Reionization - II

Tirthankar Roy Choudhury
National Centre for Radio Astrophysics
Tata Institute of Fundamental Research
Pune

NCRA • TIFR

Cosmology - The Next Decade
ICTS-TIFR, Bangalore
17 January 2019

Topics to be covered

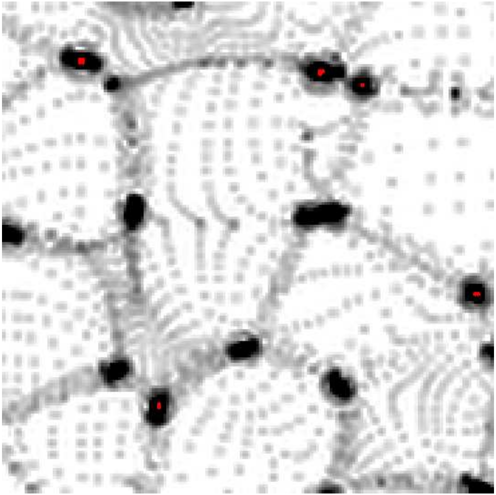
Concentrate on the physics of underlying structure of the IGM

- Observational constraints on reionization
- Theoretical models of reionization
- Future probes of reionization

References:

- Textbook: *Galaxy Formation and Evolution* by Houjun Mo, Frank van den Bosch & Simon White
- Review: *In the beginning: the first sources of light and the reionization of the universe* by Rennan Barkanaa & Abraham Loeb, Phys. Rept., 349, 125 (2001)
- Review: *Analytical Models of the Intergalactic Medium and Reionization* by T. Roy Choudhury, Current Science, 97, 841 (2009)

HI distribution: schematic diagram

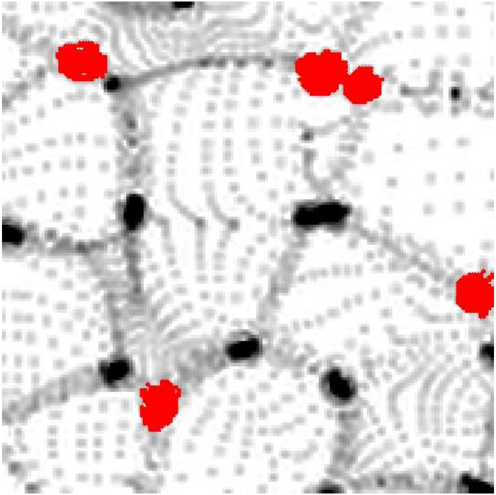


JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.

HI distribution: schematic diagram

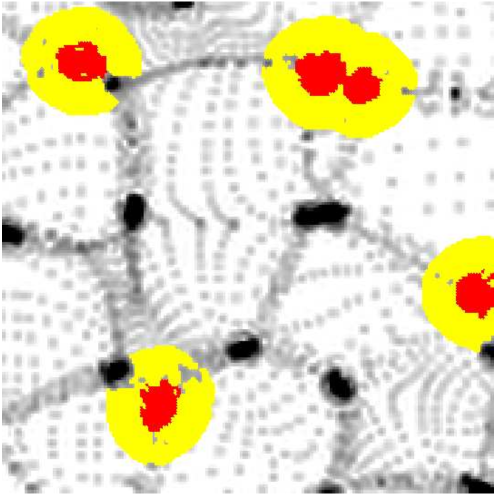


JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.
- Sources of ionizing photons

HI distribution: schematic diagram

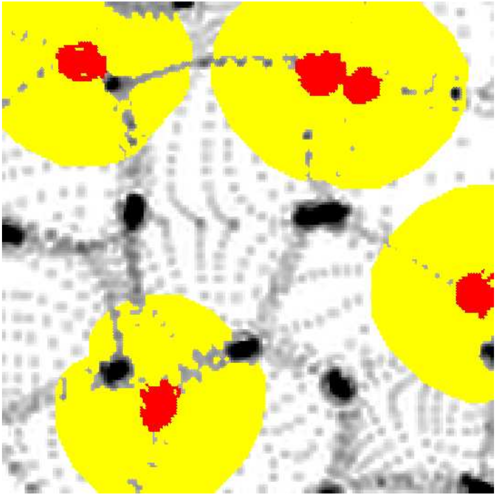


JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.
- Sources of ionizing photons
- Ionized regions

HI distribution: schematic diagram

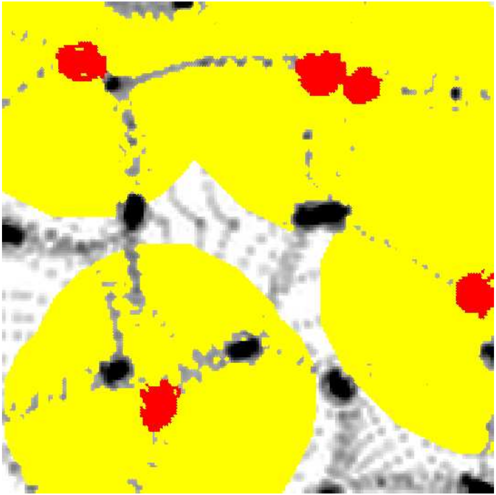


JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.
- Sources of ionizing photons
- Ionized regions
- **Started overlapping**

HI distribution: schematic diagram

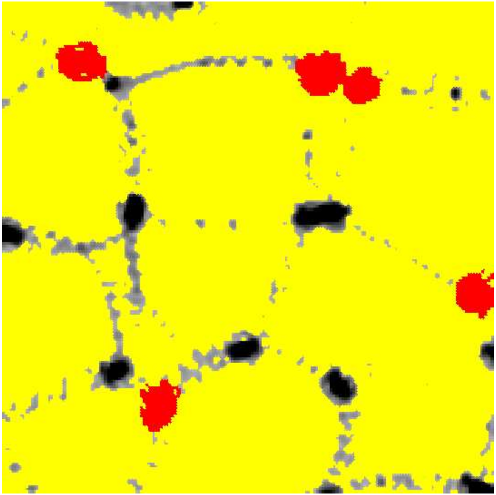


JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.
- Sources of ionizing photons
- Ionized regions
- **Started overlapping**
- Approaching reionization

HI distribution: schematic diagram

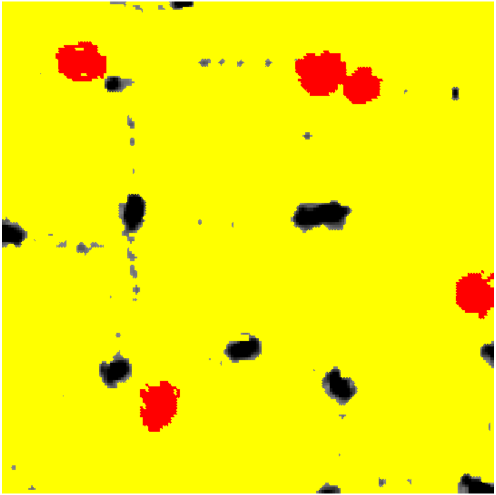


JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.
- Sources of ionizing photons
- Ionized regions
- **Started overlapping**
- Approaching reionization
- **Reionization**

HI distribution: schematic diagram



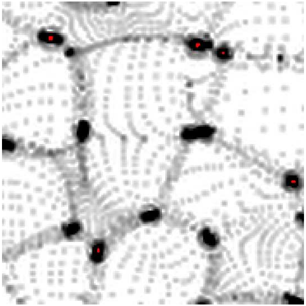
JUST A SKETCH

Based on Choudhury, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**.
- Sources of ionizing photons
- Ionized regions
- **Started overlapping**
- Approaching reionization
- **Reionization**
- **Post-reionization era**

Modelling reionization

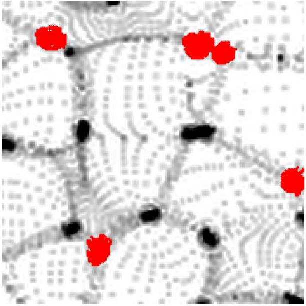
√ Formation of (dark matter) haloes:
Excursion set formalism / simulations



Modelling reionization

√ Formation of (dark matter) haloes:
Excursion set formalism / simulations

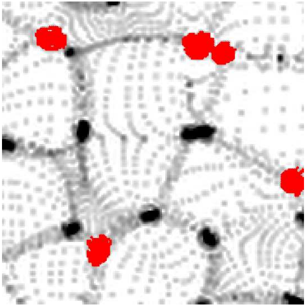
- ▸ Photon production



Modelling reionization

√ Formation of (dark matter) haloes:
Excursion set formalism / simulations

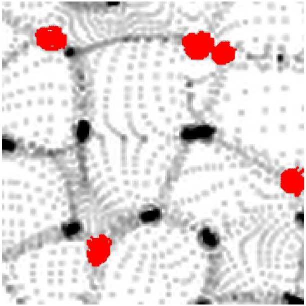
- ► Photon production
  - × Galaxy/star formation: cooling, fragmentation, feedback



Modelling reionization

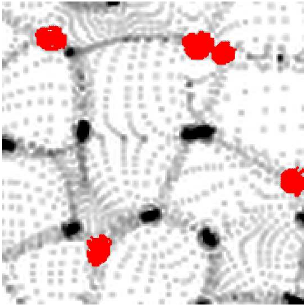
$\surd$ Formation of (dark matter) haloes:
Excursion set formalism / simulations

- Photon production
  - ✗ Galaxy/star formation: cooling, fragmentation, feedback
  - $\surd$ Radiation from stars: population synthesis



Modelling reionization

- √ Formation of (dark matter) haloes:
  Excursion set formalism / simulations
- ▸ Photon production
  - × Galaxy/star formation: cooling, fragmentation, feedback
  - √ Radiation from stars: population synthesis
  - × Escape of photons: neutral hydrogen within the host galaxy

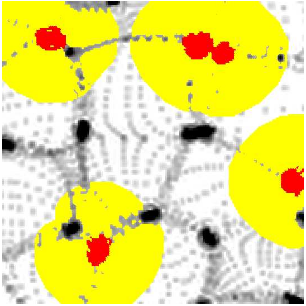


Modelling reionization

√ Formation of (dark matter) haloes: Excursion set formalism / simulations

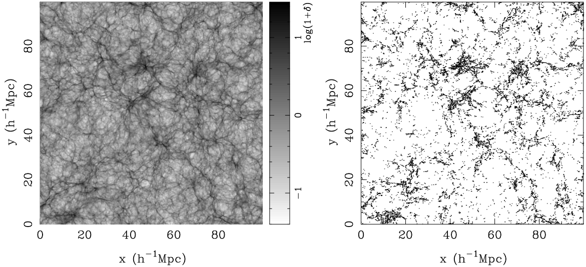
- ▸ Photon production
  - × Galaxy/star formation: cooling, fragmentation, feedback
  - √ Radiation from stars: population synthesis
  - × Escape of photons: neutral hydrogen within the host galaxy

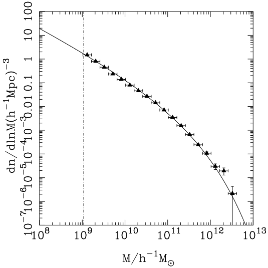
× Radiative transfer in the IGM: evolution of ionization fronts



Dark matter haloes

Number of haloes per comoving volume having mass $[M, M + \mathrm{d}M]$ at a redshift z: $n(M, z) \equiv \mathrm{d}n(z)/\mathrm{d}M$.





Star formation

- Physics of star formation involves cooling of the baryonic gas, fragmentation, formation of molecular clouds etc.
- Let the star formation rate of a galaxy in a halo be

  $$\dot{M}_*(M, t, t_{\rm form}) = f_*(M, z) \left(\frac{\Omega_b}{\Omega_m}\right) M \, \Lambda_*(t - t_{\rm form}),$$

  with

  $$\int_0^\infty {\rm d}t \; \Lambda_*(t) = 1.$$

  $t_{\rm form}$ is the formation time of the halo.
  f_* is the fraction of baryons that goes into stars.
- For constant star formation rates, we should have $\Lambda_*(t) = 1/t_{\rm SFR}$, where $t_{\rm SFR}$ is the star formation time scale.
- On the other extreme, for a starburst, we put $\Lambda_*(t) = \delta_D(t)$.
- If we assume that the star-formation time scale is $\sim$ the dynamical time scale $t_{\rm dyn}$ of the halo, then one can show that

  $$\frac{t_{\rm dyn}}{t_H} \sim \frac{1}{\sqrt{\Delta_{\rm halo}}} \sim 0.1$$

  Hence one often assumes $\Lambda_*(t) \sim \delta_D(t)$.

Radiation from stars

Given the star formation rate, IMF and the metallicity, it is possible to calculate the radiation from the galaxy using the **population synthesis models**, e.g., `STARBURST99`.

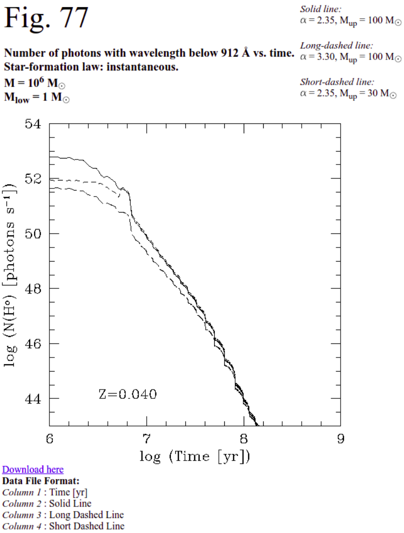


Fig. 77

Number of photons with wavelength below 912 Å vs. time.
Star-formation law: instantaneous.

$M = 10^6\ M_\odot$
$M_{low} = 1\ M_\odot$

Solid line:
$\alpha = 2.35$, $M_{up} = 100\ M_\odot$

Long-dashed line:
$\alpha = 3.30$, $M_{up} = 100\ M_\odot$

Short-dashed line:
$\alpha = 2.35$, $M_{up} = 30\ M_\odot$

Download here

Data File Format:
Column 1 : Time [yr]
Column 2 : Solid Line
Column 3 : Long Dashed Line
Column 4 : Short Dashed Line

Rate of ionizing photons

- The population synthesis codes provide the luminosity $l_\nu(t)$ per unit mass of stars formed (which is energy per unit time per frequency range) for a burst of star formation at $t = 0$. It is sometimes called the **specific luminosity**.

Rate of ionizing photons

- The population synthesis codes provide the luminosity $l_\nu(t)$ per unit mass of stars formed (which is energy per unit time per frequency range) for a burst of star formation at $t = 0$. It is sometimes called the **specific luminosity**.
- The number of ionizing photons produced per unit time in a halo is

$$\dot{N}_\gamma(M, t, t_{\rm form}) = f_* \left(\frac{\Omega_b}{\Omega_m}\right) M \int_{t_{\rm form}}^{\infty} {\rm d}t' \, \Lambda_*(t' - t_{\rm form}) \int_{\nu_H}^{\infty} {\rm d}\nu \, \frac{l_\nu(t - t')}{h\nu}.$$

Rate of ionizing photons

- The population synthesis codes provide the luminosity $l_\nu(t)$ per unit mass of stars formed (which is energy per unit time per frequency range) for a burst of star formation at $t = 0$. It is sometimes called the **specific luminosity**.
- The number of ionizing photons produced per unit time in a halo is

$$\dot{N}_\gamma(M, t, t_{\mathrm{form}}) = f_* \left(\frac{\Omega_b}{\Omega_m}\right) M \int_{t_{\mathrm{form}}}^{\infty} \mathrm{d}t' \, \Lambda_*(t' - t_{\mathrm{form}}) \int_{\nu_H}^{\infty} \mathrm{d}\nu \, \frac{l_\nu(t - t')}{h\nu}.$$

- For ionizing photons produced by massive stars, we can approximate

$$\int_{\nu_H}^{\infty} \mathrm{d}\nu \, \frac{l_\nu(t)}{h\nu} = \eta_\gamma \, \delta_D(t)$$

  where

$$\eta_\gamma = \int_0^{\infty} \mathrm{d}t \, \int_{\nu_H}^{\infty} \mathrm{d}\nu \, \frac{l_\nu(t)}{h\nu}$$

  is the total number of ionizing photons produced in the halo per unit mass of stars.

Rate of ionizing photons

- The population synthesis codes provide the luminosity $l_\nu(t)$ per unit mass of stars formed (which is energy per unit time per frequency range) for a burst of star formation at $t = 0$. It is sometimes called the **specific luminosity**.
- The number of ionizing photons produced per unit time in a halo is

$$\dot{N}_\gamma(M, t, t_{\rm form}) = f_* \left(\frac{\Omega_b}{\Omega_m}\right) M \int_{t_{\rm form}}^{\infty} \mathrm{d}t' \; \Lambda_*(t' - t_{\rm form}) \int_{\nu_H}^{\infty} \mathrm{d}\nu \; \frac{l_\nu(t - t')}{h\nu}.$$

- For ionizing photons produced by massive stars, we can approximate

$$\int_{\nu_H}^{\infty} \mathrm{d}\nu \; \frac{l_\nu(t)}{h\nu} = \eta_\gamma \; \delta_D(t)$$

  where

$$\eta_\gamma = \int_0^{\infty} \mathrm{d}t \; \int_{\nu_H}^{\infty} \mathrm{d}\nu \; \frac{l_\nu(t)}{h\nu}$$

  is the total number of ionizing photons produced in the halo per unit mass of stars.
- Hence

$$\dot{N}_\gamma(M, t, t_{\rm form}) = f_* \; \eta_\gamma \left(\frac{\Omega_b}{\Omega_m}\right) M \; \Lambda_*(t - t_{\rm form}).$$

Global photon production rate

- Haloes once formed may not survive forever, the smaller ones will merge to form larger haloes.

Global photon production rate

- Haloes once formed may not survive forever, the smaller ones will merge to form larger haloes.
- The number of ionizing photons produced per unit time per unit comoving volume as

$$\dot{n}_{\gamma}(t) = \int_0^t \mathrm{d}t_{\mathrm{form}} \int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M \, \frac{\partial^2 n}{\partial t_{\mathrm{form}} \, \partial M} \, p(t|t_{\mathrm{form}}) \, \dot{N}_{\gamma}(M, t, t_{\mathrm{form}}),$$

  where the mass integral is over all haloes with mass above M_{min} that can cool and form stars. $p(t|t_{\mathrm{form}})$ be the fraction of haloes that formed at t_{form}) and survive till $t > t_{\mathrm{form}}$.

Global photon production rate

- Haloes once formed may not survive forever, the smaller ones will merge to form larger haloes.
- The number of ionizing photons produced per unit time per unit comoving volume as

$$\dot{n}_\gamma(t) = \int_0^t \mathrm{d}t_{\rm form} \int_{M_{\rm min}}^{\infty} \mathrm{d}M \, \frac{\partial^2 n}{\partial t_{\rm form} \, \partial M} \, p(t|t_{\rm form}) \, \dot{N}_\gamma(M, t, t_{\rm form}),$$

  where the mass integral is over all haloes with mass above $M_{\rm min}$ that can cool and form stars. $p(t|t_{\rm form})$ be the fraction of haloes that formed at $t_{\rm form}$) and survive till $t > t_{\rm form}$.
- Taking $\Lambda_*(t - t_{\rm form}) \approx \delta_D(t - t_{\rm form})$,

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \int_{M_{\rm min}}^{\infty} \mathrm{d}M \, f_* \, \eta_\gamma M \frac{\partial^2 n}{\partial t \, \partial M}.$$

Escape of photons

- Not all of the photons produced by stars in the halo will escape into the surrounding IGM. A fraction will absorbed by dense neutral hydrogen in the interstellar medium of the galaxy itself.

Escape of photons

- Not all of the photons produced by stars in the halo will escape into the surrounding IGM. A fraction will absorbed by dense neutral hydrogen in the interstellar medium of the galaxy itself.
- Let the fraction of photons that escape into the IGM be denoted as f_{esc}. This can, in principle, be a function of M and z (and perhaps other conditions like the environment).

Escape of photons

- Not all of the photons produced by stars in the halo will escape into the surrounding IGM. A fraction will absorbed by dense neutral hydrogen in the interstellar medium of the galaxy itself.
- Let the fraction of photons that escape into the IGM be denoted as $f_{\rm esc}$. This can, in principle, be a function of M and z (and perhaps other conditions like the environment).
- This quantity is poorly modelled, and also there are very few observational constraints, particularly at high redshifts.

Escape of photons

- Not all of the photons produced by stars in the halo will escape into the surrounding IGM. A fraction will absorbed by dense neutral hydrogen in the interstellar medium of the galaxy itself.
- Let the fraction of photons that escape into the IGM be denoted as f_{esc}. This can, in principle, be a function of M and z (and perhaps other conditions like the environment).
- This quantity is poorly modelled, and also there are very few observational constraints, particularly at high redshifts.
- So, the quantity that is relevant for reionization studies is

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M \; f_{\mathrm{esc}} \; f_* \; \eta_\gamma M \frac{\partial^2 n}{\partial t \; \partial M}.$$

The reionization efficiency parameter

- The number of ionizing photons in the IGM per unit time per unit comoving volume:

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \int_{M_{\rm min}}^{\infty} {\rm d}M \; f_{\rm esc} \; f_* \; \eta_\gamma M \frac{\partial^2 n}{\partial t \; \partial M}.$$

The reionization efficiency parameter

- The number of ionizing photons in the IGM per unit time per unit comoving volume:

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \int_{M_{\rm min}}^{\infty} {\rm d}M\ f_{\rm esc}\ f_*\ \eta_\gamma M \frac{\partial^2 n}{\partial t\ \partial M}.$$

- Note that the unknown quantities $f_{\rm esc}$, f_* and η_γ appear as a combination of multiplicative factors, so we do not need to know them individually.

The reionization efficiency parameter

- The number of ionizing photons in the IGM per unit time per unit comoving volume:
$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \int_{M_{\rm min}}^{\infty} {\rm d}M \; f_{\rm esc} \; f_* \; \eta_\gamma M \frac{\partial^2 n}{\partial t \, \partial M}.$$
- Note that the unknown quantities $f_{\rm esc}$, f_* and η_γ appear as a combination of multiplicative factors, so we do not need to know them individually.
- It is customary to define a dimensionless parameter
$$N_{\rm ion} = f_{\rm esc} \; f_* \; \eta_\gamma \; m_p$$
so that the expression for the photon production rate becomes
$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \int_{M_{\rm min}}^{\infty} {\rm d}M \; \frac{N_{\rm ion}}{m_p} \; M \frac{\partial^2 n}{\partial t \, \partial M}.$$
$N_{\rm ion}$ can be interpreted as the number of ionizing photons entering the IGM per baryon in the halo.

Ionizing photons and the collapsed fraction

- Take $N_{\rm ion}$ to be independent of the halo mass M:

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \frac{N_{\rm ion}(t)}{m_p} \frac{\mathrm{d}}{\mathrm{d}t} \left(\int_{M_{\rm min}}^{\infty} \mathrm{d}M \, M \, \frac{\mathrm{d}n}{\mathrm{d}M}\right)$$

Ionizing photons and the collapsed fraction

- Take N_{ion} to be independent of the halo mass M:

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \frac{N_{\text{ion}}(t)}{m_p} \frac{\mathrm{d}}{\mathrm{d}t} \left(\int_{M_{\text{min}}}^{\infty} \mathrm{d}M \, M \, \frac{\mathrm{d}n}{\mathrm{d}M} \right)$$

- We can define the **collapsed fraction** as

$$f_{\text{coll}}(t) = \frac{1}{\bar{\rho}_m} \int_{M_{\text{min}}}^{\infty} \mathrm{d}M \, M \, \frac{\mathrm{d}n}{\mathrm{d}M},$$

  where $\bar{\rho}_m$ is the mean comoving density of matter. Note that $\bar{\rho}_m$ does not evolve with time.

Ionizing photons and the collapsed fraction

- Take N_{ion} to be independent of the halo mass M:

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \frac{N_{\mathrm{ion}}(t)}{m_p} \frac{\mathrm{d}}{\mathrm{d}t} \left(\int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M\, M\, \frac{\mathrm{d}n}{\mathrm{d}M}\right)$$

- We can define the **collapsed fraction** as

$$f_{\mathrm{coll}}(t) = \frac{1}{\bar{\rho}_m} \int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M\, M\, \frac{\mathrm{d}n}{\mathrm{d}M},$$

  where $\bar{\rho}_m$ is the mean comoving density of matter. Note that $\bar{\rho}_m$ does not evolve with time.
- Keep in mind that $f_{\mathrm{coll}}(t)$ depends on the value of M_{min}.

Ionizing photons and the collapsed fraction

- Take $N_{\rm ion}$ to be independent of the halo mass M:

$$\dot{n}_\gamma(t) = \left(\frac{\Omega_b}{\Omega_m}\right) \frac{N_{\rm ion}(t)}{m_p} \frac{\mathrm{d}}{\mathrm{d}t} \left(\int_{M_{\rm min}}^{\infty} \mathrm{d}M\, M\, \frac{\mathrm{d}n}{\mathrm{d}M}\right)$$

- We can define the **collapsed fraction** as

$$f_{\rm coll}(t) = \frac{1}{\bar{\rho}_m} \int_{M_{\rm min}}^{\infty} \mathrm{d}M\, M\, \frac{\mathrm{d}n}{\mathrm{d}M},$$

  where $\bar{\rho}_m$ is the mean comoving density of matter. Note that $\bar{\rho}_m$ does not evolve with time.
- Keep in mind that $f_{\rm coll}(t)$ depends on the value of $M_{\rm min}$.
- We can then write

$$\begin{aligned} \dot{n}_\gamma(t) &= N_{\rm ion}(t) \left(\frac{\Omega_b}{\Omega_m}\right) \frac{\bar{\rho}_m}{m_p} \frac{\mathrm{d}f_{\rm coll}}{\mathrm{d}t} \\ &= N_{\rm ion}(t) \frac{\bar{\rho}_b}{m_p} \frac{\mathrm{d}f_{\rm coll}}{\mathrm{d}t} \\ &= N_{\rm ion}(t)\, \bar{n}_b\, \frac{\mathrm{d}f_{\rm coll}}{\mathrm{d}t}, \end{aligned} \tag{1}$$

  where we have used $\bar{n}_b = \bar{\rho}_b / m_p$ and ignored the presence of helium.

Radiative transfer challenge

- Assume that locations of the sources and their luminosities are known. We can calculate the volume-averaged emissivity $\epsilon_\nu(t, \mathbf{x})$.

Radiative transfer challenge

- Assume that locations of the sources and their luminosities are known. We can calculate the volume-averaged emissivity $\epsilon_\nu(t, \mathbf{x})$.
- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$ $\Longrightarrow$ either inaccurate or inefficient

$$\frac{\partial I_\nu}{\partial t} + \frac{c}{a(t)}\hat{\mathbf{n}} \cdot \nabla_{\mathbf{x}} I_\nu - H(t)\nu\frac{\partial I_\nu}{\partial \nu} + 3H(t)I_\nu = -c\kappa_\nu I_\nu + \frac{c}{4\pi}\epsilon_\nu$$

Radiative transfer challenge

- Assume that locations of the sources and their luminosities are known. We can calculate the volume-averaged emissivity $\epsilon_\nu(t, \mathbf{x})$.
- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$ $\implies$ either inaccurate or inefficient

$$\frac{\partial I_\nu}{\partial t} + \frac{c}{a(t)} \hat{\mathbf{n}} \cdot \nabla_{\mathbf{x}} I_\nu - H(t) \nu \frac{\partial I_\nu}{\partial \nu} + 3H(t) I_\nu = -c\kappa_\nu I_\nu + \frac{c}{4\pi} \epsilon_\nu$$

- Numerical simulations employ some approximate schemes (e.g., spherical symmetry, ray-tracing, Monte-Carlo sampling, ...)

Radiative transfer challenge

- Assume that locations of the sources and their luminosities are known. We can calculate the volume-averaged emissivity $\epsilon_\nu(t, \mathbf{x})$.
- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$ $\Longrightarrow$ either inaccurate or inefficient

$$\frac{\partial I_\nu}{\partial t} + \frac{c}{a(t)} \hat{\mathbf{n}} \cdot \nabla_{\mathbf{x}} I_\nu - H(t)\nu \frac{\partial I_\nu}{\partial \nu} + 3H(t) I_\nu = -c\kappa_\nu I_\nu + \frac{c}{4\pi}\epsilon_\nu$$

- Numerical simulations employ some approximate schemes (e.g., spherical symmetry, ray-tracing, Monte-Carlo sampling, …)
- Alternatives: analytic or semi-numeric

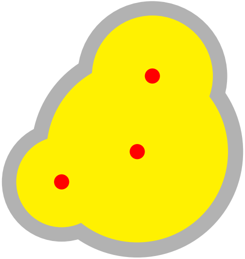
Growth of ionized regions

Number of photons produced per unit volume

$$\dot{n}_\gamma \, \Delta t = \boxed{n_H \, \Delta Q_{\mathrm{HII}}} + \boxed{\Gamma_{\mathrm{HI}} \, (n_{\mathrm{HI}} \, Q_{\mathrm{HII}}) \, \Delta t}$$

ionization of neutral regions

ionizing HI in already ionized regions



Photoionization equilibrium within ionized regions:

$$n_{\mathrm{HI}} \, \Gamma_{\mathrm{HI}} = \alpha_B \, \left(\mathcal{C} \, n_H^2\right) \, a^{-3}$$

clumping factor: $\mathcal{C} = \langle n_H^2 \rangle / \langle n_H \rangle^2$.

$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = \frac{\dot{n}_\gamma}{n_H} - Q_{\mathrm{HII}} \, \mathcal{C} \, \alpha_B \, n_H \, a^{-3}$$

Photon production

Photon production rate:

$$\frac{\dot{n}_\gamma}{n_H} = \boxed{N_{\rm ion}} \boxed{\frac{\mathrm{d}f_{\rm coll}}{\mathrm{d}t}}$$

Number of ionizing photons in the IGM per baryons

Collapse rate of dark matter haloes

$$N_{\rm ion} = f_* \, f_{\rm esc} \times \text{number of photons per baryons in stars} \times \left(\frac{\Omega_b}{\Omega_m}\right)$$

Minimum mass of star-forming haloes

- In case the gas cools only by atomic transitions, $M_{\rm min} \sim 10^8 M_{\odot}$. Presence of molecules makes $M_{\rm min} \sim 10^6 M_{\odot}$.

Minimum mass of star-forming haloes

- In case the gas cools only by atomic transitions, $M_{\rm min} \sim 10^8 M_\odot$. Presence of molecules makes $M_{\rm min} \sim 10^6 M_\odot$.
- Feedback effects can increase the value of $M_{\rm min}$.

Minimum mass of star-forming haloes

- In case the gas cools only by atomic transitions, $M_{\rm min} \sim 10^8 M_\odot$. Presence of molecules makes $M_{\rm min} \sim 10^6 M_\odot$.
- Feedback effects can increase the value of $M_{\rm min}$.
- **Radiative feedback:** heating due to reionization leads to inefficient cooling in small mass haloes.

Minimum mass of star-forming haloes

- In case the gas cools only by atomic transitions, $M_{\rm min} \sim 10^8 M_\odot$. Presence of molecules makes $M_{\rm min} \sim 10^6 M_\odot$.
- Feedback effects can increase the value of $M_{\rm min}$.
- **Radiative feedback:** heating due to reionization leads to inefficient cooling in small mass haloes.
- **Mechanical feedback:** energetic events (e.g., supernova explosions) can deplete the gas from shallow potential wells (small mass haloes).

Minimum mass of star-forming haloes

- In case the gas cools only by atomic transitions, $M_{\rm min} \sim 10^8 M_{\odot}$. Presence of molecules makes $M_{\rm min} \sim 10^6 M_{\odot}$.
- Feedback effects can increase the value of $M_{\rm min}$.
- **Radiative feedback:** heating due to reionization leads to inefficient cooling in small mass haloes.
- **Mechanical feedback:** energetic events (e.g., supernova explosions) can deplete the gas from shallow potential wells (small mass haloes).
- **Chemical feedback:** polluting the medium with metals (from supernova explosions) can change the chemistry of star-formation (e.g., PopIII → PopII transition)

The relevant equations

The master equation:

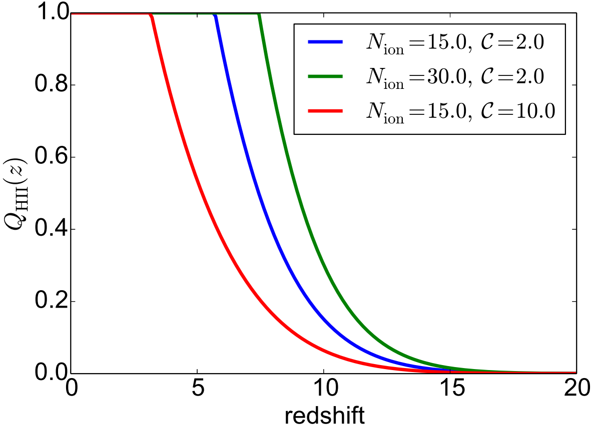
$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = N_{\mathrm{ion}} \, \frac{\mathrm{d}f_{\mathrm{coll}}}{\mathrm{d}t} - Q_{\mathrm{HII}} \, \mathcal{C} \, \alpha_B \, n_H \, a^{-3}$$

CMBR optical depth

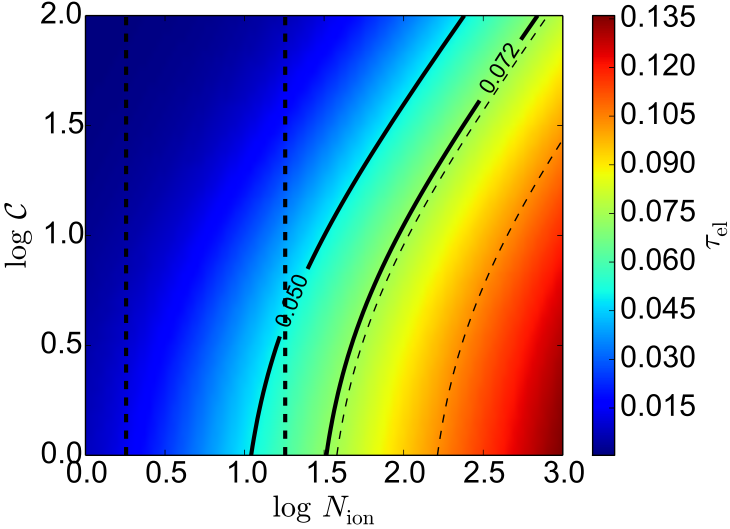
$$\tau_{\mathrm{el}} = c \, \sigma_T \, n_H \int_0^{z_{\mathrm{LSS}}} \mathrm{d}t \; Q_{\mathrm{HII}}(t) \; a^{-3}$$

Dependence on parameters

$$M_{\rm min} = 10^8 h^{-1} M_\odot$$

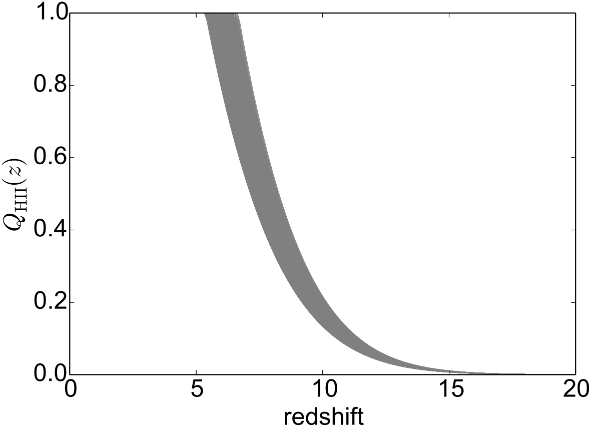


Constraints from $\tau_{\rm el}$ (and quasar spectra)



Recall $\Gamma_{\rm HI} \propto \dot{n}_\gamma\ \lambda_{\rm mfp}$

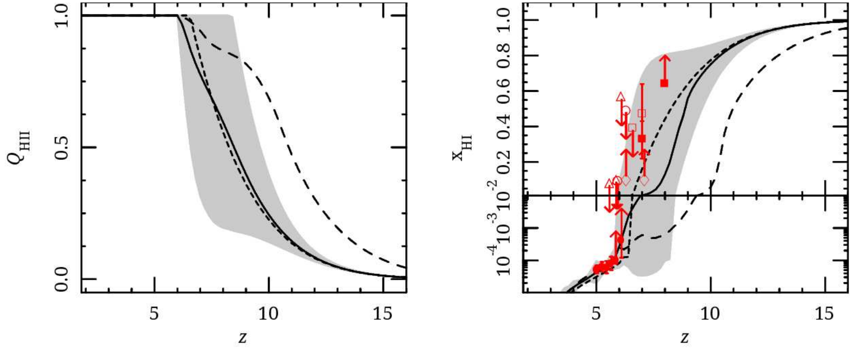
Allowed reionization histories



remember that $N_{\rm ion}$ and $\mathcal{C}$ are constants

Data constrained models

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



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

reionization starts at $z \sim 12$

Reionization effects on cosmological parameters

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

Parameter	WMAP7	WMAP7 + ASTRO
Ω_m	0.266 ± 0.029	0.273 ± 0.027
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02183 ± 0.00054
h	0.710 ± 0.025	0.698 ± 0.023
n_s	0.963 ± 0.014	0.958 ± 0.013
σ_8	0.801 ± 0.030	0.794 ± 0.027
τ_{el}	0.088 ± 0.015	0.080 ± 0.012

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

Constraints on non-standard cosmology

- Warm dark matter models Dayal, **TRC**, Bromm & Pacucci (2017)

Constraints on non-standard cosmology

- Warm dark matter models Dayal, **TRC**, Bromm & Pacucci (2017)
- Cosmic magnetic fields Pandey, **TRC**, Sethi & Ferrara (2015)

Constraints on non-standard cosmology

- Warm dark matter models Dayal, **TRC**, Bromm & Pacucci (2017)
- Cosmic magnetic fields Pandey, **TRC**, Sethi & Ferrara (2015)
- Non-flat models Mitra, **TRC** & Ratra (2018)