Reionization

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NCRA • TIFR

Saha Theory Workshop: Cosmology at the Interface
Saha Institute for Nuclear Physics, Kolkata
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Plan of the talk

- Why is reionization important for cosmology?
- Current constraints on reionization
- Future: do we need to revise the constraints?
- The SKA

Dark ages and reionization

Big Bang | Universe expanding and cooling | Present day

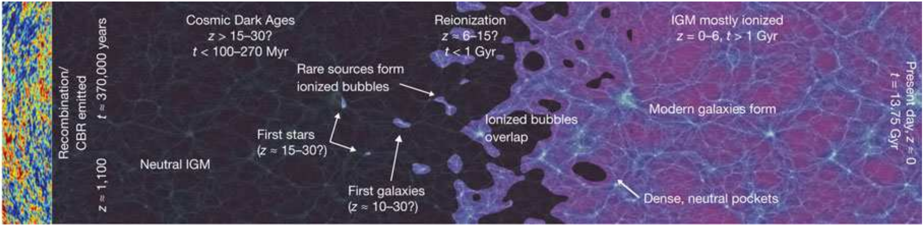
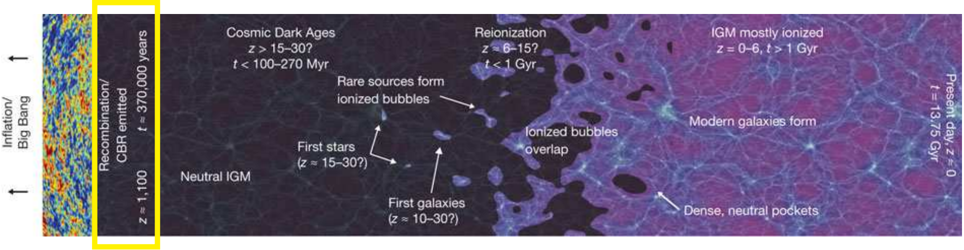


Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Dark ages and reionization

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

Dark ages and reionization

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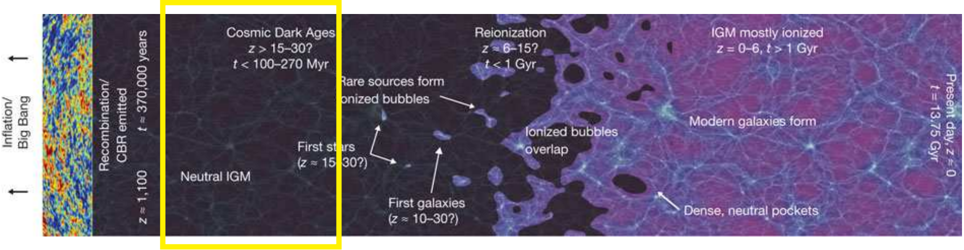
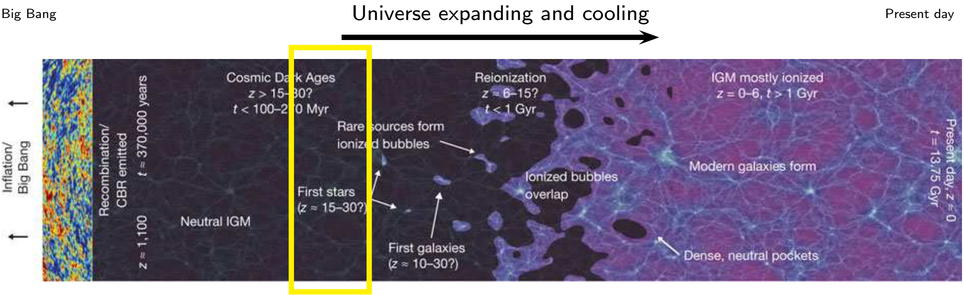


Dark ages

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

Dark ages and reionization



First stars form

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

Dark ages and reionization

Big Bang

Universe expanding and cooling

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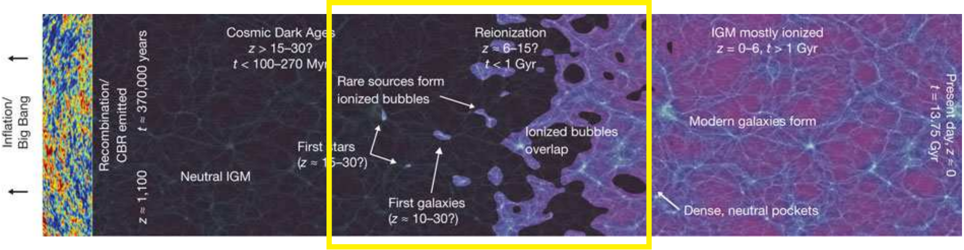

Reionization

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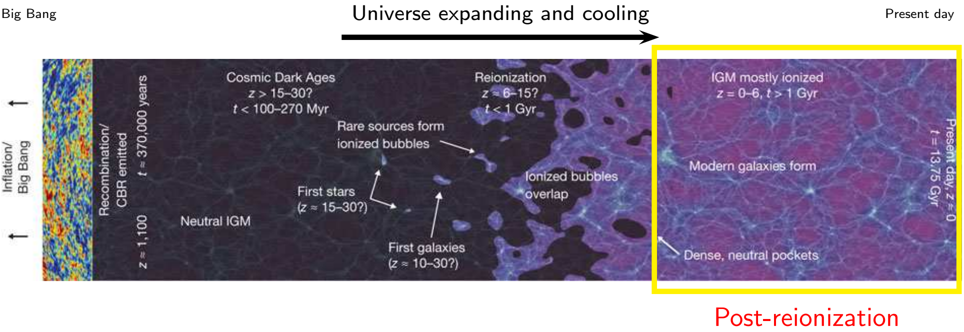
Dark ages and reionization



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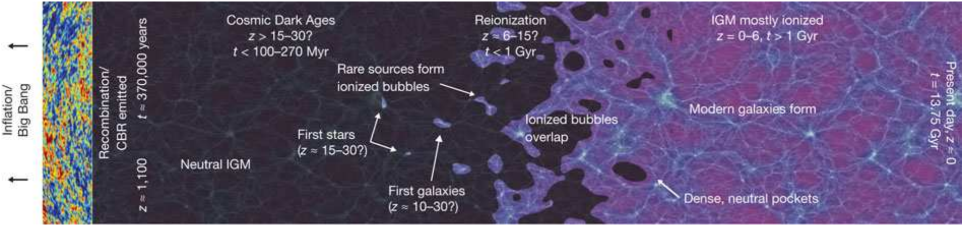
Dark ages and reionization

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

Dark ages and reionization

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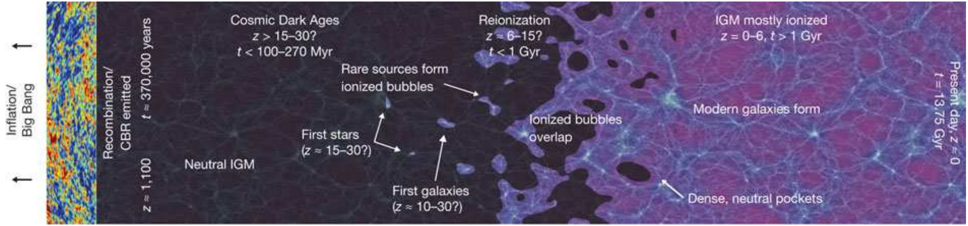


Dark ages

Strong probe of cosmology

Reionization

1. First stars
2. Cosmology

Post-reionization

1. Galaxy formation
2. Cosmology

Phase transition

"Final frontier" of observational cosmology

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

Reionization and cosmology

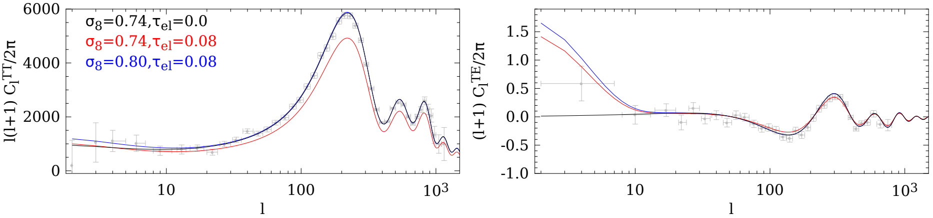
- Details of reionization history affects estimation of cosmological parameters? Implications for precision cosmology?
- Reionization is driven by first sources which are (high–σ) fluctuations in the cosmic density field $\Longrightarrow$ anything which affects the small-scale power spectrum can be constrained by reionization experiments (e.g., neutrino mass, mass of WDM particles, primordial magnetic field)

Electron scattering optical depth

- CMBR photons scatter off free electrons and produce polarization signal (at angular scales corresponding to the horizon size at the epoch of scattering)
- Optical depth due to Thomson scattering off **free electrons**:

$$\tau_{\rm el} = \sigma_T c \int_0^{z[t]} {\rm d}t \; n_e \; (1+z)^3$$

Provided by reionization → n_e

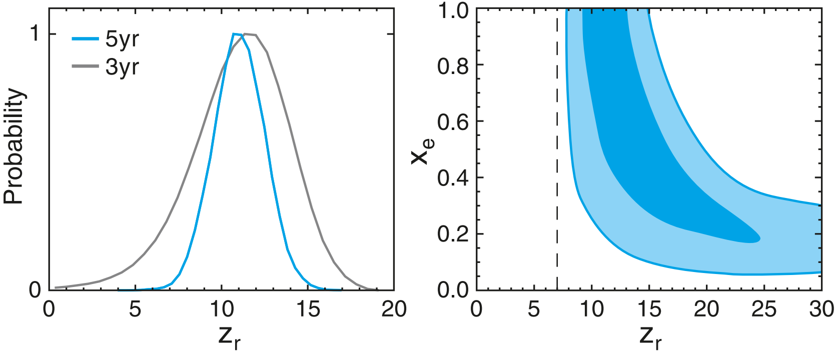


Constraints from WMAP

Optical depth due to Thomson scattering off **free electrons**:

$$\tau_{\rm el} = \sigma_T c \int_0^{z[t]} {\rm d}t \; n_e \; (1+z)^3$$

Provided by reionization



Dunkley et al. (2008)

Constraints assume a sudden and complete reionization at a redshift $z_{\rm re}$.

General reionization scenarios

What happens when general reionization scenarios are taken into account?

Parameter	WMAP7	WMAP7 + PC
Ω_m	0.266 ± 0.029	0.243 ± 0.032
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02321 ± 0.00076
h	0.710 ± 0.025	0.735 ± 0.033
n_s	0.963 ± 0.014	0.994 ± 0.023
σ_8	0.801 ± 0.030	0.805 ± 0.026
τ_{el}	0.088 ± 0.015	0.093 ± 0.010

Mortonson & Hu (2008), Pandolfi et al (2010)

Are the constraints physical?

- The previous analysis ignores physical processes related to reionization
- For example, A_s and $\tau_{\rm el}$ cannot be completely independent – changing A_s will affect $\tau_{\rm el}$ through formation of dark matter haloes
- Also, the analysis does not account for other data sets related to reionization, like Lyman-α forest

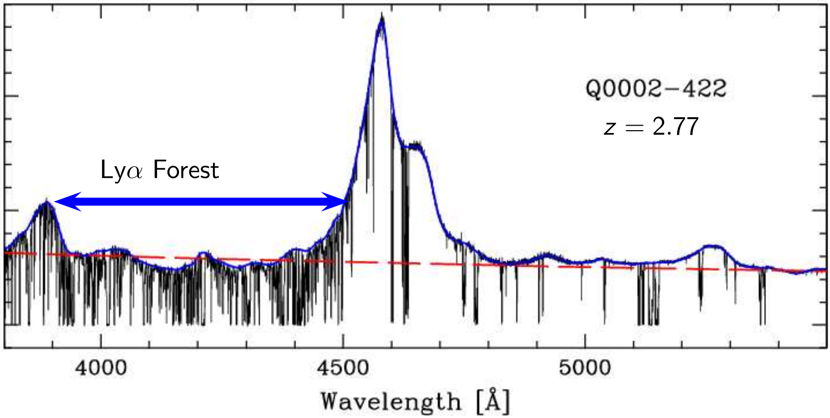
Cosmological parameters: WMAP7 + Astro

Pandolfi, Ferrara, **Choudhury**, Melchiorri & Mitra (2012)

Parameter	WMAP7	WMAP7 + PC	WMAP7 + ASTRO
Ω_m	0.266 ± 0.029	0.243 ± 0.032	0.273 ± 0.027
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02321 ± 0.00076	0.02183 ± 0.00054
h	0.710 ± 0.025	0.735 ± 0.033	0.698 ± 0.023
n_s	0.963 ± 0.014	0.994 ± 0.023	0.958 ± 0.013
σ_8	0.801 ± 0.030	0.805 ± 0.026	0.794 ± 0.027
τ_{el}	0.088 ± 0.015	0.093 ± 0.010	0.080 ± 0.012

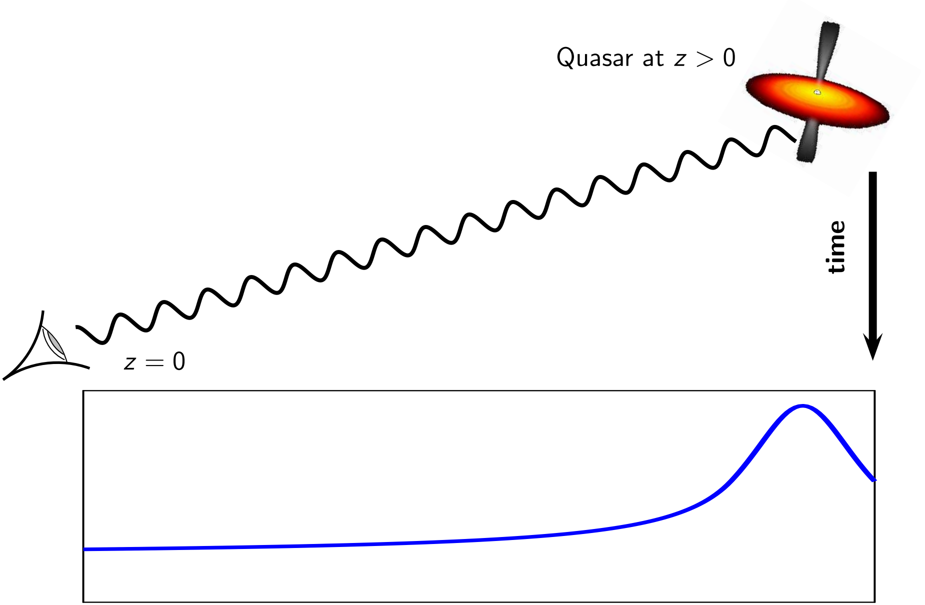
when astrophysical data sets are included and physically motivated models used, parameters become more constrained than PC analysis

Evidence for reionization: Lyman-α forest



The absorption lines blueward of the emission line arise from Lyα transition ($n = 1$ to $n = 2$) of neutral hydrogen (HI) present between the quasar and us.

Origin of the absorption lines



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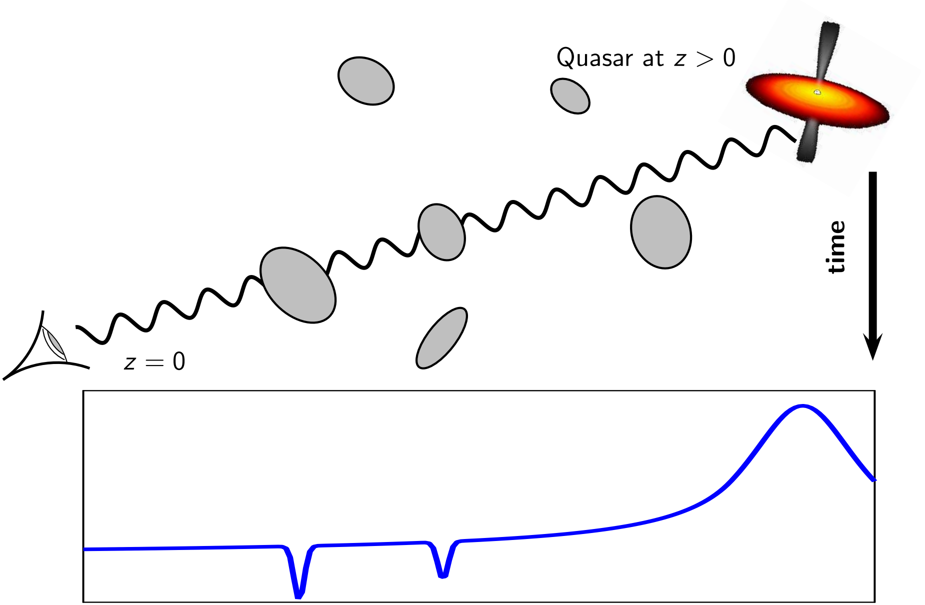
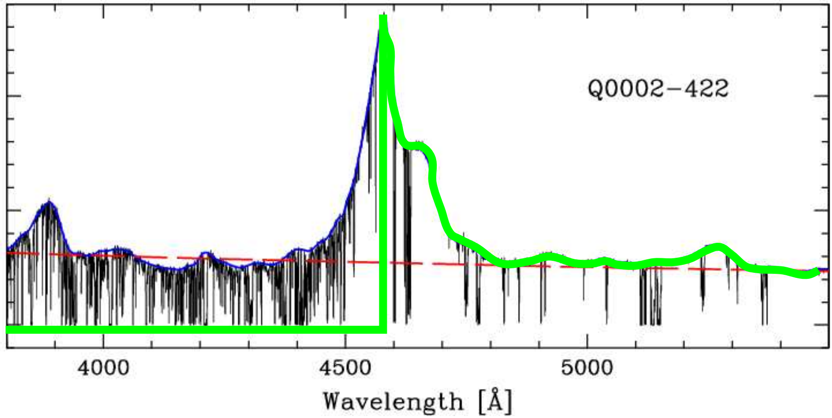


Gunn-Peterson effect



Observed flux $\sim$ Unabsorbed flux $\times$ $\exp\left(-10^5\ x_{\rm HI}\right)$, where $x_{\rm HI} = \rho_{\rm HI}/\rho_H$.

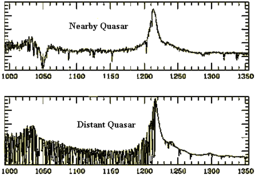
The fact that there is non-zero flux implies that $x_{\rm HI} \simeq 10^{-5}$

Non-zero flux observed till $z \sim 5.5$

QSO absorption lines at $z \sim 6$

$z \approx 0$

$z \approx 3$



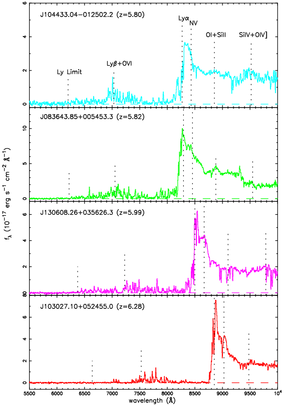
$x_{\mathrm{HI}} \lesssim 10^{-5}$

$z = 5.80$

$z = 5.82$

$z = 5.99$

$z = 6.28$



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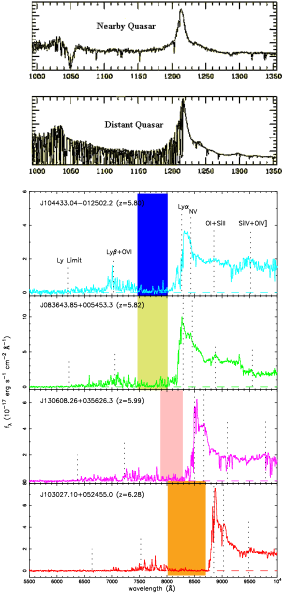


$x_{\mathrm{HI}} \lesssim 10^{-5}$

Does this absorption mean high neutrality?

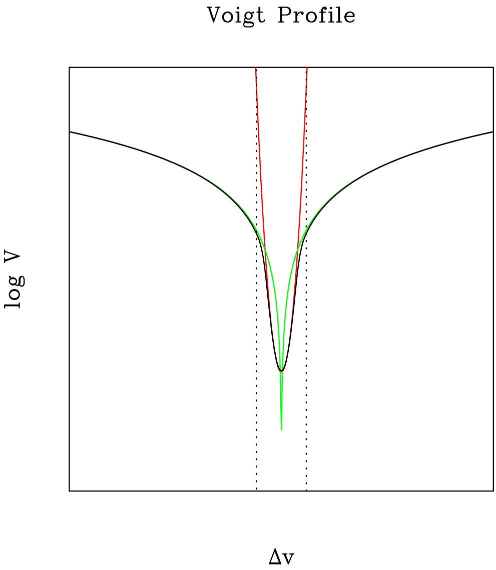
QSO absorption lines at $z \sim 6$

- Gunn-Peterson optical depth:

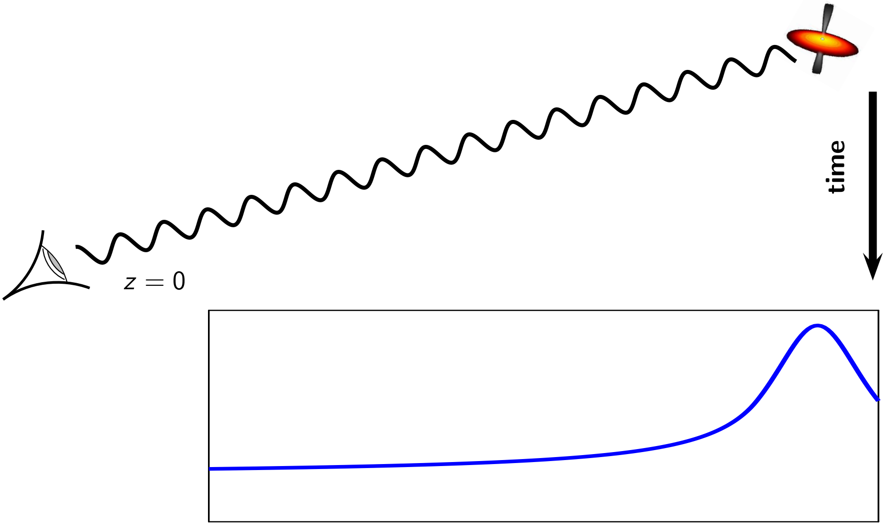
$$\tau_{\rm GP} \approx 3.6 \left(\frac{\Omega_b h^2}{0.022}\right) \sqrt{\frac{0.15}{\Omega_m h^2}} \left(\frac{1-Y}{0.76}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{\bar{x}_{\rm HI}}{10^{-5}}\right) \Delta^{\beta}$$

- So, even a neutral fraction $x_{\rm HI} \approx 10^{-4}$ would produce **complete absorption**!
- Lyα transition "too strong", saturates too easily....
- Possible to do detailed modelling:
  distribution of "dark gaps"
  Gallerani, **Choudhury** & Ferrara (2006), Gallerani, Ferrara, Fan & **Choudhury** (2008)
  size of ionized region around the quasar
  Maselli, Gallerani, Ferrara & **Choudhury** (2007)
  fraction of "dark pixels"
  McGreer, Mesinger & D'Odorico (2014)
  Most likely that $x_{\rm HI} \lesssim 0.1$ at $z \sim 6$

Lyman-α absorption cross section



Damping wings and near zones



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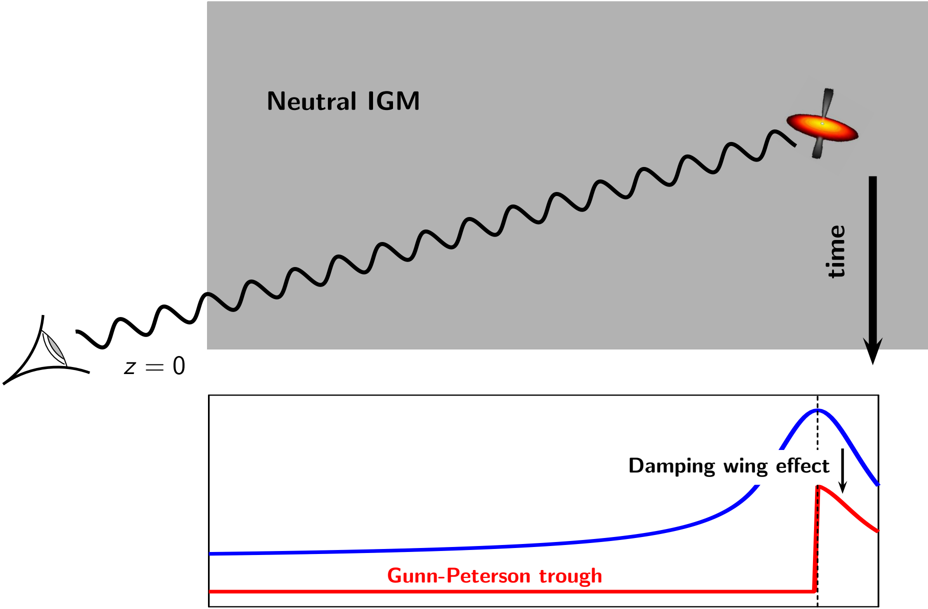

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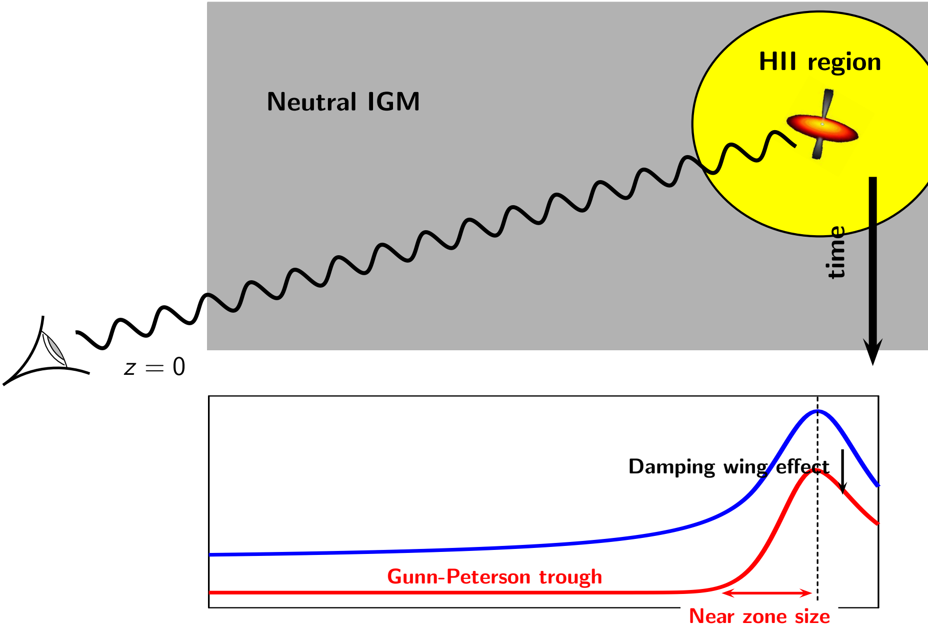
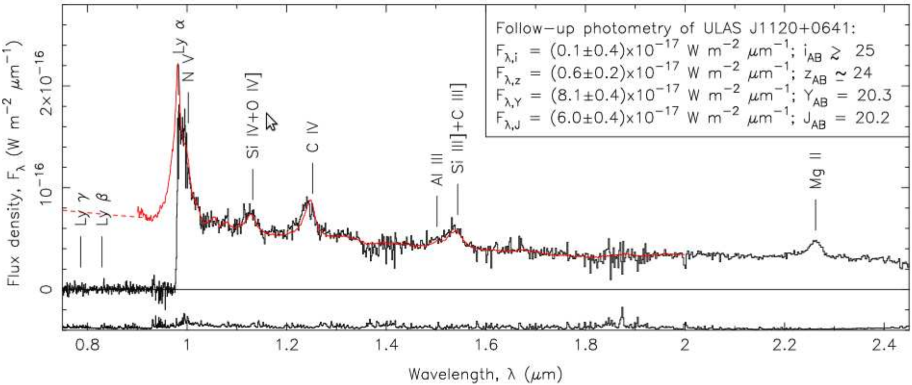


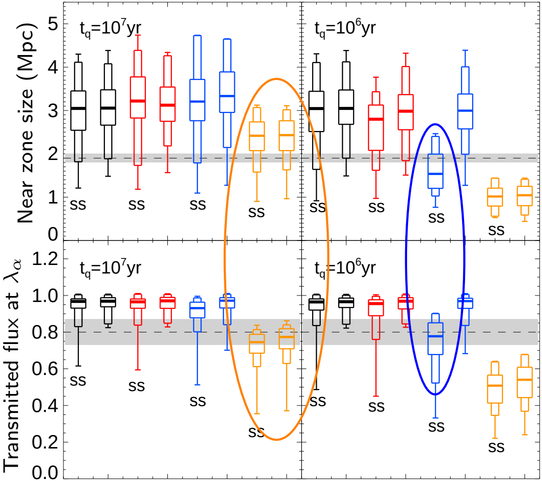
Discovery of a QSO at $z \approx 7$



United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS)

Mortlock et al. (2011)

Neutral hydrogen at $z \approx 7$



$x_{\rm HI} = 5\times10^{-4}$ 0.006 0.11 1.0 5×10^{-4} 0.006 0.11 1.0

$x_{\rm HI} \gtrsim 0.1$

at $z \approx 7$

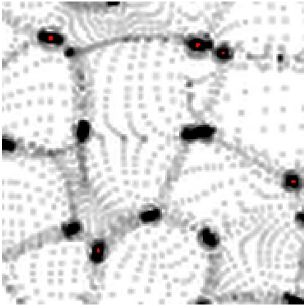
Bolton et al. (2011)

√ Formation of (dark matter) haloes:

Analytical: Press-Schechter/Sheth-Tormen formalism:

$$\frac{\mathrm{d}n(M,z)}{\mathrm{d}M} = \sqrt{\frac{2}{\pi}} \frac{\rho_m}{M} \frac{\delta_c(z)}{\sigma^2(M)} \left|\frac{\mathrm{d}\sigma(M)}{\mathrm{d}M}\right| \mathrm{e}^{-\delta_c^2(z)/2\sigma^2(M)}$$

Simulations: DM only N-body codes



Reionization models

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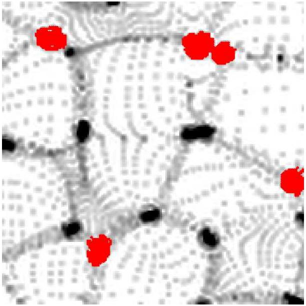
Simulations: DM only N-body codes

- Photon production $\dot{n}_\gamma$



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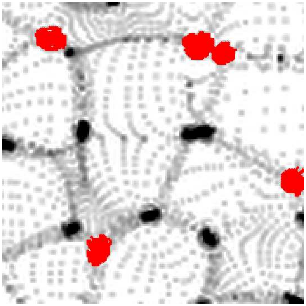

- Photon production $\dot{n}_\gamma$
  - × Galaxy/star formation: cooling, fragmentation, feedback (radiative, mechanical, chemical)

Reionization models

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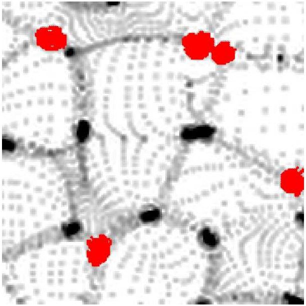
Simulations: DM only N-body codes

- Photon production $\dot{n}_\gamma$
  - × Galaxy/star formation: cooling, fragmentation, feedback (radiative, mechanical, chemical)
  - √ Radiation from stars: population synthesis.



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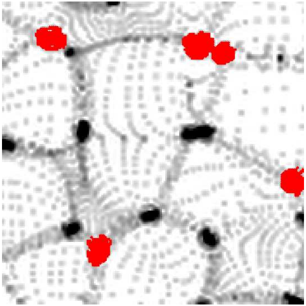


- Photon production $\dot{n}_\gamma$
  - × Galaxy/star formation: cooling, fragmentation, feedback (radiative, mechanical, chemical)
  - √ Radiation from stars: population synthesis.
  - × Escape of photons f_{esc}: neutral hydrogen within the host galaxy

Reionization models

$\surd$ Formation of (dark matter) haloes:

Analytical: Press-Schechter/Sheth-Tormen formalism:

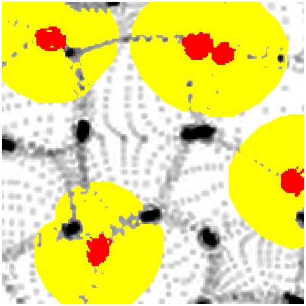
$$\frac{\mathrm{d}n(M,z)}{\mathrm{d}M} = \sqrt{\frac{2}{\pi}} \frac{\rho_m}{M} \frac{\delta_c(z)}{\sigma^2(M)} \left|\frac{\mathrm{d}\sigma(M)}{\mathrm{d}M}\right| \mathrm{e}^{-\delta_c^2(z)/2\sigma^2(M)}$$

Simulations: DM only N-body codes

- Photon production $\dot{n}_\gamma$
  - $\times$ Galaxy/star formation: cooling, fragmentation, feedback (radiative, mechanical, chemical)
  - $\surd$ Radiation from stars: population synthesis.
  - $\times$ Escape of photons f_{esc}: neutral hydrogen within the host galaxy

$\times$ Radiative transfer in the IGM: evolution of ionization fronts

Simulations, semi-numerical, analytical



A semi-analytical model **Choudhury** & Ferrara (2005, 2006)

- Photon production rate:

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

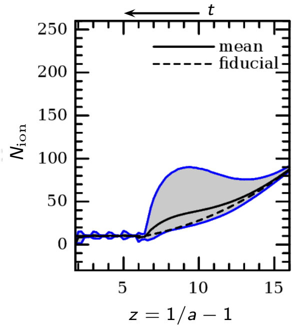
Number of ionizing photons in the IGM per baryons

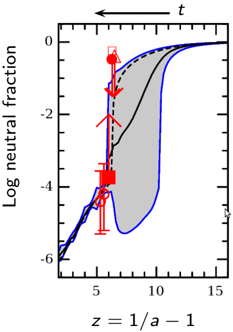
Collapse rate of dark matter haloes

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

- Study the evolution of globally-averaged ionized mass fraction.
- Supplemented by temperature and species evolution equations

Constraints on reionization history





- **Choudhury** & Ferrara, Mon. Not. R. Astron. Soc. 361 577 (2005)
- **Choudhury** & Ferrara, Mon. Not. R. Astron. Soc. 380 L6 (2007)
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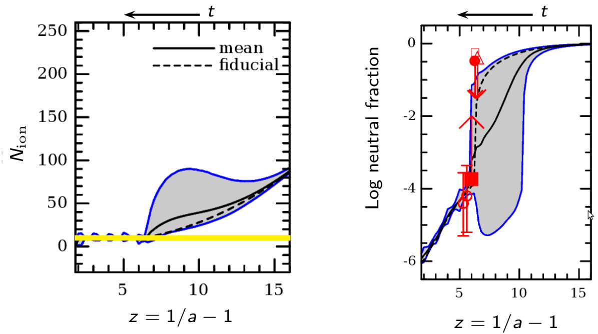

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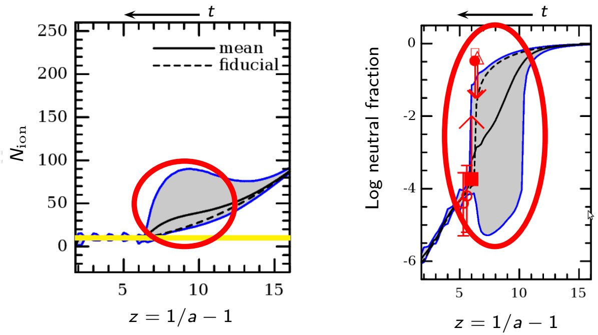

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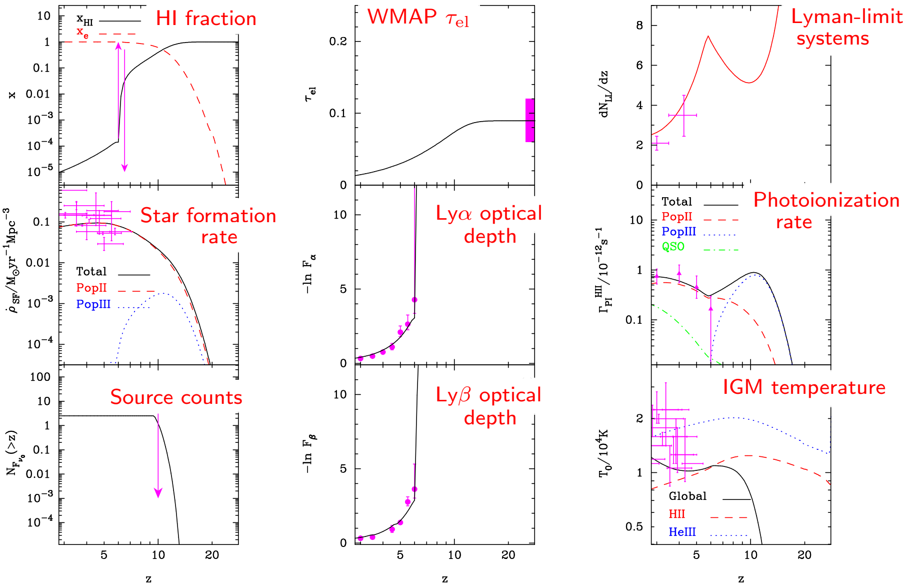
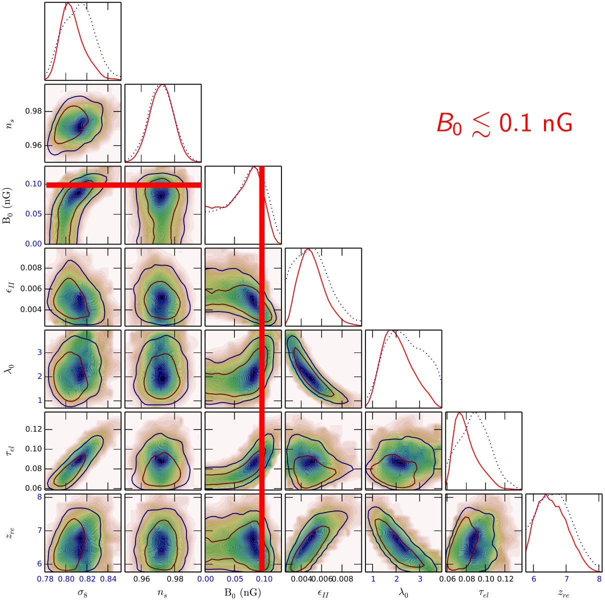
Best-fit reionization history

- H-reionization starts at $z \approx 15$ [early reionization].
- Completes at $z \approx 6$
- Feedback regulated. Extended. "Slow".
- Require substantial sources of photons at $z \approx 10$.
- How to obtain more constraints? What about HeII reionization?

Comparing with other observations **Choudhury** (2009)



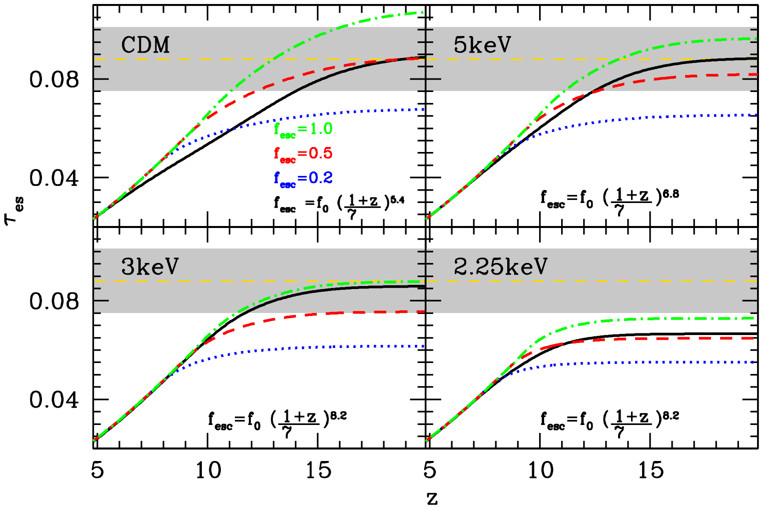
Primordial magnetic field Pandey, **Choudhury**, Sethi & Ferrara (2014)



$B_0 \lesssim 0.1$ nG

Warm dark matter Dayal, **Choudhury**, Bromm & Pacucchi (2015)

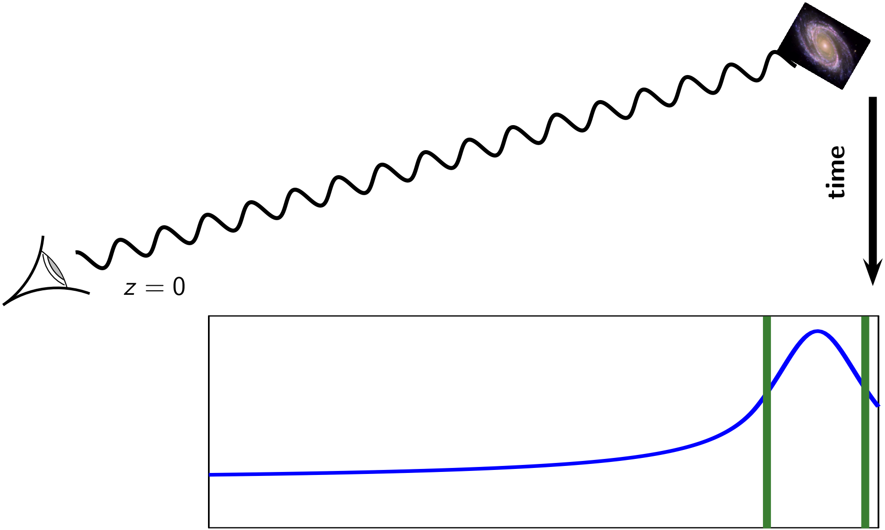
$m_{\rm WDM} \gtrsim 2$ keV



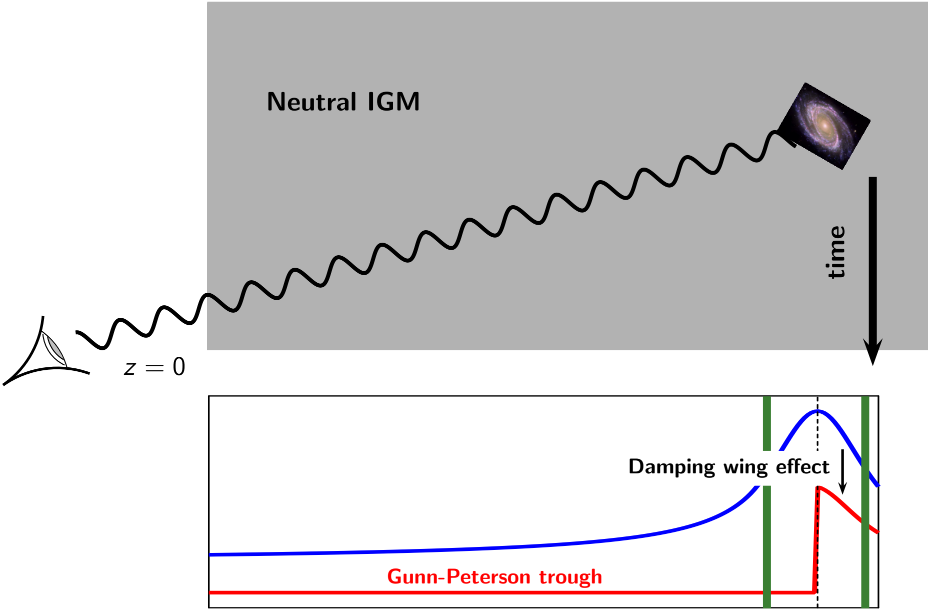
Other probes of reionization

- Spectra of high-z GRBs
  transient events, difficult to obtain high S/N spectra, absorption in the host galaxy
- High redshift galaxies
  conversion from UV luminosity to ionizing photons uncertain, escape fraction unknown
- Abundance of Lyα emitters at $z > 6$
  a number of systematic effects like the Lyα line profile, peculiar velocity effects, . . .

Lyman-α emitters

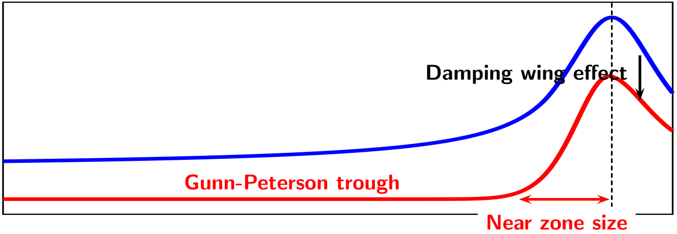


Lyman-α emitters



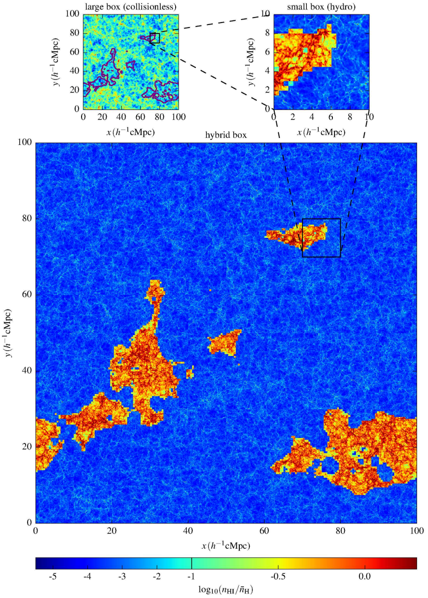
Lyα emitters and reionization

- Detection of Lyα emitters depends on **transparency of the medium**: a neutral IGM at high-z can weaken the Lyα emission (damping wing effect).



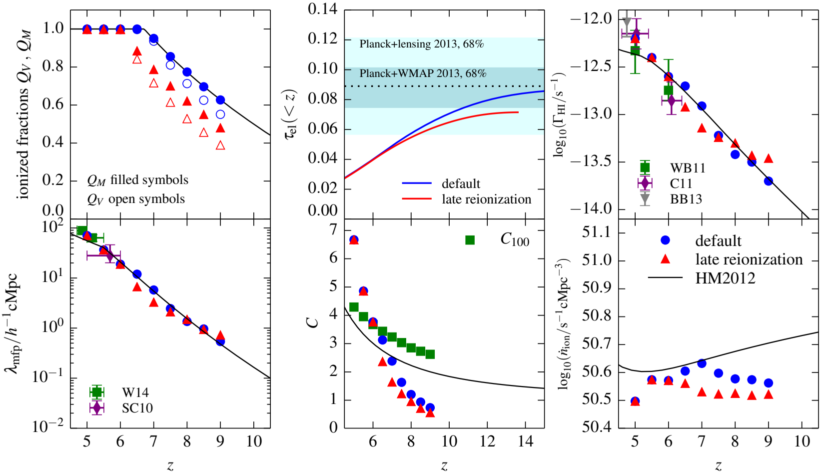
- Uncertainties: (i) size of HII regions (depends on galaxies surrounding the LAE, which depends on clustering), (ii) peculiar velocity effects.
- Construct the luminosity function of Lyα emitters at different redshifts and check if they evolve. The evolution can put limits on the neutral hydrogen fraction.

"Hybrid" simulations **Choudhury**, Puchwein, Haehnelt & Bolton (2014)



Consistent reionization history

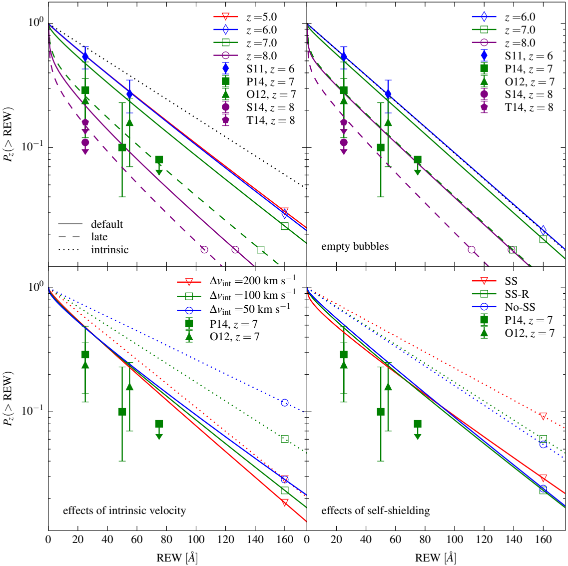
Choudhury, Puchwein, Haehnelt & Bolton (2014)



Best-fit reionization model

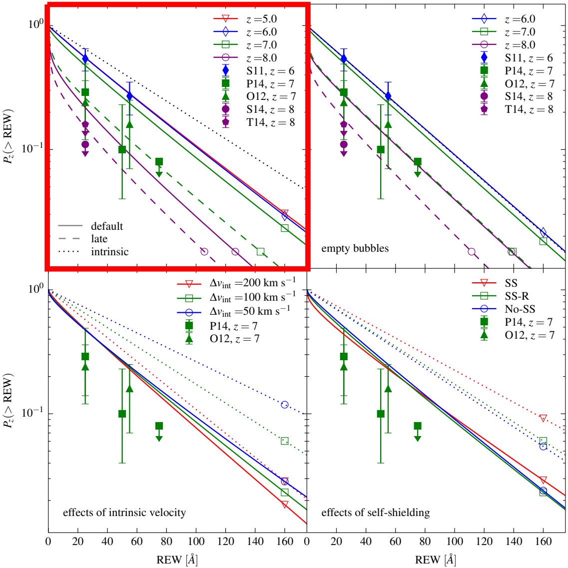
Evolution of Lyα emitters

Choudhury, Puchwein, Haehnelt & Bolton (2014)



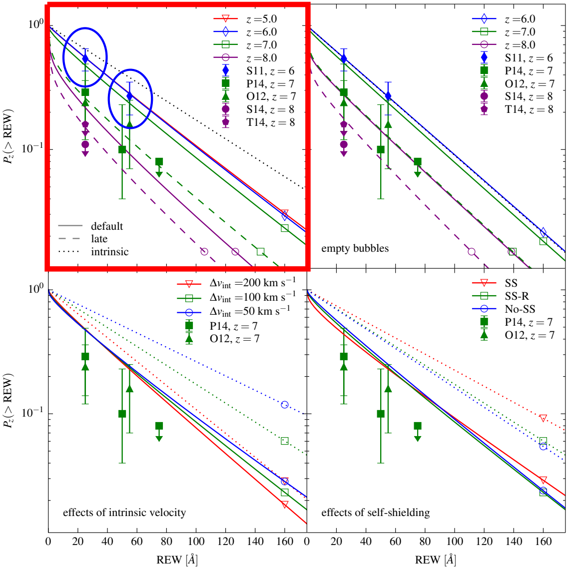
Evolution of Lyα emitters

Choudhury, Puchwein, Haehnelt & Bolton (2014)



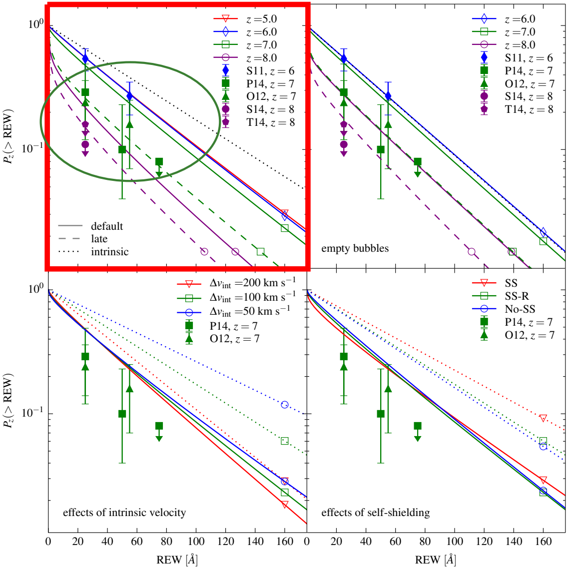
Evolution of Lyα emitters

Choudhury, Puchwein, Haehnelt & Bolton (2014)



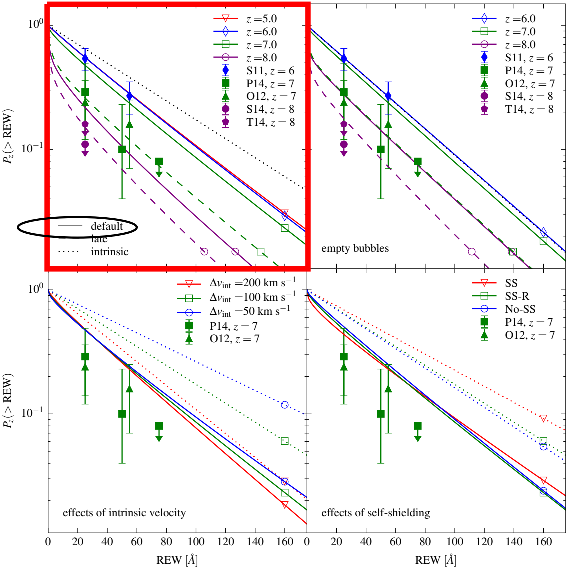
Evolution of Lyα emitters

Choudhury, Puchwein, Haehnelt & Bolton (2014)



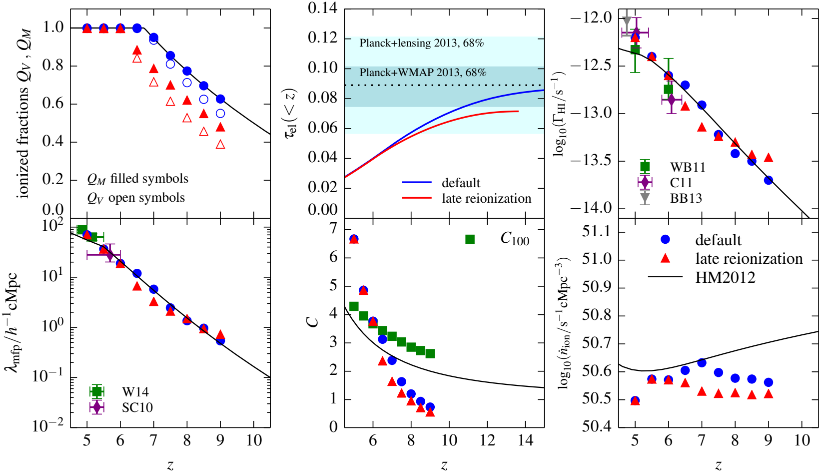
Evolution of Lyα emitters

Choudhury, Puchwein, Haehnelt & Bolton (2014)



A different reionization history

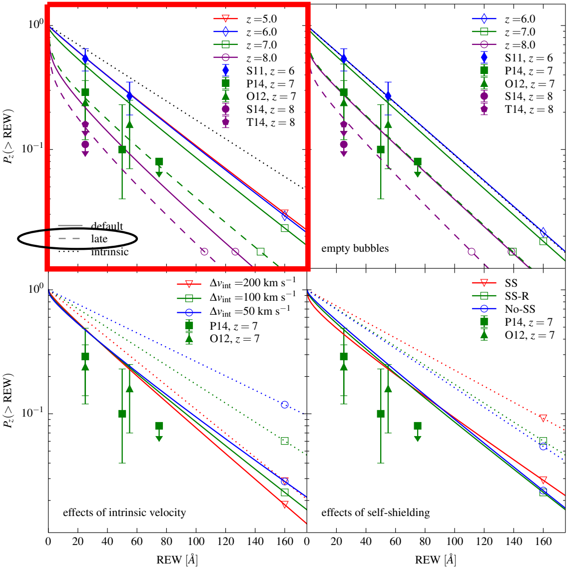
Choudhury, Puchwein, Haehnelt & Bolton (2014)



Late reionization model (latest Planck results?)

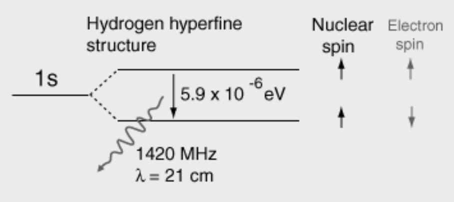
Need to revise reionization models?

Choudhury, Puchwein, Haehnelt & Bolton (2014)



Probing HI through 21 cm line

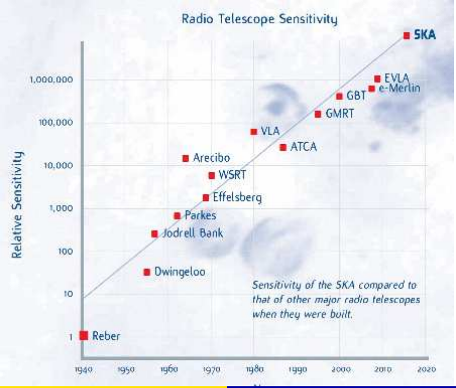
- Lyα is a line transition, but too "strong" $\Longrightarrow$ lines become saturated for $x_{\rm HI} \gtrsim 10^{-4}$
- CMBR probes the integrated effect, relatively less sensitive to the details of reionization
- Good option would be to work with a line transition which is "weak"
- 21 cm hyperfine transition



- Number of experiments planned, SKA being the most ambitious of them.

Square Kilometre Array

- Most ambitious radio astronomy project ever attempted
- Multi-national project



Indian involvement in the SKA

- India has been involved in the SKA from the beginning!
- It is one of the ten member countries in the SKA organization.
- NCRA leads one of the technical packages (the telescope manager), collaboration with IT industry.
- Indian scientists are directly involved in the International Science Working Groups.
- GMRT provides useful tests for SKA science.

SKA-India

- Number of activities ongoing and planned within India to prepare ourselves for the SKA science.
- Seven science working groups within India. Represented by various Institutes/Universities/Centres
  http://www.ncra.tifr.res.in:8081/~tirth/SKA-India/index.html
  Drop me an email if interested!
- Plans for organizing workshops, training schools, conferences etc.
- One-day workshop on Feb 16, just before the ASI meeting at NCRA-TIFR.
- A formal setting up of SKA-India Consortium expected soon! Interested organizations would be encouraged to join.
- This Consortium will oversee most of the SKA-related activities within India.

Summary

- Reionization is crucially linked to the first stars and cosmology.
- Good progress in theoretical modelling, possible to construct models consistent with available data.
- Do we need to revise the reionization models? Waiting for Planck results . . .
- Field driven by observational data:
  - QSO absorption lines + GRBs
  - high-redshift galaxies,
  - CMBR polarization + SZ signal,
  - Lyα emitters,
  - 21 cm experiments

  Wealth of data expected in the next few years!
- Important to develop detailed analytical and numerical models to extract the maximum information about the relevant physical processes out of the expected **large and complex data sets**.
- Looking forward to SKA-India Consortium.

Thank you