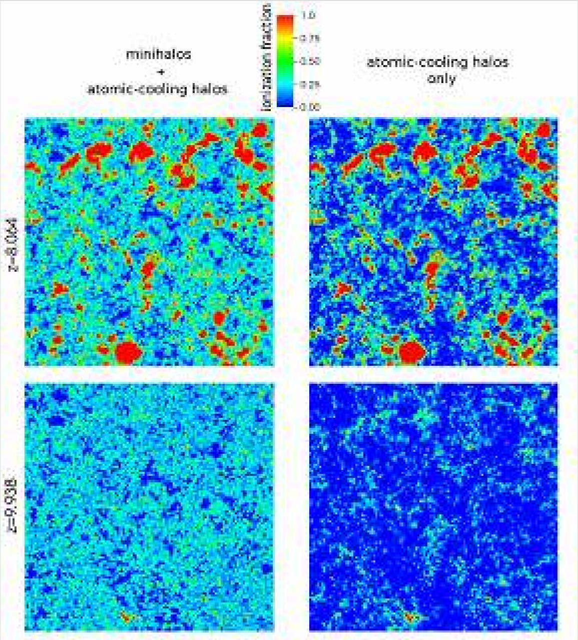
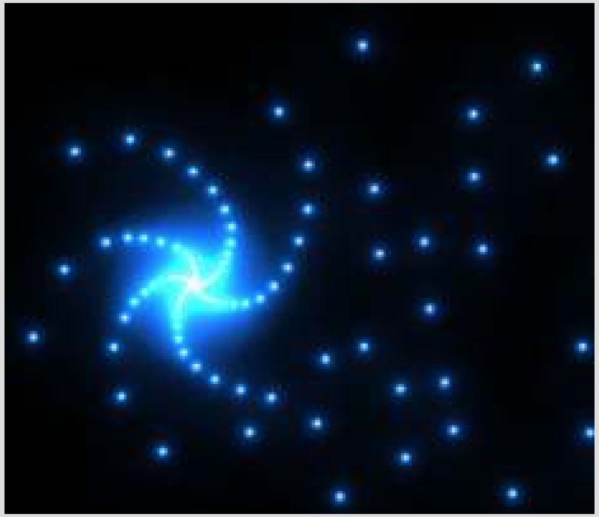
Simulation of Cosmic Reionization: small things matter





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SKA Science Workshop, Jodrell Bank

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(Some of) Observational constraints on Reionization

- When reionization completed (from high- z QSO spectra)
  - GP effect: z_{ov} ~ 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%) ~ 4.4 – 7.9 (2σ 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, 1σ level)
  - $\tau = 0.089 +0.012- 0.014$ (Planck+WMAP pol, 1σ 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 (ℓ <~ 60)
  - Cons: numerical resolution

- Resolving sources
  - atomic-cooing halos (ACH): $M \gtrsim 10^8\, M_\odot$ ($T_{vir} \gtrsim 10^4$ K)
  - minihalos (MH): $\sim 10^{4-5}\, M_\odot < M \lesssim 10^8\, M_\odot$ ($T_{vir} \lesssim 10^4$ K)
  - ACH: e.g. Box ~ 160 Mpc, $N_{particle} \sim 3000^3$, $M_{min} \sim 10^8\, M_\odot$
  - MH : e.g. Box ~ 16 Mpc, $N_{particle} \sim 3000^3$, $M_{min} \sim 10^5\, M_\odot$
  - 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 >~ Mpc
  - for statistics: Box >~ 10 Mpc, but larger (large- k small- k coupled; e.g. Visbal et al. 2012; McQuinn, O'Leary 2012)
  - for physics: Box <~ 1 Mpc (e.g. Stacey, Bromm, Loeb 2011; Greif, White, Klessen, Springel 2011)
- Observation (z_{ov}, τ, …)
  - tune e.g. emissivity
  - carry grain of salt

Simulation Requirement: Box size & resolution

- Other physics at cosmological scales (length, time)
  - X-ray: Flux~ $1/r^2$, zone of influence <~ 1 Gpc (more?)
  - Lyman-Werner: Flux~ $f_{mod} \times 1/r^2$, zone of influence <~ 100 Mpc (KA, Shapiro, Iliev, Mellema, Pen 2009)
  - non-Gaussianity: halo & ionization bias at ~ 1-10 Gpc (small-k large-k coupling; Joudaki et al. 2011)
  - light-cone effect: cosmological length scale → 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 (<~ Mpc) physics on large-scale (>~ 100 Mpc) simulation, with correct initial condition
  - subgrid treatment

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~ 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 <~ 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 (<~ Mpc) contribution on large-scale (>~ 100 Mpc) simulation
  - calculate in observing frame (velocity)
  - CHORES (for SKA): 21cm power spectrum, 21cm PDF, topology, μ-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
  - $N_{particle}$~ 3000^3
  - N-body halo resolution: 10^8 $M_\odot$
  - subgrid: minihalos (one 100-300 $M_\odot$ Pop III star/minihalo, M>=10^5 $M_\odot$)
  - LW feedback ($J_{LW,th}$=0.01-0.1x10^{-21} erg cm^{-2} s^{-1} sr^{-1})
  - dynamical feedback (only newly formed halos every 2Myrs active)

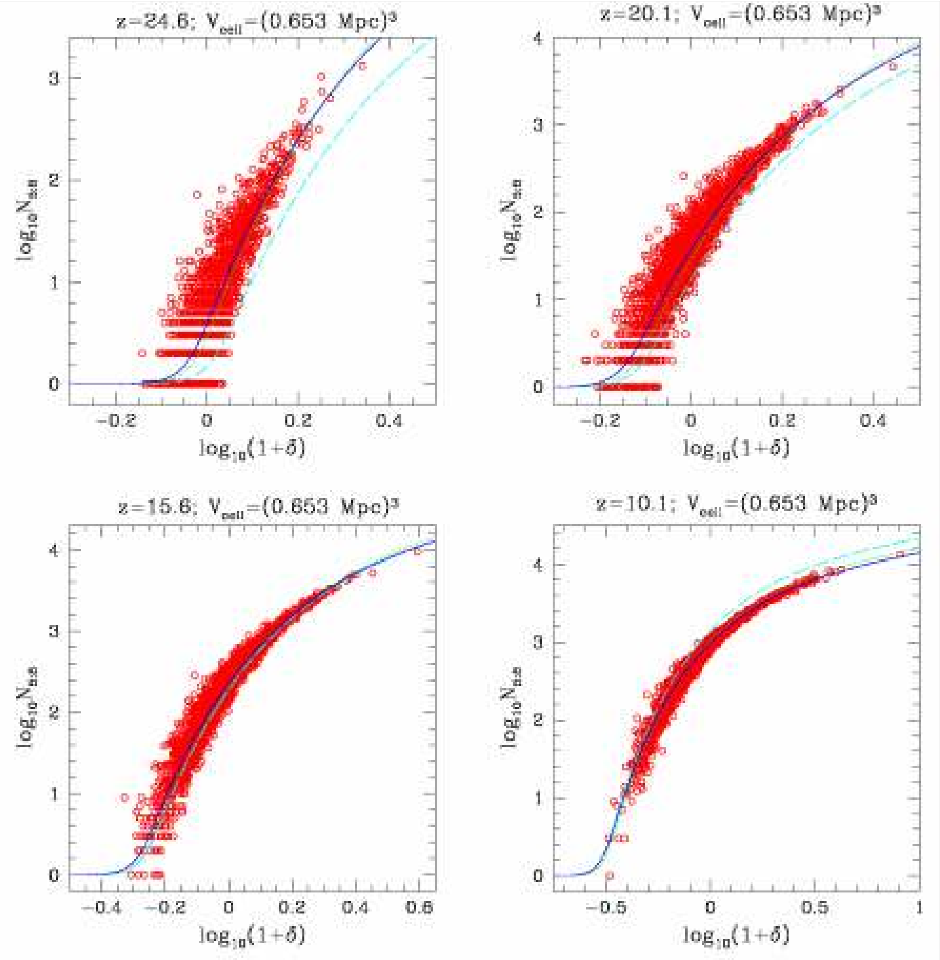
- large-scale physics
  - H II bubble size
  - LW feedback
  - not ~Gpc simulation yet, no non-gaussianity, no X-ray, no hydro

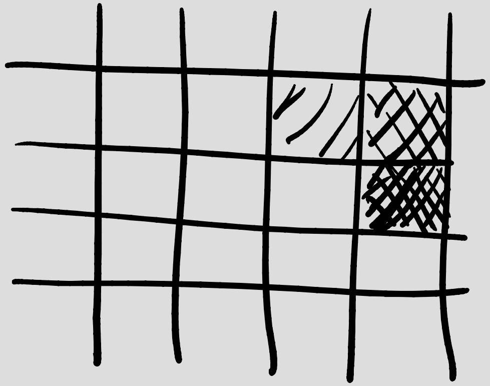
- observation
  - Late reionization(z_{ov}<7) & high τ conditions: hard to match simultaneously
  - hard w/ observed high-z luminosity function
  - hard in numerical simulations (Iliev et al.; Zahn et al.; Trac & Cen; …)

- (one of) simple answer: minihalos
  - hints from semi-analytical studies by Haiman & Bryan (over-boosting τ); Wyithe & Cen; …
  - inhomogeneous LW feedback treated too crudely (e.g. homogeneous feedback) in semi-analytical studies → 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_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





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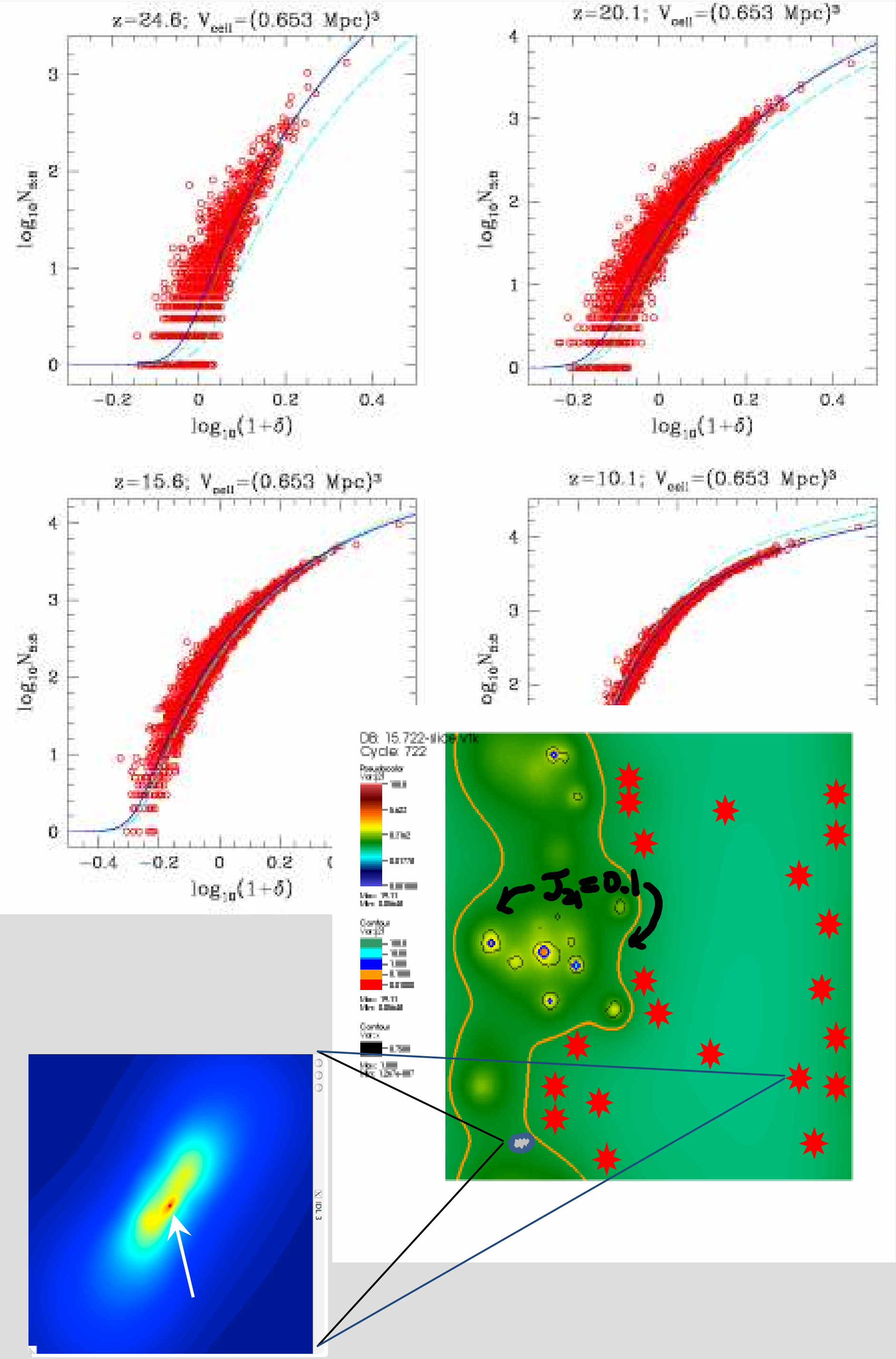
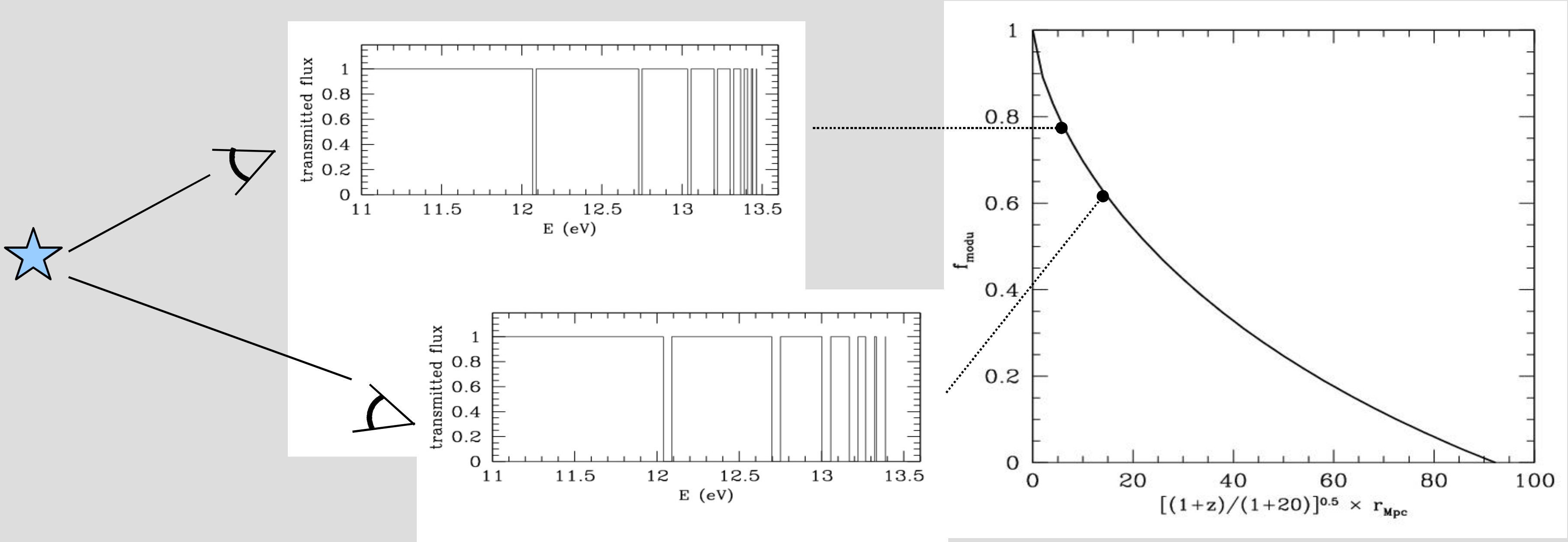
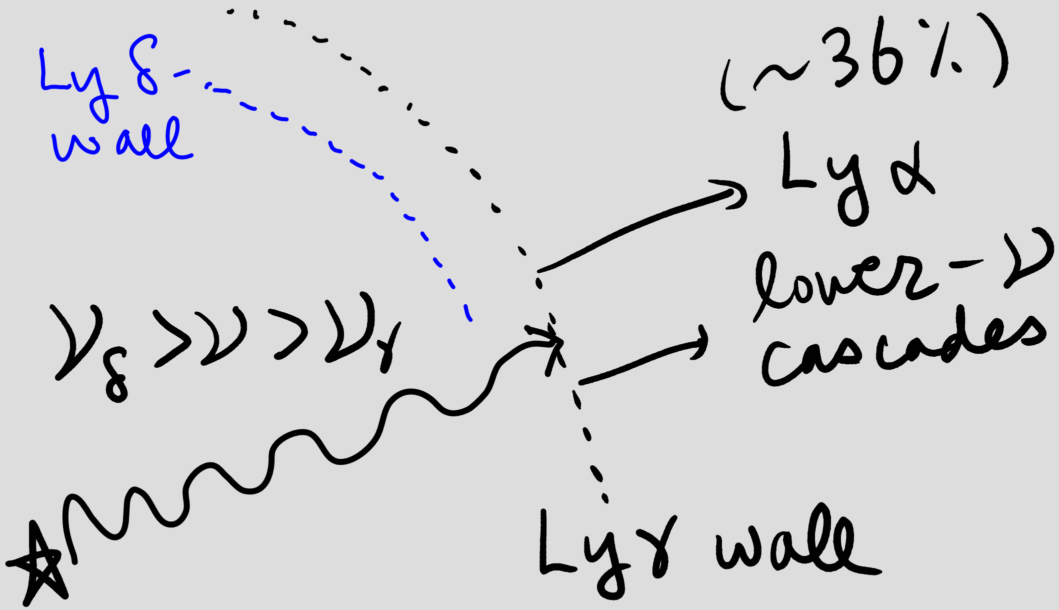


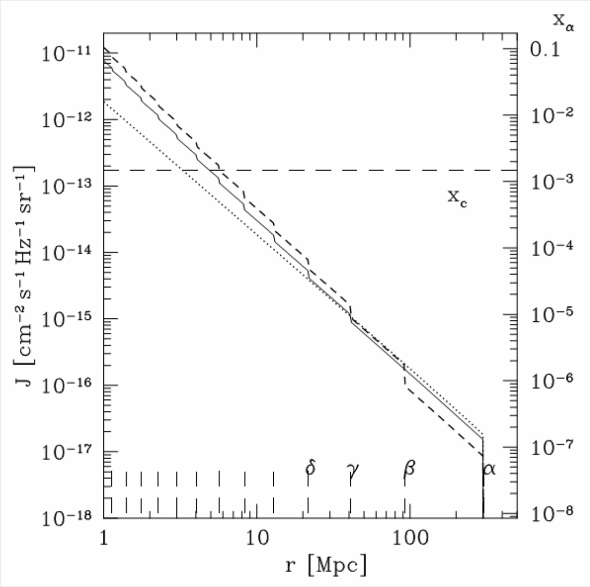
How LW transfer done: Picket-Fence Modulation Factor (KA et al. 2009)

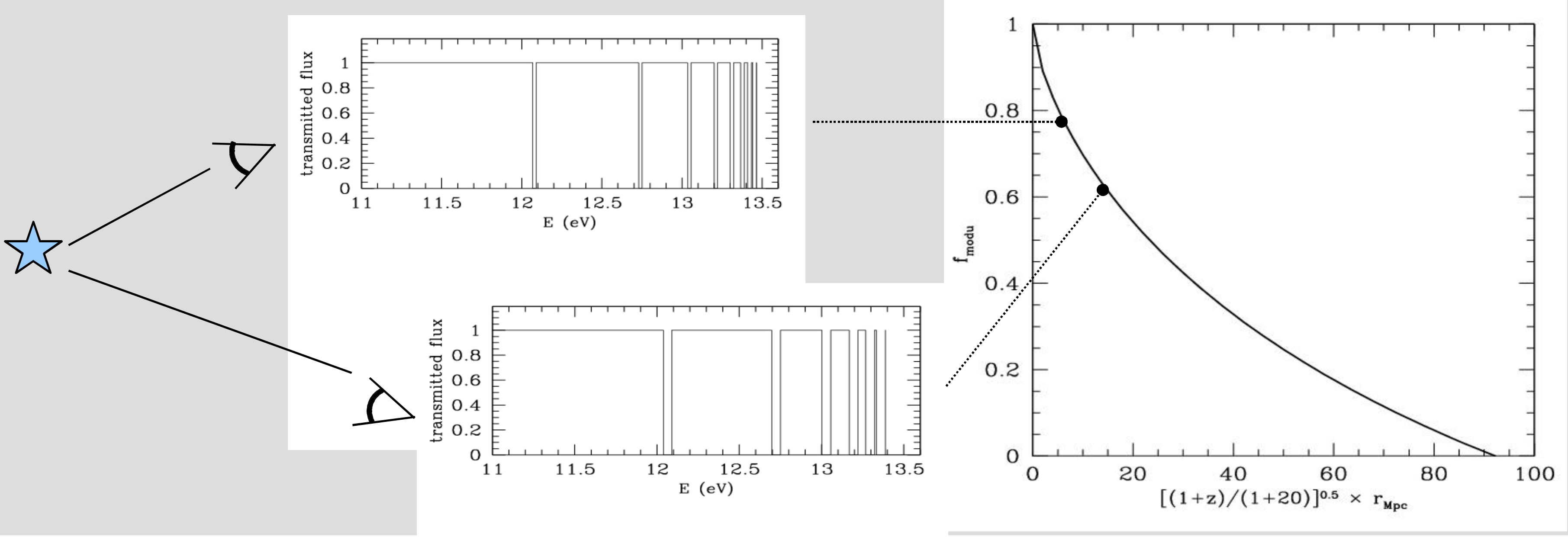
- Sources distributed inhomogeneously: Need to sum individual contribution
- One single source is observed as a picket-fence in spectrum
- Obtain pre-calculated “picket-fence modulation” factor and multiply it to L/D_L^2. This becomes mean intensity to be distributed among H_2 ro-vibrational lines.
  - Relative flux averaged over E=[11.5 – 13.6] eV
  - multi-frequency phenomenon → single-frequency calculation with pre-calculated factor → Huge alleviation computationally.



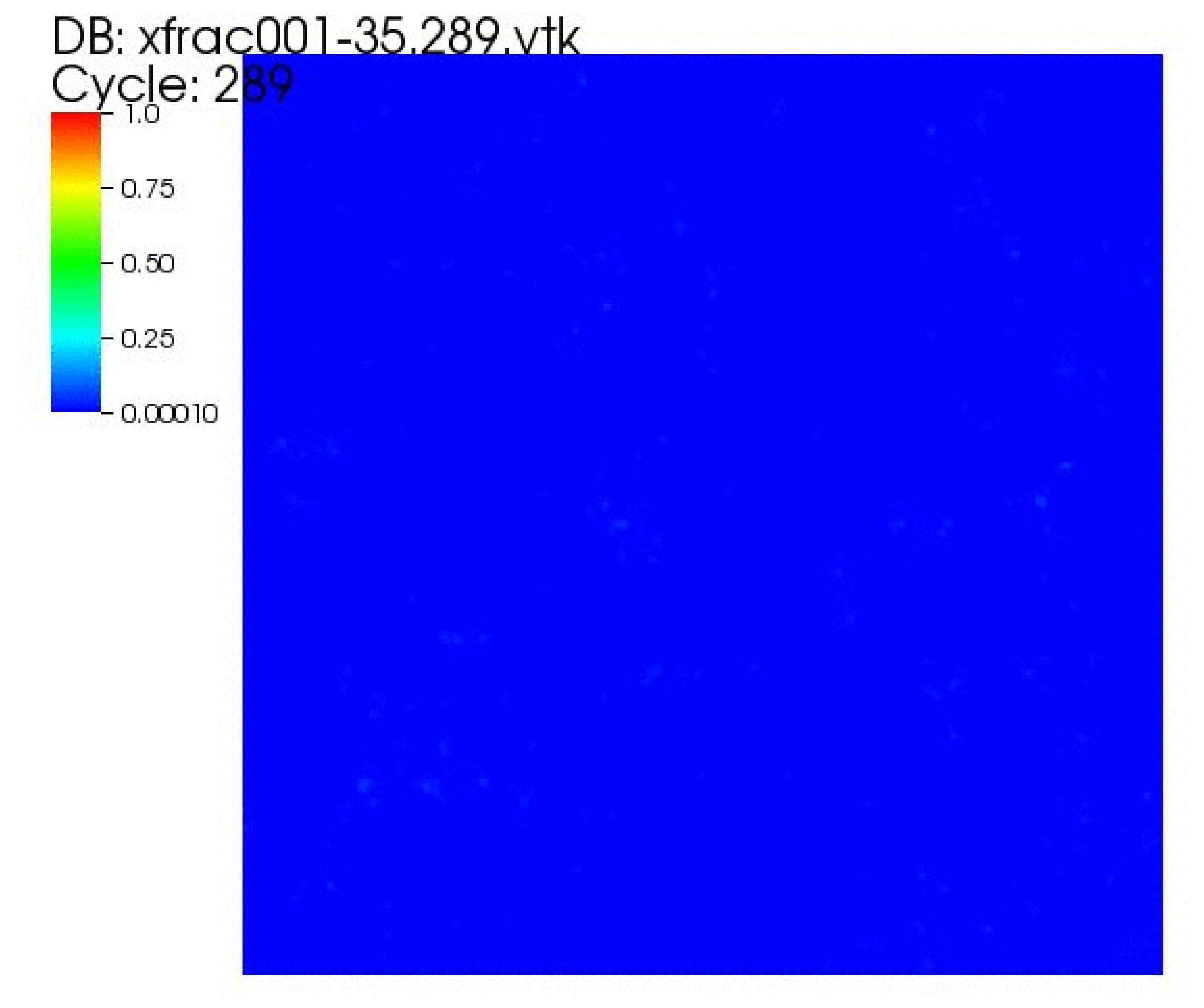
How LW transfer done: Picket-Fence Modulation Factor (KA et al. 2009) ~ Pritchard & Furlanetto (2006)



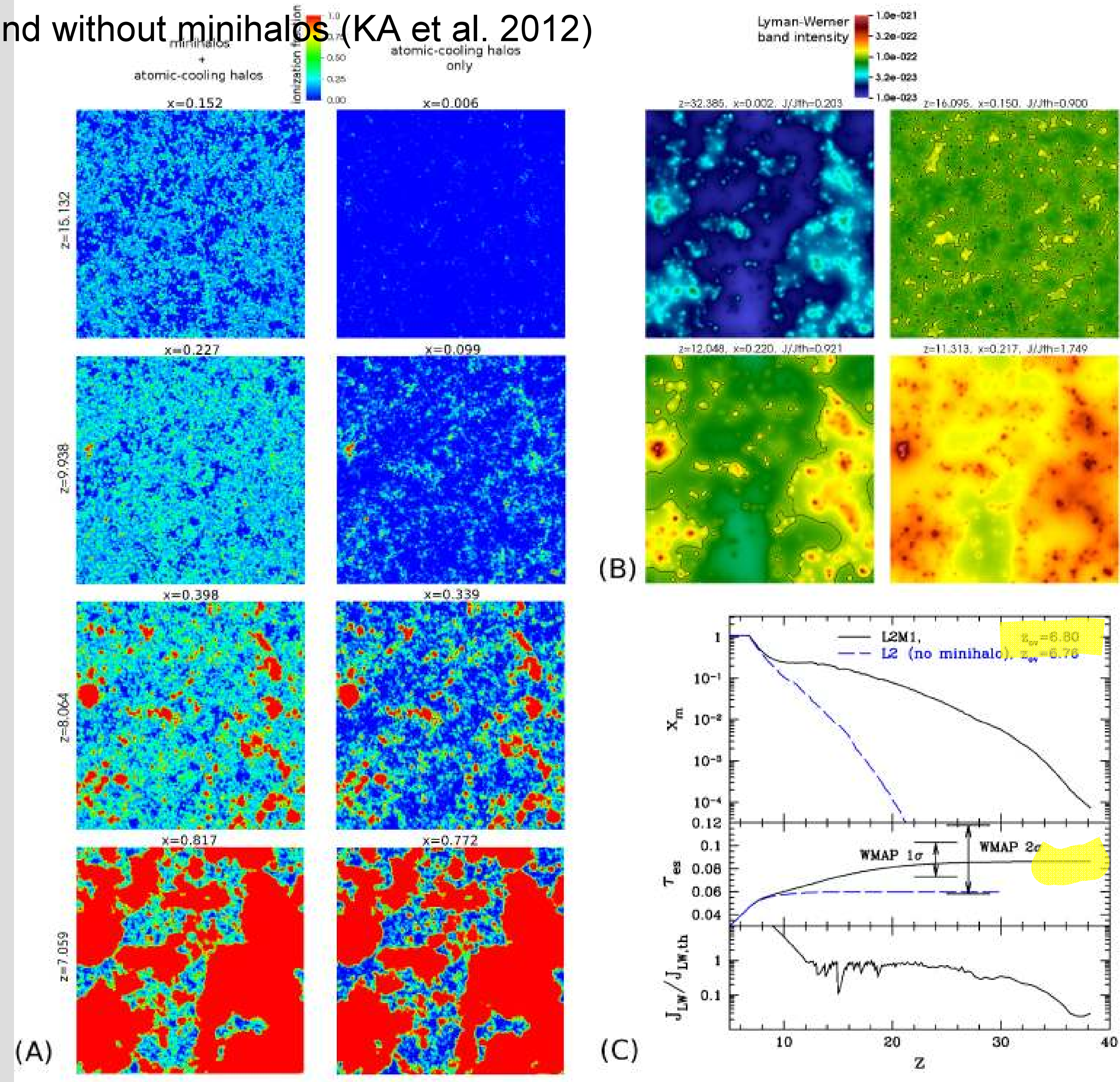




114/h Mpc, w/ Minihalo+ACH, M(Pop III star)=300$M_\odot$, $J_{LW,th}$=0.1x10^{-21} erg cm^{-2} s^{-1} sr^{-1}

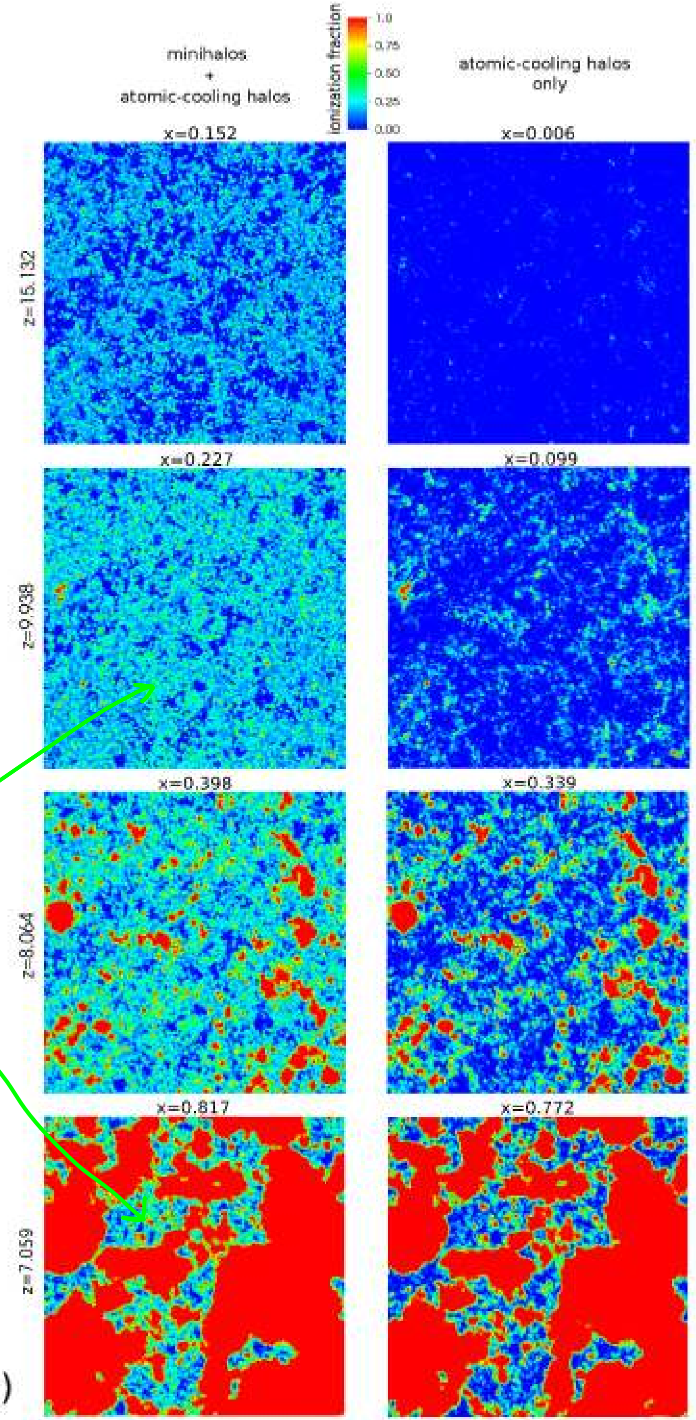


With and without minihalos (KA et al. 2012)

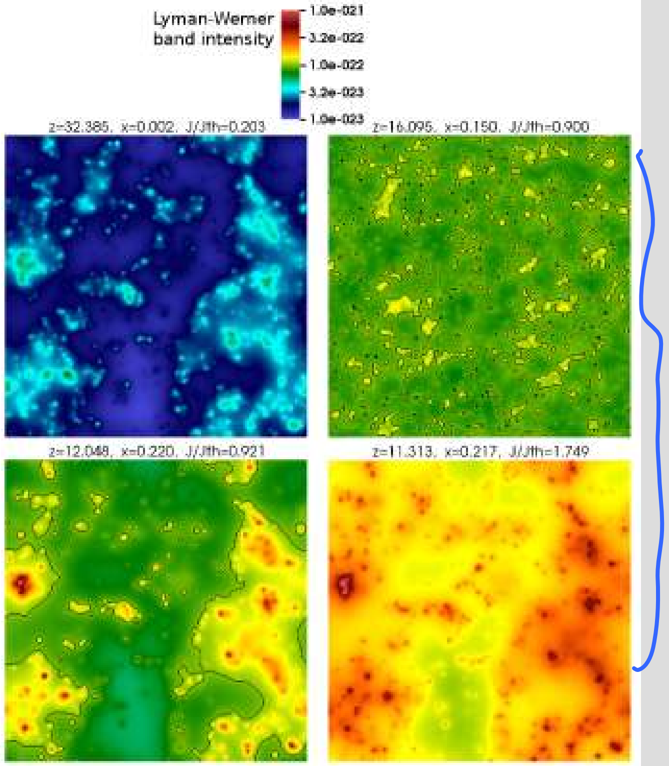


not shown in paper

With and Without Minihalos

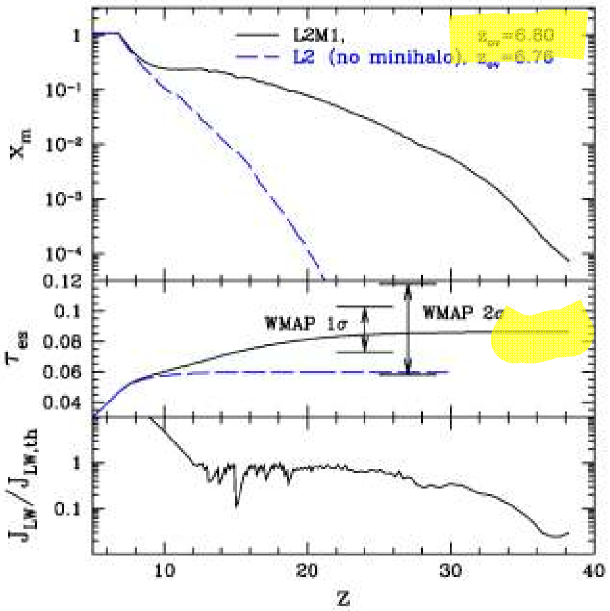


(A)



(B)

not shown in paper



(C)

partial ionization

Storyline

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

- Massive halos (>~ $10^8 M_\odot$)
  - determines when reionization is completed

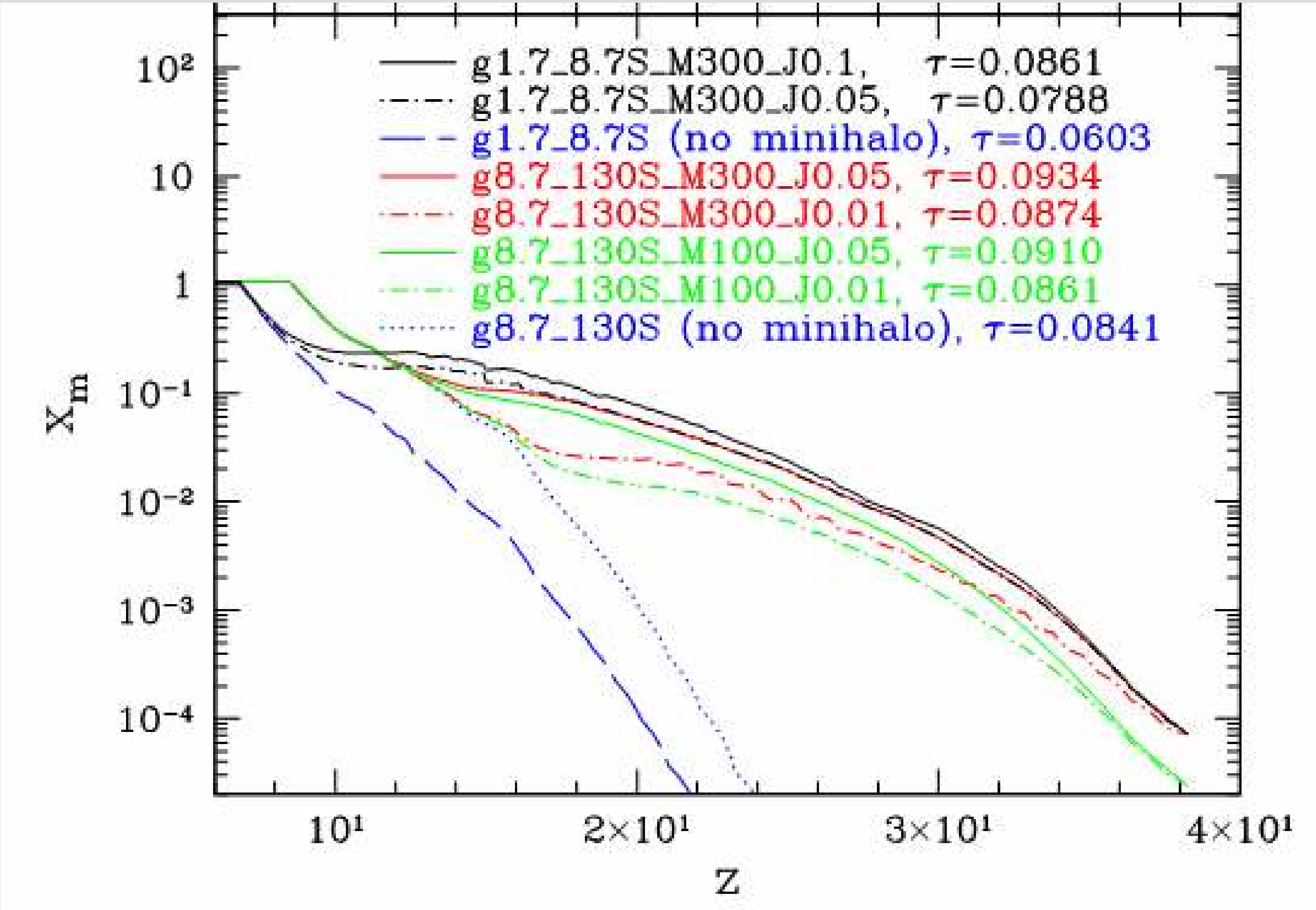
- Late- reionization- completion prior (z<~ 7)
  - small emissivity in massive halo sources required
  - not large enough optical depth ONLY with massive halo sources

- Early reionization models
  - large optical depth possible only with massive halo sources
  - reionization completes too early (z>~ 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?

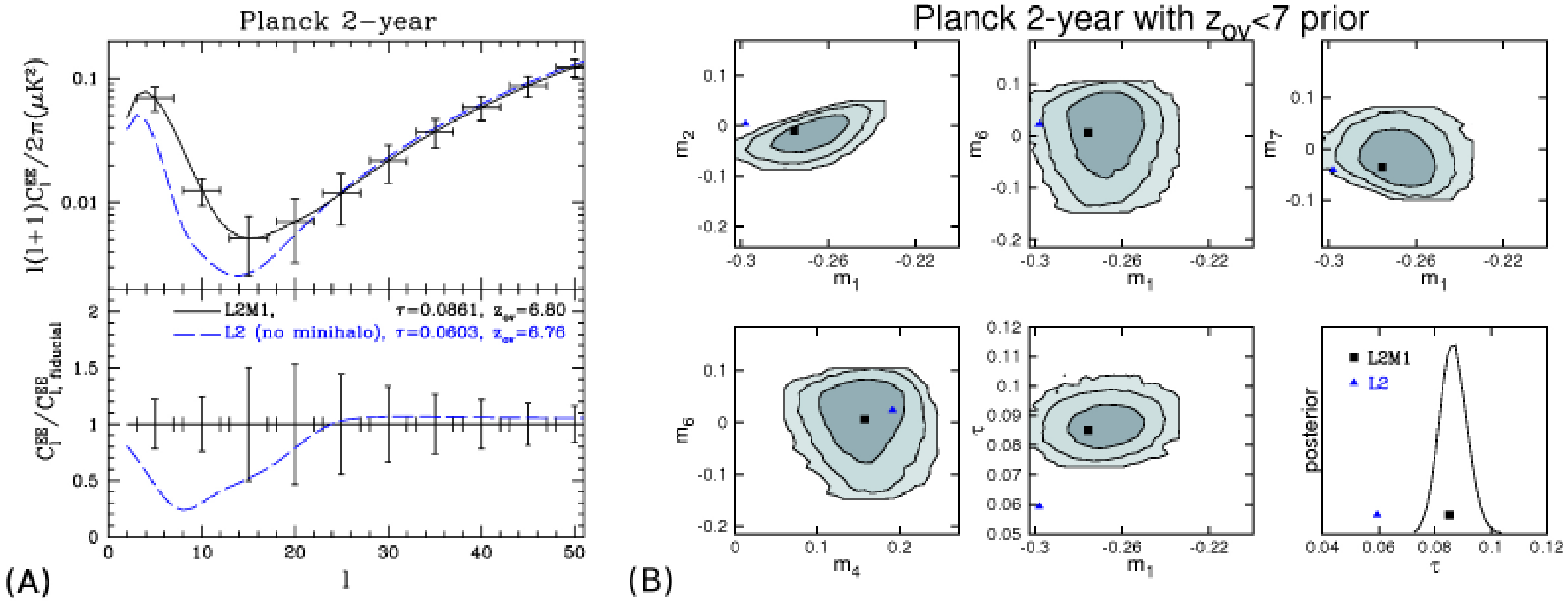
- COSMOMC (Lewis, Briddle)
  - Aimed at CMB / matter power spectrum (linked with CAMB, also at Antony's shop at http://cosmologist.info)
  - Does it all
  - Can be tailored for generic application
  - Can be tailored for your custom universe
  - Publicly available
  - Parallelized
- COSMOMC allowing for generic ionization histories (Mortonson & Hu)
  - Principal component analysis

$$x_\epsilon(z) = \underbrace{x_{\epsilon,\,\mathrm{fid}}(z)}_{\text{model-independent}} + \sum_{\mu=1}^{N_{\max}} \overset{\text{amplitude (model)}}{m_\mu} \underbrace{S_\mu(z)}_{\text{principal component (basis)}}$$

Planck Forecast

$z_{ov} < 7$,
(common)

high-τ vs. low-τ
(w/ minihalo) (wo/ minihalo)
(w/ first star) (wo/ first star)



Hu & Holder; Motonson & Hu: PCA for reionization

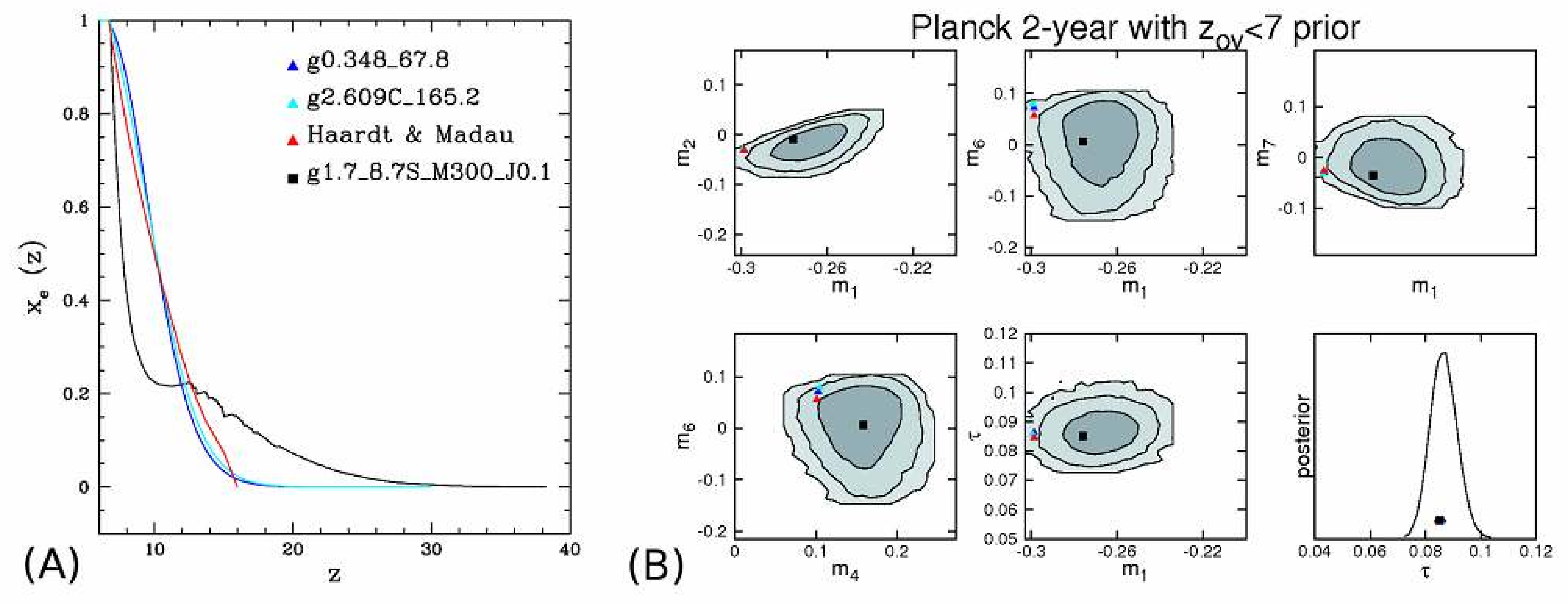
Planck Forecast (z_{ov} constraint makes contours small)

$\tau \sim 0.085$

common

$z_{ov} < 7$

w/ first star (black) vs. w/o first star (red, blue, cyan)

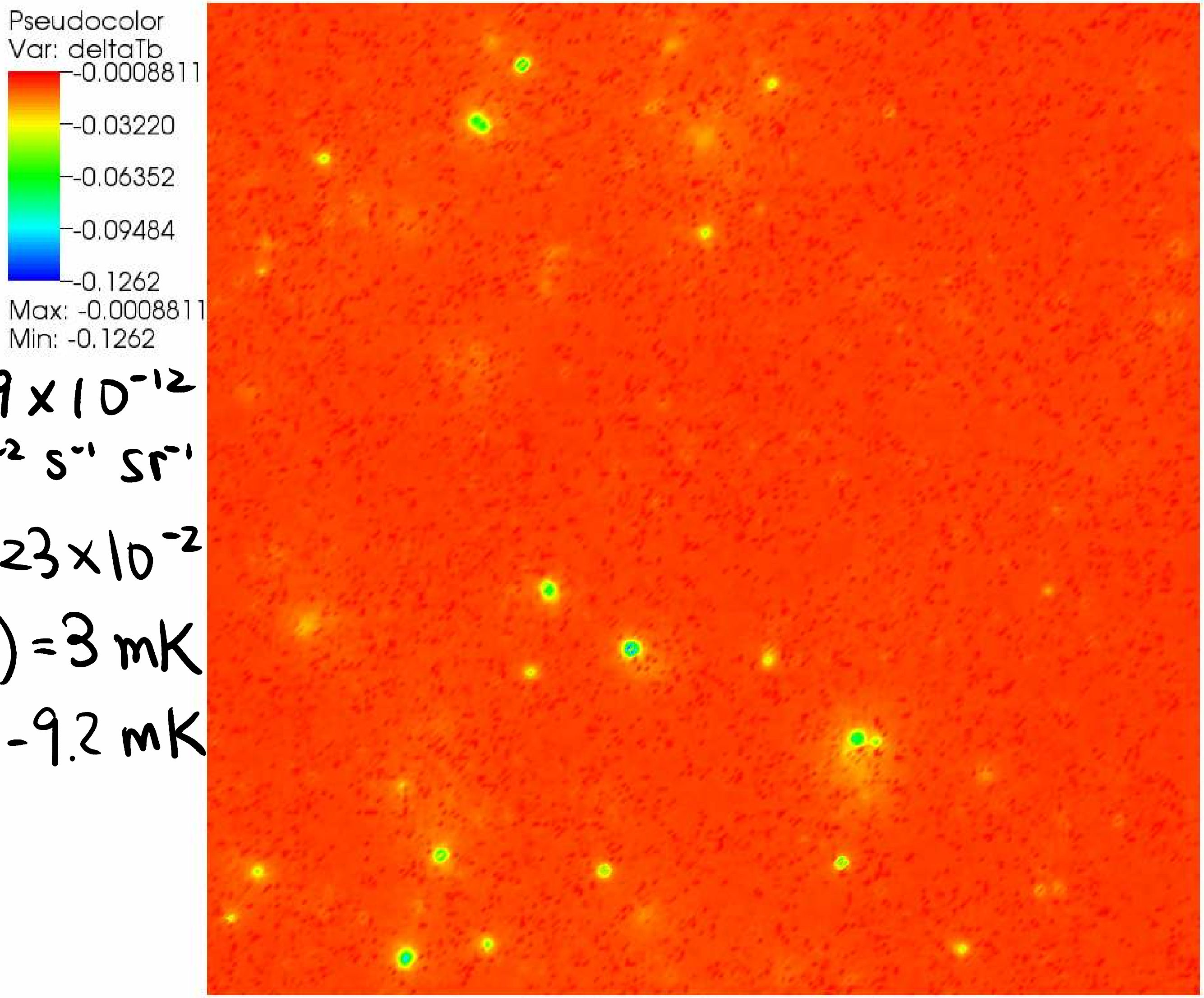


21cm forecast from minihalo-included simulation

- what I did (literally) until yesterday
  - get IGM temperature (adiabatic)
  - do Lya transfer (with retarded time; convolving Pritchard’s compilation with source luminosity)
  - get δT_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)

Lyα, kinetic pumping



$\langle J_\alpha \rangle = 3.9 \times 10^{-12}$ $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$

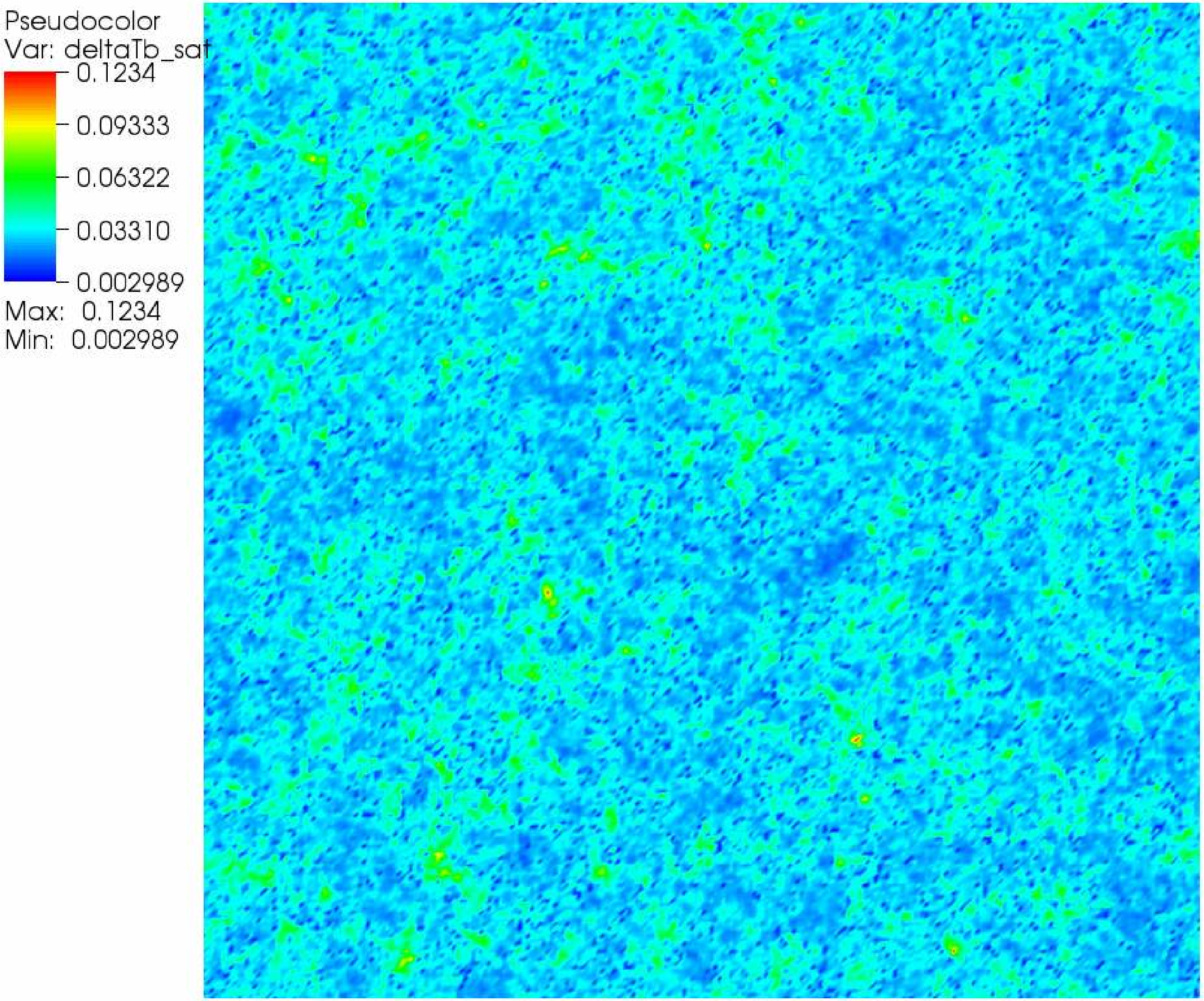
$\langle x_\alpha \rangle = 4.23 \times 10^{-2}$

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

$\langle \delta T_b \rangle = -9.2$ mK

21cm forecast from minihalo-included simulation (z=15)

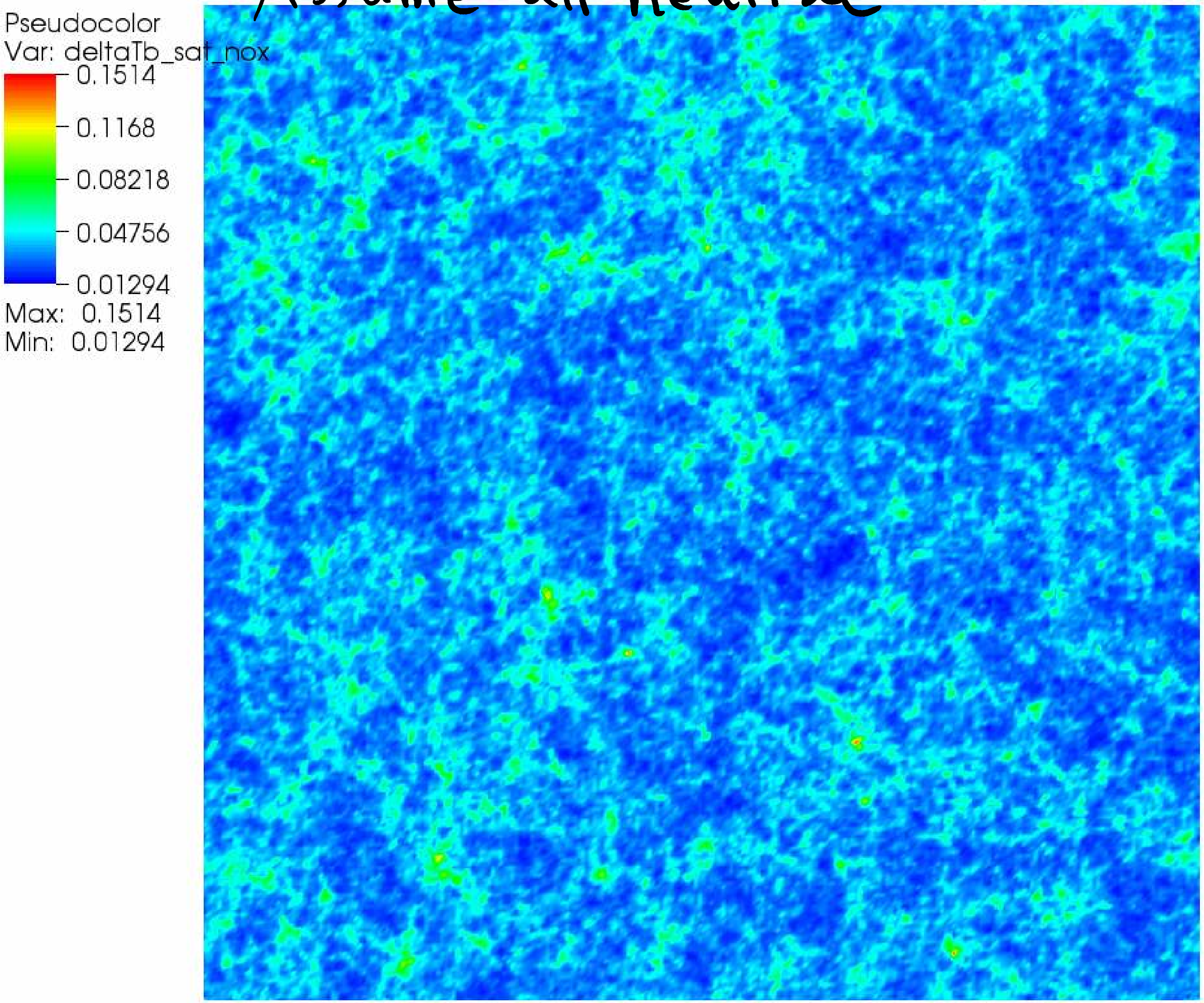
Assume $T_S \gg T_{CMB}$ (X-ray heating)



21cm forecast from minihalo-included simulation (z=15)

Assume $T_s \gg T_{CMB}$ (X-ray heating)

Assume all neutral



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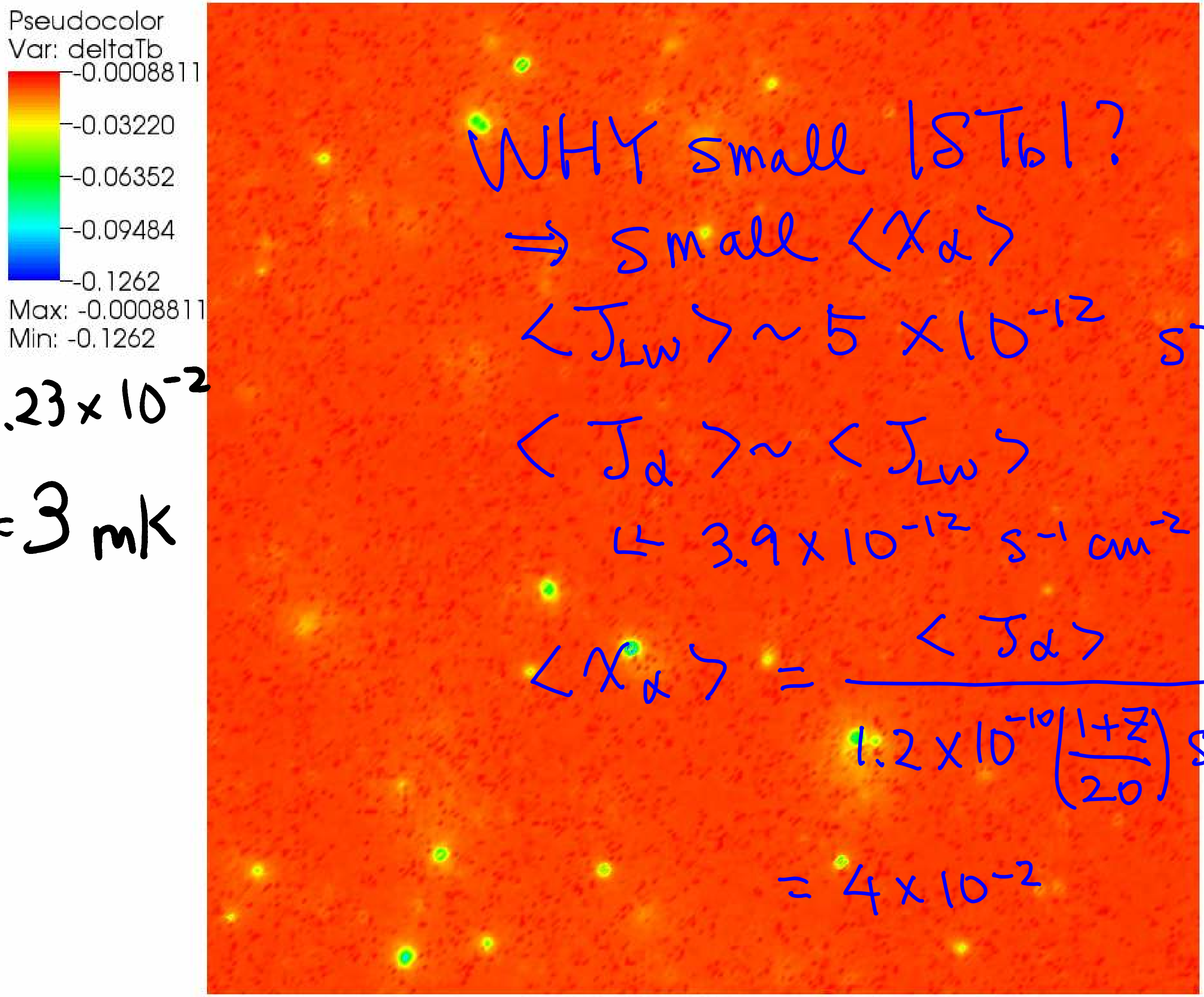


$\langle x_\alpha \rangle = 4.23 \times 10^{-2}$

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

WHY small $|\delta T_b|$?

$\Rightarrow$ small $\langle x_\alpha \rangle$

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

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

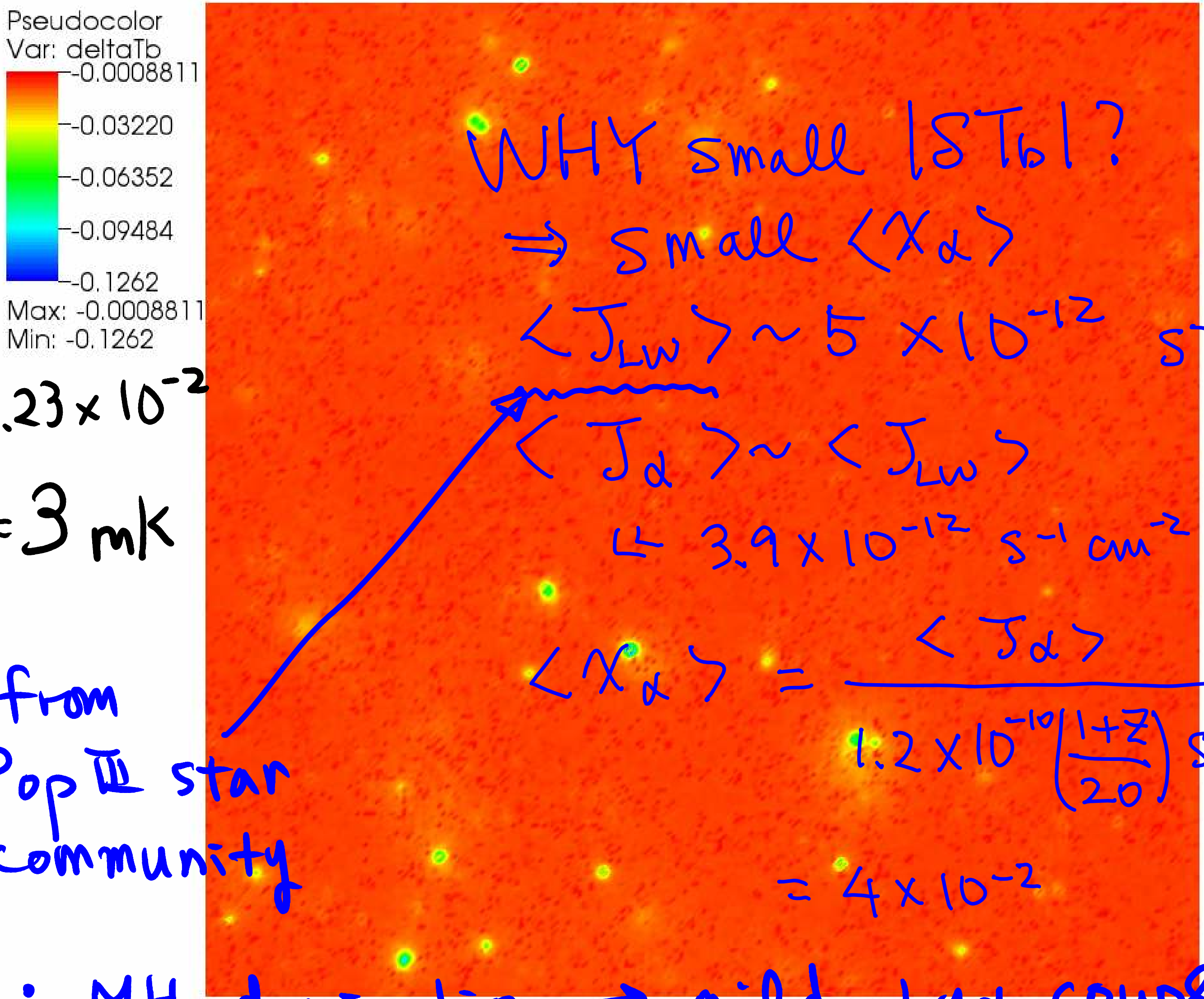
$\Leftarrow 3.9 \times 10^{-12}\ s^{-1}\,cm^{-2}\,sr^{-1}$

$$\langle x_\alpha \rangle = \frac{\langle J_\alpha \rangle}{1.2 \times 10^{-10}\left(\frac{1+z}{20}\right) s^{-1}\,cm^{-2}\,sr^{-1}}$$

$= 4 \times 10^{-2}$

21cm forecast from minihalo-included simulation (z=15)

Lyα, kinetic pumping



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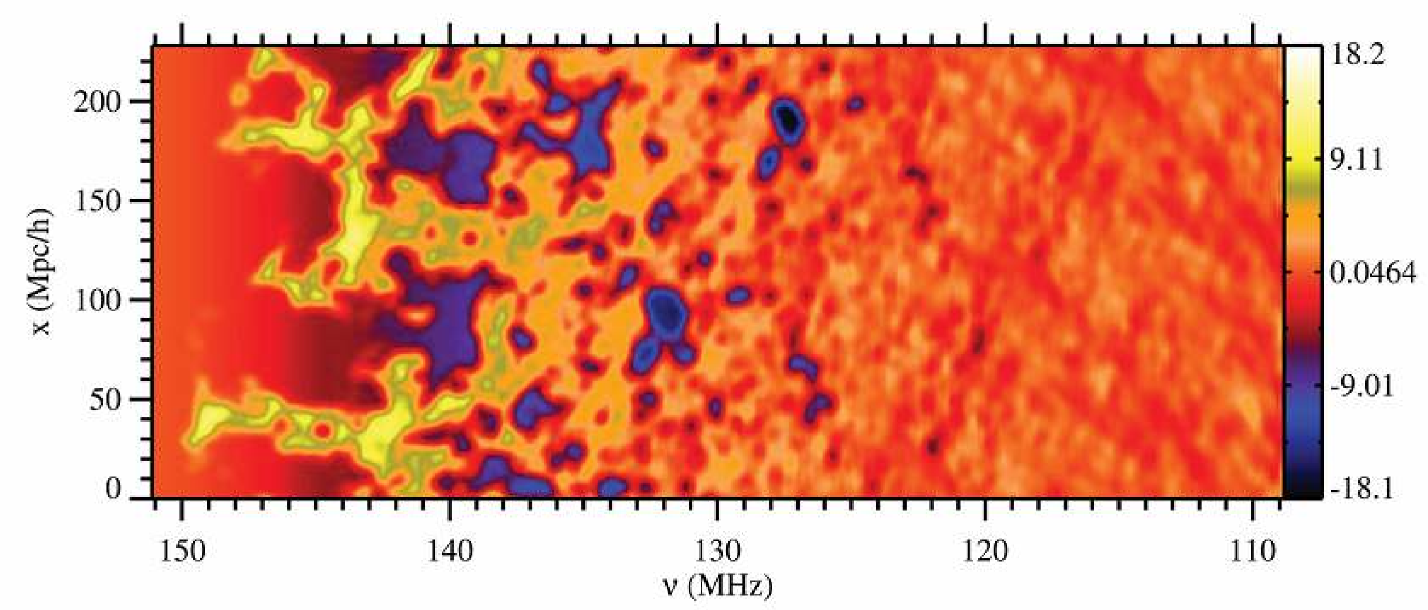
from Pop III star community

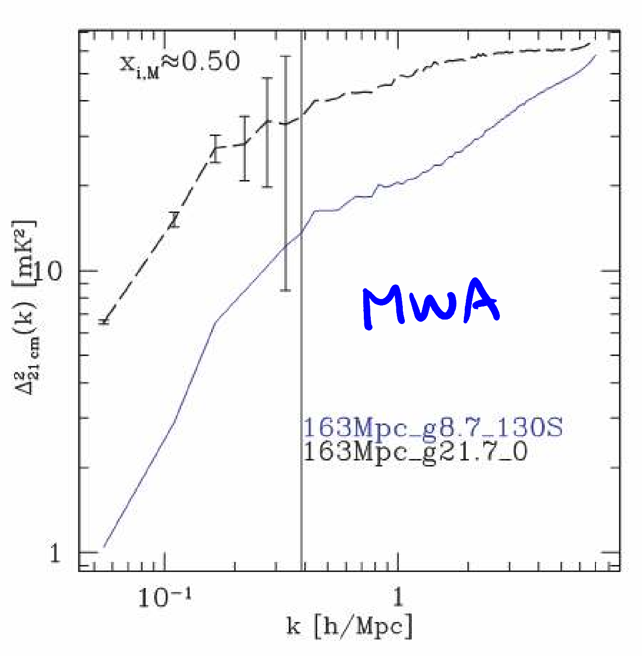
$$\langle x_\alpha \rangle = \frac{\langle J_\alpha \rangle}{1.2\times10^{-10}\left(\frac{1+z}{20}\right)\ \mathrm{s^{-1}\,cm^{-2}\,sr^{-1}}}$$

$= 4\times10^{-2}$

∴ MH-domination → 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~ 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)

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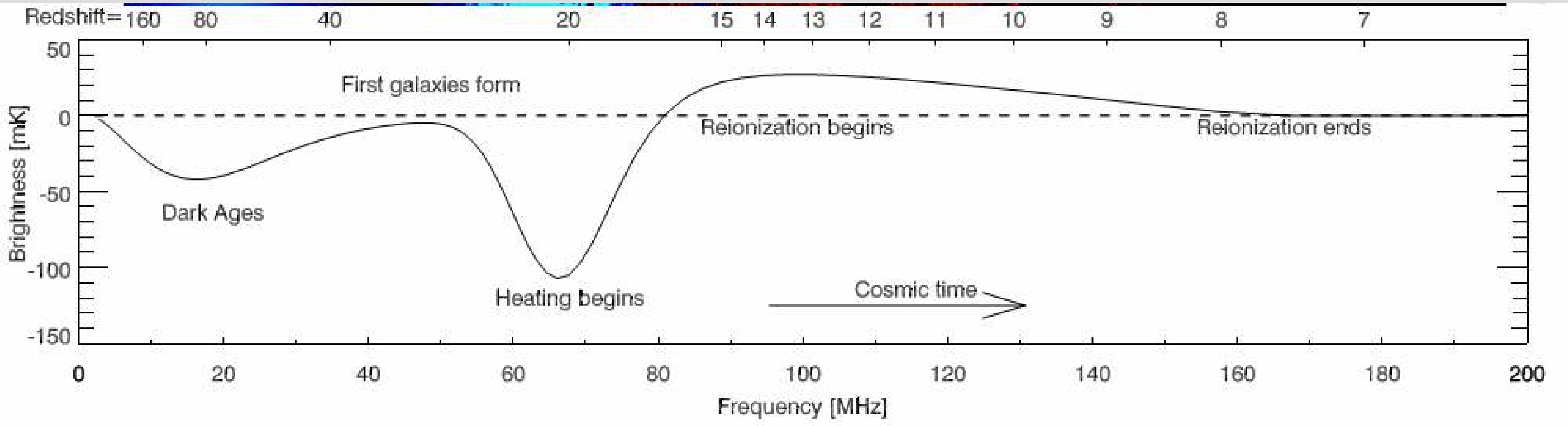
  - minihalo- dominated era (30~ >z>~ 10): if no X- ray, $\delta T_b\sim$ mK, some ~ 10mK peaks, absorption
  - minihalo- dominated era (30~ >z>~ 10): if X- ray, $\delta T_b\sim$ 10mK, emission



↳ Pritchard

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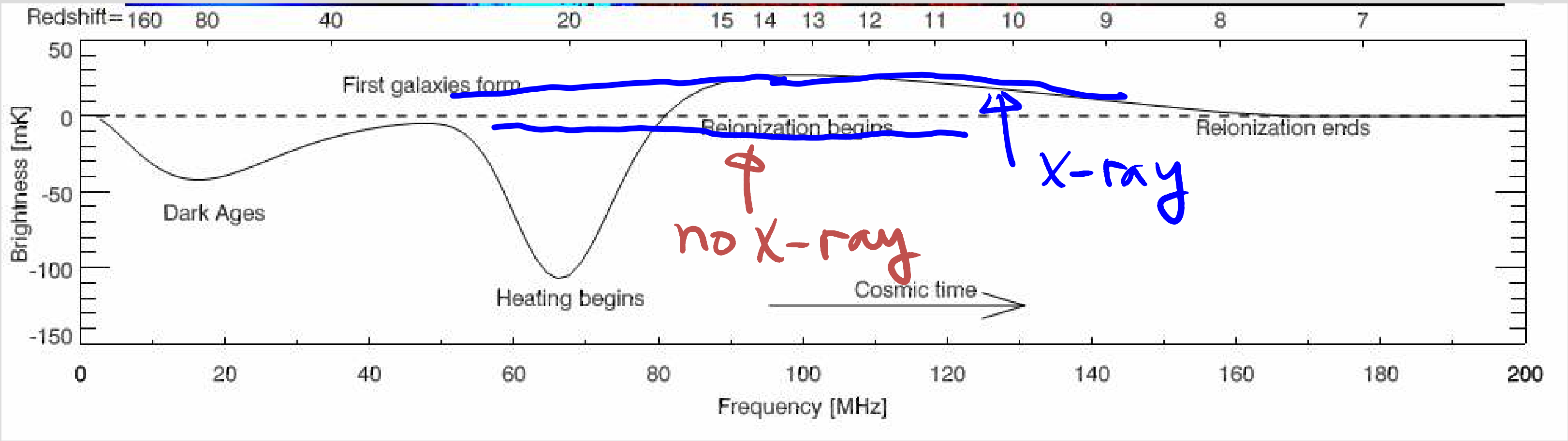

Summary

microphysics: MH (first stars) included simulation

  - z~ 7 Lya + CMB observations matched
  - very extended $\Delta z \sim 6.5$, 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~ >z>~ 10): if no X- ray, $\delta T_b \sim$ mK, some ~ 10mK peaks, absorption
  - minihalo- dominated era (30~ >z>~ 10): if X- ray, $\delta T_b \sim$ 10mK, emission
  - hard to get strong Lya coupling to generate ~ 100 mK signal
  - needs strong Lya coupling to generate ~ 100 mK signal → 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)