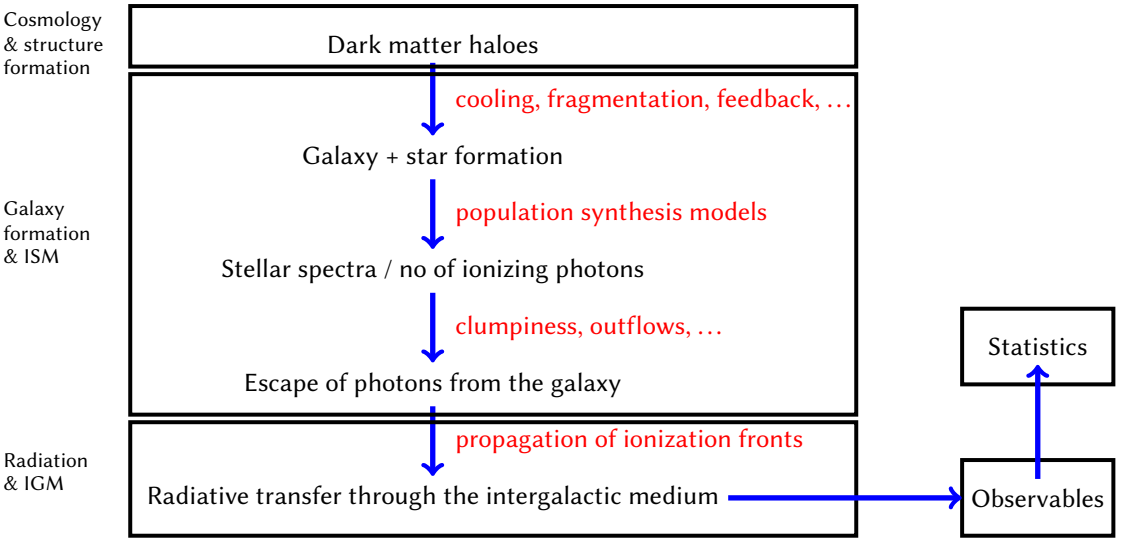

Main/direct observational probes of reionization

- Lyman-α absorption of UV light from distant quasars by intervening neutral hydrogen (Gunn-Peterson effect). Directly probes the amount of neutral hydrogen in the Universe.

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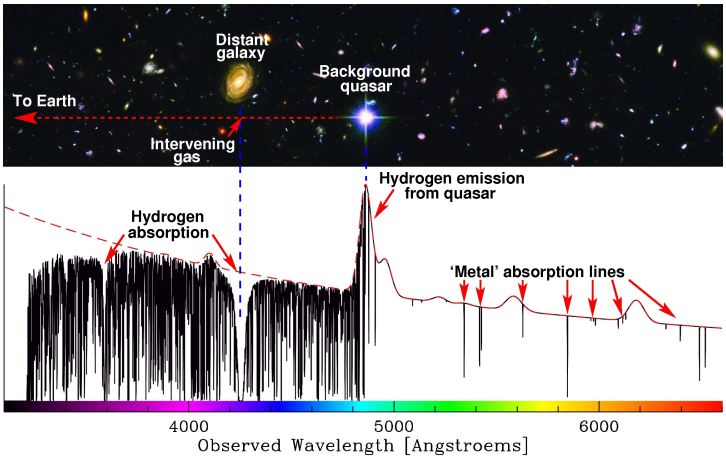
- Scattering of CMB photons by free electrons, probes the ionized component of the Universe.
- Also exist other (indirect) probes of reionization, e.g., high-redshift galaxies, temperature of the intergalactic medium, …
- Aside: the epoch of reionization is preceded by another very interesting phase: Cosmic Dawn (not to be covered in this talk).

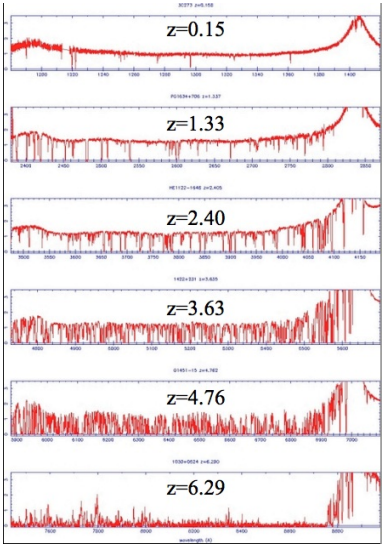
Lyman-α absorption spectra of quasars

The neutral hydrogen at $z \lesssim 6$ is detected through the absorption features it produces in the spectrum of a background bright source of light (typically a quasar).



Courtesy: Michael Murphy

Lyman-α absorption at $z \sim 6$



https://blackholeswithrevelations.wordpress.com/2013/09/19/stfcastro-lyman-alpha-forest/

- More absorption at high-z
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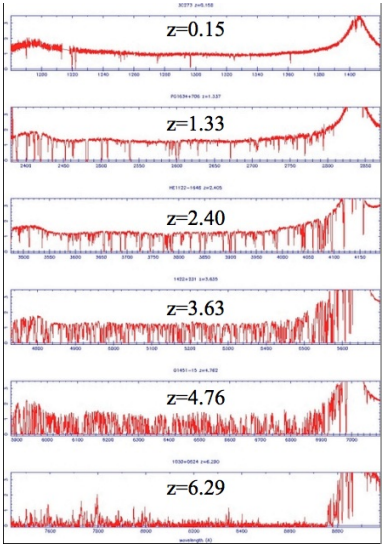

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$$F(\lambda) = \frac{\text{Observed flux}(\lambda)}{\text{Continuum}(\lambda)}$$

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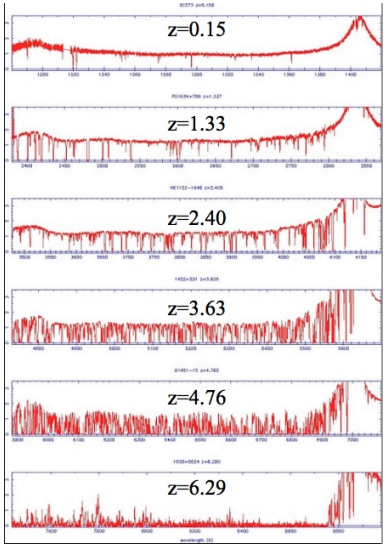

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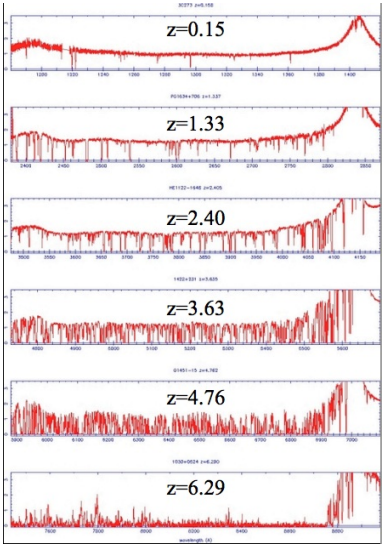

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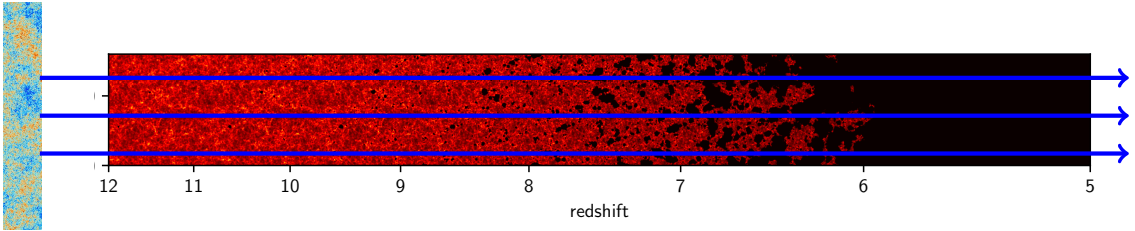
- It is clear that the universe is highly ionized at $z \lesssim 5$, i.e., reionization must be over by then.
- The Lyα absorption also sets the amount of ionizing radiation present at the end of reionization.

CMB optical depth



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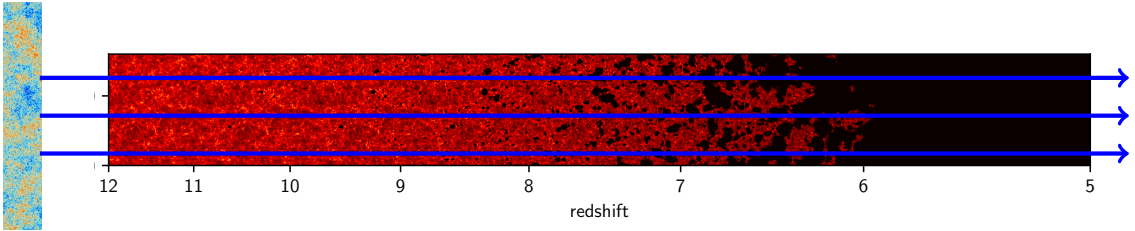

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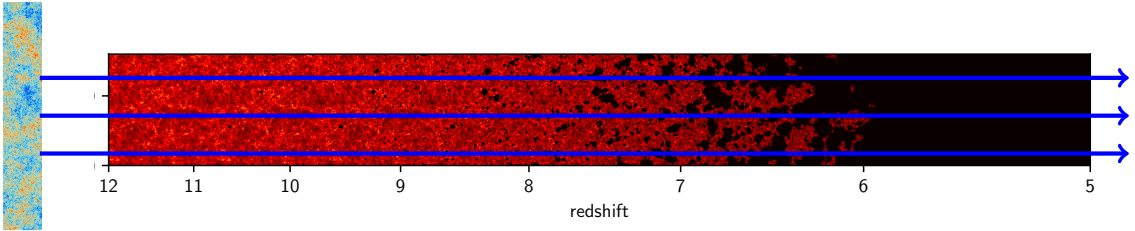

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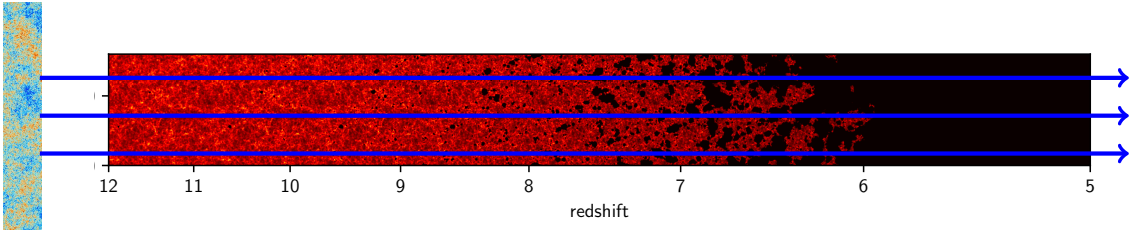

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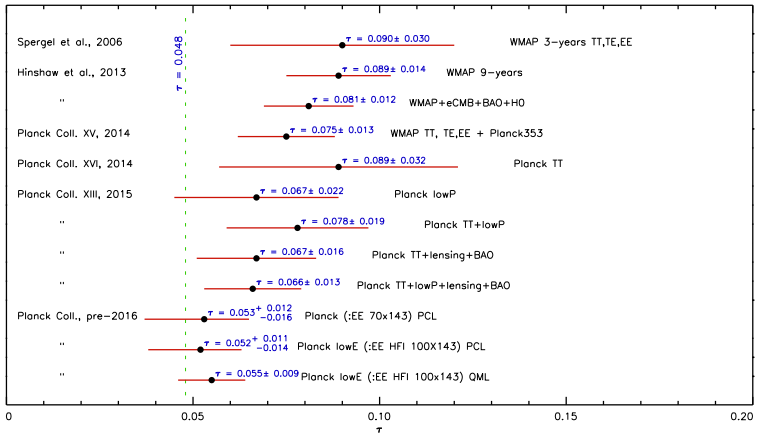
- For the CMB angular power spectra, τ is strongly degenerate with the amplitude of the primordial power spectrum. Implications for cosmological parameter estimation.

Thomson scattering τ from CMB missions

$$\tau = \sigma_T c \int_0^{z_{\rm LSS}} {\rm d}z \left| \frac{{\rm d}t}{{\rm d}z} \right| \bar{n}_e \, (1+z)^3$$

Planck Collaboration (2016)



Modelling approaches

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Reionization constraints using analytical models

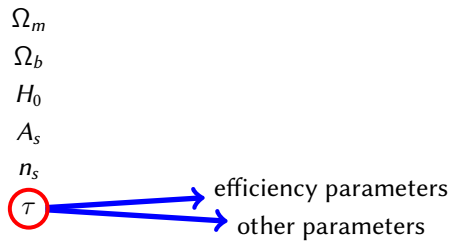
6-parameter flat ΛCDM model

Ω_m
Ω_b
H_0
A_s
n_s
τ

Data: CMB, BAO, SN, …

Reionization constraints using analytical models

6-parameter flat ΛCDM model including reionization



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CosmoReionMC: cosmology + reionization

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- The core component is a physically-motivated analytical model for reionization and thermal history of the Universe.

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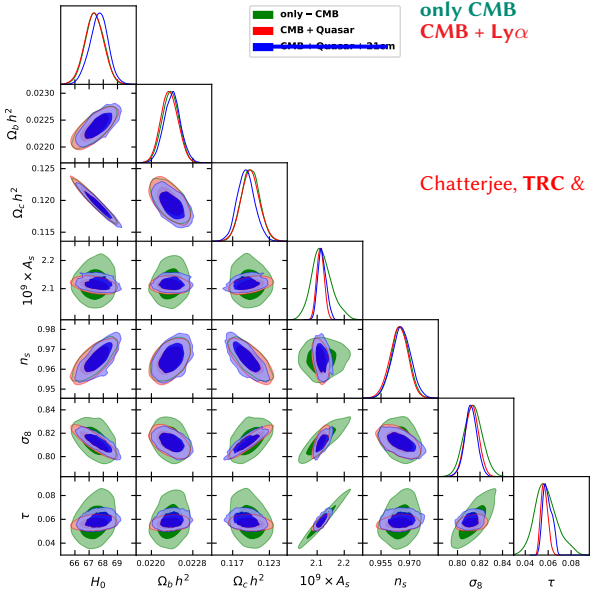
- Plan to make it publicly available in the near future.

Effect of including reionization observations



only CMB

CMB + Lyα

Chatterjee, **TRC** & Mitra (2021)

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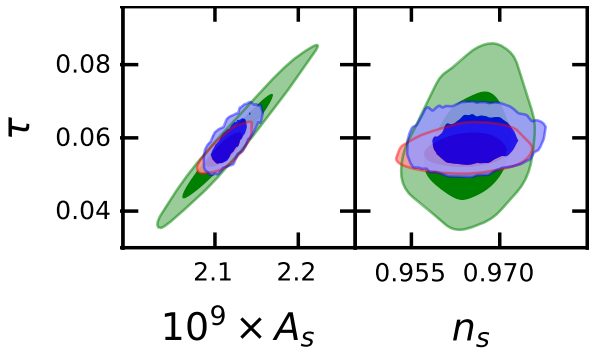
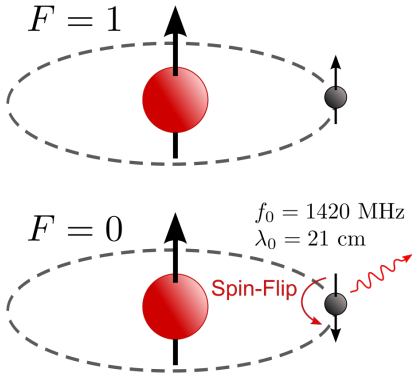


Note: τ is a derived parameter for CMB + Lyα

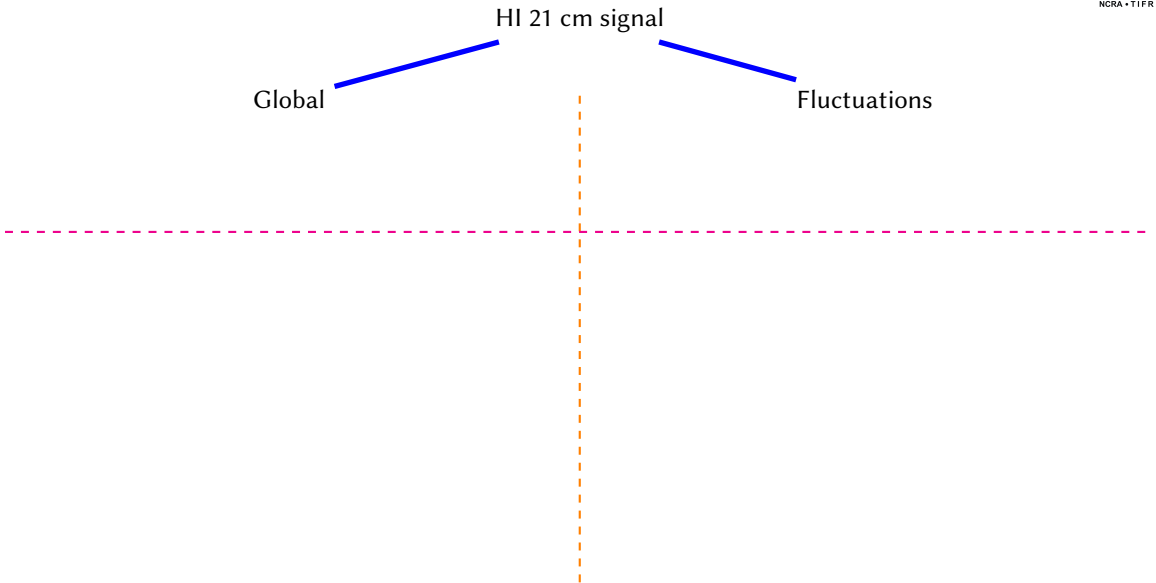
Caveat: evolution, mass-dependence, environment-dependence of the efficiency parameters?

Future: 21 cm radiation



- Hyperfine transition of the hydrogen ground state.
- Only possible when hydrogen is neutral, no radiation when ionization happens (i.e., the electron dissociates).
- Target is to detect the signal from reionization using low-frequency radio telescopes.

Observational probes of the 21 cm signal



Observational probes of the 21 cm signal

HI 21 cm signal

Global

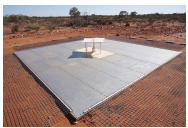
Fluctuations

Cosmic Dawn

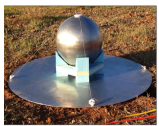
$\sim 50 - 100$ MHz

Reionization

$\sim 100 - 200$ MHz



EDGES



SARAS-2

LEDA

Observational probes of the 21 cm signal

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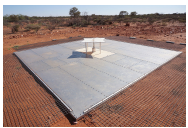
  - Post-reionization: $\gtrsim 200$ MHz



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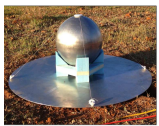


SARAS-2

LEDA

MWA

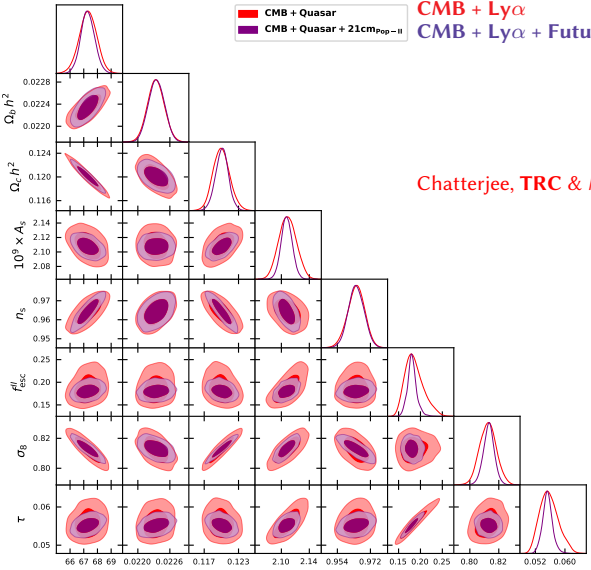
LOFAR

GMRT

CHIME

MeerKAT

Effect of adding global 21 cm data (forecast)



CMB + Lyα

CMB + Lyα + Future global 21 cm

Chatterjee, **TRC** & Mitra (2021)

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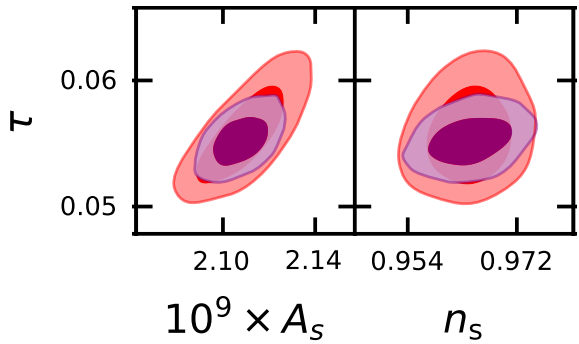

CMB + Lyα

CMB + Lyα + Future global 21 cm

Is reionization important for cosmology?

- The formation of the first structures depend on the matter power spectrum, particularly the smaller scales $k \gtrsim 1h/\mathrm{cMpc}$. Reionization modelling and observations can affect the constraints on the primordial power spectrum.

Is reionization important for cosmology?

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- The formation of the first structures depend on the matter power spectrum, particularly the smaller scales $k \gtrsim 1h/\mathrm{cMpc}$. Reionization modelling and observations can affect the constraints on the primordial power spectrum.
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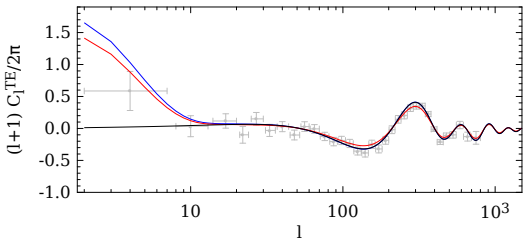

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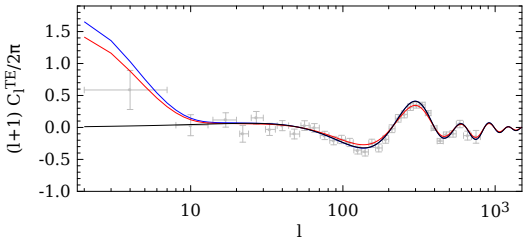
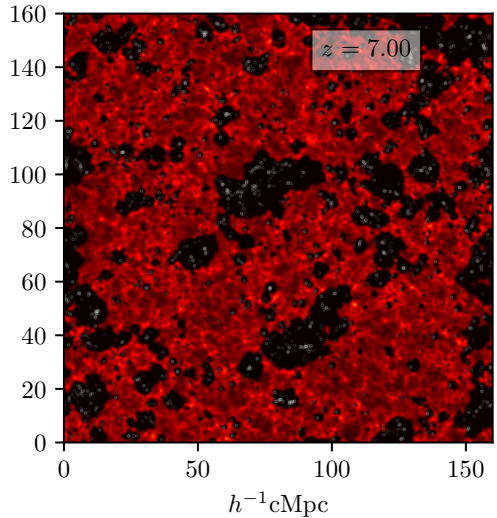


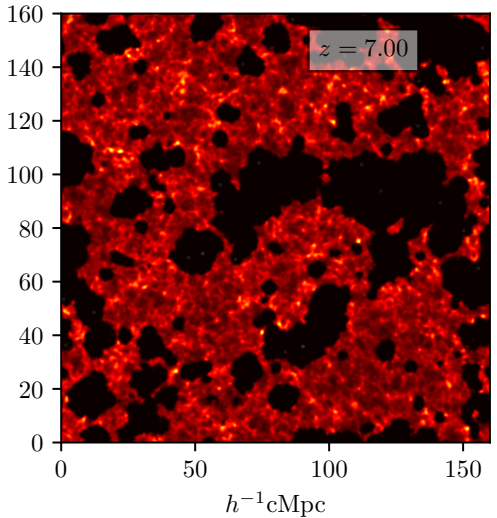
- Challenge: uncertainties in the galaxy formation modelling can often weaken the constraints on cosmological parameters.

What next? Fluctuations in the ionized field

"Faint" galaxies (abundant)



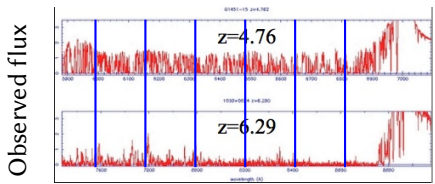
"Bright" galaxies (rare)



Probing the fluctuations

- Fluctuations in the Lyman-α absorption at $z \sim 6$

  Bosman et al (2018), Kulkarni et al (2019), **TRC**, Paranjape & Bosman (2021), Yang et al (2020)



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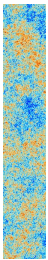

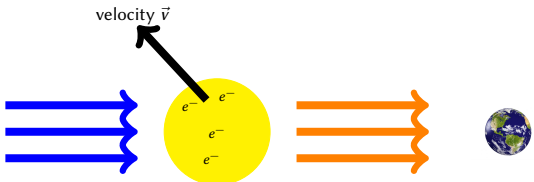

$$\Delta T(\hat{n}) \propto n_e \, \hat{n} \cdot \vec{v}$$

signal at angular scales corresponding to the bubble size

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- Modelling requires simulations, either full numerical or semi-numerical

Semi-numerical codes: approximate but efficient

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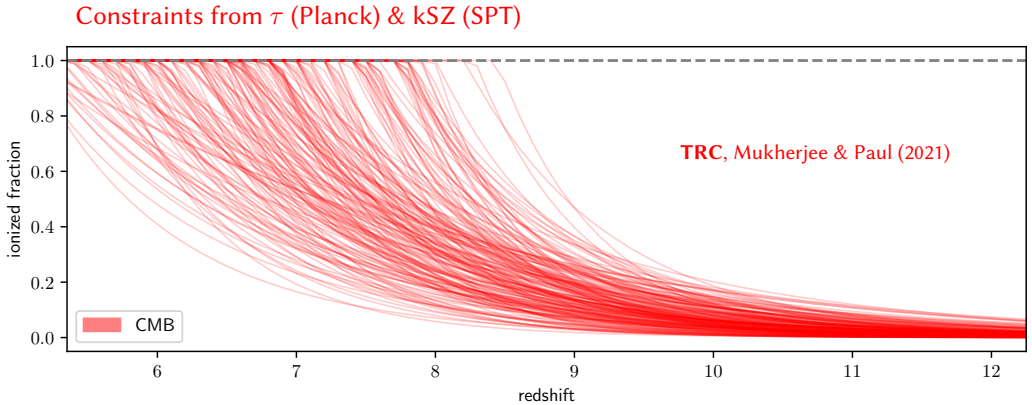
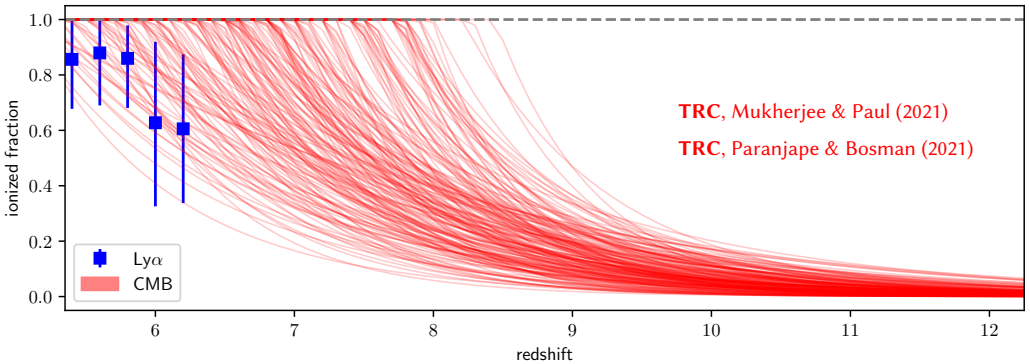
- Need photon-conserving models to solve the convergence problem.
- Our contribution: SCRIPT (**S**emi-numerical **C**ode for **Rel**onization with **P**ho**T**on-conservation), publicly available at `https://bitbucket.org/rctirthankar/script`.
  TRC & Paranjape (2018), **TRC**, Paranjape & Bosman (2021), **TRC**, Mukherjee & Paul (2021), Maity & **TRC** (2022)

Present constraints using MCMC



Present constraints using MCMC

Constraints from τ (Planck) & kSZ (SPT) and Lyman-α absorption



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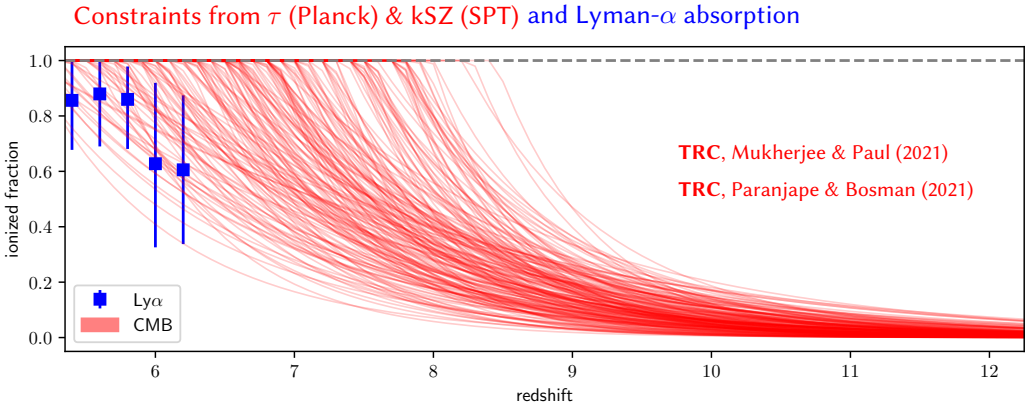

A combined analysis of the two data sets should restrict the parameter space significantly.

Also need to find ways to vary cosmological parameters.

Future: 21 cm fluctuations

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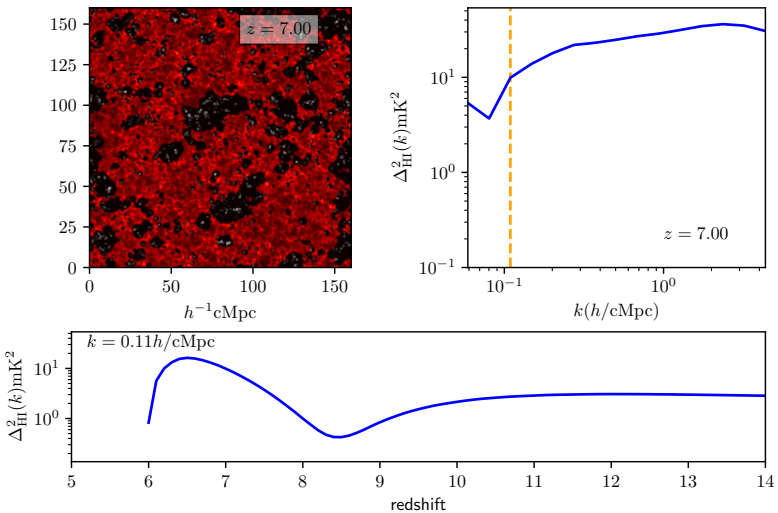
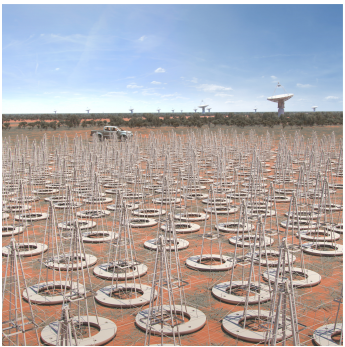
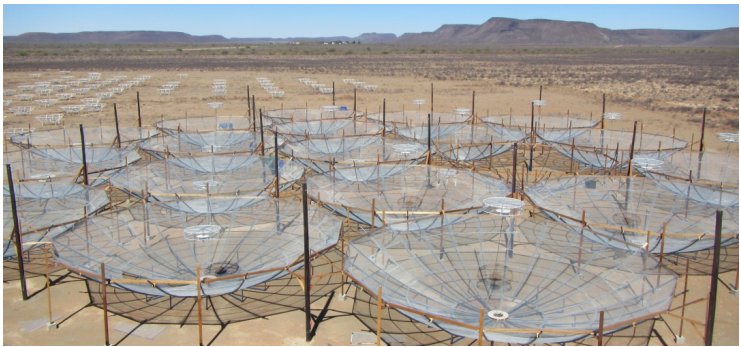


Future interferometers



SKA-LOW



HERA

The SKA

- Most ambitious radio astronomy project ever attempted.
- To be built in Australia and South Africa.
- First science 2027. Main science goals include reionization and cosmic dawn.
- India is a member of the SKA international collaboration (lead by NCRA-TIFR). GMRT often provides useful test-bed for SKA.

Summary

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Thank you

This presentation was prepared using the Beamer class of LaTeX