Simulation of Cosmic Reionization: small things matter

Kyungjin Ahn
Chosun University
UCSD (visiting)
SKA Science Workshop, Jodrell Bank
Mar 2013
(Some of) Observational constraints on Reionization

• When reionization completed (from high- z QSO spectra)
  – GP effect: \( z_{ov} \sim 6.5 \) ??? (only lower limit to neutral fraction at \( z>6.5 \))
  – \( z=7 \) objects: QSO(Mortlock et al. 2011), LAE in LBGs(Pentericci et al. 2011), LAEs(Ota et al. 2010) → all indicating neutral fraction > 10% at \( z=7 \) !!!!!!! (Bolton, Haehnelt 2013)

• Reionization history
  – kinetic Sunyaev- Zeldovich effect on CMB
  – SPT: \( z(x=99\%) - z(x=20\%) \sim 4.4 - 7.9 \) (2\( \sigma \) level, Zahn+ 2011) ← debunked? (Park, Komatsu, Shapiro, Iliev, KA & Mellema 2013)

• Electron content, in terms of Thomson scattering optical depth of CMB
  – \( \tau = 0.089 \pm 0.014 \) (WMAP9, 1\( \sigma \) level)
  – \( \tau = 0.089 +0.012- 0.014 \) (Planck+WMAP pol, 1\( \sigma \) level)
Simulation Requirement: Box size & resolution

- **Statistics**
  - H II bubble ~ 20 Mpc (typical), with outliers
  - Box >~ 100 Mpc (~ 40 arcmin) minimum
  - Box >~ 1 Gpc for large-bubble outliers (i<~ 60)
  - Cons: numerical resolution

- **Resolving sources**
  - atomic-cooing halos (ACH): M >~ $10^8 \, M_\odot$ ($T_{\text{vir}}$>~ 10$^4$ K)
  - minihalos (MH): ~ $10^4$-$5 \, M_\odot$ < M <~ $10^8 \, M_\odot$ ($T_{\text{vir}}$<~ 10$^4$ K)
  - ACH: e.g. Box ~ 160 Mpc, $N_{\text{particle}}$ ~ 3000$^3$, $M_{\text{min}}$ ~ $10^8 \, M_\odot$
  - MH: e.g. Box ~ 16 Mpc, $N_{\text{particle}}$ ~ 3000$^3$, $M_{\text{min}}$ ~ $10^5 \, M_\odot$
  - MHs host Pop III stars (Norman, Wise, Yoshida, Bromm, Abel, ...), and most abundant halo type.
Simulation Requirement: Box size & resolution

• Initial Condition
  – Baryon – Dark matter offset (Tseliakhovich & Hirata 2010)
  – baryon velocity (w.r.t. DM) coherent over $>\sim 10$ Mpc
  – for statistics: Box $>\sim 10$ Mpc, but larger (large- k small- k coupled; e.g. Visbal et al. 2012; McQuinn, O’Leary 2012)
  – for physics: Box $<\sim 1$ Mpc (e.g. Stacey, Bromm, Loeb 2011; Greif, White, Klessen, Springel 2011)

• Observation ($z_{ov}$, $\tau$, ...)
  – tune e.g. emissivity
  – carry grain of salt
Other physics at cosmological scales (length, time)
  – X-ray: $\text{Flux} \sim 1/r^2$, zone of influence $<~ 1 \text{ Gpc}$ (more?)
  – Lyman-Werner: $\text{Flux} \sim f_{\text{mod}} \times 1/r^2$, zone of influence $<~ 100 \text{ Mpc}$ (KA, Shapiro, Iliev, Mellema, Pen 2009)
  – non-Gaussianity: halo & ionization bias at $\sim 1-10 \text{ Gpc}$ (small- $k$ large- $k$ coupling; Joudaki et al. 2011)
  – light-cone effect: cosmological length scale $\rightarrow$ delayed time impact (KA et al. 2009); delayed time observation (Datta+ 2012)

What-to-do
  – brute-force full-dynamic-range simulation: impossible
  – implementation of small-scale ($<~ \text{ Mpc}$) physics on large-scale ($>~ 100 \text{ Mpc}$) simulation, with correct initial condition
  – subgrid treatment

Simulation Requirement: Box size & resolution
Simulation Method 1: full radiative transfer

• pros
  – most natural (causal): ray-tracing
  – N-body + radiation + chemistry (+ hydro)
  – suited for EoR study (nonlinear & directional physics)
  – solves for “partial” ionization fraction $x_e = 0 \sim 1(1.08, 1.16)$

• cons
  – numerical resolution limited
  – expensive
  – slow
Simulation Method 2: semi-numerical (Furlanetto)

• pros
  – fast
  – suited for parameter search (e.g. Zahn+ 2012)

• cons
  – still numerical resolution limited
  – no partial ionization treated
  – some discrepancy (from ray- tracing ones) in small scales
Reading simulation results with grain of salt

• resolution, resolution
  – any missing clumps?
  – correct clumping factor?
  – correct coupling coefficients? (e.g. Lya transfer)
  – keep open-minded, (try to) exhaust models
21cm-Calculation Requirement: box-size, resolution, etc.

- for 21cm prediction, post-processing only
  - Halo-scale Lya line transfer
  - Large-scale Lya line transfer: Flux~ $1/r^{2.3}$, zone of influence $<\sim 200$ Mpc (Pritchard, Furlanetto 2006; Semelin, Combes, Baek 2007; Vonlanthen, Semelin, Baek, Revaz 2011; ...)
  - Halo-scale density & temperature modulation (Shapiro, KA, Alvarez, Iliev, Martel, Ryu 2006; ...)
  - Cosmic-scale density & temperature modulation (Bharadwaz, Ali 2004; McQuinn, O’Leary 2012; ...)

- What-to-do
  - 3D Lya line transfer (see Benoit’s talk)
  - Do not miss small-scale ($<\sim$ Mpc) contribution on large-scale ($>\sim 100$ Mpc) simulation
  - calculate in observing frame (velocity)
  - CHORES (for SKA): 21cm power spectrum, 21cm PDF, topology, $\mu$-decomposition, “halo-stacking” (Semelin), ...
Subgrid-treated/large-box simulation (with minihalos)

- MH- included simulation (KA, Iliev, Shapiro, Mellema, Koda, Mao 2012)
  - 114/h Mpc box
  - N\textsubscript{particle} \sim 3000^3
  - N- body halo resolution: 10^8 M\odot
  - subgrid: minihalos (one 100-300 M\odot Pop III star/minihalo, M\geq 10^5 M\odot)
  - LW feedback \(J_{\text{LW,th}}=0.01-0.1 \times 10^{-21} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\)
  - dynamical feedback (only newly formed halos every 2Myrs active)

- large- scale physics
  - H II bubble size
  - LW feedback
  - not \sim Gpc simulation yet, no non- gaussianity, no X- ray, no hydro

- observation
  - Late reionization (z_{\text{ov}}<7) & high \(\tau\) conditions: hard to match simultaneously
  - hard w/ observed high- z luminosity function
  - hard in numerical simulations (Iliev et al.; Zahn et al.; Trac & Cen; ...)

- (one of) simple answer: minihalos
  - hints from semi- analytical studies by Haiman & Bryan (over- boosting \(\tau\)); Wyithe & Cen; ...
  - inhomogeneous LW feedback treated too crudely (e.g. homogeneous feedback) in semi- analytical studies \rightarrow still need simulation
What’s new?

- **Populating grid with minihalos (first stars!)**
  - small-box (6.3/h Mpc) simulation resolving minihalos
  - correlation between density & minihalo population (nonlinear bias: KA et al. in preparation)
  - put one Pop III star per newly-born minihalo

- **Considering photo-dissociation of coolant, H\textsubscript{2}**
  - calculate transfer of Lyman-Werner Background (KA, Shapiro, Iliev, Mellema, Pen 2009; related to Semelin’s)
  - remove first star from minihalos, if LW intensity over-critical
What’s new?

- Populating grid with minihalos (first stars!)
  - small-box (6.3/h Mpc) simulation resolving minihalos
  - correlation between density & minihalo population (nonlinear bias: KA et al. in preparation)
  - put one Pop III star per newly-born minihalo

- Considering photo-dissociation of coolant
  - calculate transfer of Lyman-Werner Background (KA, Shapiro, Iliev, Mellema, Pen 2009)
  - remove first star from minihalos, if LW intensity over-critical
How LW transfer done: Picket-Fence Modulation Factor (KA et al. 2009)

- Sources distributed inhomogeneously: Need to sum individual contribution
- One single source is observed as a picket-fence in spectrum
- Obtain pre-calculated “picket-fence modulation” factor and multiply it to $L/D_L^2$. This becomes mean intensity to be distributed among $H_2$ ro-vibrational lines.

  - Relative flux averaged over $E=[11.5 – 13.6]$ eV
  - multi-frequency phenomenon $\rightarrow$ single-frequency calculation with pre-calculated factor $\rightarrow$ Huge alleviation computationally.
114/h Mpc, w/ Minihalo+ACH, M(Pop III star)=300\(M_\odot\), \(J_{\text{LW,th}}=0.1\times10^{-21}\) erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)
With and without minihalos (KA et al. 2012)
With and Without Minihalos

(A) Partial ionization

(B) Lyman-Werner band intensity

(C) L2M1 and L2 (no minihalos)
Storyline

• Minihalos ($<\sim 10^8 M_\odot$)
  – starts reionization
  – very extended reionization history
  – 20% ionization, boost in optical depth by $\sim$ 40% possible

• Massive halos ($>\sim 10^8 M_\odot$)
  – determines when reionization is completed

• Late- reionization- completion prior ($z<\sim 7$)
  – small emissivity in massive halo sources required
  – not large enough optical depth ONLY with massive halo sources

• Early reionization models
  – large optical depth possible only with massive halo sources
  – reionization completes too early ($z>\sim 8$), violating observational constraint

• Late reionization, large optical depth: both can be achieved only with help of minihalo sources, or namely the first stars

Puzzle solvable
Early vs. Late Reionization Models
No-minihalo vs. Minihalo Models
Question: hypothesis-testing at what confidence level?

• COSMOMC (Lewis, Briddle)
  – Aimed at CMB / matter power spectrum (linked with CAMB, also at Antony’s shop at http://cosmologist.info)
  – Does it all
  – Can be tailored for generic application
  – Can be tailored for your custom universe
  – Publicly available
  – Parallelized

• COSMOMC allowing for generic ionization histories (Mortonson & Hu)
  – Principal component analysis

\[ x_e(z) = x_{e,\text{fid}}(z) + \sum_{\mu=1}^{N_{\text{max}}} m_\mu S_\mu(z) \]
Planck Forecast

\[
\frac{Z_{ov} < 7}{(\text{Common})} \quad \text{high-} \, T \quad \text{vs.} \quad \text{low-} \, T
\]

(\text{w/ minihalo}) \quad (\text{w/ first star})

(\text{w/ minihalo}) \quad (\text{w/ first star})

Hu & Holder; Motonson & Hu: PCA for reionization
Planck Forecast ($z_{ov}$ constraint makes contours small)

$\frac{z}{z_{\text{common}}} \sim 0.085$

$z_{ov} < 7$

$\omega_l$ first star vs. $\omega_l$ first star (black) vs. $\omega_l$ first star (red, blue, cyan)
what I did (literally) until yesterday
– get IGM temperature (adiabatic)
– do Lya transfer (with retarded time; convolving Pritchard’s compilation with source luminosity)
– get $\delta T_b$ (Lya coupling, kinetic coupling, $dr$, $dx$, $dT_K$, $dg$)
– just for $z=15$ (89MHz), not filtered yet, no $P(k)$ yet
– image resolution: 0.2’, 0.03 MHz
– image size: 51’
21cm forecast from minihalo-included simulation (z=15)

Lya, kinetic pumping

\[ \langle J_d \rangle = 3.9 \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \]
\[ \langle \chi_d \rangle = 4.23 \times 10^{-2} \]
\[ \delta T_b (\text{rms}) = 3 \text{ mK} \]
\[ \langle \delta T_b \rangle = -9.2 \text{ mK} \]
21cm forecast from minihalo-included simulation (z=15)

Assume $T_s \gg T_{CMB}$ (x-ray heating)
21cm forecast from minihalo-included simulation (z=15)

Assume $T_s \gg T_{CMB}$ (x-ray heating)
Assume all neutral
21cm forecast from minihalo-included simulation (z=15)

Lyα, kinetic pumping

WHY small $|ST_b|$?

$\langle X_\alpha \rangle = 4.23 \times 10^{-2}$

$\delta T_b (\text{rms}) = 3 \text{ mK}$

$\langle J_{LW} \rangle \sim 5 \times 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$

$\langle J_d \rangle \sim \langle J_{LW} \rangle$

$\ll 3.9 \times 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$

$\langle X_\alpha \rangle = \frac{\langle J_d \rangle}{1.2 \times 10^{-12} (1 + \frac{z}{20}) \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}}$

$\sim 4 \times 10^{-2}$
21cm forecast from minihalo-included simulation (z=15)

Lyα, kinetic pumping

WHY small $|S\Delta T_b|$?
\[ \Rightarrow \text{small } \langle X_\alpha \rangle \]
\[ \langle J_{\text{LW}} \rangle \sim 5 \times 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \]
\[ \langle J_d \rangle \sim \langle J_{\text{LW}} \rangle \]
\[ \ll 3.9 \times 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \]

\[ \langle X_\alpha \rangle = \frac{\langle J_d \rangle}{1.2 \times 10^{-11} \left( \frac{1+2}{2} \right) \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}} \]
\[ = 4 \times 10^{-2} \]

\[ \delta T_b(\text{rms}) = 3 \text{ mK} \]

$\langle X_\alpha \rangle = 4.23 \times 10^{-2}$

from Pop III star community

\[ \therefore \text{MH-domination } \rightarrow \text{ mild Lyα coupling} \]
Of course big-H II bubble easier to probe

Iliev, Mellema, Shapiro, Pen, Mao, Koda, KA 2012
Summary

- microphysics: MH (first stars) included simulation
  - $z \sim 7$ Lya + CMB observations matched
  - very extended $\Delta z \sim 6.5$, debunking SPT claim $\Delta z \sim 4$ (by Zahn+): Park,
  - Planck can smell the first stars! (polarization, 2014)
Summary

- microphysics: MH (first stars) included simulation
  - $z \sim 7$ Lya + CMB observations matched
  - very extended $\Delta z \sim 6.5$, debunking SPT claim $\Delta z \sim 4$ (by Zahn+): Park,
  - Planck can smell the first stars! (polarization, 2014)
- 21cm observation (prelim)
  - minihalo- dominated era ($30 \sim >z\sim 10$): if no X-ray, $\delta T_b \sim \text{mK}$, some $\sim 10\text{mK}$ peaks, absorption
  - minihalo- dominated era ($30 \sim >z\sim 10$): if X-ray, $\delta T_b \sim 10\text{mK}$, emission

![Graph showing frequency and brightness over cosmic time.](image)
Summary

• microphysics: MH (first stars) included simulation
  – z~ 7 Lya + CMB observations matched
  – very extended Δz~ 6.5, debunking SPT claim Δz~ 4 (by Zahn+): Park,
  – Planck can smell the first stars! (polarization, 2014)
• 21cm observation (prelim)
  – minihalo- dominated era (30~ >z>~ 10): if no X-ray, δT_b~ mK, some ~10mK peaks, absorption
  – minihalo- dominated era (30~ >z>~ 10): if X-ray, δT_b~ 10mK, emission
Summary

microphysics: MH (first stars) included simulation
- $z \approx 7$ Lya + CMB observations matched
- very extended $\Delta z \approx 6.5$, debunking SPT claim $D_{l=3000, kSZ=}$ or $\Delta z < 4$ (by Zahn+): Park+2013 (fuzzy partial ionization field)
- Planck can smell the first stars! (polarization, 2014)

• 21cm observation (prelim)
  - minihalo- dominated era ($30 \gg z > 10$): if no X- ray, $\delta T_b \sim mK$, some $\sim 10 mK$ peaks, absorption
  - minihalo- dominated era ($30 \gg z > 10$): if X- ray, $\delta T_b \sim 10 mK$, emission
  - hard to get strong Lya coupling to generate $\sim 100$ mK signal
  - needs strong Lya coupling to generate $\sim 100$ mK signal $\rightarrow$ atomic- cooling halos “but” low $f_{esc}$ for ionizing photons
  - will try different frequencies, so stay tuned

• Needed habit for reading simulation
  - resolution, microphysics (e.g. halo mass resolution)
  - capability for partial ionization for big box (not yet for semi-numerical ones: e.g. 21CMFAST, reionFAST; 21CMFAST starting to do partial ionization)