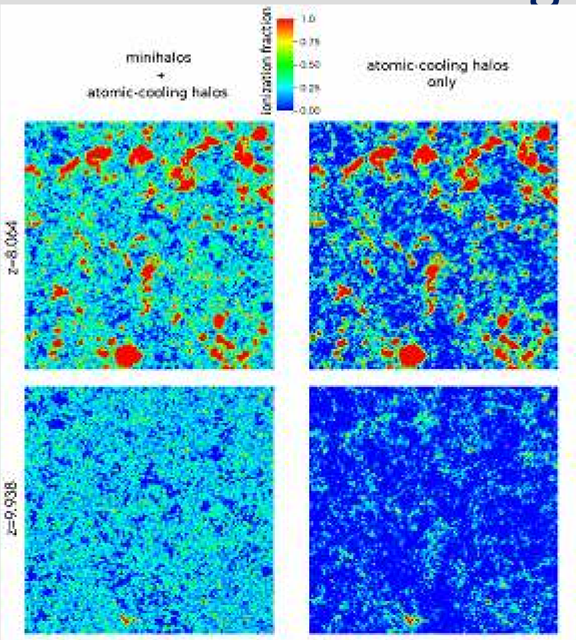
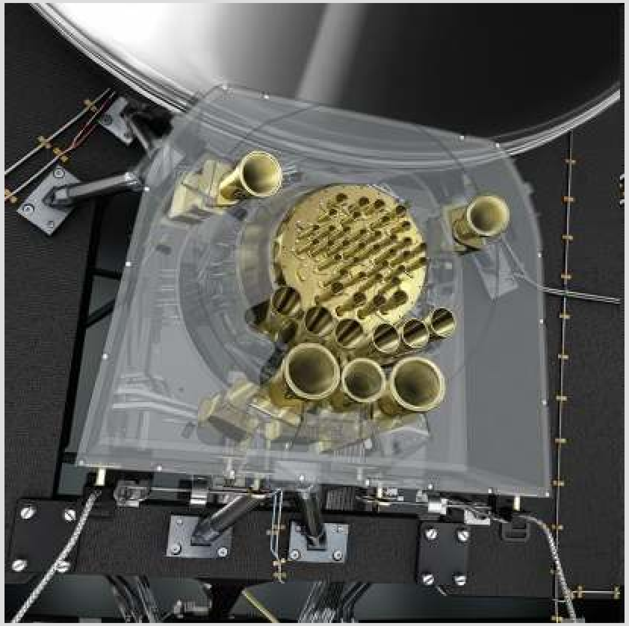
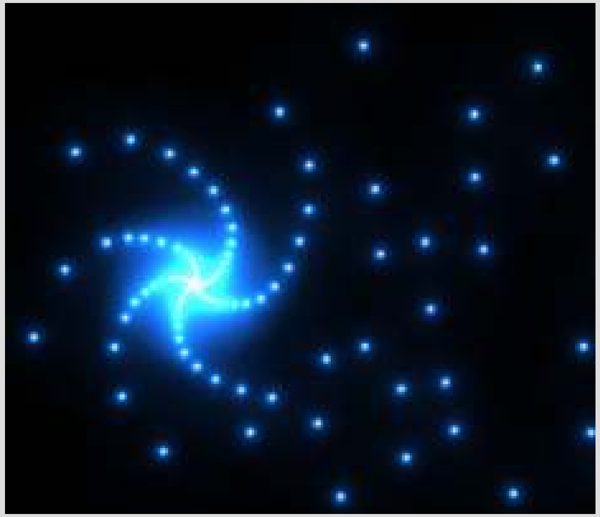
# Impact of the First Stars on Cosmic Reionization and Probing Their Existence through Planck





Kyungjin Ahn

Chosun University / UC San Diego - visiting

Reionization in the Red Centre, Uluru Australia

Jul 2013

Collaborators:

Paul Shapiro, Texas

Ilian Iliev, Sussex

Garrelt Mellema, Stockholm

Yi Mao, IAP

Dongsu Ryu, Korea

Hyunbae Park, Texas

Mike Norman+, UCSD

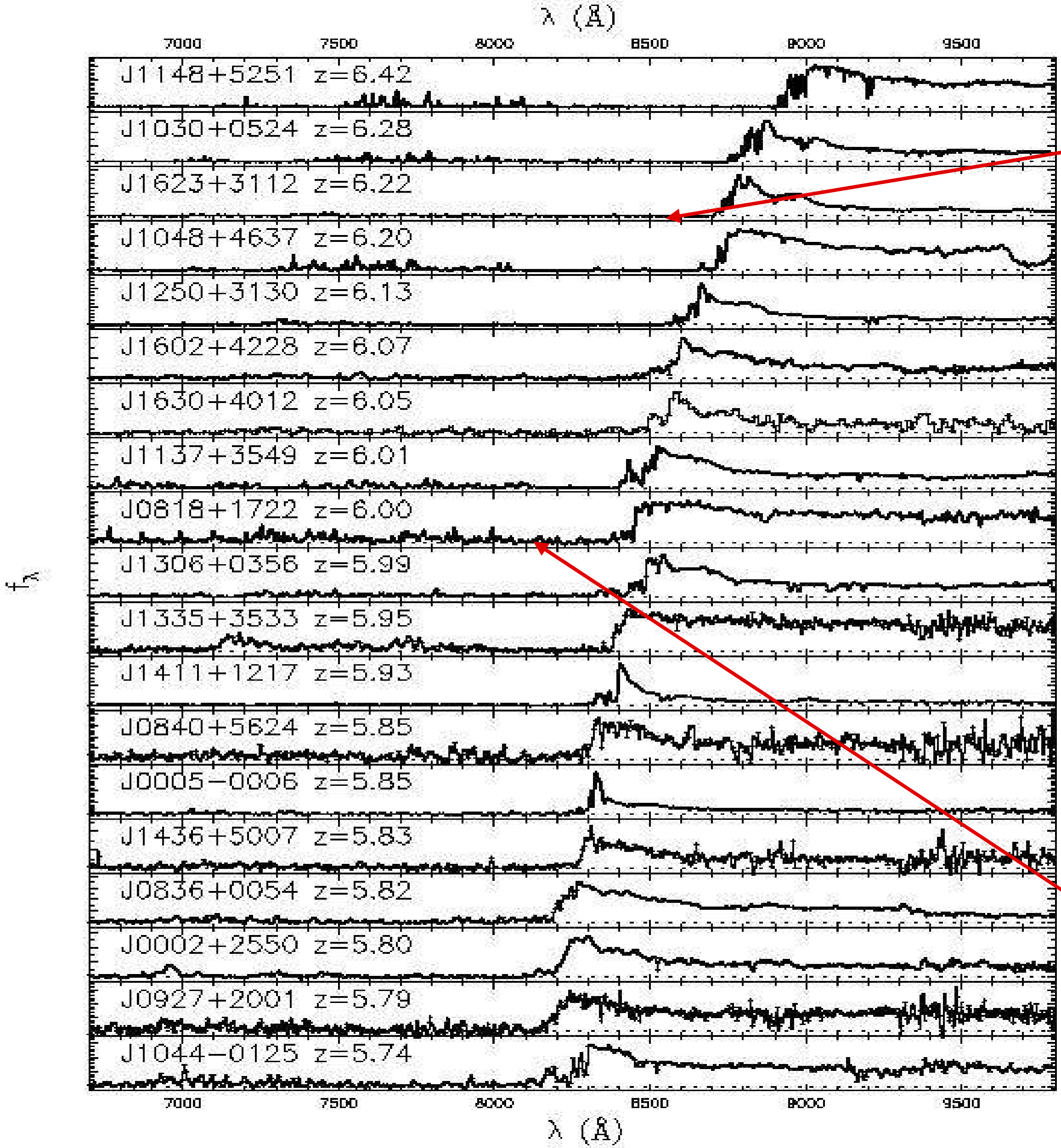
and others

# Observational constraints

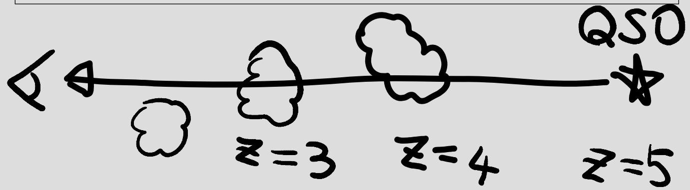
# Current observational constraints on Reionization

- 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+ 2011), LAE in LBGs (Pentericci+ 2011), LAEs(Ota+ 2010) → all indicating neutral fraction > 10% at z=7 !!!!!!

# when reionization completed:
## z~6 QSO spectra (Fan+ 2006)




Gunn-Peterson Trough
(high-z QSO spectrum)



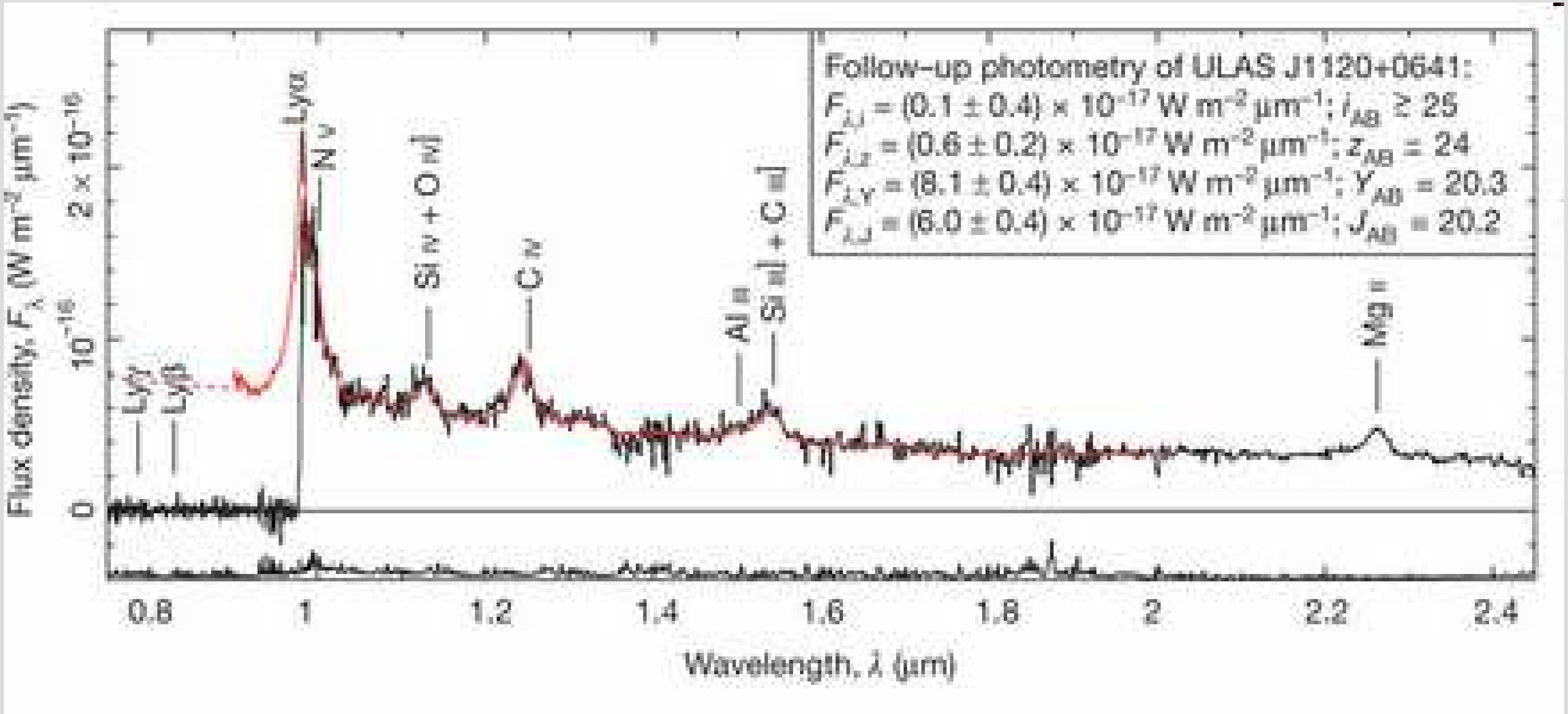

Abrupt change of intergalactic Lyα optical depth across z≈6.

f(HI) > 1e-3 at z = 6.3 vs. <1e-4 at z= 5.7

→ End of reionization at z≈6 (weak constraint though)

Lyα forest

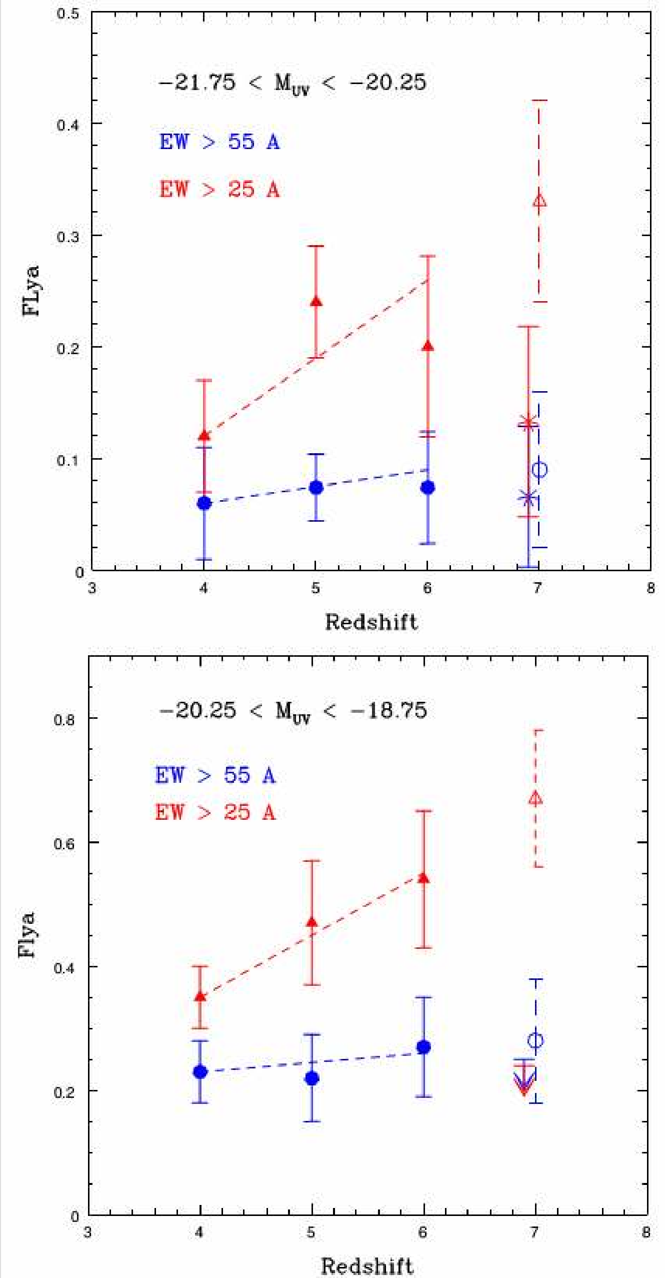
## when reionization completed:
z=7.085 QSO (Mortlock+ 2011)




very small proximity zone → high neutral fraction of >~ 0.1 at z=7 (Bolton+ 2011)

# when reionization completed:

## z=7 LBG (Pentericci+ 2011)




$$\mathrm{FLy}\alpha = \frac{\#\ \text{of Ly}\alpha\text{-emitting LBGs}}{\#\ \text{of LBGs}}$$

Decline of FLyα at z≈7.

→ large HI fraction at z ≈7

→ drastic change in $x_e$?

- Pentericci+: ~ 50% per dz~1
- Bolton+: >~ 10% per dz~1

→ reionization ended at z < 7 !!

# Current observational constraints on Reionization

- Electron content + bulk movement
  - kinetic Sunyaev- Zeldovich effect on CMB
  - South Pole Telescope:
    z(x=99%)- z(x=20%) ~ 4.4 – 7.9 (2$\sigma$ level foreground modeling, Zahn+ 2011; see also Mesinger+ 2012)

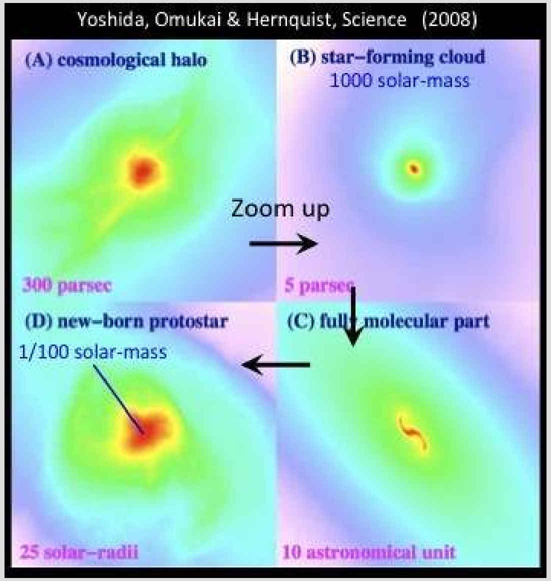
- Electron content, in terms of Thomson scattering optical depth of CMB
  - $\tau$ = 0.089 ± 0.014 (WMAP9, 1$\sigma$ level)
  - $\tau$ = 0.089 +0.012 - 0.014 (Planck+WMAP polarization, 1$\sigma$ level)

$$\tau = \int_{z_{\text{reionization beginning}}}^{z=0} n_e \, \sigma_T \, dl$$

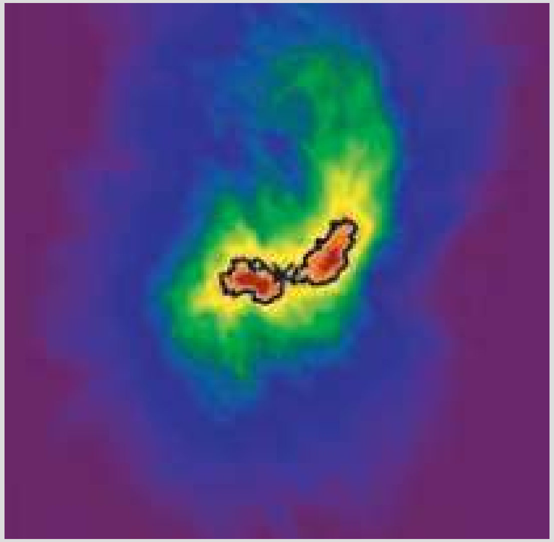
# New Developments in First Star Theory

## New developments - First star formation

- 1 star / 1 halo paradigm (Abel, Yoshida, Bromm, …)
  - star ~ 100 $M_\odot$
  - until ~ 5 years ago




- paradigm shift? (e.g. Turk, Abel, O'Shea 2009)
  - 1 binary / 1 halo
  - stars ~ 7 $M_\odot$ + ~ 20 $M_\odot$ → weaker UV output?
  - stellar binary → x- ray binary → x- ray source?
  - caveat: universality unknown



# New developments – baryon-DM offset

- baryon moving against dark matter
  - velocity offset @ recombination (Naoz & Barkana 2005)
  - ~ a few km/s velocity offset @ z~20 (Tseliakhovich & Hirata 2010)
- baryon formation offset
  - velocity offset → formation offset (O'Leary & McQuinn 2012)
  - Jeans mass up → suppression of star formation (Greif+ 2011)
  - mechanical heating → 21cm boost (McQuinn & O'Leary 2012)

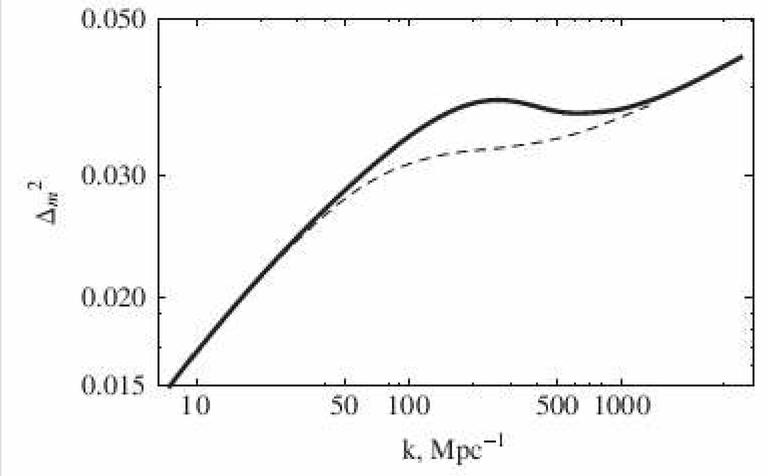
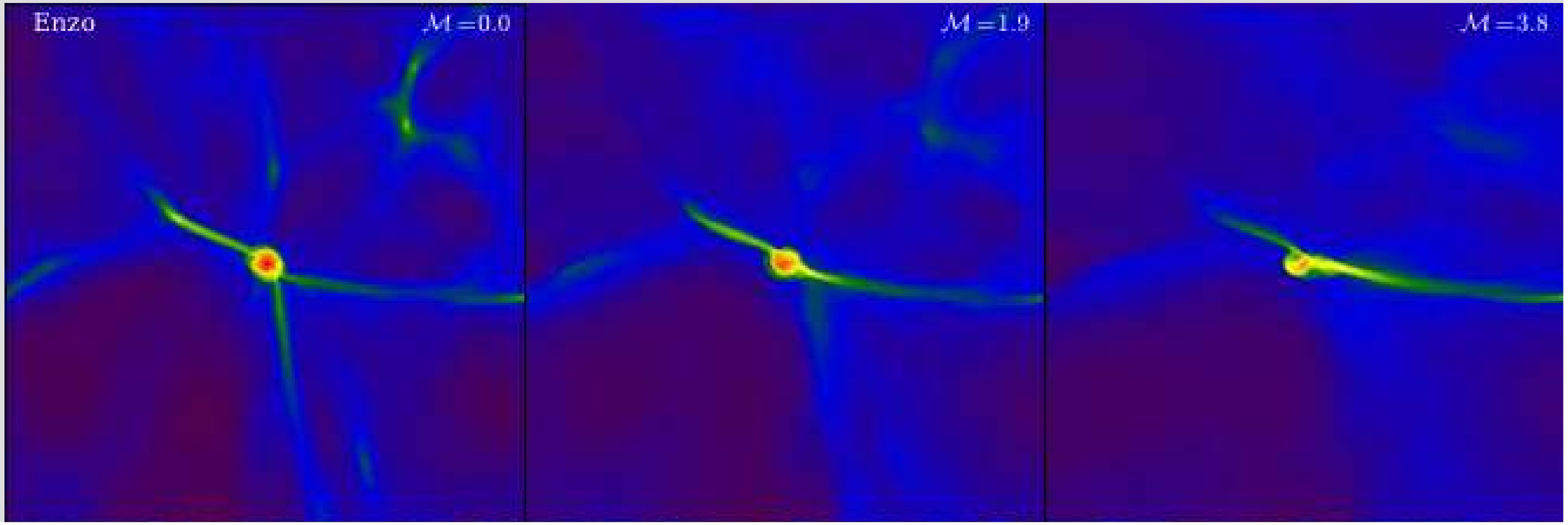



FIG. 2. Power spectrum of matter distribution in the first order CDM model (solid line) and with the $v_{bc}$ effect included (dashed line) at the redshift of $z = 40$.



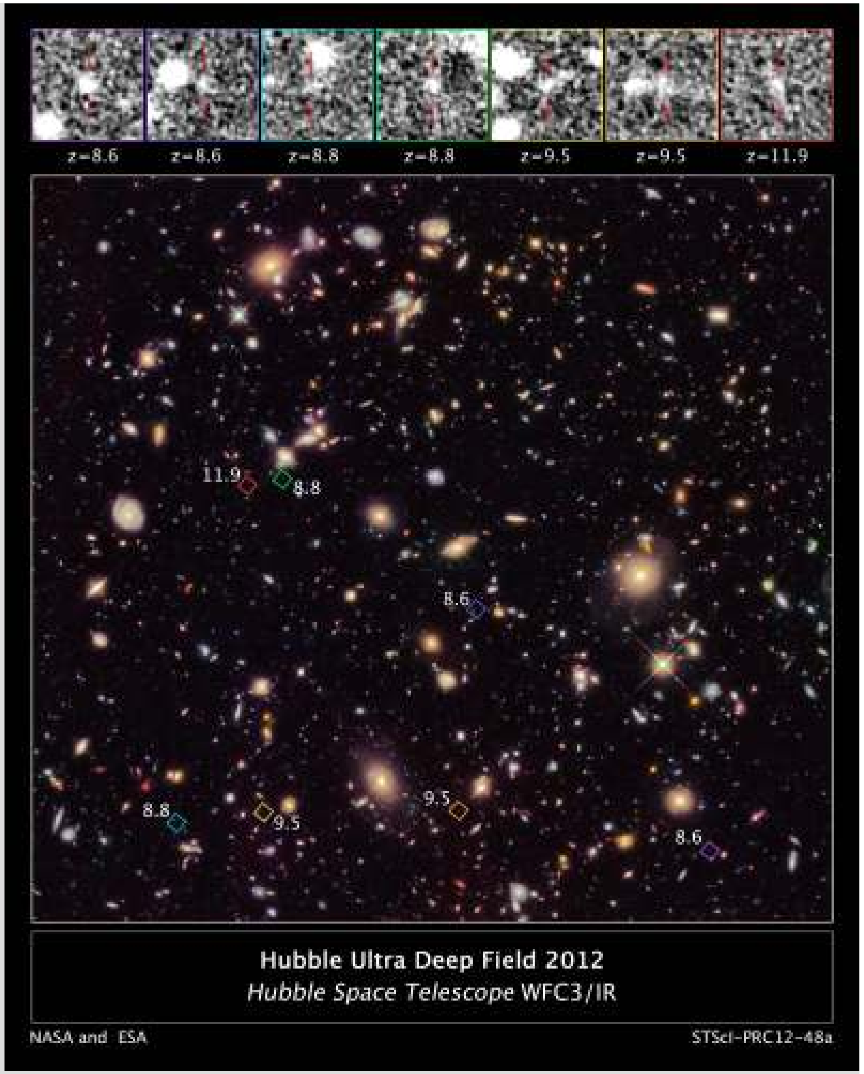
# Simulation (w/ first stars)

# Numerical Simulations of Reionization

- Process is nonlinear and directional: need simulation
- Status of state- of- art numerical simulation so far
  - Need big box for statistics (H II bubble ~ 20 Mpc)
  - numerical resolution limited
  - Minihalos (<~ $10^8$ $M_{\odot}$) not resolved
  - Minihalos are the cradle for the first stars!! (Norman, Wise, Yoshida, Bromm, Abel, …) Most abundant halo type.
- In this talk, Minihalos ~ First Stars

# Motivation/Puzzle/Our answer

- Lost photon budget
  - first stars in minihalos
- Late reionization($z_{ov}$<7) & high $\tau$ conditions: hard to match simultaneously w/o first stars
  - hard in numerical simulations (Iliev+; Zahn+; Trac & Cen)
  - hard with observed galaxies (Robertson+ 2013, HUDF12) →
- Simple answer: minihalos
  - hints from semi- analytical studies by Haiman & Bryan (over- boosting $\tau$); Wyithe & Cen; …
  - inhomogeneous physical processes → Yes, we still need numerical simulations!!

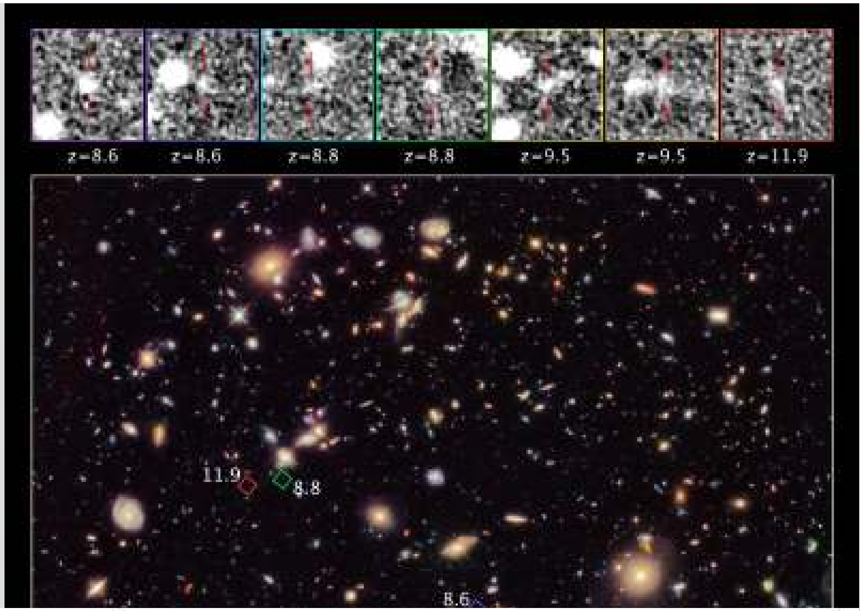


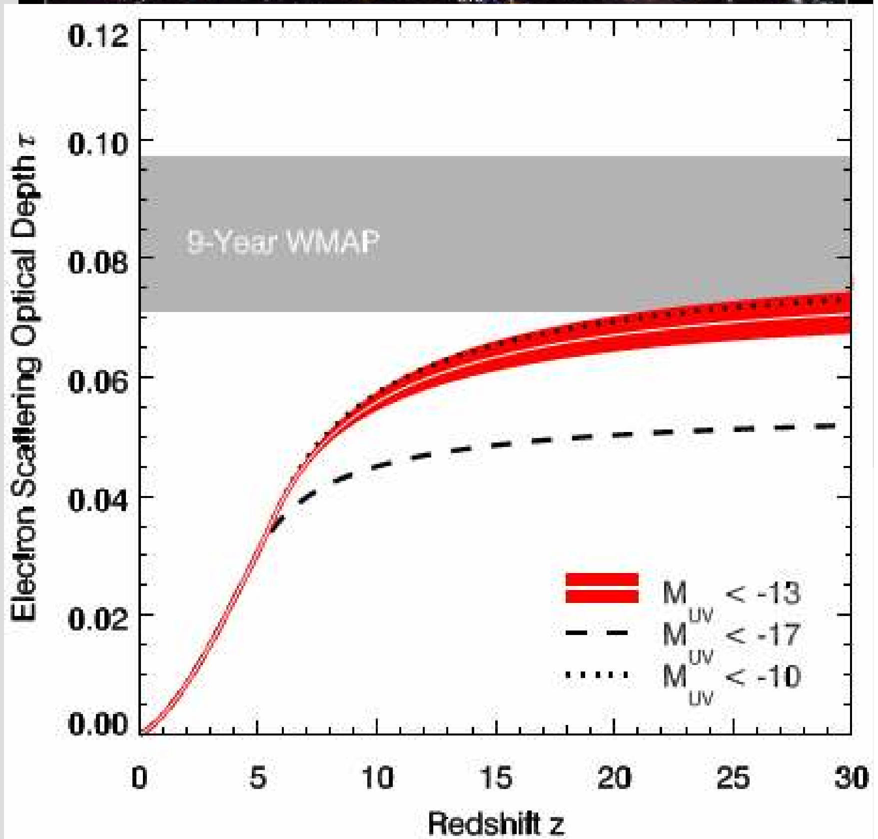
# Motivation/Puzzle/Our answer

- Lost photon budget
  - first stars in minihalos

- Late reionization($z_{ov}$<7) & high $\tau$ conditions: hard to match simultaneously w/o first stars
  - hard in numerical simulations (Iliev+; Zahn+; Trac & Cen)
  - hard with observed galaxies (Robertson+ 2013, HUDF12) →

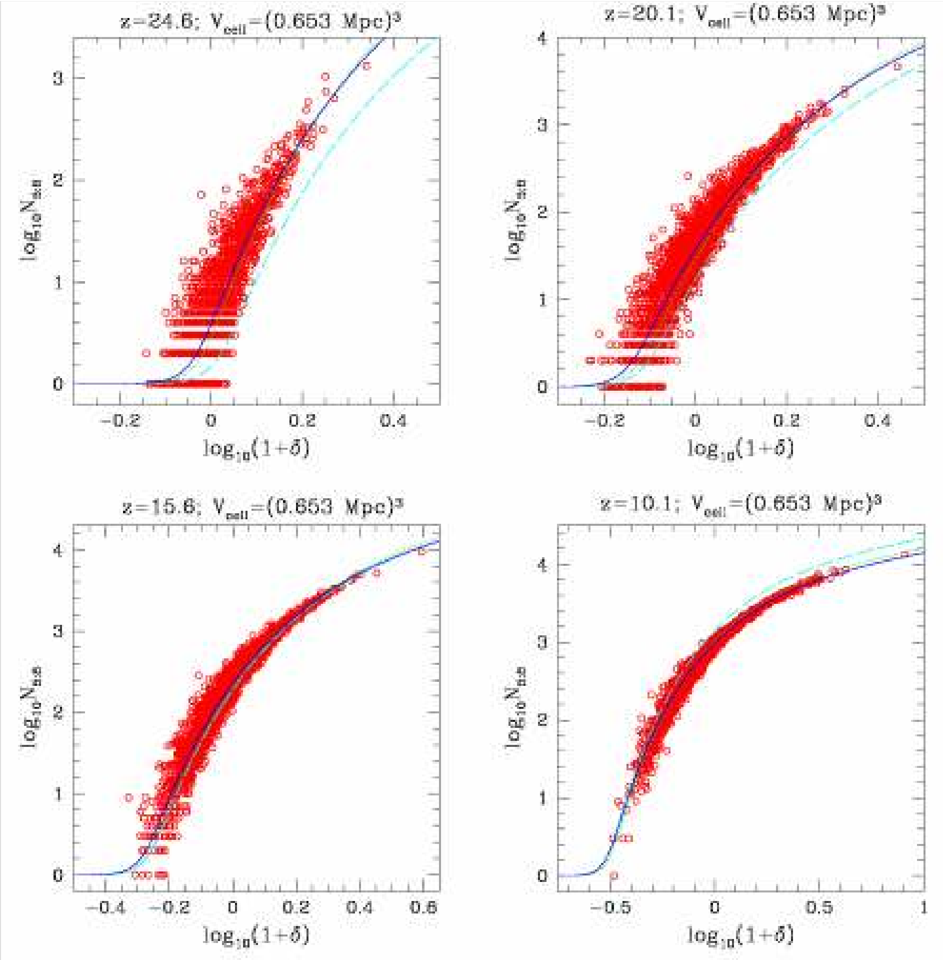
- Simple answer: minihalos
  - hints from semi- analytical studies by Haiman & Bryan (over- boosting $\tau$); Wyithe & Cen; …
  - inhomogeneous physical processes → Yes, we still need numerical simulations!!

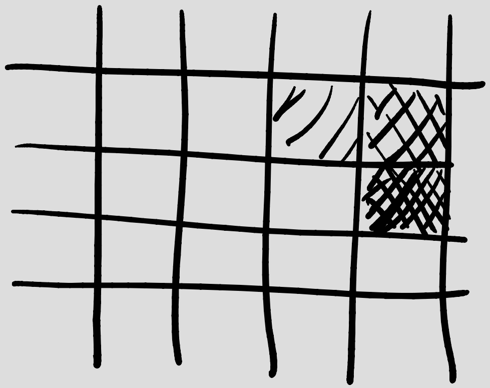


# What's new?

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

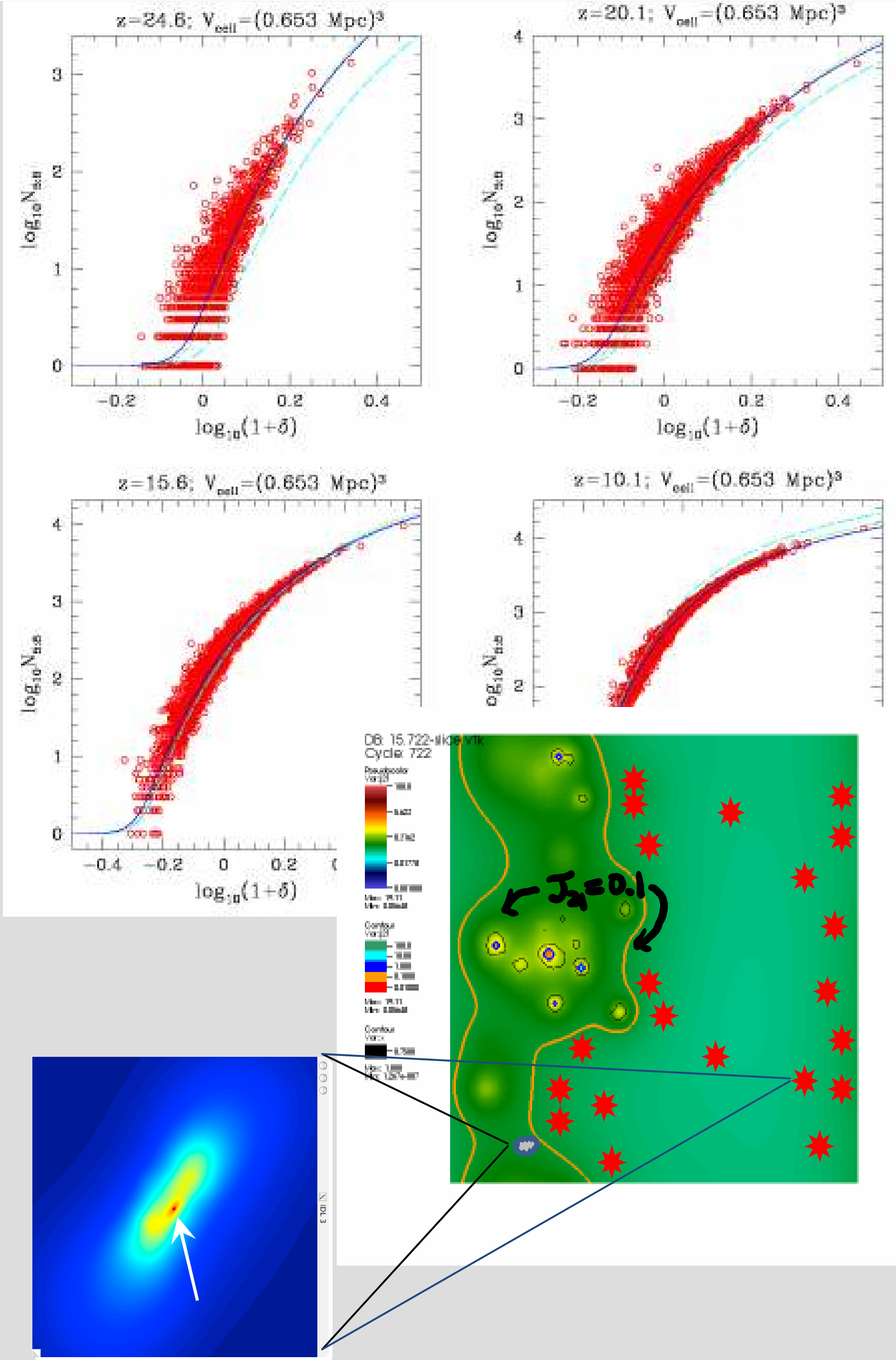


# What's new?

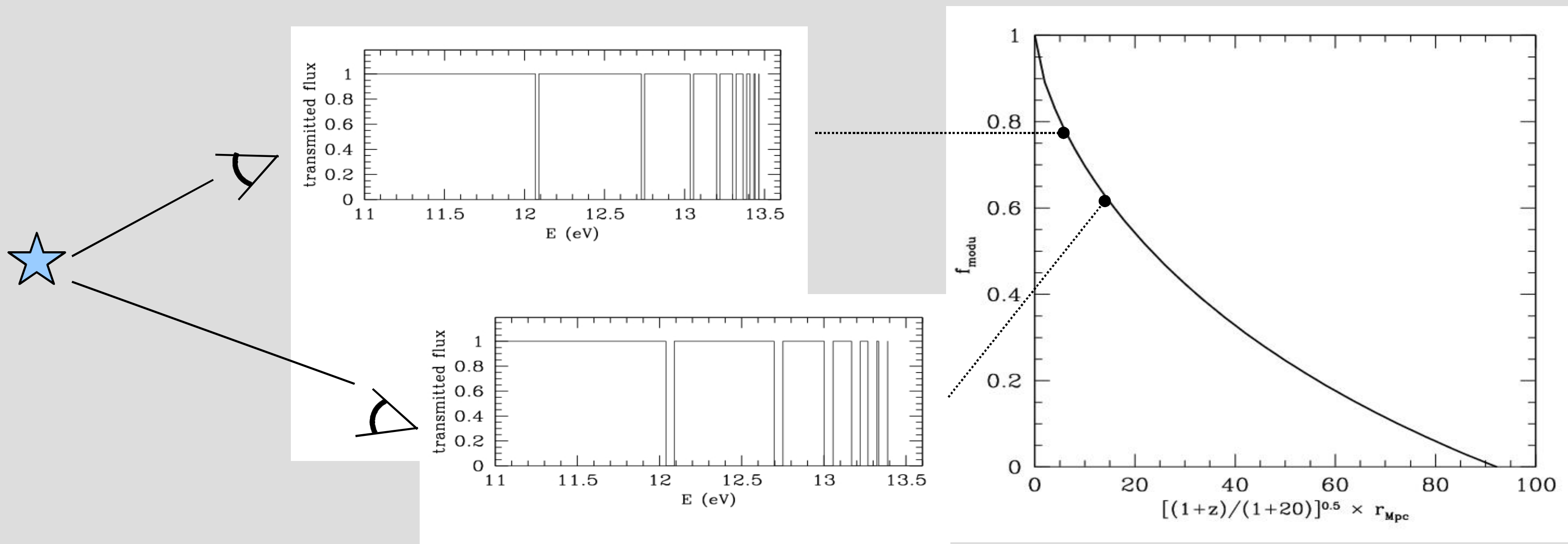
- Populating grid with minihalos (first stars!)
  - small- box (6.3/h Mpc) simulation resolving minihalos
  - correlation between density & minihalo population (nonlinear bias: KA+ in preparation)
  - put one Pop III star per minihalo

- Considering photo-dissociation of coolant
  - calculate transfer of Lyman-Werner Background (KA+ 2009)
  - remove first star from minihalos, if LW intensity over-critical



# How LW transfer done: Picket-Fence Modulation Factor (KA+ 2009)

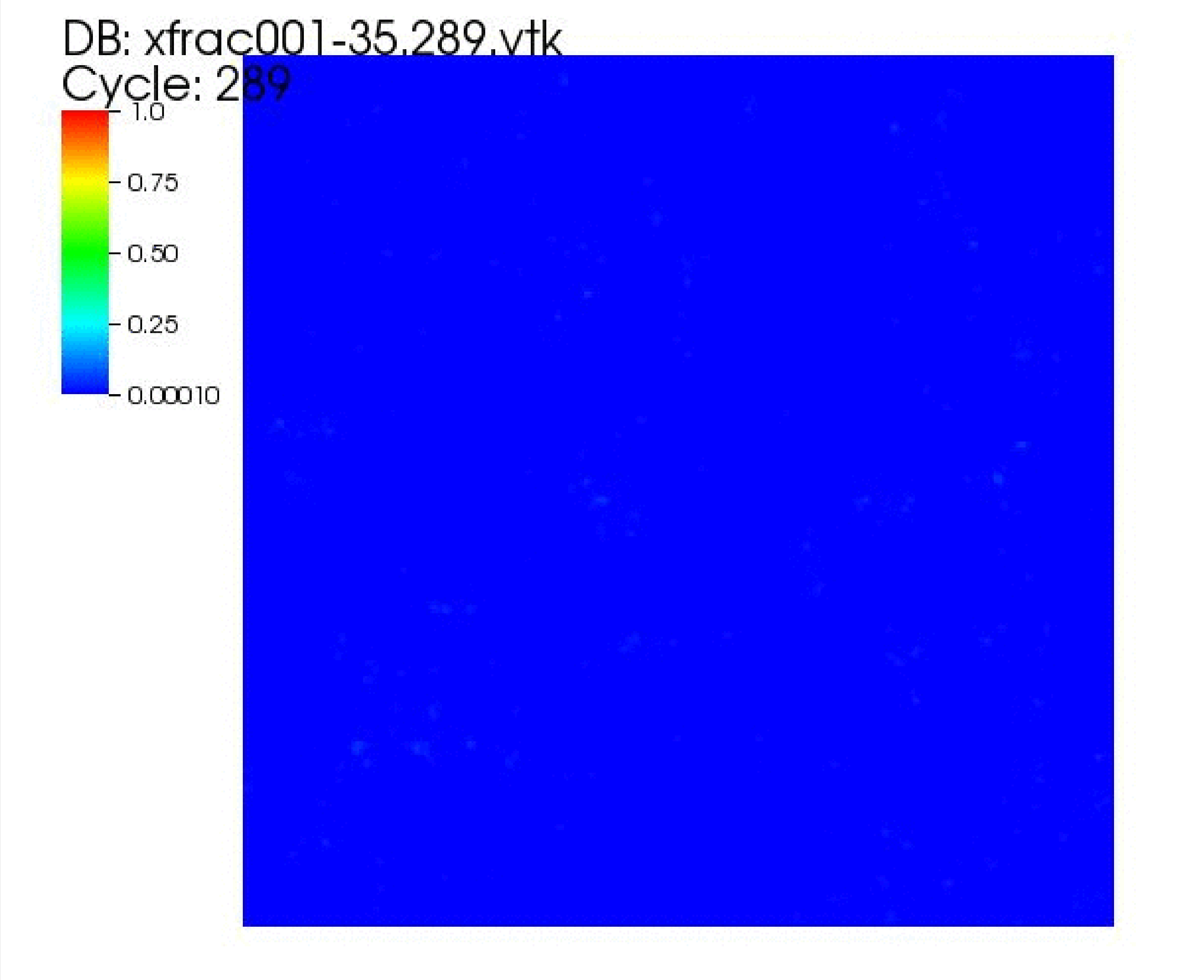
- Sources distributed inhomogeneously: Need to sum individual contribution
- One single source is observed as a picket-fence in spectrum
- Obtain pre-calculated "picket-fence modulation" factor and multiply it to $L_\nu / D_L^2$. This becomes mean intensity to be distributed among $H_2$ ro-vibrational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



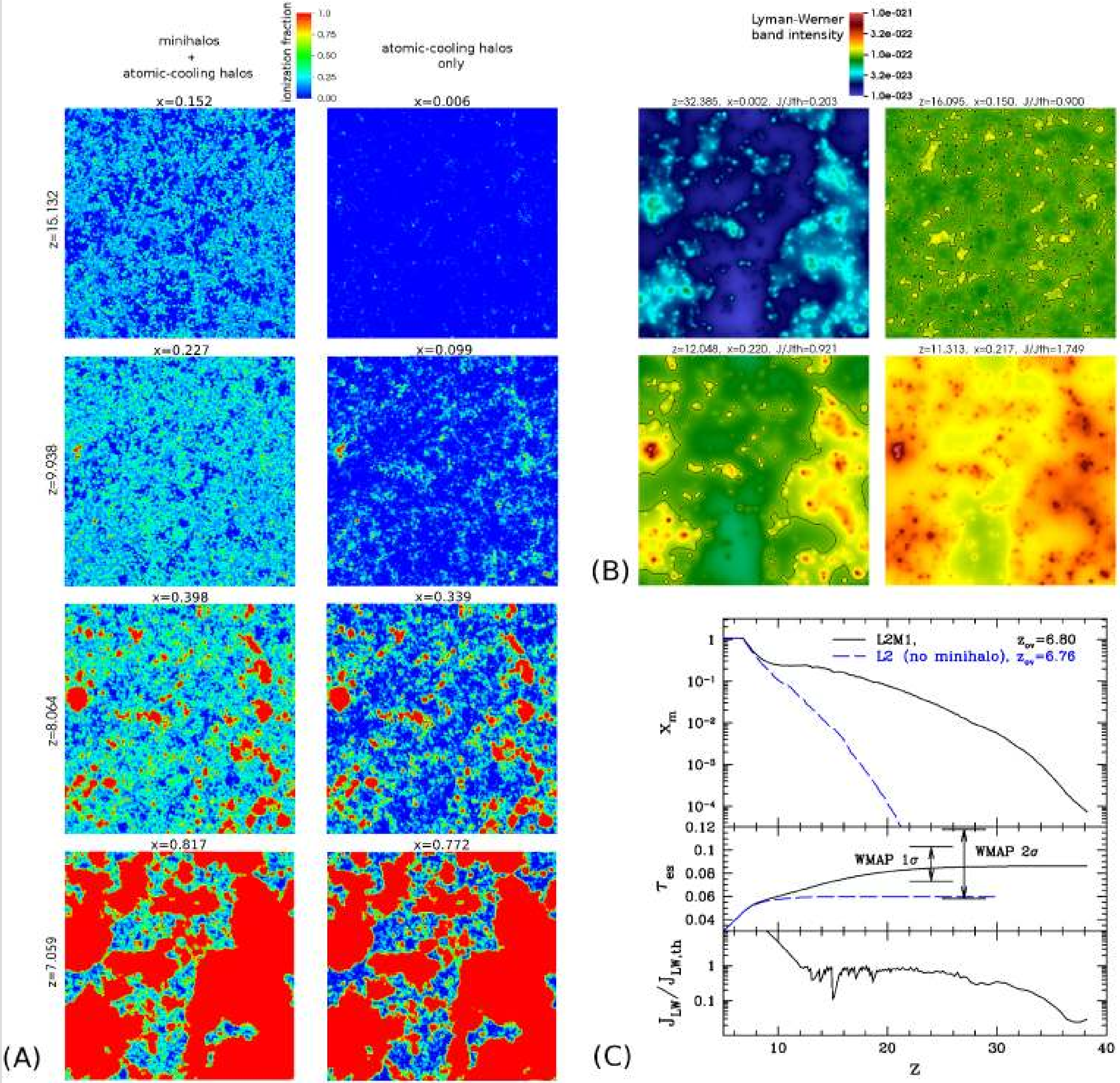
## What do we expect

- More extended reionization
- Same $x_e$ but different morphology, with and without minihalos (c.f. McQuinn+ 2007)
- More electron content → stronger polarization of CMB
- Earlier heating of intergalactic medium
- Earlier Ly$\alpha$ pumping on 21cm
- result in KA+ 2012

114/h Mpc, w/ Minihalo+ACH, M(Pop III star)=$300M_{\odot}$, $J_{LW,th}=0.1\times10^{-21}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$



# With and Without Minihalos

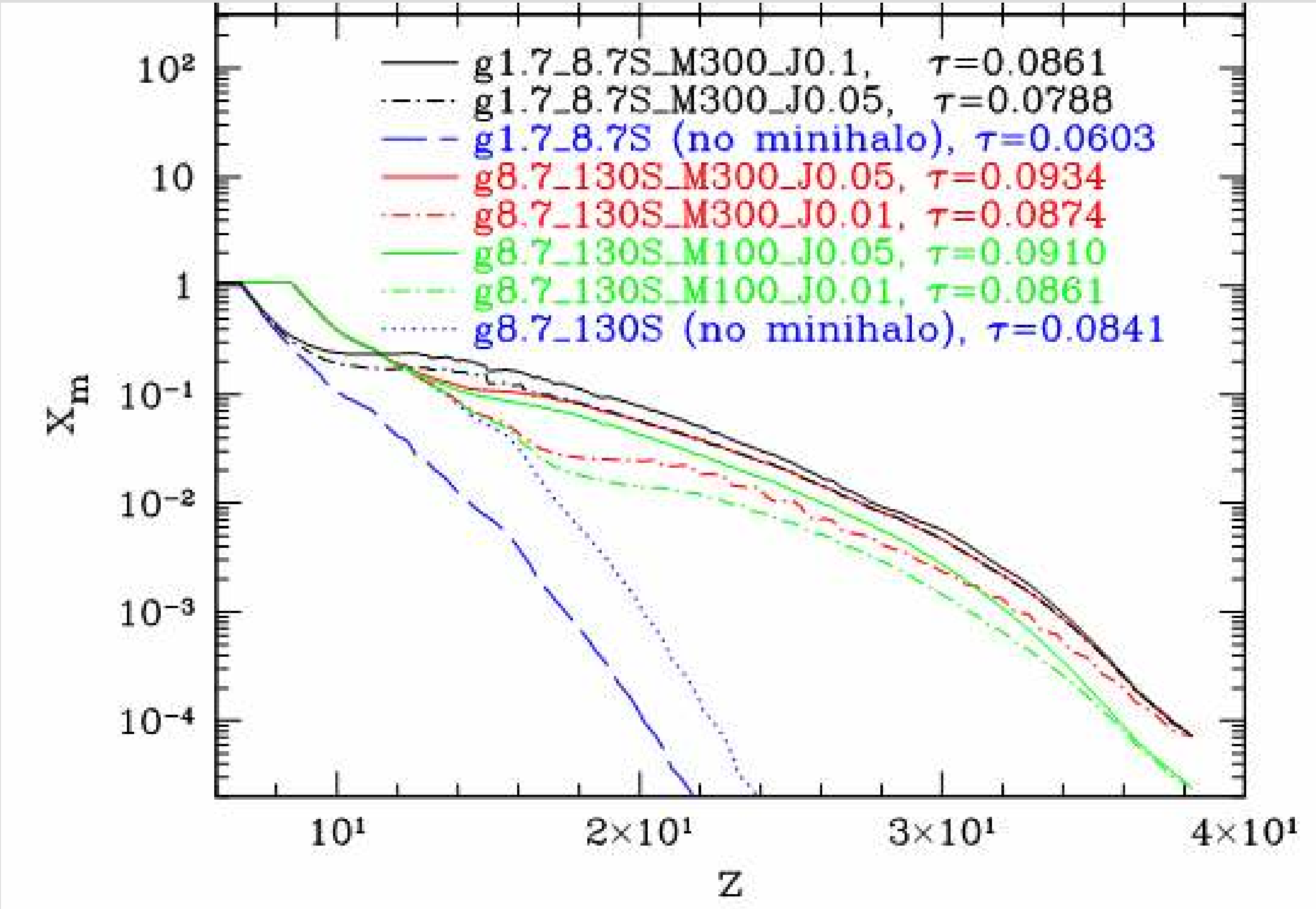


## Storyline

- 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
- Same ionization fraction → same H II morphology ??
  - cf. McQuinn+ 2007
  - same ionization fraction very different morphology among models (contradicting McQuinn+ 2007)
- Late reionization, large optical depth: both can be achieved only with help of minihalo sources, or namely the first stars
- Observations will nail it

puzzle solvable

# Early vs. Late Reionization Models
# No-minihalo vs. Minihalo Models



# Observational prospects –
# large-scale CMB (E-mode polarization)

## Q: Can Planck smell first stars? (WMAP not that accurate)

- 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

$$x_e(z) = x_{e,\,\mathrm{fid}}(z) + \sum_{\mu=1}^{N_{\max}} m_\mu S_\mu(z)$$

amplitude (model)

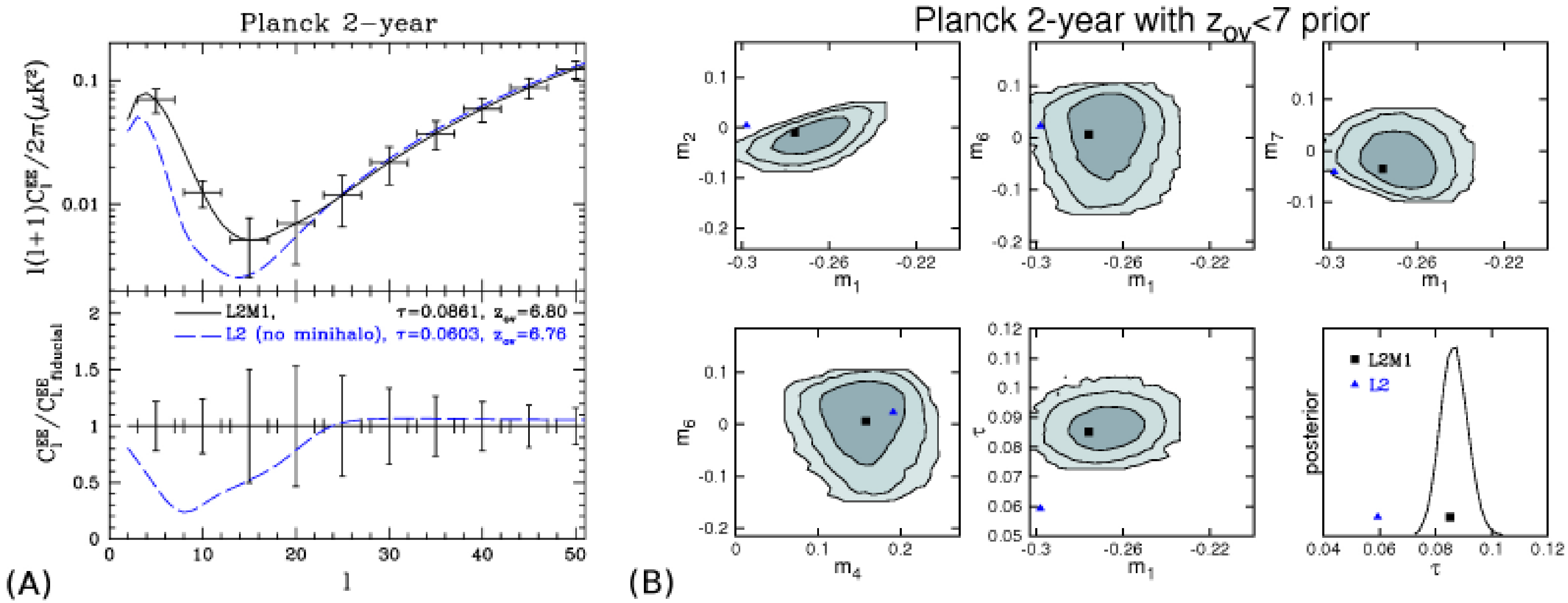
model-independent

principal component (basis)

## Planck Forecast

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

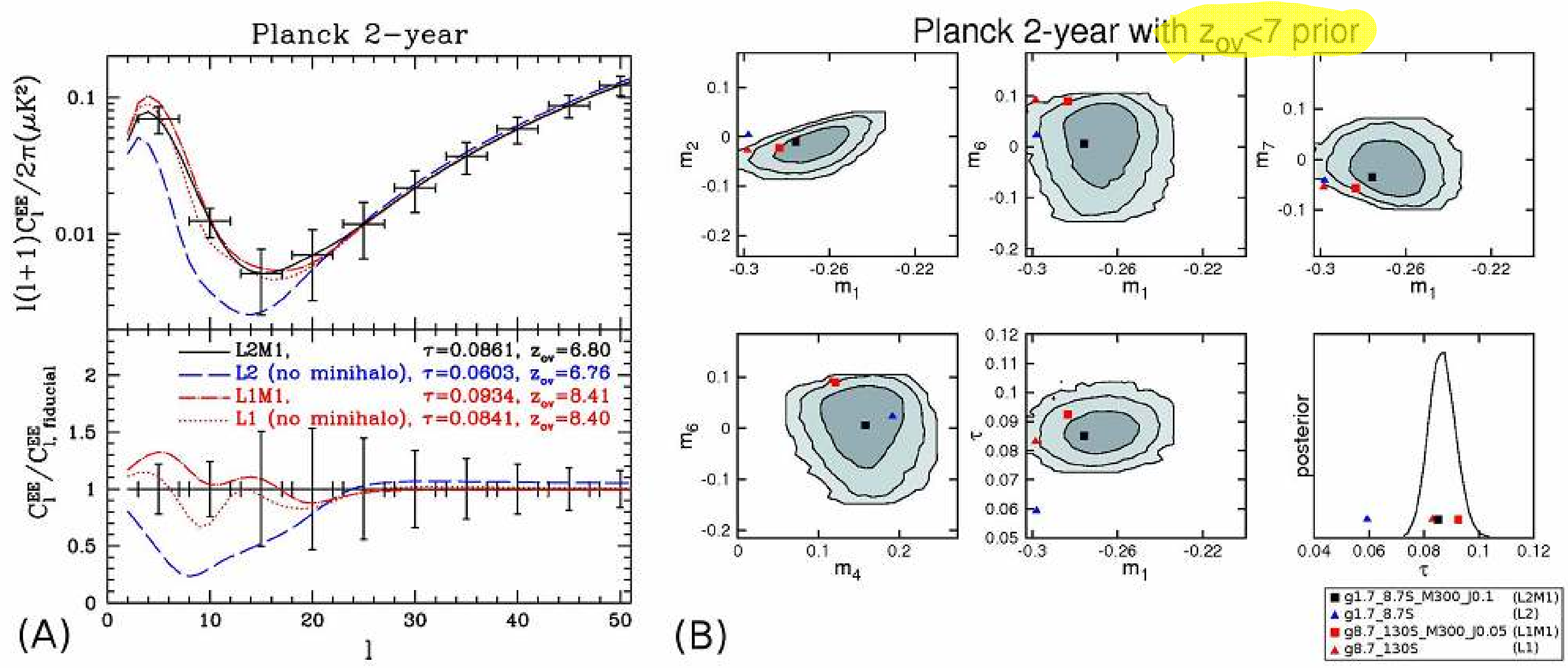
high-τ (w/ minihalo) (w/ first star) vs. low-τ (w/o minihalo) (w/o first star)




Hu & Holder; Motonson & Hu: PCA for reionization

# Planck Forecast

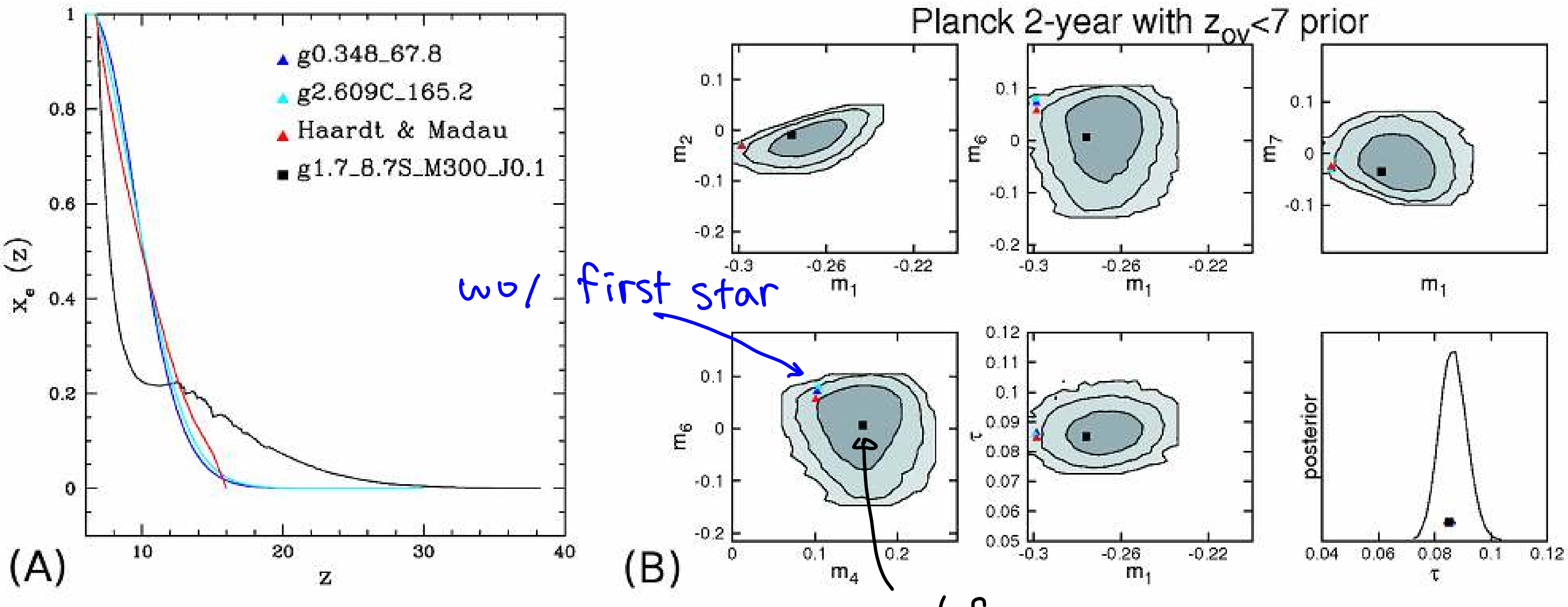
$\tau \sim 0.085$ (common), late ($z_{ov}<7$) (black) (w/ first star) vs. early ($z_{ov}>7$) (red) (w/ or wo/ first star)



# Planck Forecast

τ ~ 0.085
(common)
$z_{ov} < 7$

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

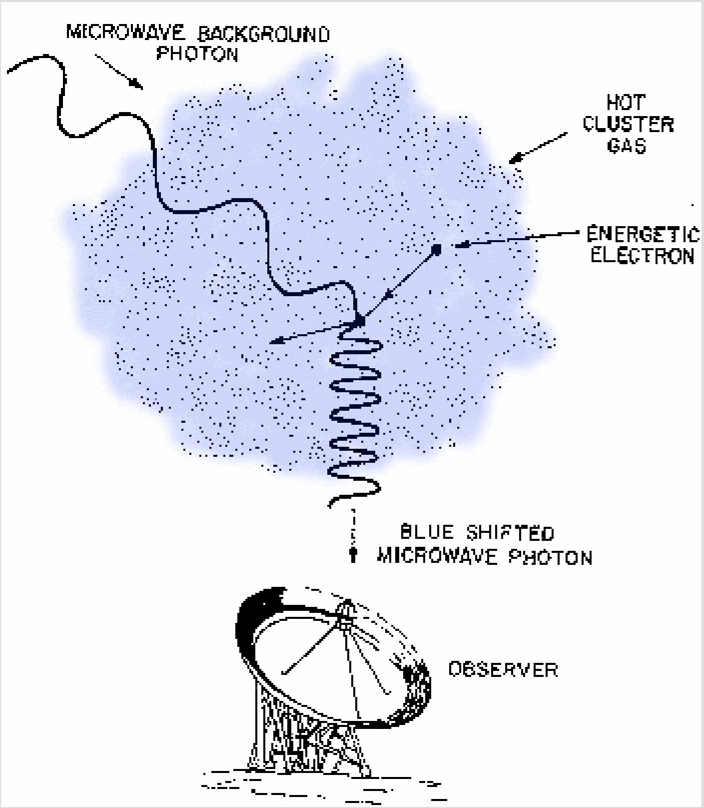


# Observational prospects –
# small-scale CMB (temperature)

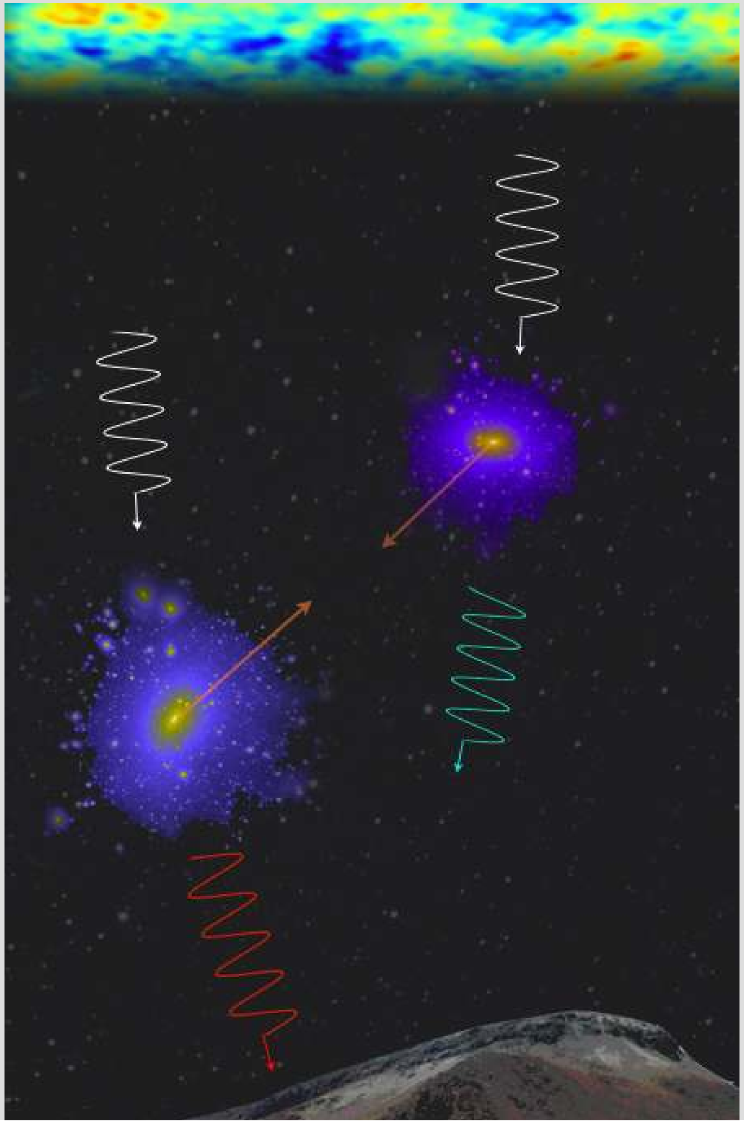
# Dominant process

Sunyaev- Z'eldovich effect

thermal

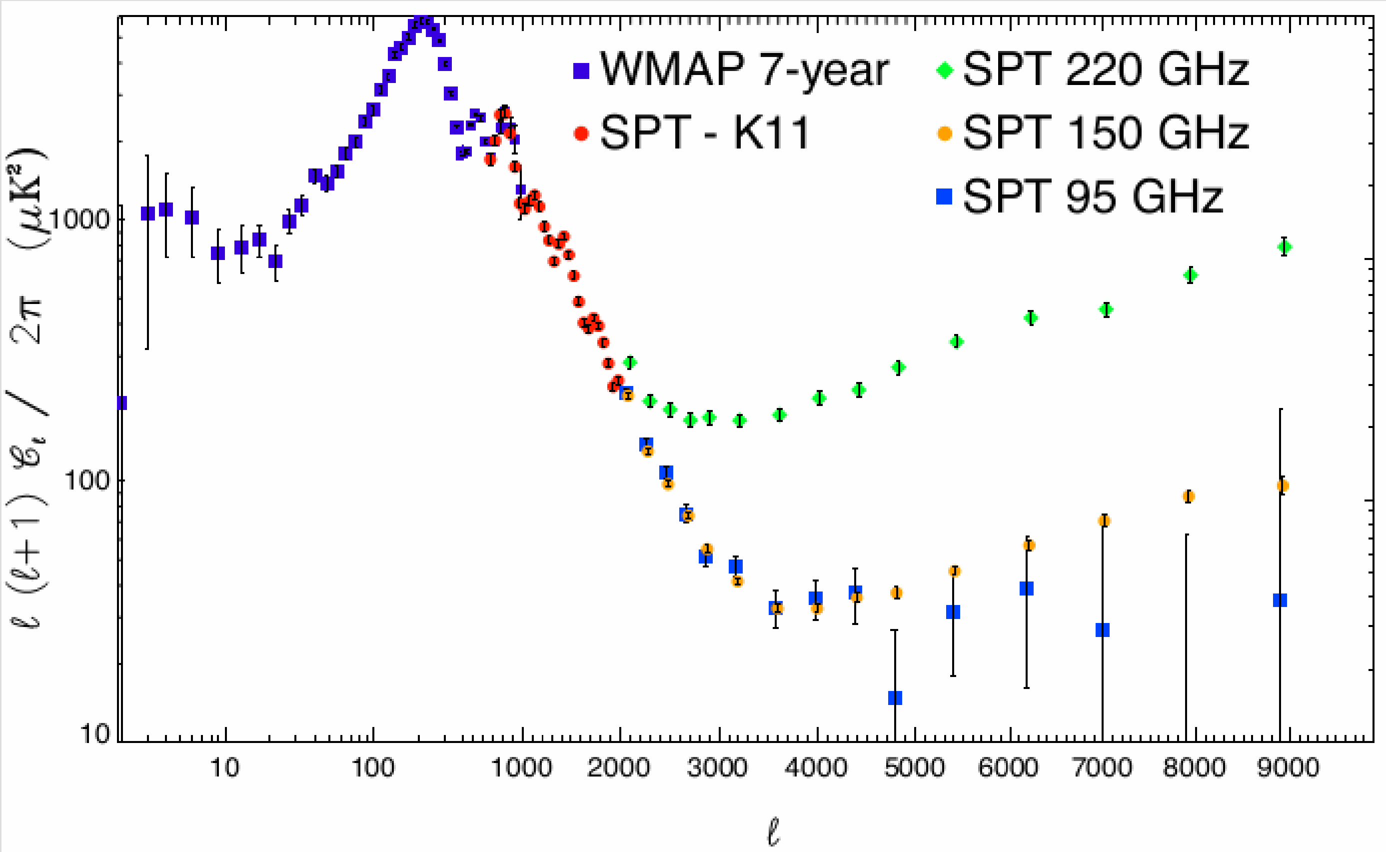



kinetic

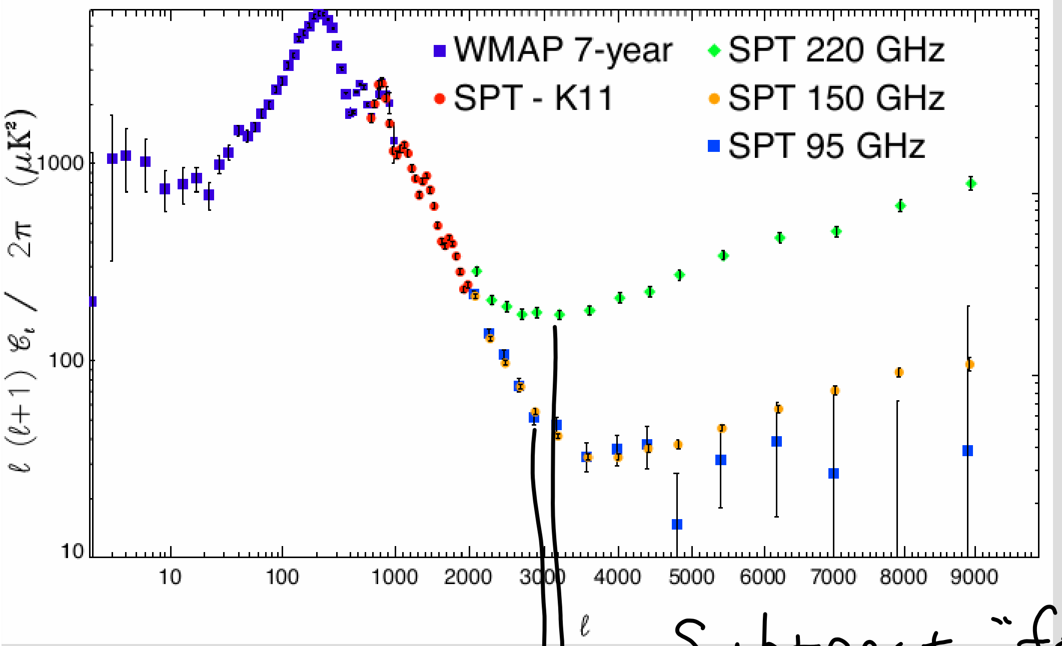


# CMB temperature anisotropy at small scale

Reichardt+ 2012
South Pole Telescope (SPT)



# CMB temperature anisotropy at small scale




Reichardt+ 2012
South Pole Telescope (SPT)

Subtract "foreground" by modeling

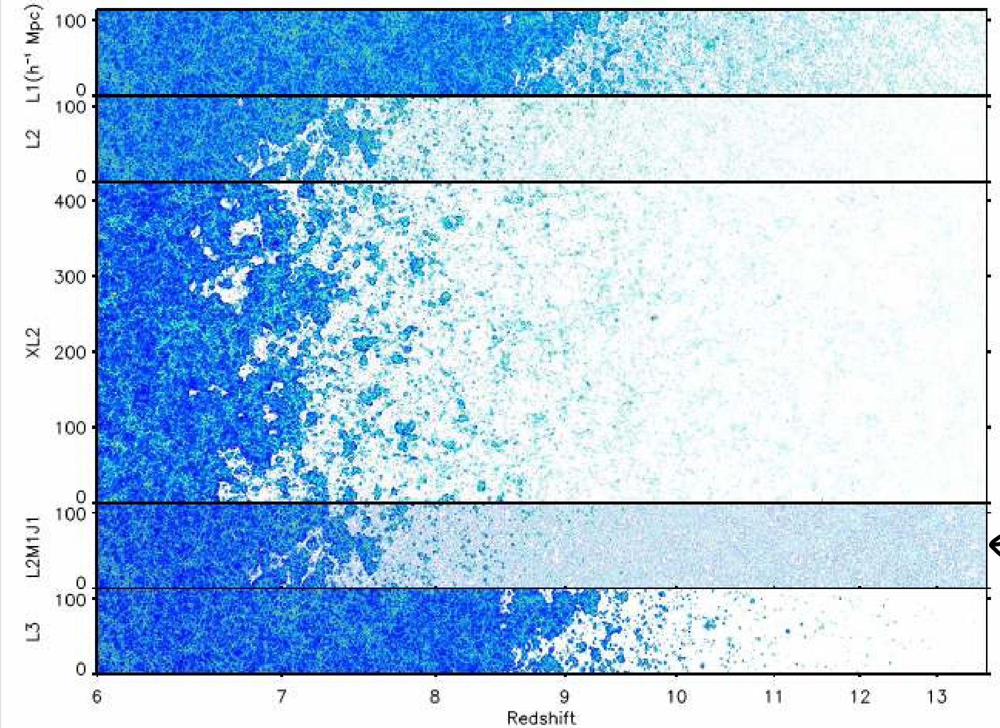
~ 2.1 μK² for kinetic SZ from EoR HII bubbles

→ $\Delta z_{EoR} \leq 4.4 \sim 7.9$ @ 2σ

Zahn+ 2012

model-dependent.

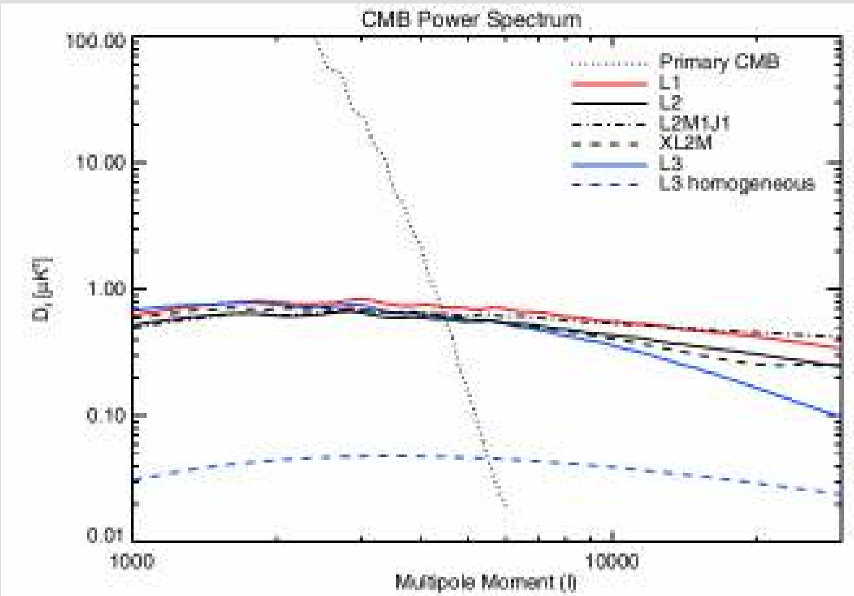
# CMB temperature anisotropy at small scale




Park+ 2013

← First-Star included sim.

$\Delta z = 6.5$



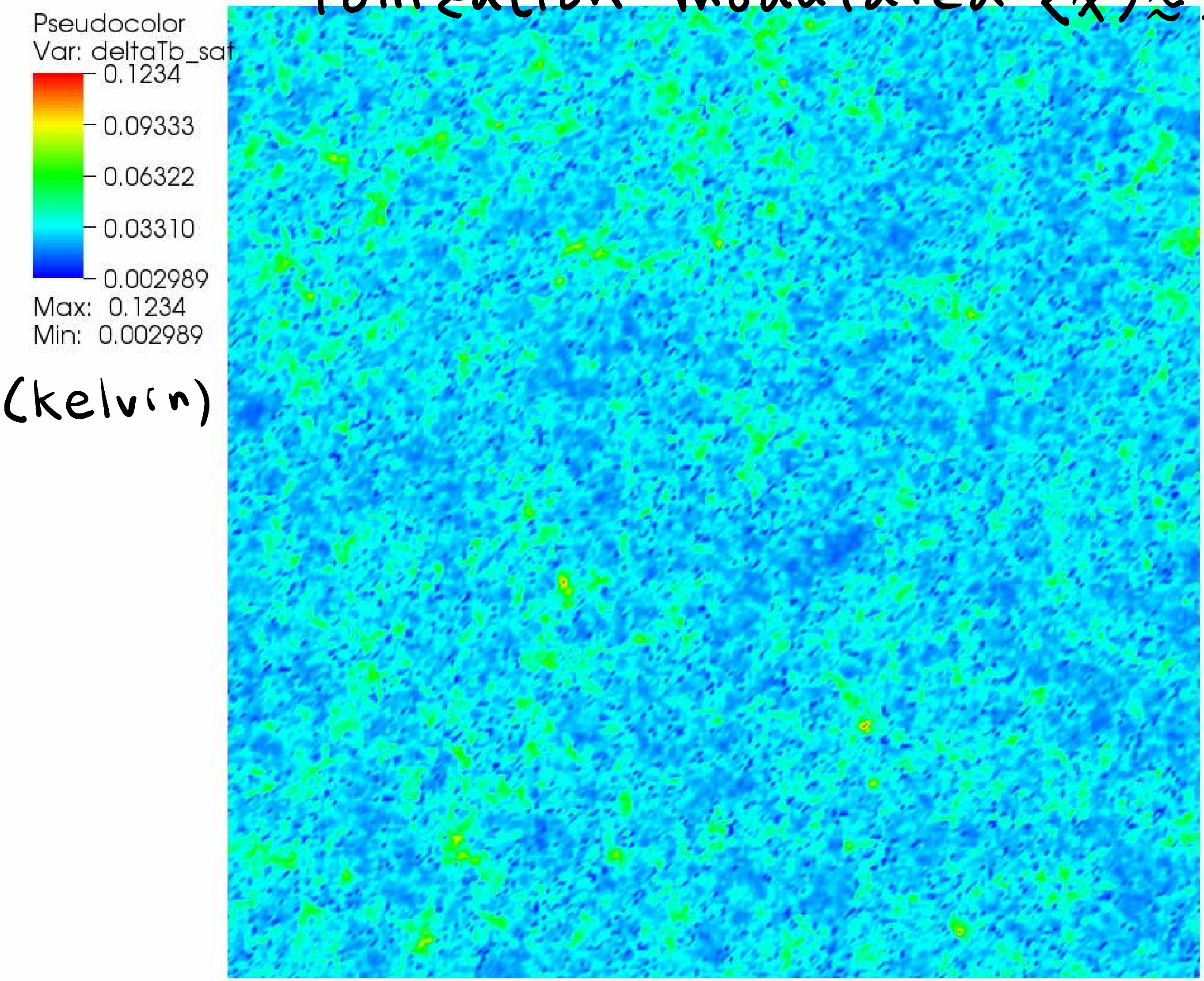

SPT upper limit by Zahnt

Similar behavior by partial ionization: Mesinger+ 2013

# Observational prospects – 21cm background (preliminary)

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

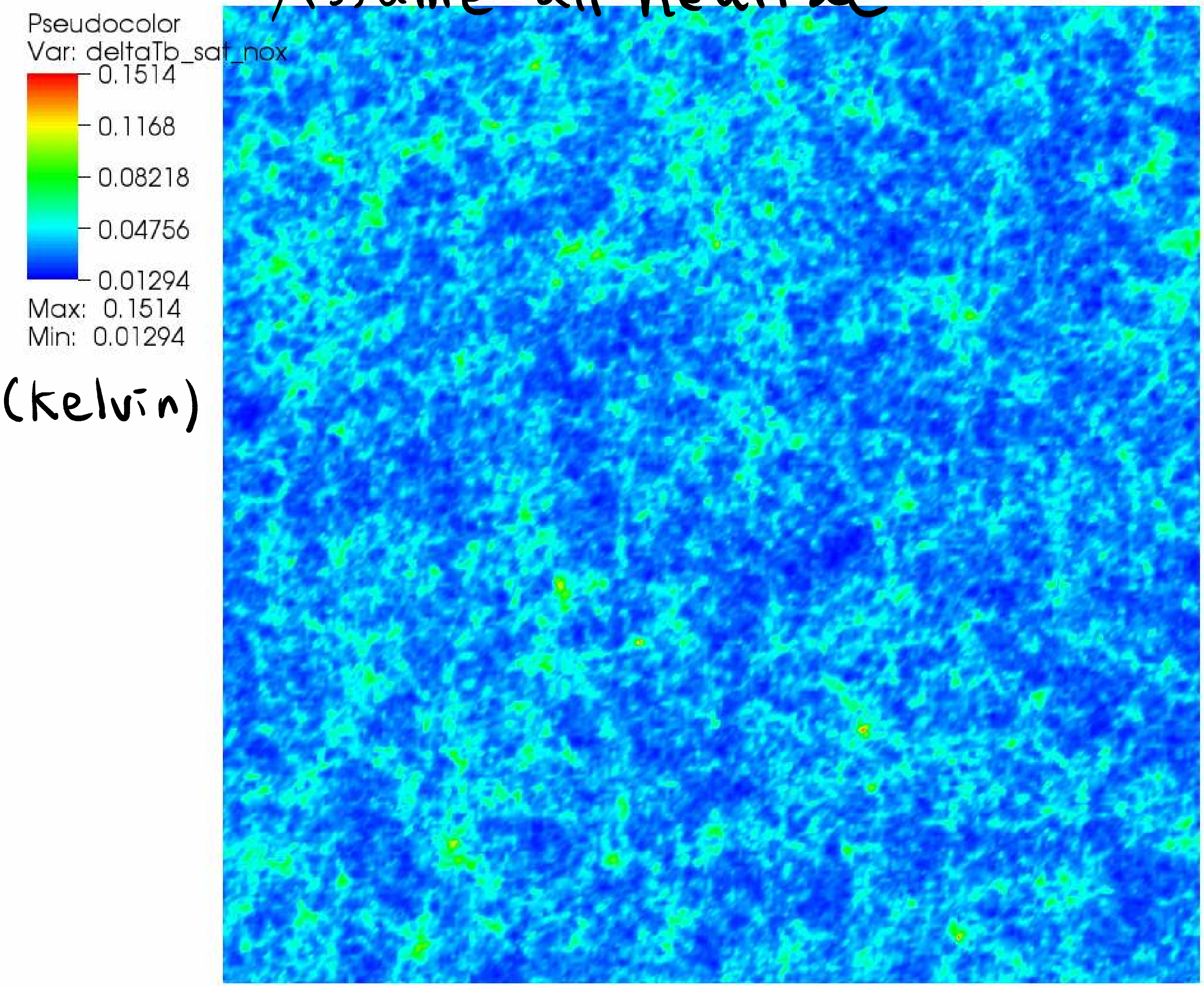
Assume $T_S \gg T_{CMB}$ (x-ray heating)
ionization modulated $\langle x \rangle \approx 20\%$



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

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

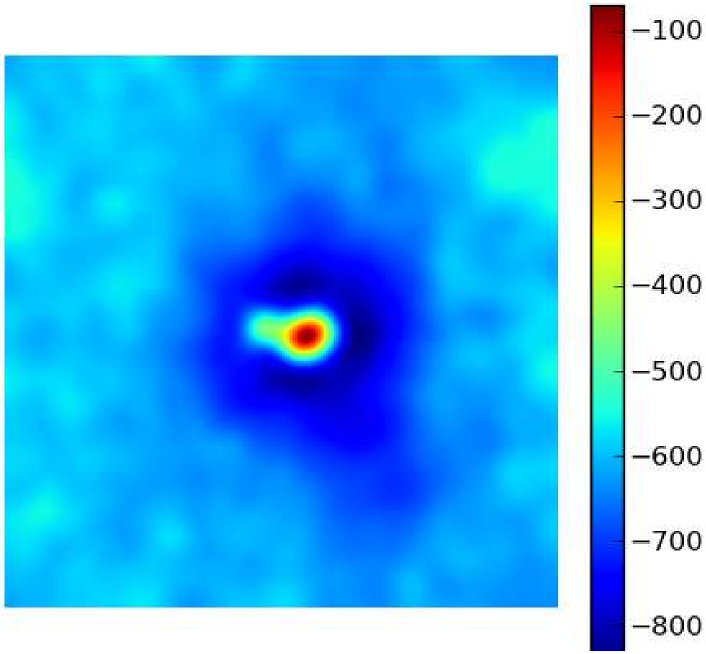
Assume all neutral

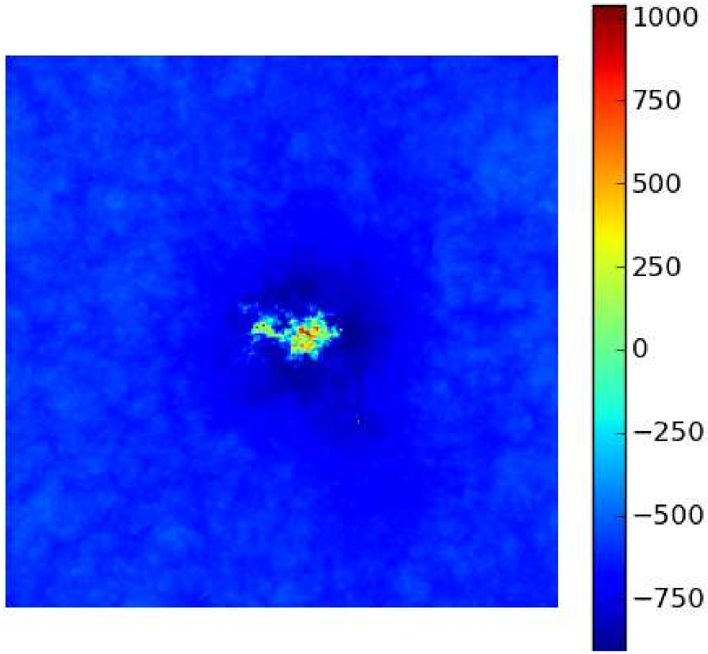



(kelvin)

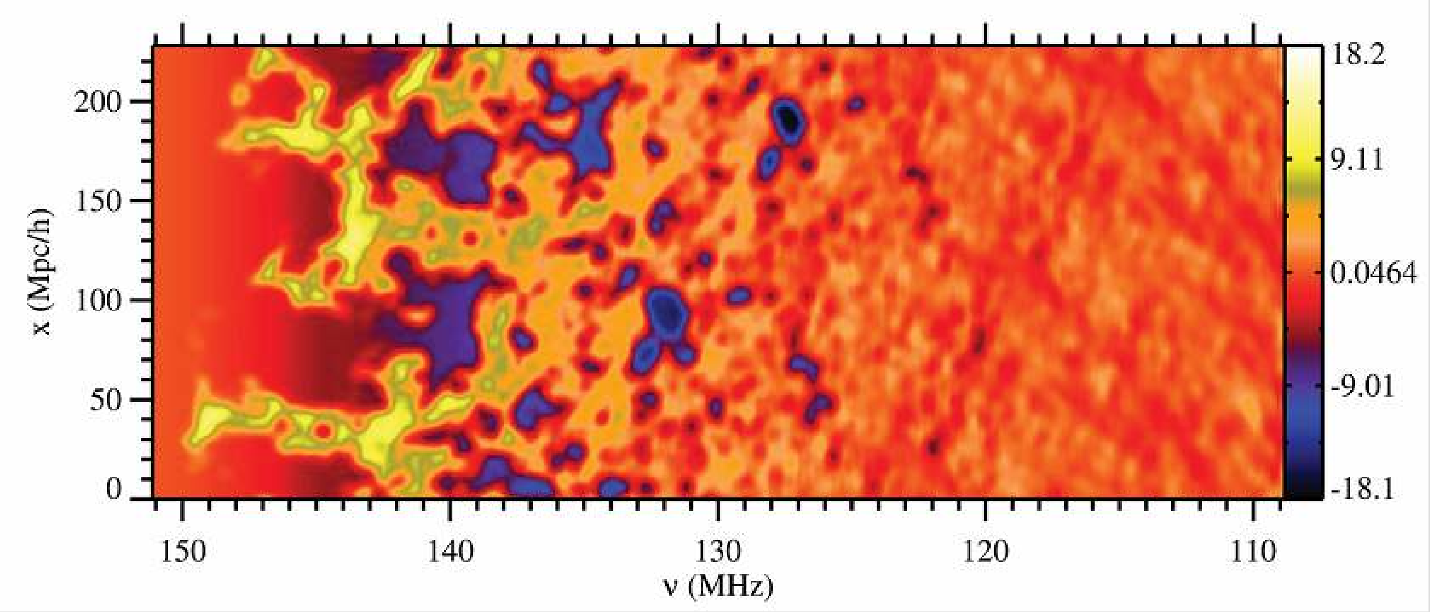
# Weather forecast from San Diego: 21cm forecast (KA+ in prep) for "rare peak" (Xu+ 2013)

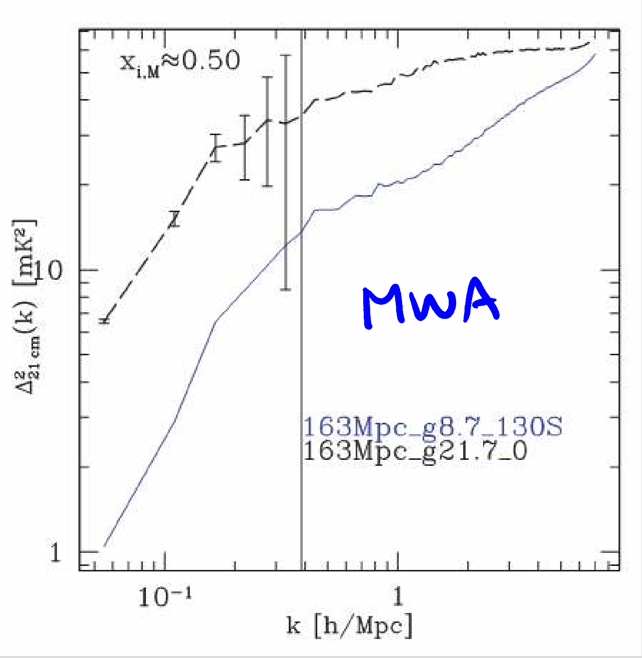
- Very rare, high- density peak
  - size ~ 20 Mpc comoving
  - UV only result (Hao+ 2013)
  - UV (Pop III, Pop II) + X- ray (Pop III) (Hao+ in prep)
- 21cm forecast
  - x- ray heating (Pop III) included
  - Lyman alpha pumping (Pop III, Pop II) by cascading Lyman resonant lines (Pritchard & Furlanetto) included
  - retarded time emissivity
  - rare peak in emission, rest in absorption at ~ several 100 mK (unfiltered)
  - 1', 0.2 MHz filtering (~ SKA) → all in absorption at ~ a few 100 mK



# Of course big-H II bubble structure easier to probe




Iliev+ 2012

# Summary

- New theoretical, observational developments in cosmic reionization

- Minihalo (first stars) included simulation (KA+)
  - full dynamic range for ionizing sources (minihalos+atomic cooling halos) achieved in simulation
  - z~7 LAE (reionization ending) + CMB observations (high optical depth) achieved simultaneously
  - very extended $\Delta z \sim 6.5$, contradicting SPT claim $\Delta z < 4$ (by Zahn+)
  - Planck can smell the first stars! (polarization, 2014)
  - post-Planck EoR language: not just $\{\tau, z_{reion}\}$: $m_1$, $m_2$, $m_3$, …

- Good fun expected before 21cm observation for reionization-history digging (high-z 21cm observation will surely nail it; better kSZ constraint too…)