Challenges in modelling the cosmic reionization

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Workshop on the Epoch of Reionization
CTS, IIT Kharagpur, India
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Studying the epoch of reionization

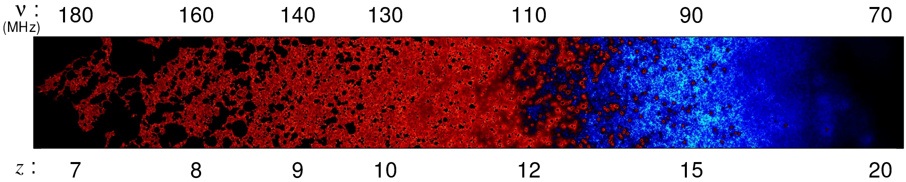


Figure courtesy Raghunath Ghara

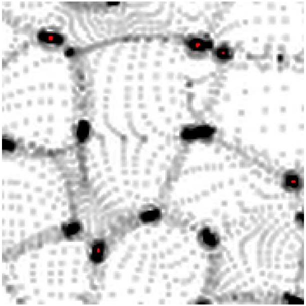
- universe getting ionized by the first stars
- aim is to study the neutral hydrogen fraction $x_{\mathrm{HI}}(\mathbf{x}, z)$ as it decreases from ~ 1 to ~ 0
- get insights on the nature of the first stars

Reionization model ingredients

√ Formation of (dark matter) haloes:

Analytical: Press-Schechter/Sheth-Tormen formalism:

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



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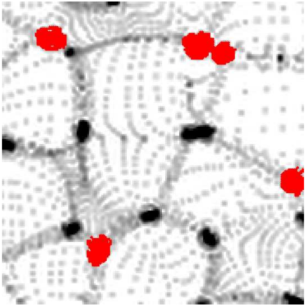

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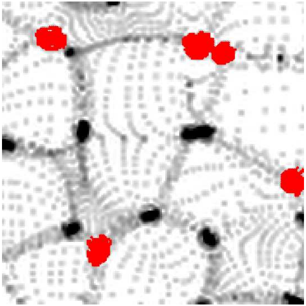

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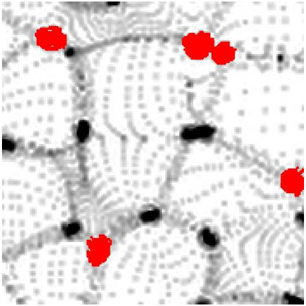

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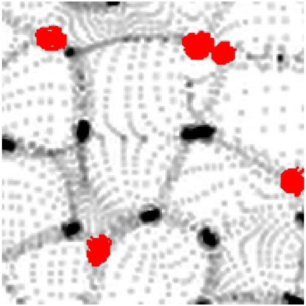

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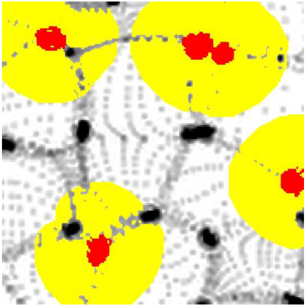
× Radiative transfer in the IGM: evolution of ionization fronts

Simulations, semi-numerical, analytical



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- Analytical formulation, based on *excursion set formalism* and *spherical collapse* gives the mass function of haloes (Press-Schechter)

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- Most reionization calculations depend on the *collapse fraction*

$$f_{\mathrm{coll}}(z) = \frac{1}{\rho_m}\ \int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M'\ M'\ \frac{\mathrm{d}n(M',z)}{\mathrm{d}M'}$$

Depends on M_{min}, the smallest halo that can produce and send ionized photons into the IGM.

Extensions to the analytical models

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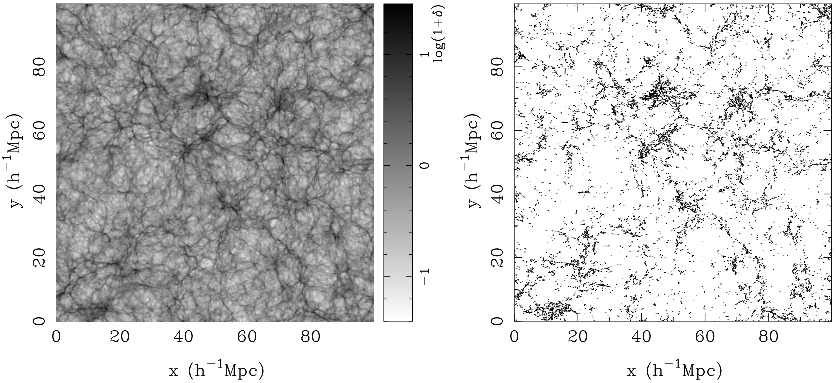
- Possible tools: *merger histories* (Lacey & Cole formalism), *formation and destruction rates* (Sasaki formalism), ...
- More recent models include, e.g., *excursion set peak* based formalism

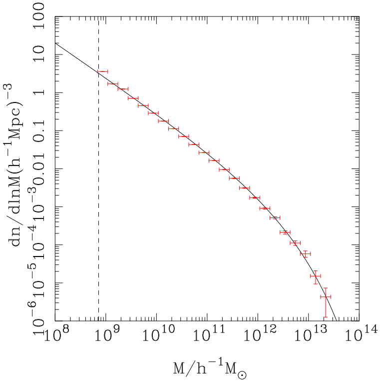
Dark matter haloes: simulations

- N-body simulations (to generate the density distribution) + Friends-of-Friends / Spherical overdensity algorithm (to identify collapsed objects)



Dark matter haloes: simulations

- *N*-body simulations (to generate the density distribution) + Friends-of-Friends / Spherical overdensity algorithm (to identify collapsed objects)
- Matches well with analytical predictions at high-*z*



Dynamic range in simulations

- Reionization simulations require box sizes $\sim 100 - 200$ Mpc
- Minimum halo mass to be resolved: $\sim 10^8 M_\odot$.
- Particle number $\sim 3000^3$, often beyond the reach of present simulations.
- Require sub-grid prescription to include small mass haloes.

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- Given a cell with δ, R, use conditional mass function
- Introduce scatter through random sampling
- Simple prescriptions may lead to haloes “disappearing” and “appearing” randomly.
- **Question:** How to follow the history of halo formation using sub-grid prescription?

Photon production

- Photon production rate:

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

Number of ionizing photons in the IGM per baryons

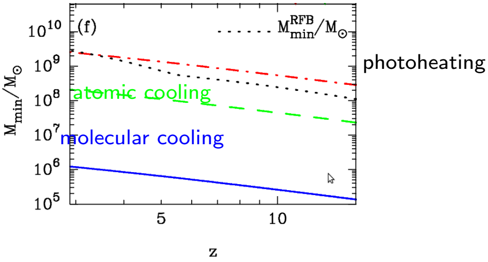
Collapse rate of dark matter haloes

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

- Possible to introduce M, z dependence on $N_{\rm ion}$, however exact dependence unknown.

Feedback

- Photoheating (associated with photoionization of H) stops star formation in low mass haloes (Jeans mass) within ionized regions: **radiative feedback**.



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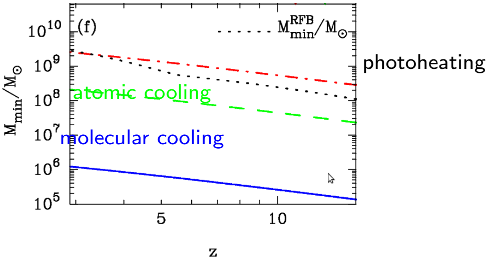

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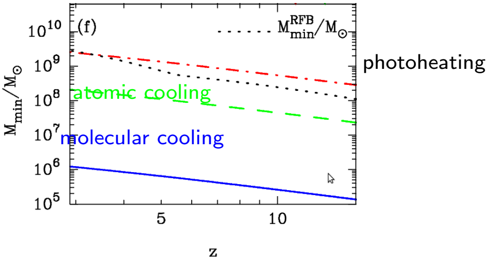

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- Metal injection by stars change the fragmentation mode $\Longrightarrow$ **chemical feedback**.
  First stars are zero metallicity (PopIII) stars.
  Possibly have different IMF (top-heavy) and spectra (hard).
  Extremely efficient sources of ionizing photons. Destroyed by chemical feedback.
  PopIII $\longrightarrow$ PopII transition poorly understood.

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- Mechanical feedback: important or not?
- Chemical feedback: simple merger tree based methods, cannot deal with "mixing" of metals

Radiative transfer simulations

- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$
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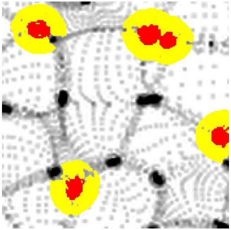
- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$
  $\implies$ either inaccurate or inefficient
- **Question:** Should we develop our own radiative transfer simulation?
- Alternatives: semi-analytic or semi-numeric

Semi-analytical models

- Averaging over globally representative volumes (and under certain approximations), the radiative transfer equation reduces to

$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = \frac{\dot{n}_\gamma}{n_H} - Q_{\mathrm{HII}}\mathcal{C}_{\mathrm{HII}}\frac{n_e}{a^3}\alpha_R(T)$$

Evolution of volume filling factor of ionized regions



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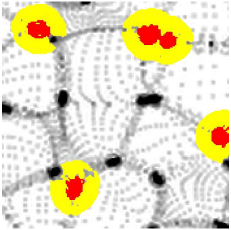

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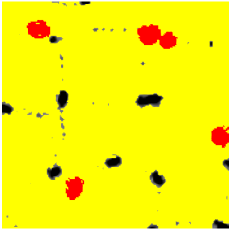

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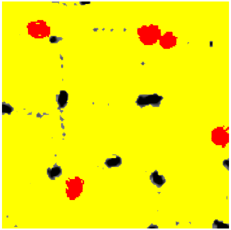
- What about feedback?



Feedback in semi-analytical models

- Radiative feedback: use a different $M_{\rm min}$ for ionized regions:

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- How do we calculate the mean free path $\lambda_{\rm mfp}$?

Density-dependent reionization

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- Assume all regions with $\Delta < \Delta_{\rm crit}$ are ionized first (pre-overlap era). Subsequently the radiation fronts penetrate the high density $\Delta > \Delta_{\rm crit}$ regions (post-overlap era).

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- Requires some assumption about $P(\Delta)$.

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- Assume all regions with $\Delta < \Delta_{\rm crit}$ are ionized first (pre-overlap era). Subsequently the radiation fronts penetrate the high density $\Delta > \Delta_{\rm crit}$ regions (post-overlap era).
- Post-overlap era

$$\frac{\mathrm{d}[F_M(\Delta_{\rm HII})]}{\mathrm{d}t} = \frac{\dot{n}_\gamma(z)}{n_H} - R(\Delta_{\rm HII})\frac{n_e}{a^3}\alpha_R(T)$$

- Pre-overlap era

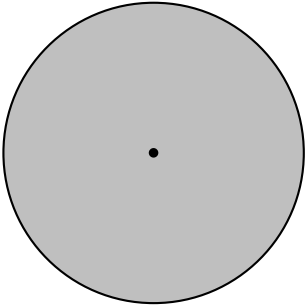
$$\frac{\mathrm{d}[Q_{\rm HII}F_M(\Delta_{\rm HII,crit})]}{\mathrm{d}t} = \frac{\dot{n}_\gamma(z)}{n_H} - Q_{\rm HII}R(\Delta_{\rm HII,crit})\frac{n_e}{a^3}\alpha_R(T)$$

- Clumping Factor: $C(\Delta_{\rm HII}) = \int_0^{\Delta_{\rm HII}} \mathrm{d}\Delta\ \Delta^2\ P(\Delta)$
- Mean free path:$\lambda_{\rm mfp} \propto [1 - F_V(\Delta_{\rm HII})]^{-2/3}$
- Requires some assumption about $P(\Delta)$.
- Possible to develop detailed semi-analytical models and compare with observations

  Choudhury & Ferrara (2005, 2006)

Fluctuations and bubbles

Semi-numerical calculation of ionization fronts (accounts for bubble overlap)



Self-ionization condition:

$n_{\rm phot}(R) \geq n_H(R) \Longrightarrow \zeta f_{\rm coll}(R) \geq 1$

Very similar to the halo formation problem

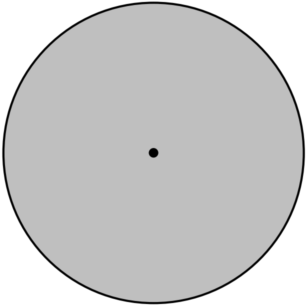
Furlanetto, Zaldarriaga & Hernquist (2004)

Recent improvement: better treatment based on peaks of the density field

Photon conservation issues

Paranjape & **Choudhury** (2014), Paranjape, **Choudhury** & Padmanabhan (2016)

Accounting for recombinations

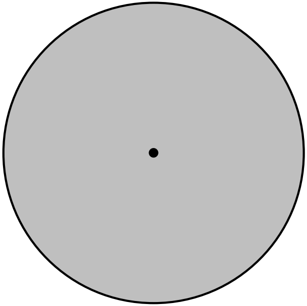


Self-ionization condition:
$\zeta f_{\rm coll} \geq 1$
Assume $R < R_{\rm max} = \lambda_{\rm mfp}$

A three parameter model for reionization: $N_{\rm nion}$, $M_{\rm min}$ and $\lambda_{\rm mfp}$.

Greig, Mesinger & Pober (2016)

Detailed model for recombinations



Self-ionization condition:

$\zeta f_{\rm coll} \geq 1$

Uniform recombination:

$\zeta f_{\rm coll} \geq 1 + \bar{N}_{\rm rec}$

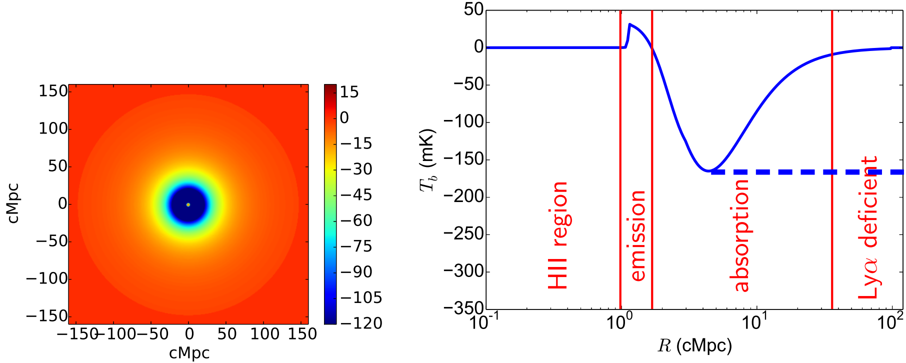
Inhomogeneous recombination:

$\zeta f_{\rm coll} \geq 1 + N_{\rm rec} \Delta^2$

Flux $\leq (n_H L) \times (1 + N_{\rm rec})$

Reionization: very early stages

- Very early stage when sources started to form (cosmic dawn) can be probed by 21 cm signal
- Require modelling of T_S (in addition to $x_{\rm HI}$) $\Longrightarrow$ X-ray heating and Lyα radiation flux
- **Question:** Semi-numerical simulations for generating X-ray field and Lyα radiation field?



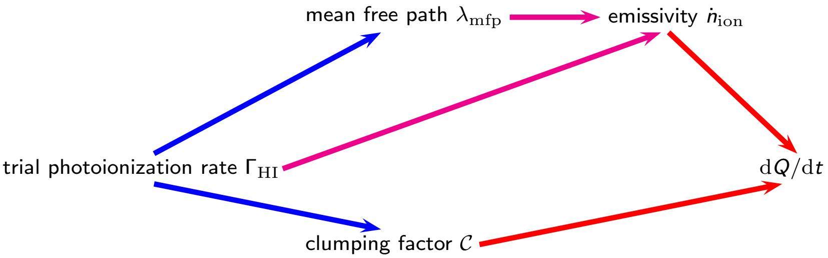
Alvarez, Pen & Chang (2010), Yajima & Li (2014), Ghara, **Choudhury** & Datta (2015)

Reionization: very late stages

- Final stages of reionization should match observations at $z \sim 6$ (quasar absorption spectra, Lyα emitters)
- Require modelling of the IGM physics
- Account for self-shielding $\Longrightarrow$ dynamic range problem
- **Question:** Is it possible to devise faster methods for generating high-dynamic range boxes?

Self-consistent reionization from simulations

Assume $Q(z)$ to be given. Choose a z:



ionization field, self-shielding

invert $\Gamma_{\mathrm{HI}} \propto \dot{n}_{\mathrm{ion}}\ \lambda_{\mathrm{mfp}}$

solve $\mathrm{d}Q/\mathrm{d}t = \dot{n}_{\mathrm{ion}}/n_H - \mathcal{C} n_H \alpha_{\mathrm{rec}}$

Questions

- How to follow the history of halo formation using sub-grid prescription?
- Should we develop our own radiative transfer simulation?
- Semi-numerical simulations for generating X-ray field and Lyα radiation field?
- Is it possible to devise faster methods for generating high-dynamic range boxes?

Questions

- How to follow the history of halo formation using sub-grid prescription?
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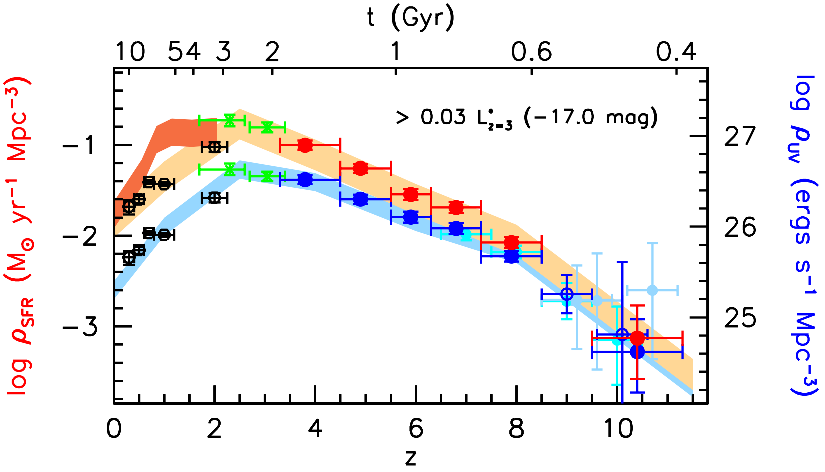
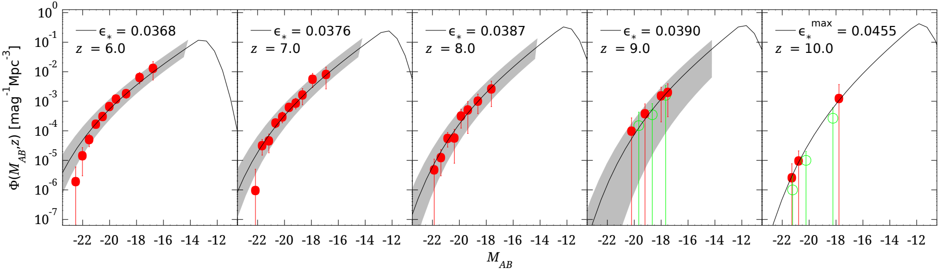
Thank you

UV luminosity function at $z > 6$



Galaxy luminosity function

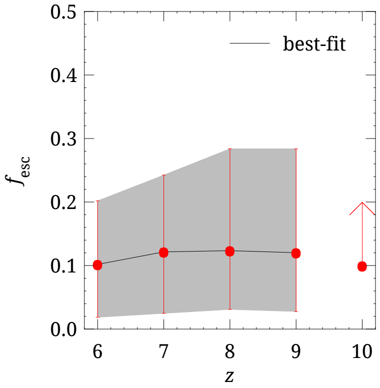
$N_{\rm ion} = f_{\rm esc}\, \epsilon_* \times$ number of photons per baryons in stars



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

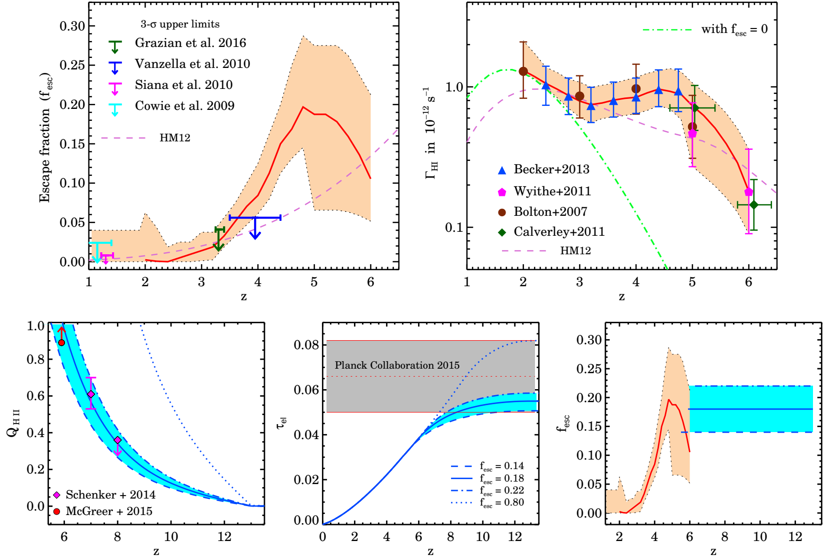
Constraints on $f_{\rm esc}$

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



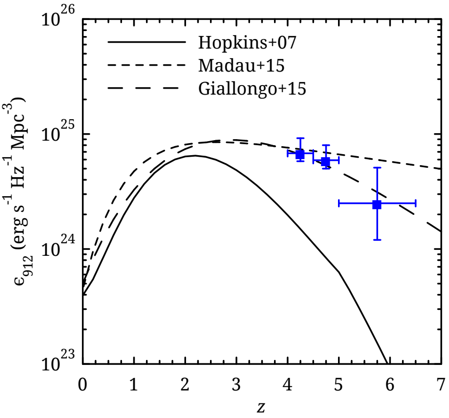
Mitra, **Choudhury** & Ferrara (2015)

f_{esc} at lower redshifts



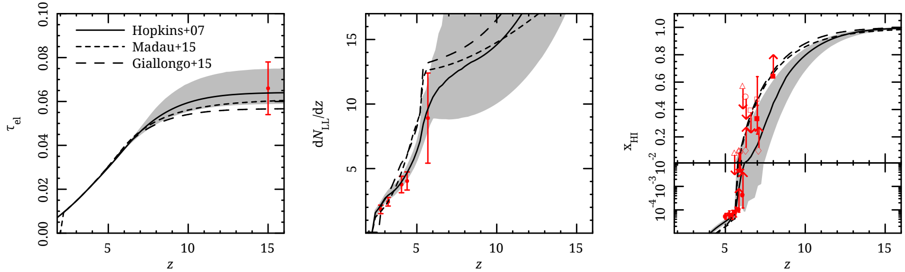
Khaire, Srianand, **Choudhury** & Gaikwad (2016)

Reionization driven by quasars?



- $\sim$ 22 faint quasar candidates detected through multi-wavelength observations Giallongo et al (2015)
- leads to higher number of ionizing photons contributed by quasars

Constraints on the galaxy contribution



Parameters	best-fit with 2-σ errors		
	H07	MH15	G15
$\epsilon_{II} \times 10^3$	$6.53^{+0.65}_{-0.98}$	< 0.04	$4.77^{+0.16}_{-0.34}$
f_{esc}	$\sim 0.16^{+0.016}_{-0.024}$	< 0.001	$0.12^{+0.004}_{-0.009}$
τ_{el}	$0.064^{+0.014}_{-0.005}$	$0.061^{+0.002}_{-0.001}$	$0.057^{+0.001}_{-0.001}$

- what about helium reionization?