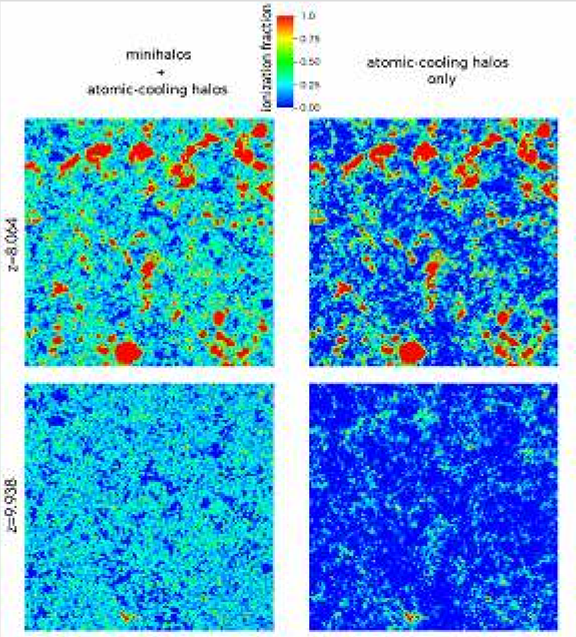
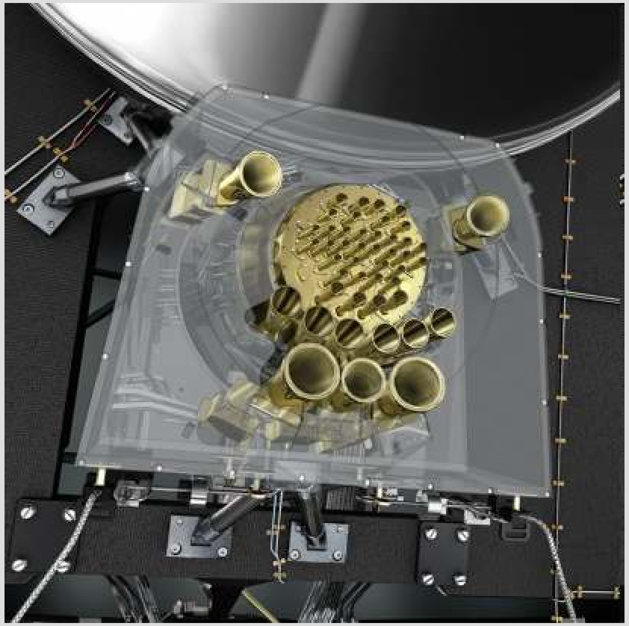
Astrophysics and Cosmology at High Redshifts





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IBS Cosmology/LSS Workshop

Jul 2014

Outline

- Nonlinear Halo bias
- High-z Astrophysics – brief intro
- Current Observational Constraints
- Theory
    - First Stars
    - Cosmic Reionization
    - Cosmology
- Observation
    - Large scale CMB polarization anisotropy
    - Small scale CMB polarization anisotropy
    - 21cm signal

Nonlinear halo bias

(KA, Iliev, Shapiro, Srisawat 2014)

Local real-space bias

- Peak- background split
  - extended Press- Schechter formalism

- Conditional mass function
  - bias in terms of underlying density and filtering scale

$$\left(\frac{dn}{dM}\right)^{\mathrm{L}}_{\mathrm{PS},\,b}(M|\delta_{\mathrm{lin}}) = -\frac{1}{\sqrt{2\pi}}\frac{d\sigma_M^2}{dM}\frac{\bar{\rho}_0}{M}\frac{(\delta_c-\delta_{\mathrm{lin}})\,/D(z)}{\left(\sigma_M^2-\sigma_{R_{\mathrm{cell}}}^2\right)^{3/2}}\exp\left[-\frac{(\delta_c-\delta_{\mathrm{lin}})^2}{2D^2(z)\left(\sigma_M^2-\sigma_{R_{\mathrm{cell}}}^2\right)}\right]$$

(Mo & White 1996)

- deterministic

Combining with top-hat collapse (Mo & White 1996)

- Mass function predictor based on linear theory
- Matching linear δ_{lin} to nonlinear δ

$$\delta = \left(\frac{10\delta_{\rm lin}}{3(1-\cos\theta)} \right)^3 - 1, \quad \delta_{\rm lin} = \frac{3\times 6^{2/3}}{20} (\theta - \sin\theta)^{2/3}, \tag{7}$$

if $\delta > 0$. Similarly, if $\delta < 0$,

$$\delta = \left(\frac{10\delta_{\rm lin}}{3(\cosh\theta - 1)} \right)^3 - 1, \quad \delta_{\rm lin} = \frac{3\times 6^{2/3}}{20} (\sinh\theta - \theta)^{2/3}. \tag{8}$$

- fully nonlinear

Hybrid schme (Barkana & Loeb 2004; KA+ 2014)

- Get "bias" or "boost factor" from peak- background

$$\left(\frac{dn}{dM}\right)^{\rm L}_{{\rm PS},b}(M|\delta_{\rm lin}) \Big/ \left(\frac{dn}{dM}\right)^{L}_{\rm PS}(M)$$

- Multiply to the "matching" average mass function
  - bias in terms of underlying density and filtering scale

$$(1+\delta)\otimes\left(\frac{dn}{dM}\right)^{\rm L}_{{\rm PS},b}(M|\delta_{\rm lin}) \Big/ \left(\frac{dn}{dM}\right)^{L}_{\rm PS}(M) \otimes \left(\frac{dn}{dM}\right)_{N\text{-body}}$$

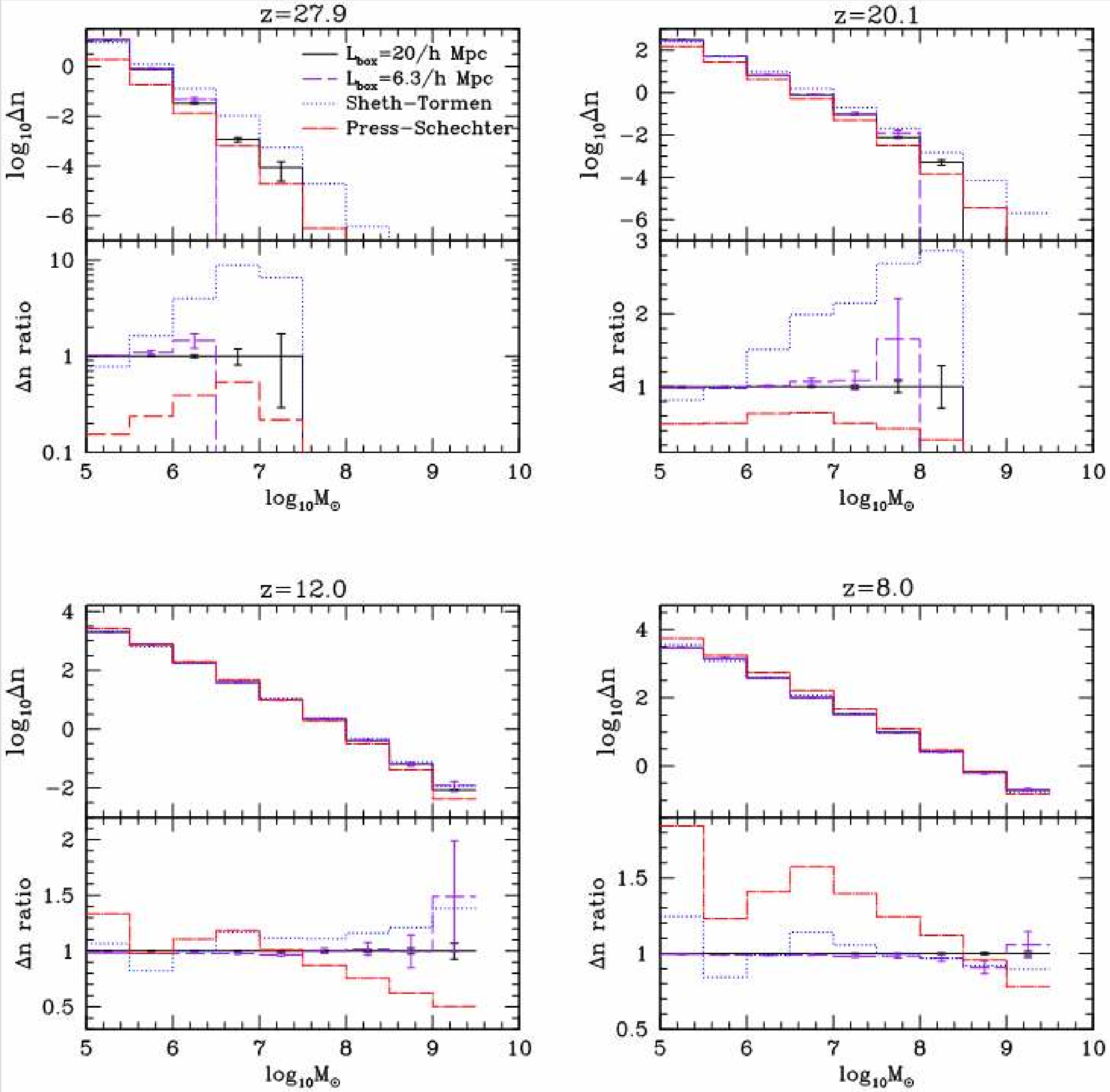
↑ Lagrangian to Eulerian

$\otimes \left(\frac{dn}{dM}\right)_{PS}$?

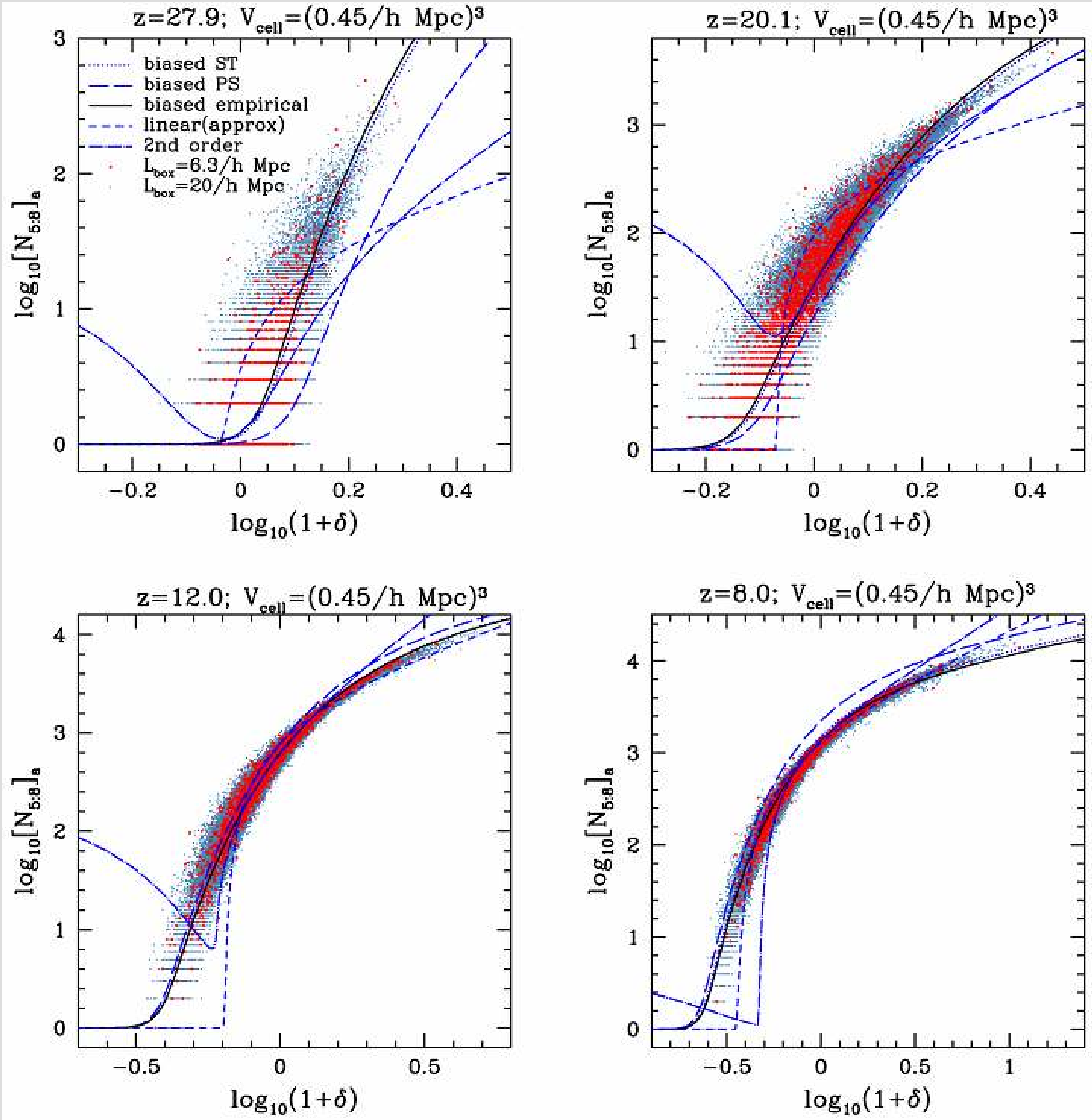
$\otimes \left(\frac{dn}{dM}\right)_{ST}$?

- deterministic

mean mass function (KA+ 2014)



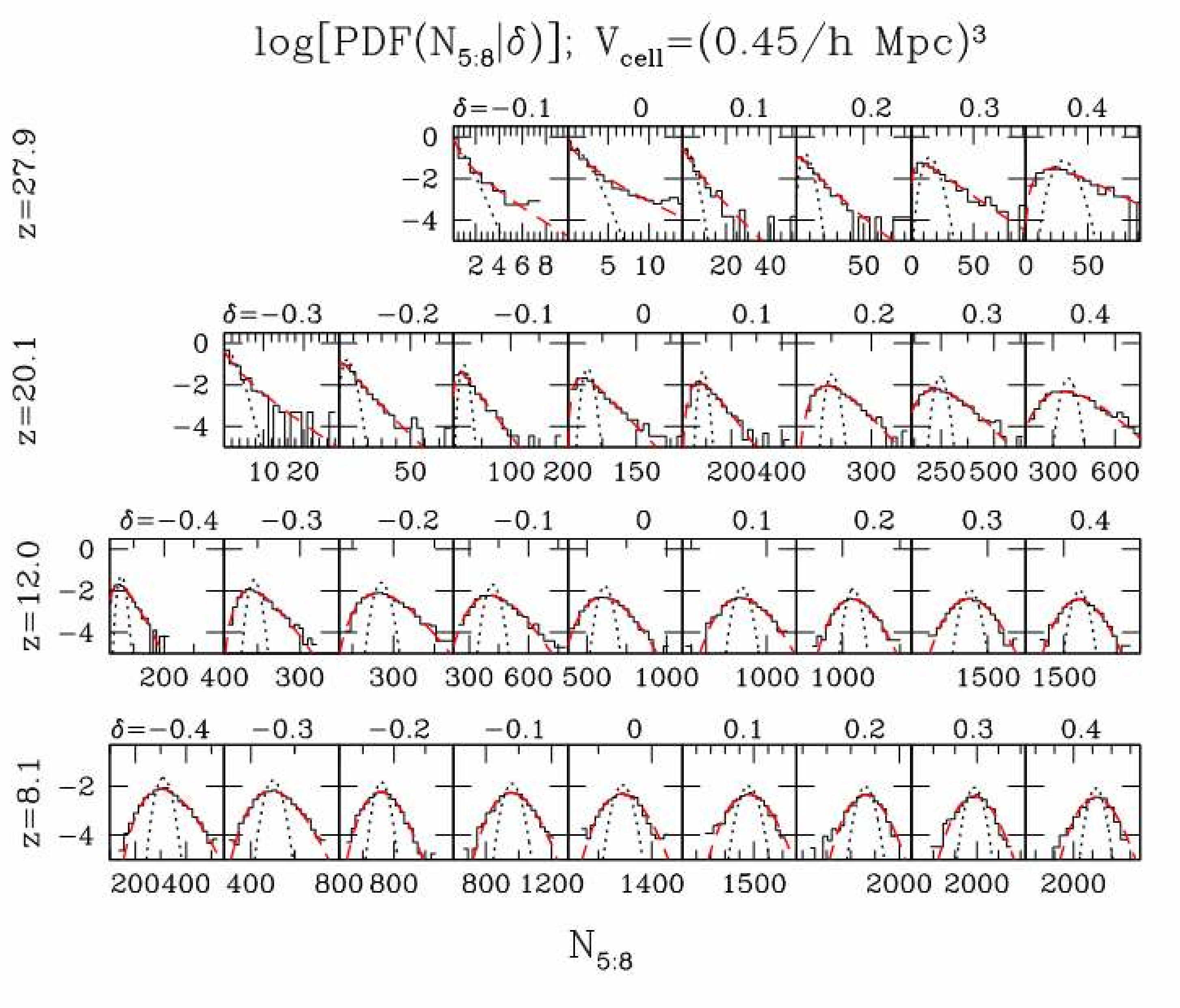
biased mass function (KA+ 2014)



stochasticity (KA+ 2014)

$$[N_1 N_2] = \left(\frac{[N]}{V_{\rm cell}}\right)^2 dV_1 dV_2 \, \{ \ldots$$

$$\sigma^2(\delta) \equiv \left[(N-[N])^2\right] = [N] + \Delta_{\rm scc}(\delta)$$



stochasticity (KA+ 2014)

$$[N_1 N_2] = \left(\frac{[N]}{V_{\rm cell}}\right)^2 dV_1 dV_2 \ \{1 + \overline{\xi_{12}}(\delta)\}$$

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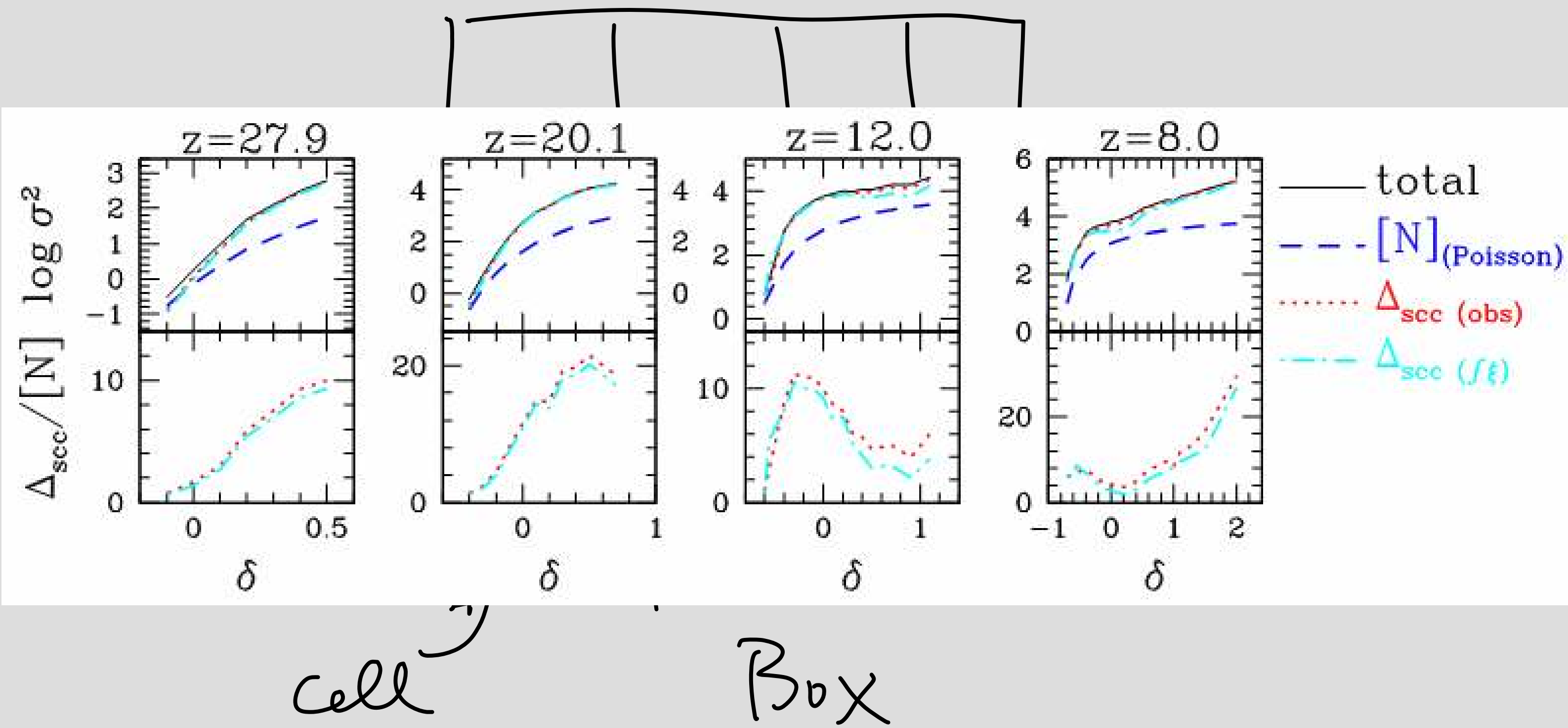

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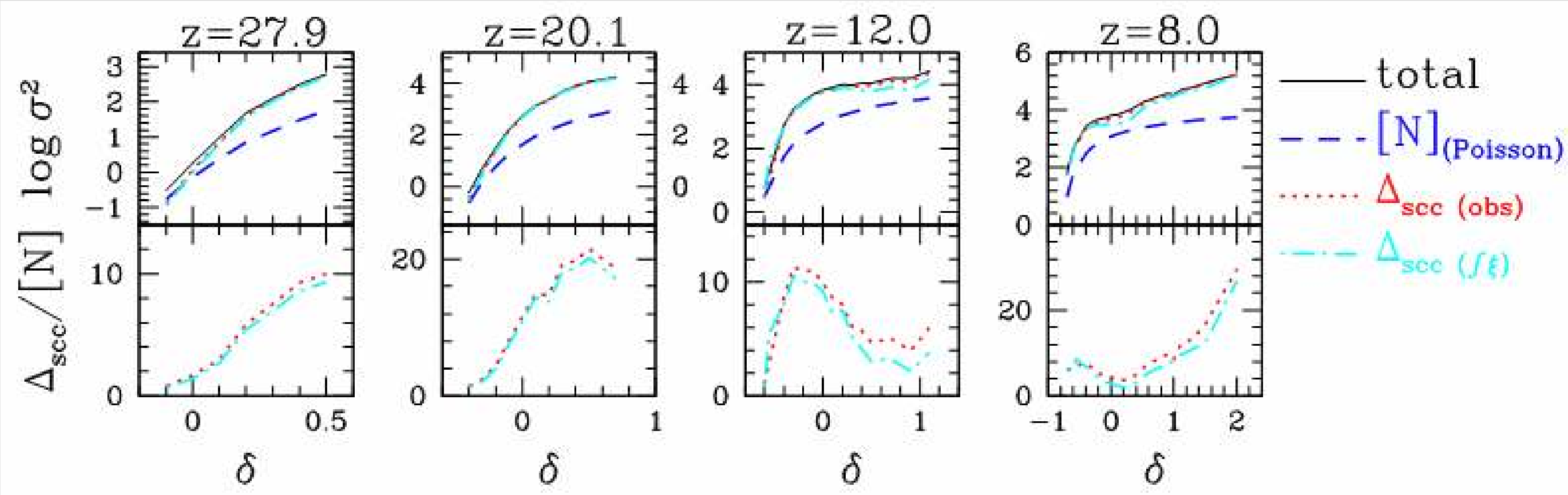
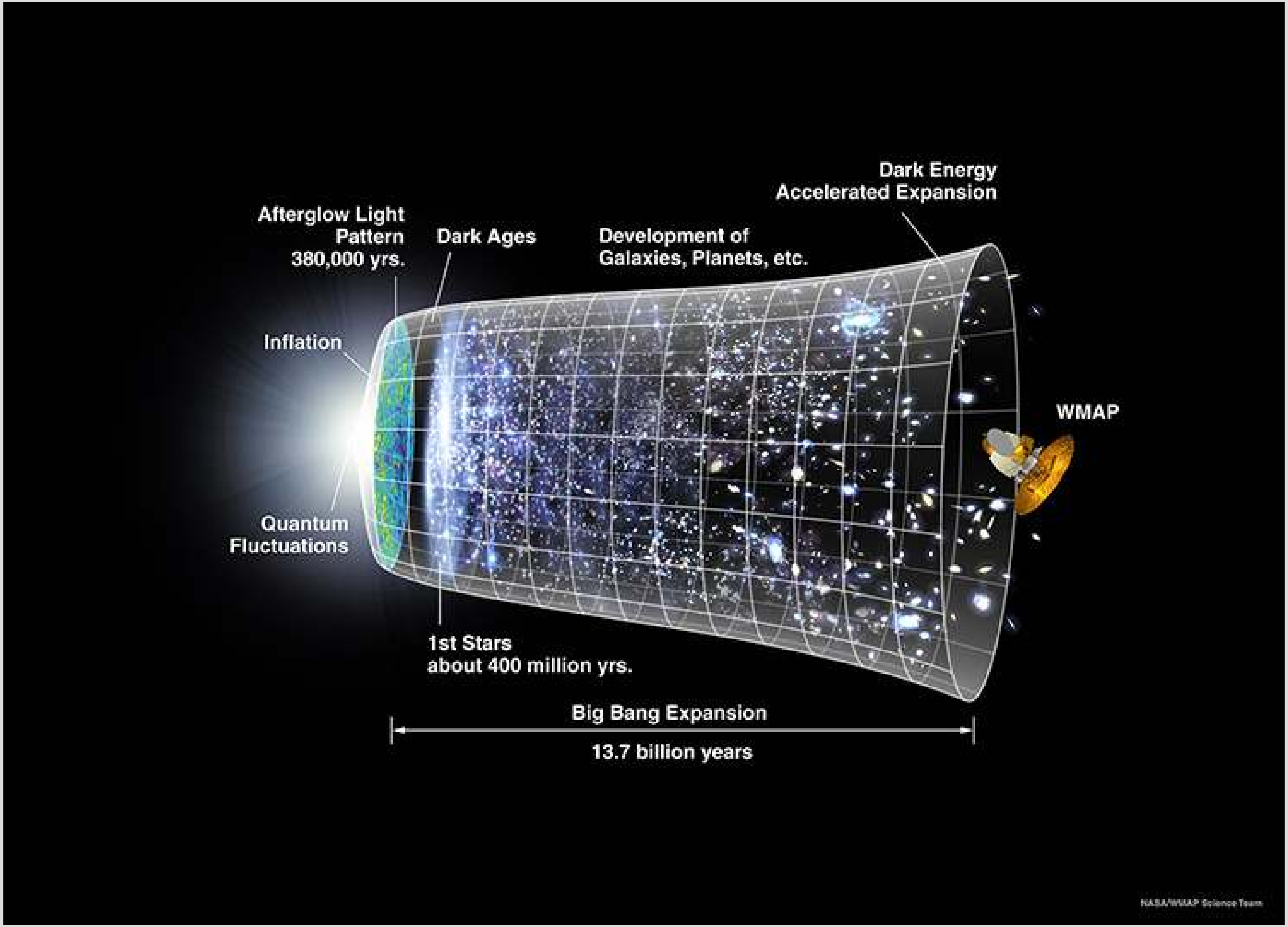


High-z Astrophysics – brief intro

Cosmic History in a Nutshell



Breakdown of High-z Universe

- Dark Ages: z =~ 1100 to ~ 40
  - Structure mostly linear
  - (almost) no stars

- Epoch of Reionization (EoR): z =~ 40 to ~ 7
  - Radiation sources emit H and He ionizing radiation
  - Global ionized fraction <x> increases in time, to reach ~ 1 at z~ 7
  - Universe stays ionized afterwards
  - Cosmic Dawn (CD), then main EoR (breakdown model-dependent, but roughly @ z~ 20- 15)

Why do high-z astrophysics / cosmology??

- golden era of precision cosmology
  - WMAP, Planck, SPT, ACT, BICEP, … → cosmological initial condition

- chance for astrophysics in cosmological perspective!
  - high redshift, nothing's been detected
  - astrophysics at primordial environment

- chance for high- z cosmology
  - wider range of k is linear → more accessible by linear theory
  - who knows there won't be surprise?

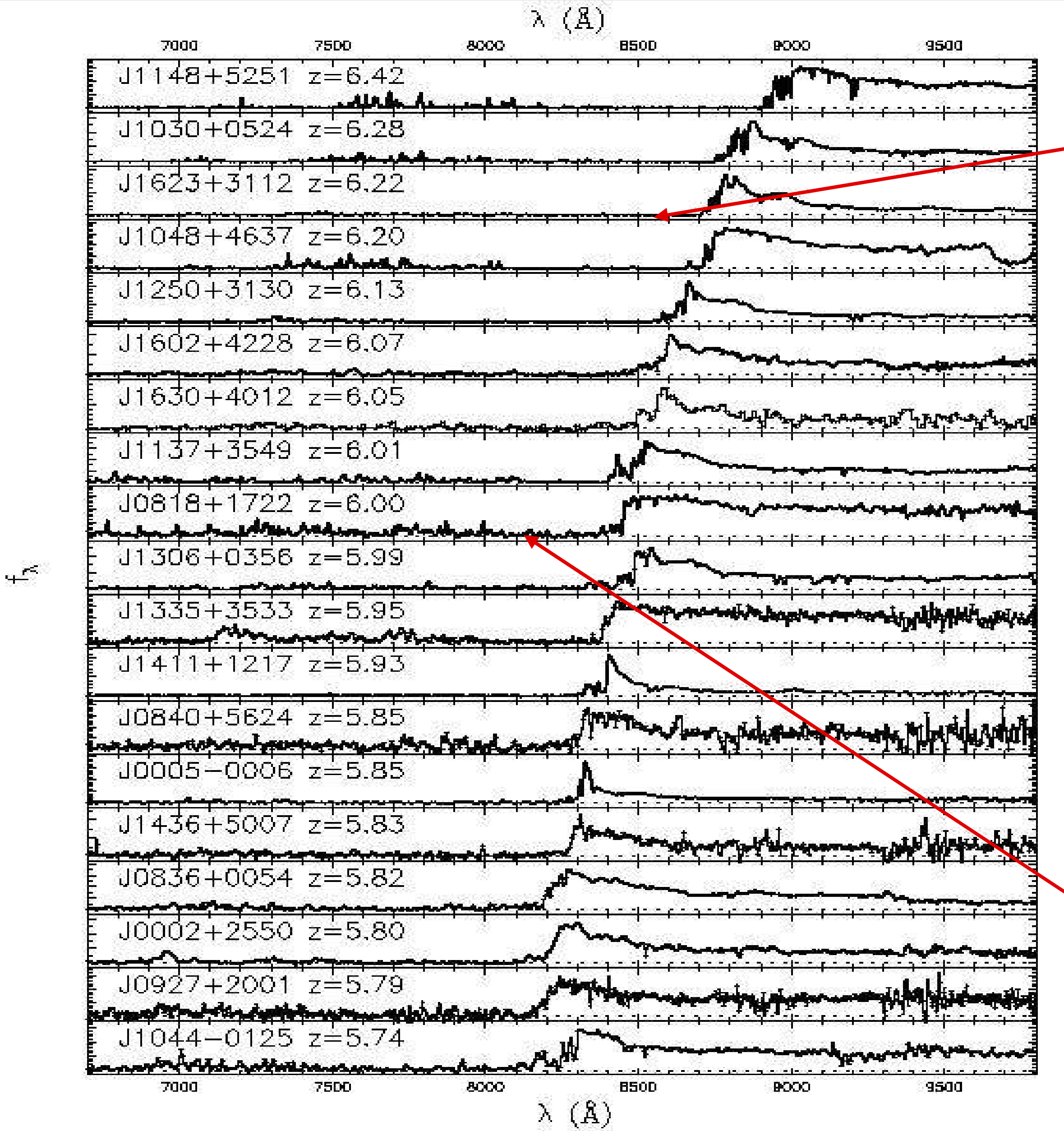
- understanding properties of high- redshift objects

Observational constraints

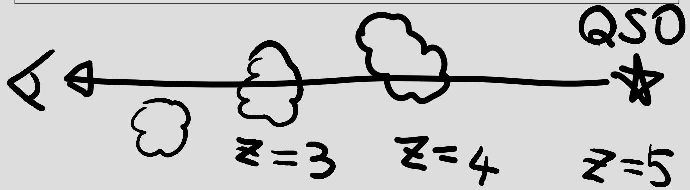
Current observational constraints on Reionization

- 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)



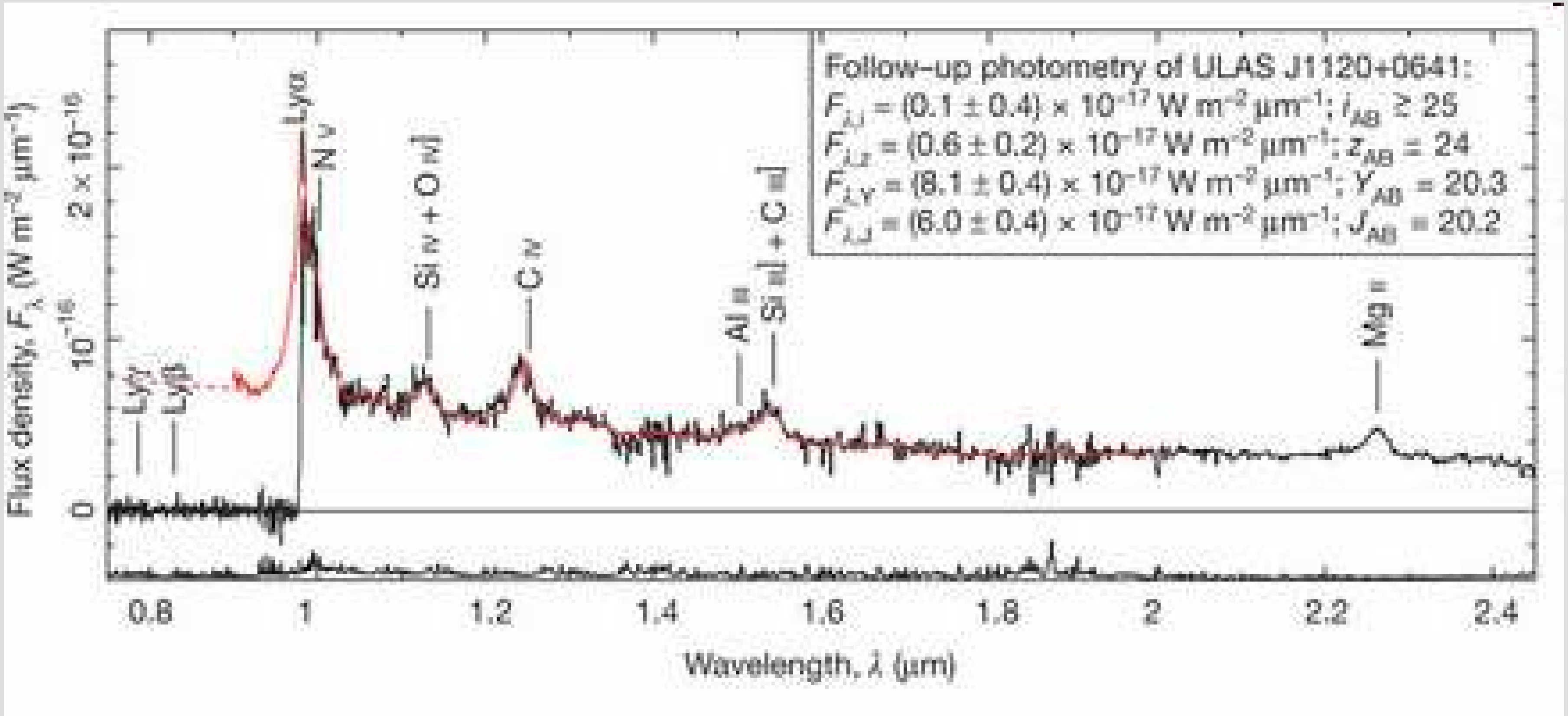
Abrupt change of intergalactic Lyα optical depth across z≈6.

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

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

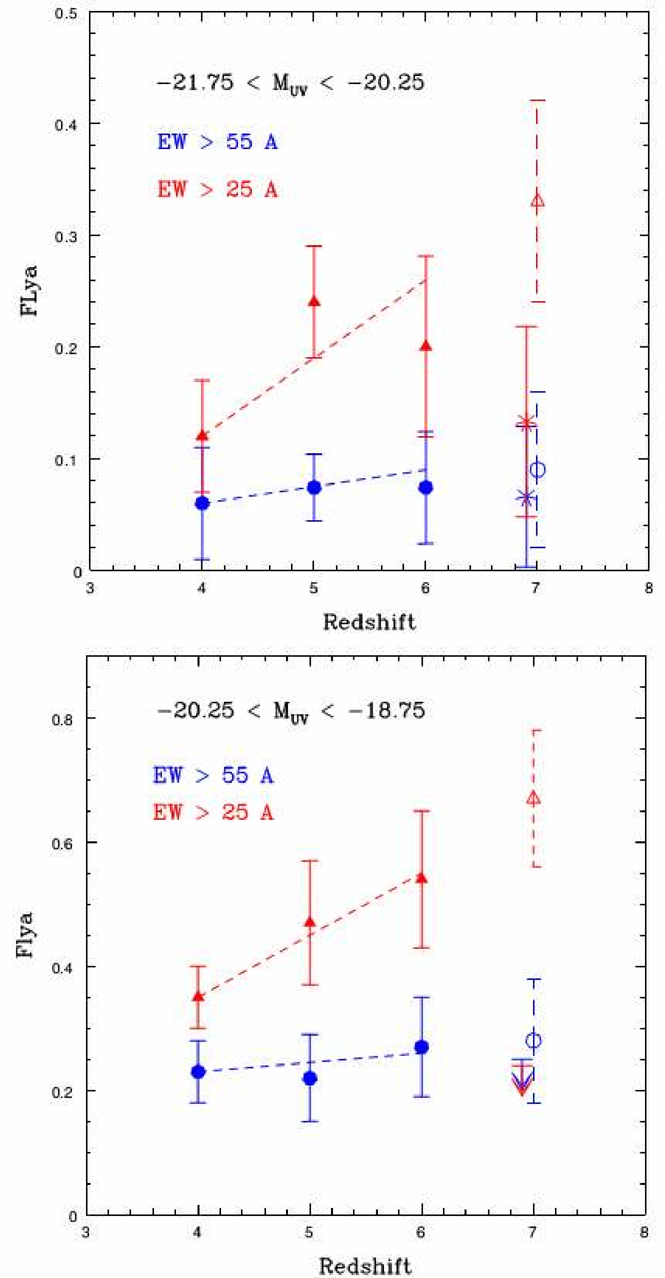
Lyα forest

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)



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

Decline of FLyα at z≈7.

→ large HI fraction at z ≈7

→ reionization ended at z < 7 !!

Current observational constraints on Reionization

- Electron content
  - kinetic Sunyaev- Zeldovich effect on CMB
  - South Pole Telescope:
    z(x=99%)- z(x=20%) ~ 4.4 – 7.9 (2σ level, Zahn+ 2011)

- 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 polarization, 1σ level)

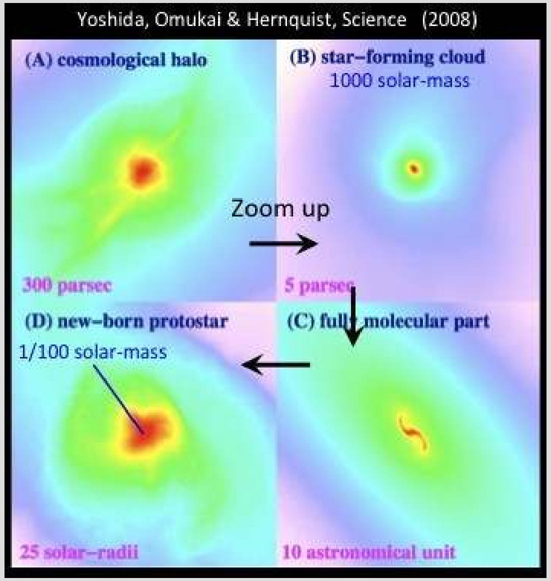
$$\tau = \int_{z_{\text{reionization beginning}}}^{z=0} n_e \sigma_T \, dl$$

- τ suppresses CMB temperature power spectrum (C_l) by $\sim e^{-2\tau}$
- τ affects CMB polarization

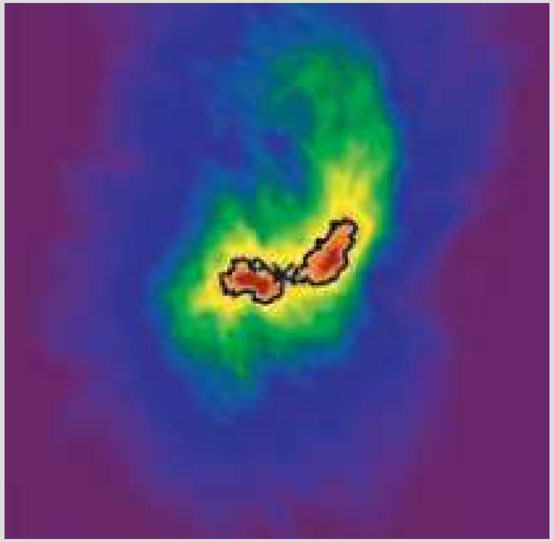
New developments in astrophysics

New developments - First star formation

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

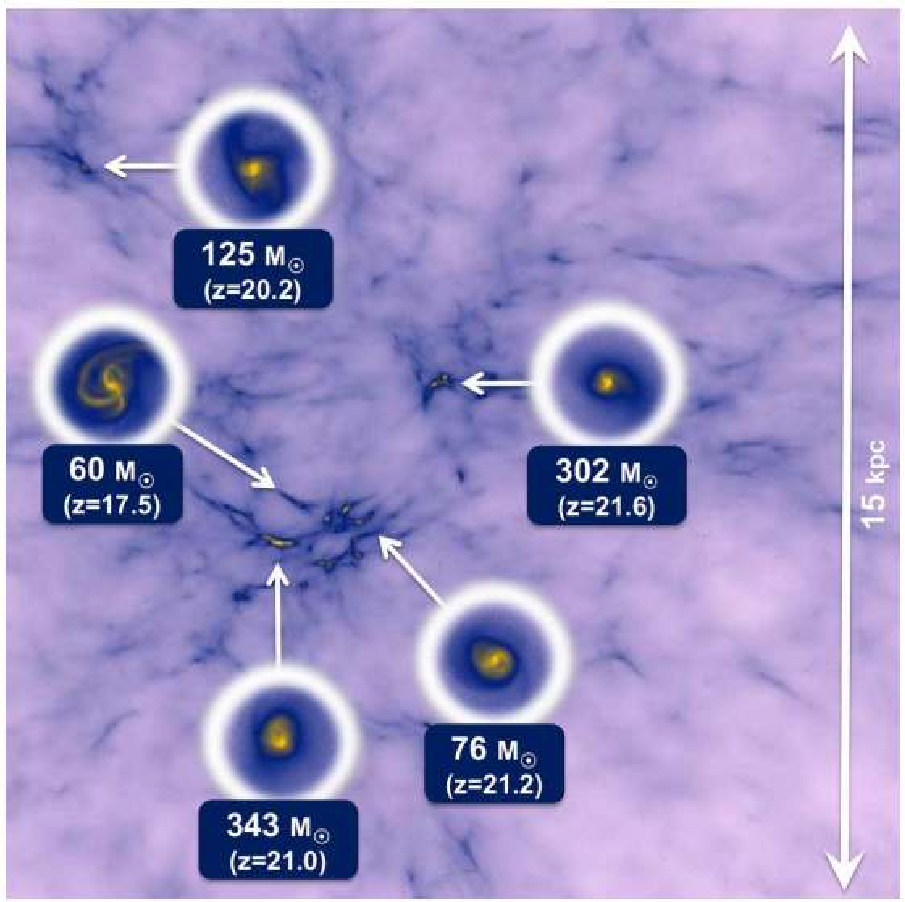


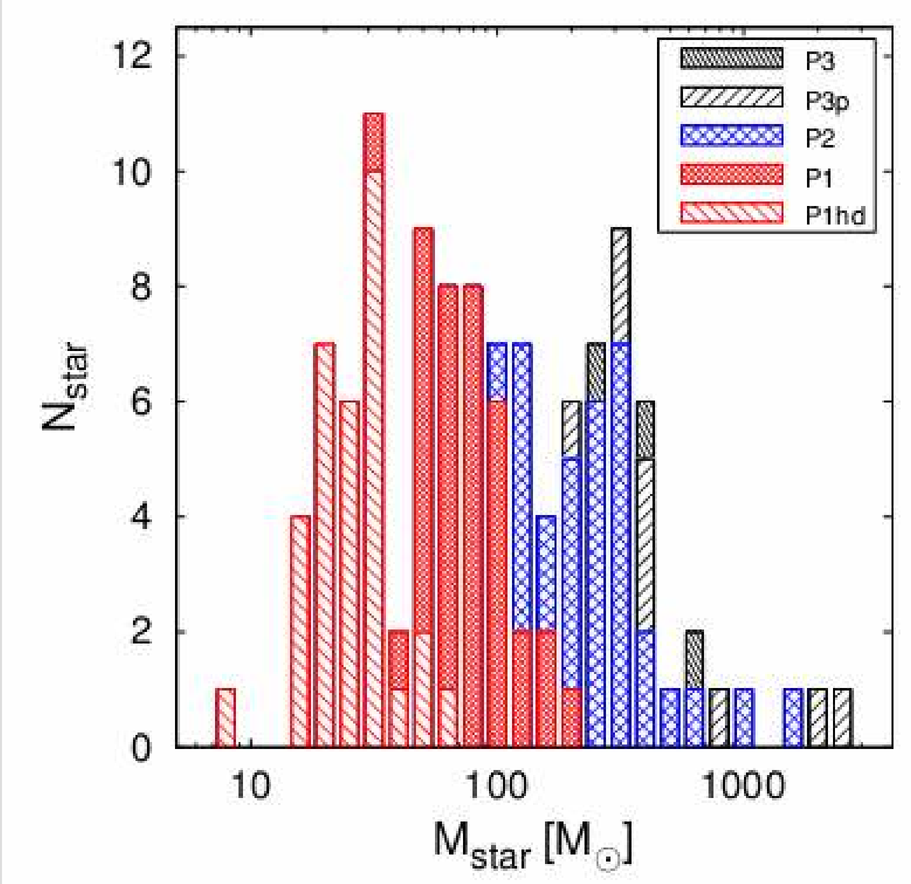
- paradigm shift? (e.g. Turk, Abel, O'Shea 2009)
  - 1 binary / 1 halo
  - stars ~ 7 $M_\odot$ + ~ 20 $M_\odot$ → weaker UV output?
  - stellar binary → x- ray binary → x- ray source?



New developments - First star formation

- 110 First Star simulation
  - Hirano+ (2014)





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)
  - heating → 21cm boost (McQuinn & O'Leary 2012)

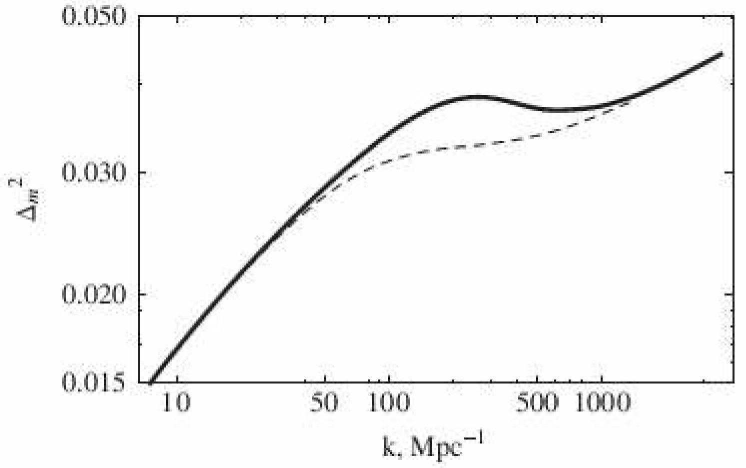
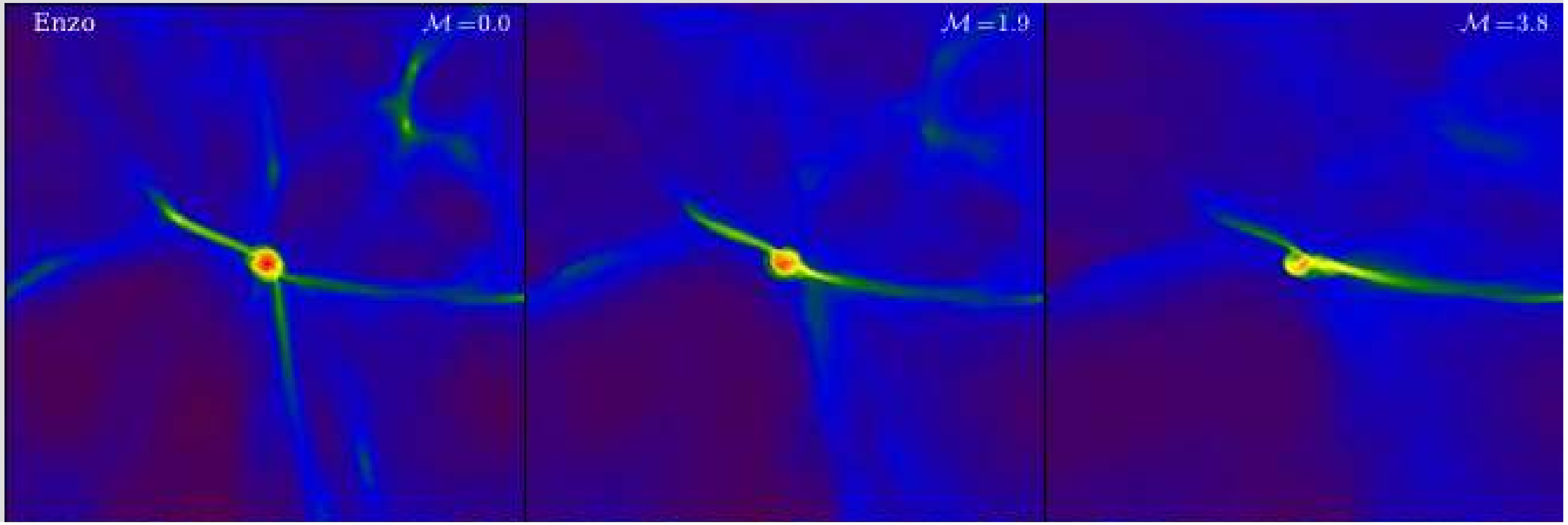


FIG. 2. Power spectrum of matter distribution in the first order CDM model (solid line) and with the v_{bc} effect included (dashed line) at the redshift of $z = 40$.



New developments - First star formation

- Cosmology what??
  - McQuinn & O'Leary (2013)
  - power spectrum by density fluctuation & offset-velocity fluctuation
  - offset- velocity (from Tseliakhovich & Hirata 2010)

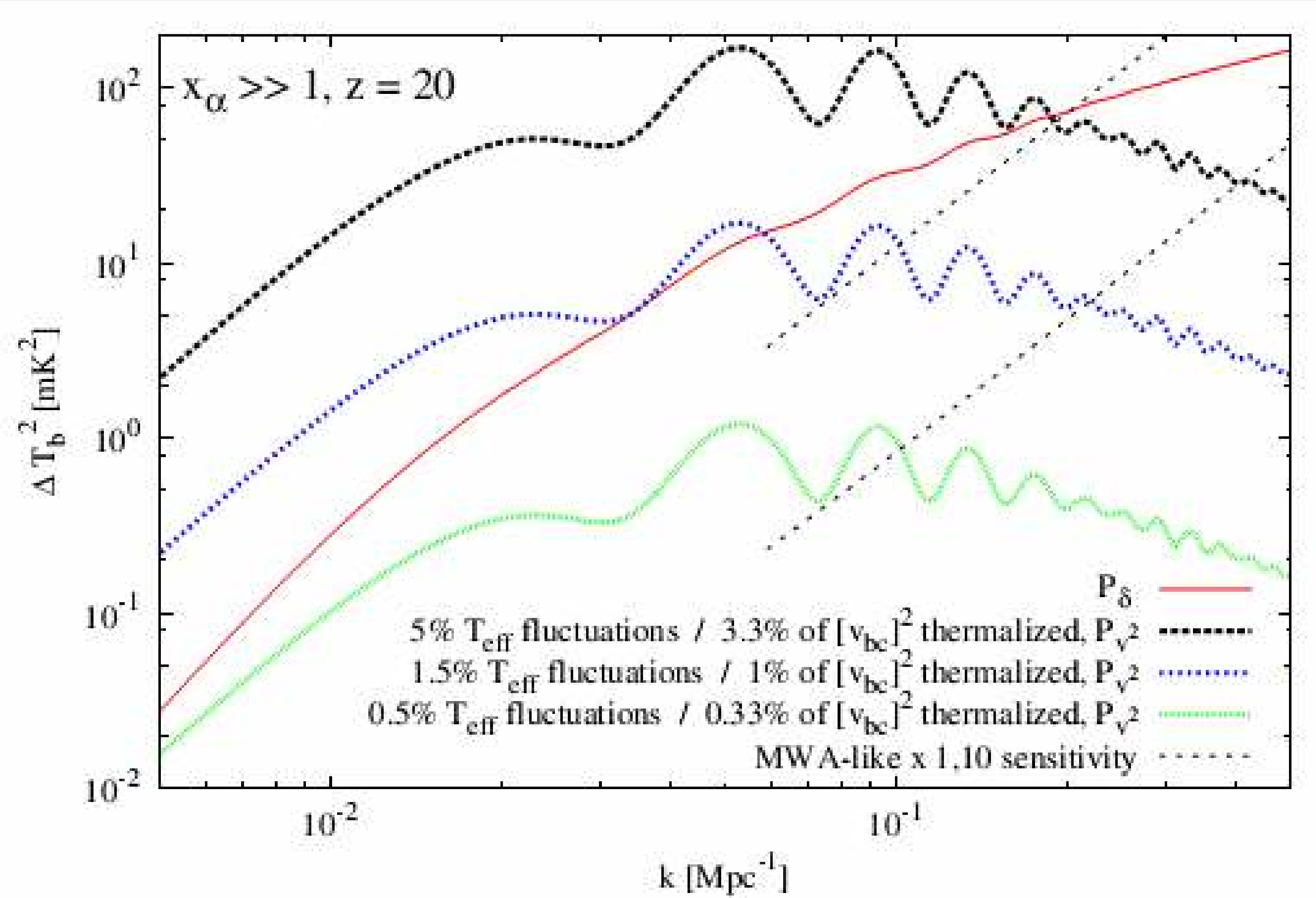
$$\tilde{v}_{\rm bc}(\boldsymbol{k}) = -i\,\frac{a\,\boldsymbol{k}}{k^2}[\dot{T}_c(k,a) - \dot{T}_b(k,a)]\tilde{\delta}_{\rm pri}$$

$$\delta T_b^{21\ {\rm cm}} \approx \bar{T}_b^{21\ {\rm cm}}\left(1 + \delta_b + \frac{1}{1+\bar{x}_\alpha}\delta_\alpha + \frac{T_{\rm CMB}}{\bar{T}_{\rm K} - T_{\rm CMB}}\delta_T - \delta_{\nabla v}\right)$$

$$\bar{T}_b^{-2} P_{21}(\boldsymbol{k}) \approx \left(1 + \frac{b_{\delta,\alpha}\,\tilde{W}_\alpha(k)}{1+\bar{x}_\alpha} + \frac{T_{\rm CMB}\,b_{\delta,T}}{\bar{T}_{\rm K} - T_{\rm CMB}} + \mu^2\right)^2 P_\delta(k) + \left(\frac{b_{v^2,\alpha}\,\tilde{W}_\alpha(k)}{1+\bar{x}_\alpha} + \frac{T_{\rm CMB}\,b_{v^2,T}}{\bar{T}_{\rm K} - T_{\rm CMB}}\right)^2 P_{v^2}(k), \quad (16)$$

New developments - First star formation

- Cosmology what??
  - McQuinn & O'Leary (2013)
  - power spectrum may be dominated by T&H effect!



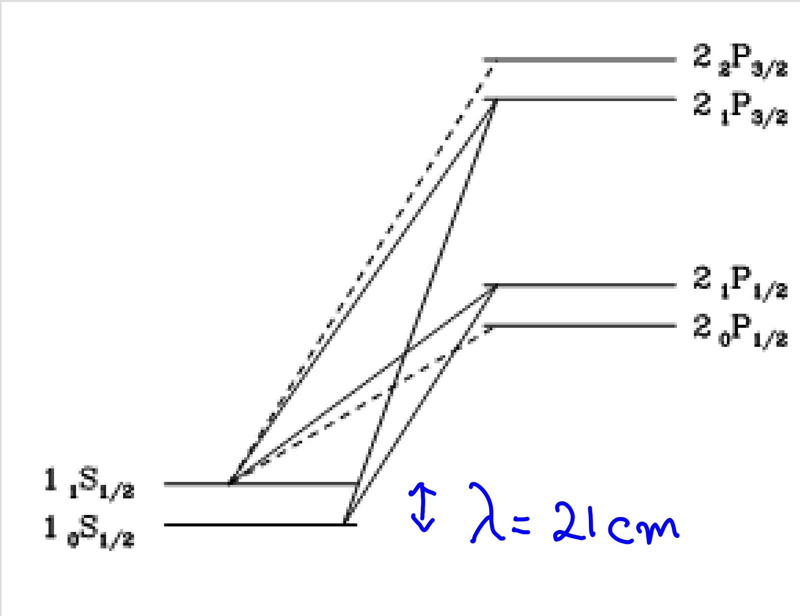
Separating Cosmology from Astrophysics

High-z (z>7) observation

- 21cm line emission
  - from neutral hydrogen
  - good tracer of density fluctuation
  - also traces radiation fluctuation

What determines 21cm strength

- CMB
  - 21cm absorption/emission
- collision
  - kinetic 21cm excitation/deexcitation
- Lyα pumping (Wouthysen- Field effect)
  - 1s → 2p → 1s



$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

T_S : spin temperature

T_R : CMB temperature

T_K : gas temperature

T_α : Lyα brightness temperature ($T_\alpha \approx T_K$)

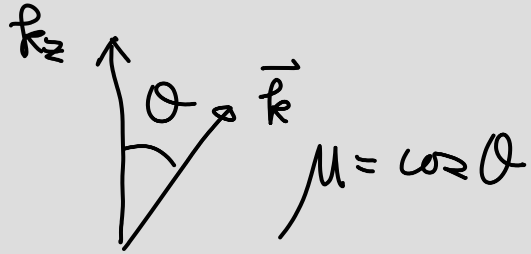
- signal strength

$$\delta T_b = \frac{T_S - T_R}{1+z}(1 - \mathrm{e}^{-\tau_\nu}) \approx \frac{T_S - T_R}{1+z}\tau$$

$\propto n_{HI}$ when $T_S \gg T_R$

Separating Cosmology : Astrophysics (Mao+ 2012)

- Cosmology
  - cosmological parameters: May improve on cosmology through CMB



- Astrophysics
  - source emissivity
  - source clustering

- But two physics appear mixed

- Separation possible in the linear regime
  - μ- decomposition scheme

$$P_{\delta T_b} = P_{\mu^0} + \mu^2 P_{\mu^2} + \mu^4 P_{\mu^4}$$

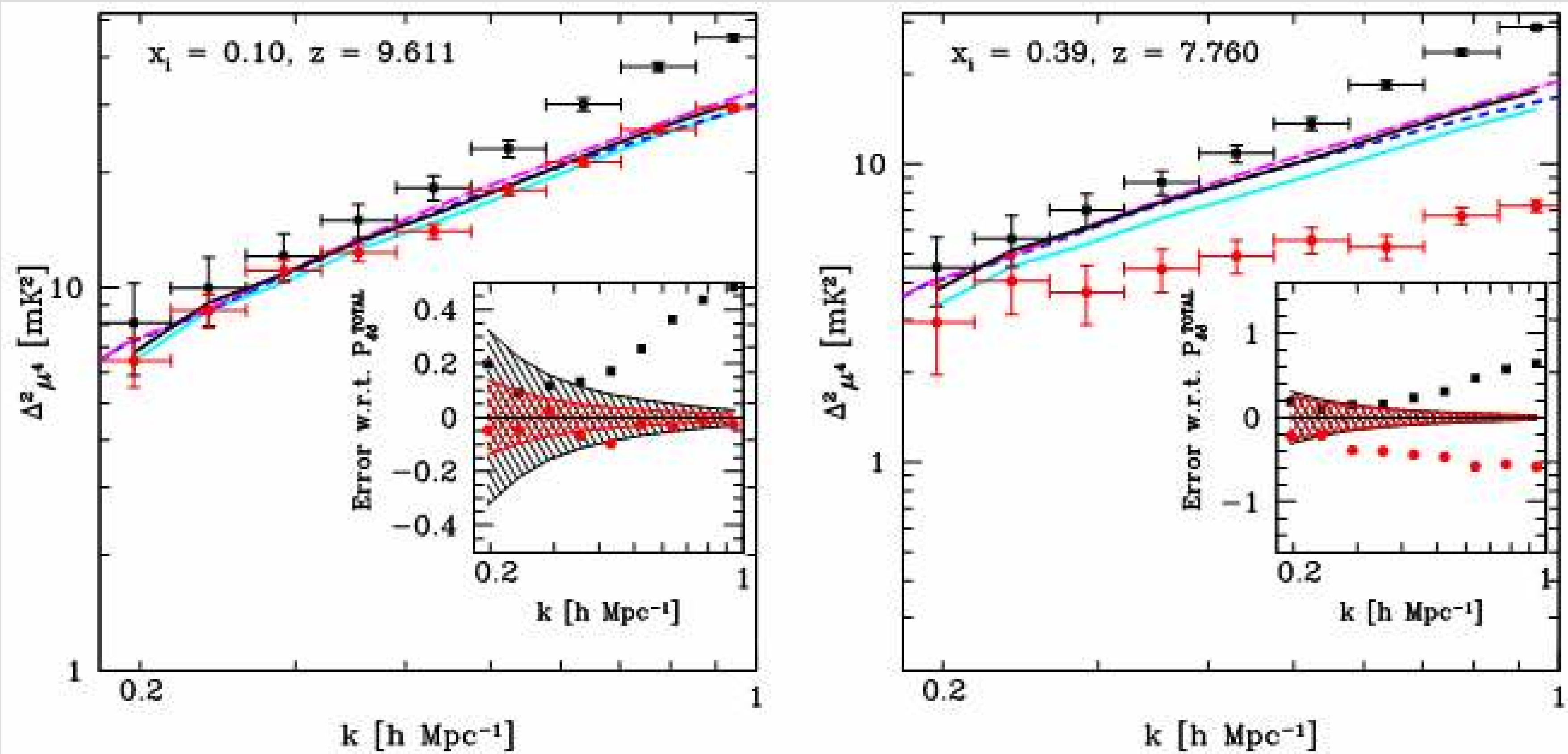
$$\begin{aligned}
P_{\mu^0}(k) &= \left(\widehat{\delta T}_b \bar{\eta}\right)^2 \Big[P^r_{\delta_{\rho_{\rm HI}},\delta_{\rho_{\rm HI}}}(k) + P^r_{\delta_\eta,\delta_\eta}(k) \\
&\quad + 2P^r_{\delta_{\rho_{\rm HI}},\delta_\eta}(k)\Big] \,, \\
P_{\mu^2}(k) &= 2\left(\widehat{\delta T}_b \bar{\eta}\right)^2 \Big[P^r_{\delta_{\rho_{\rm HI}},\delta_{\rho_{\rm H}}}(k) + P^r_{\delta_\eta,\delta_{\rho_{\rm H}}}(k)\Big] \,, \\
P_{\mu^4}(k) &= \left(\widehat{\delta T}_b \bar{\eta}\right)^2 P^r_{\delta_{\rho_{\rm H}},\delta_{\rho_{\rm H}}}(k) \,,
\end{aligned}$$

← Astro-physics (P_{μ^0}, P_{μ^2})

← cosmology (P_{μ^4})

Separating Cosmology : Astrophysics (Mao+ 2012)

- works in "linear" regime in
  - matter density fluctuation
  - ionization density fluctuation



Let’s simulate cosmic reionization with First Stars

- Process is nonlinear and directional: (usually) 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

Numerical Simulations of Reionization

- Process is nonlinear and directional: (usually) need simulation

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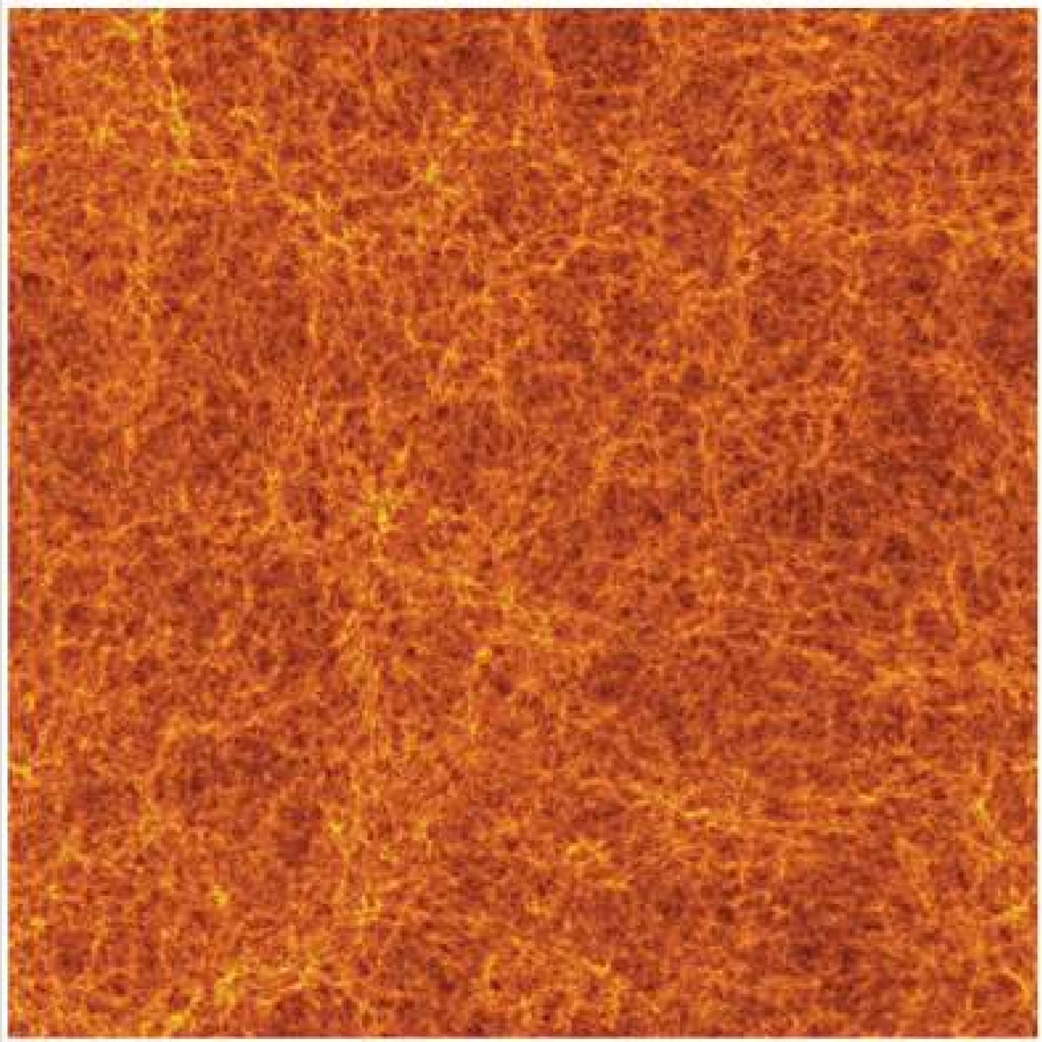
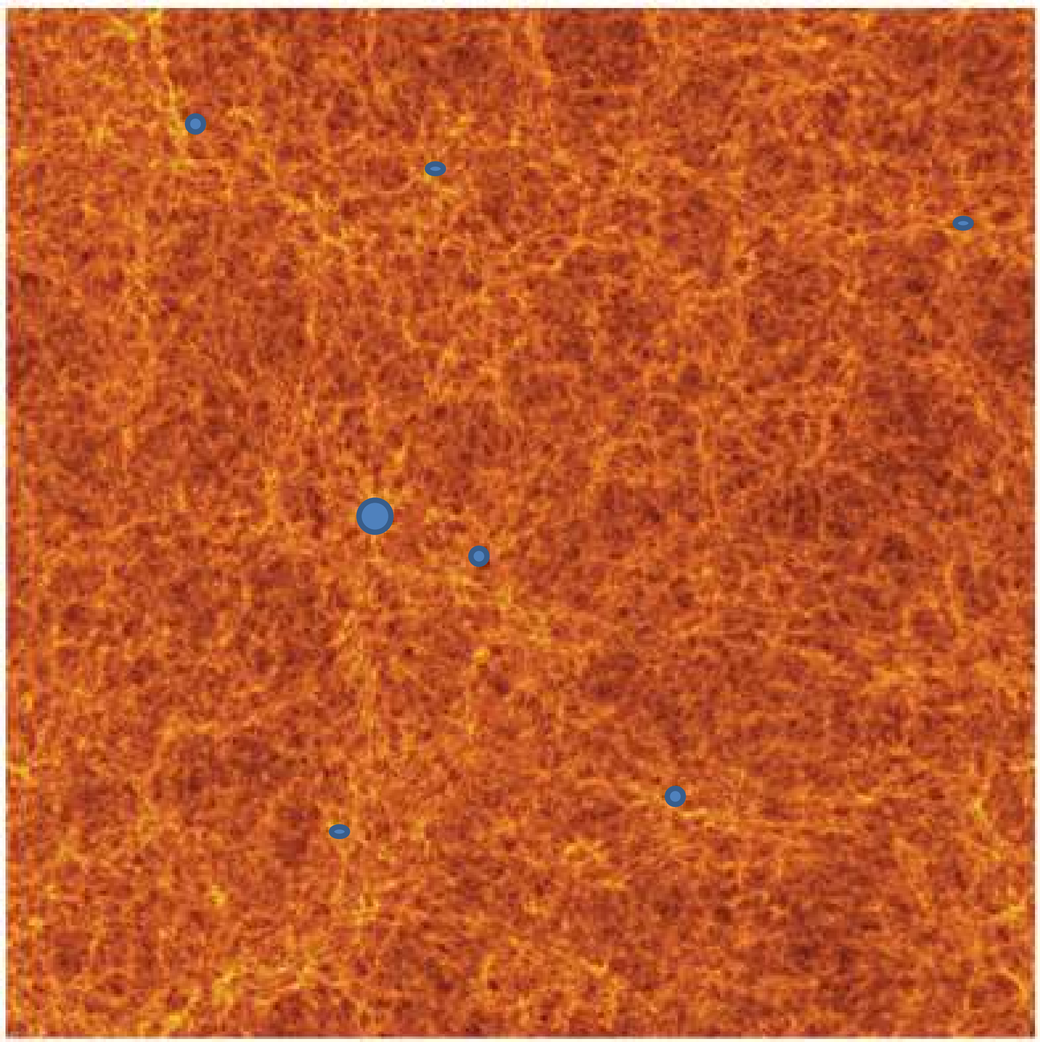
Simulation of Cosmic Reionization – 1. N-body simulation

density field



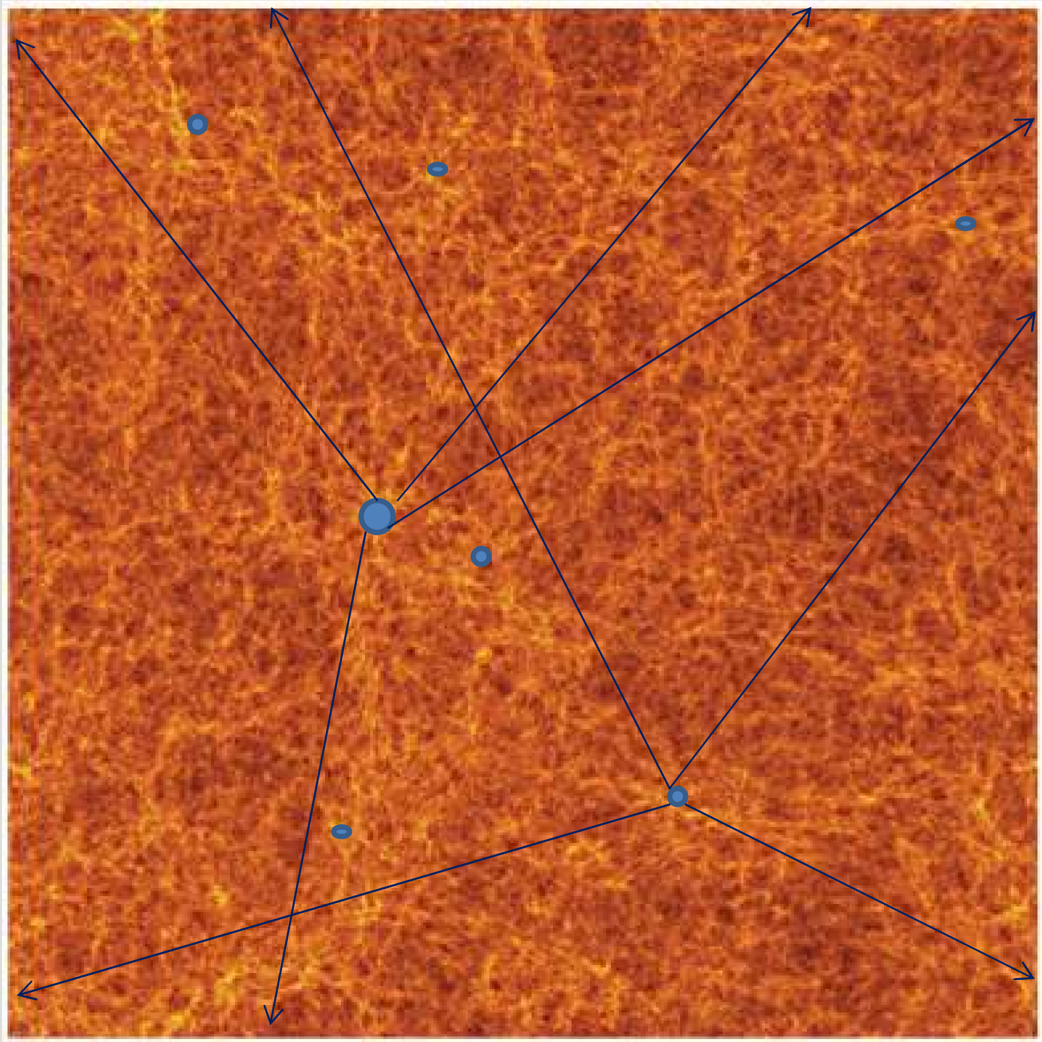
Simulation of Cosmic Reionization – 2. Halo Identification

Halo → Star → ionizing photon



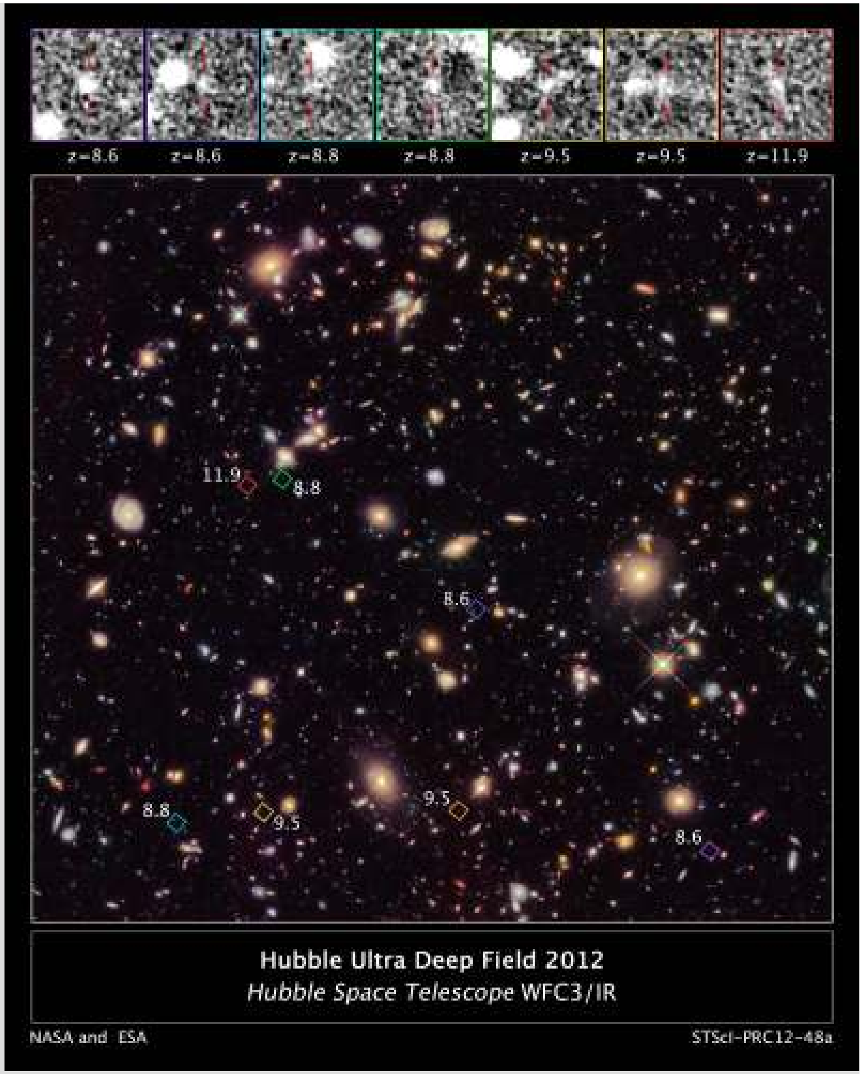
Simulation of Cosmic Reionization – 3. Ray tracing

- Draw rays into all directions from each source
- Along each ray, perform radiative transfer + chemistry calculation



Motivation/Puzzle/Our answer

- Lost photon budget
  - first stars in minihalos
- Late reionization(z_{ov}<7) & high τ 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 τ); Wyithe & Cen; …
  - inhomogeneous physical processes → Yes, we still need numerical simulations!!



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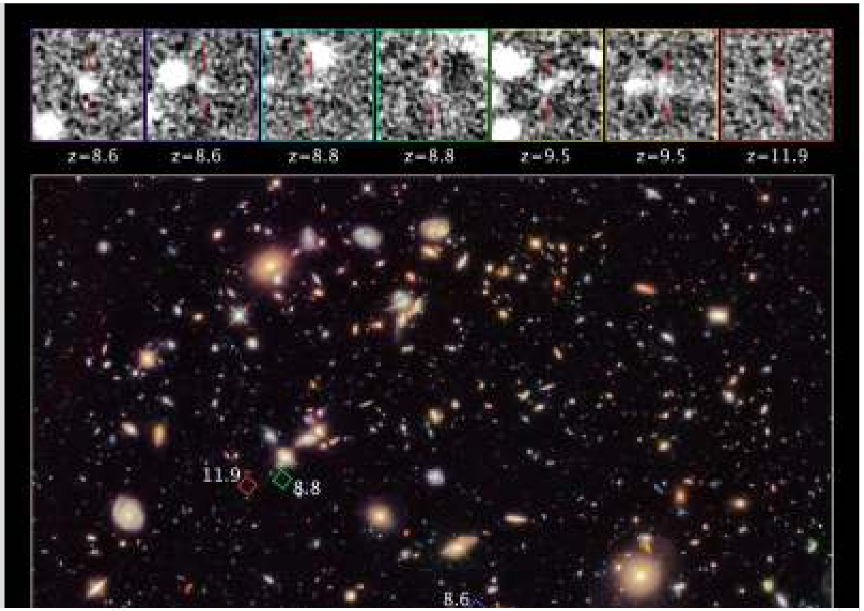
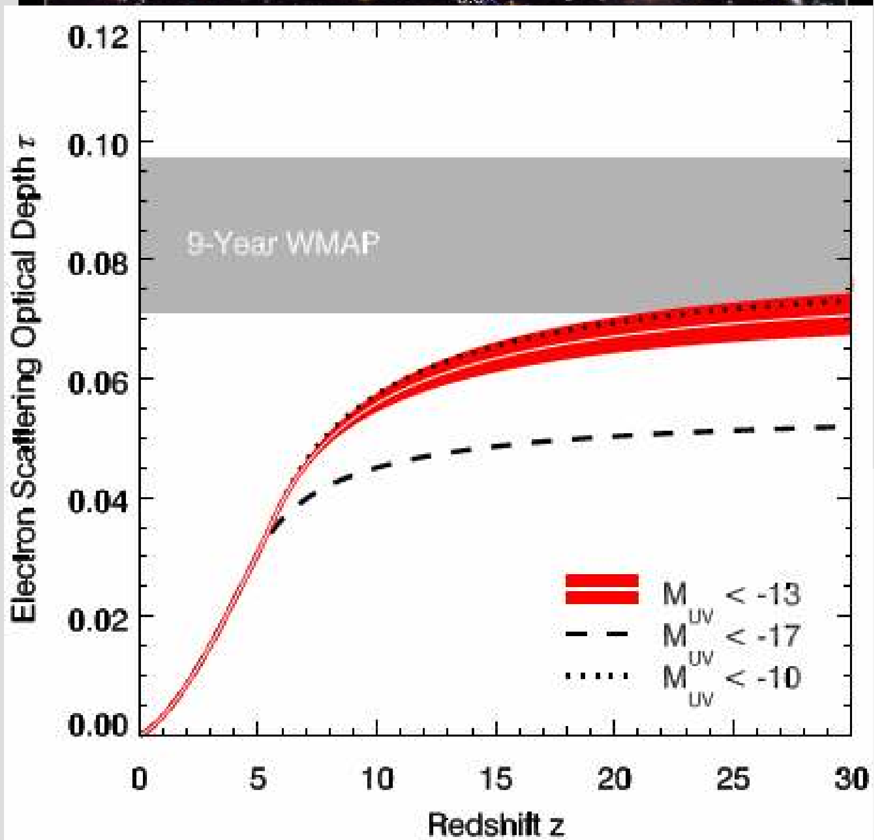
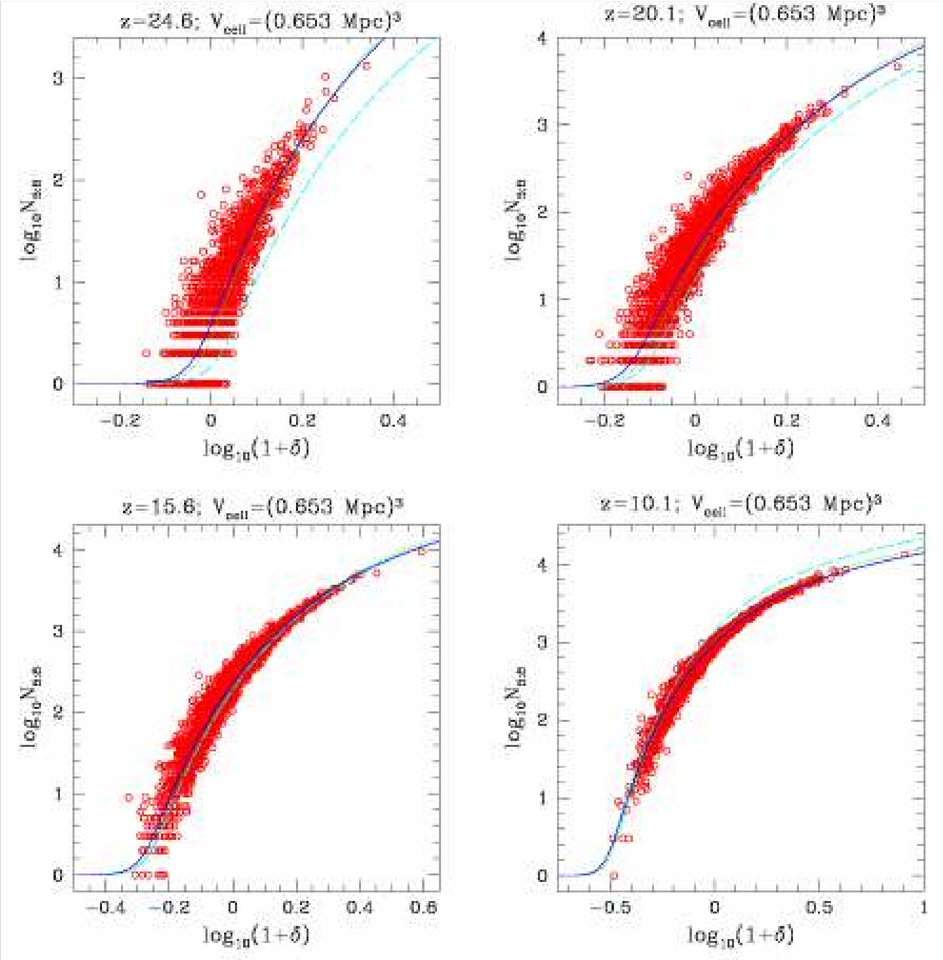
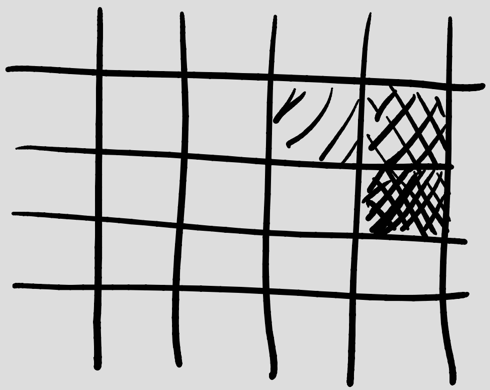




What's new?

- 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





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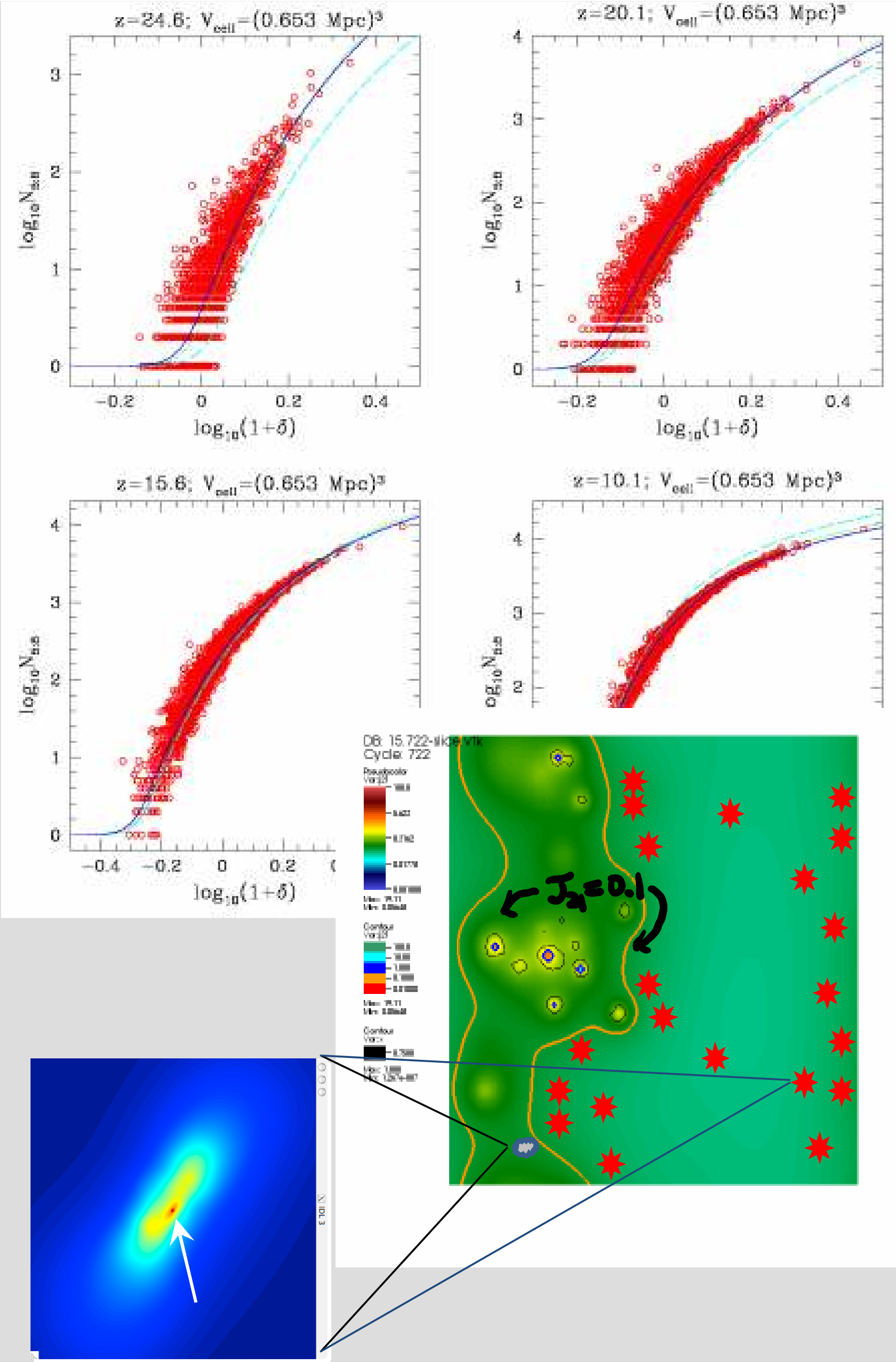
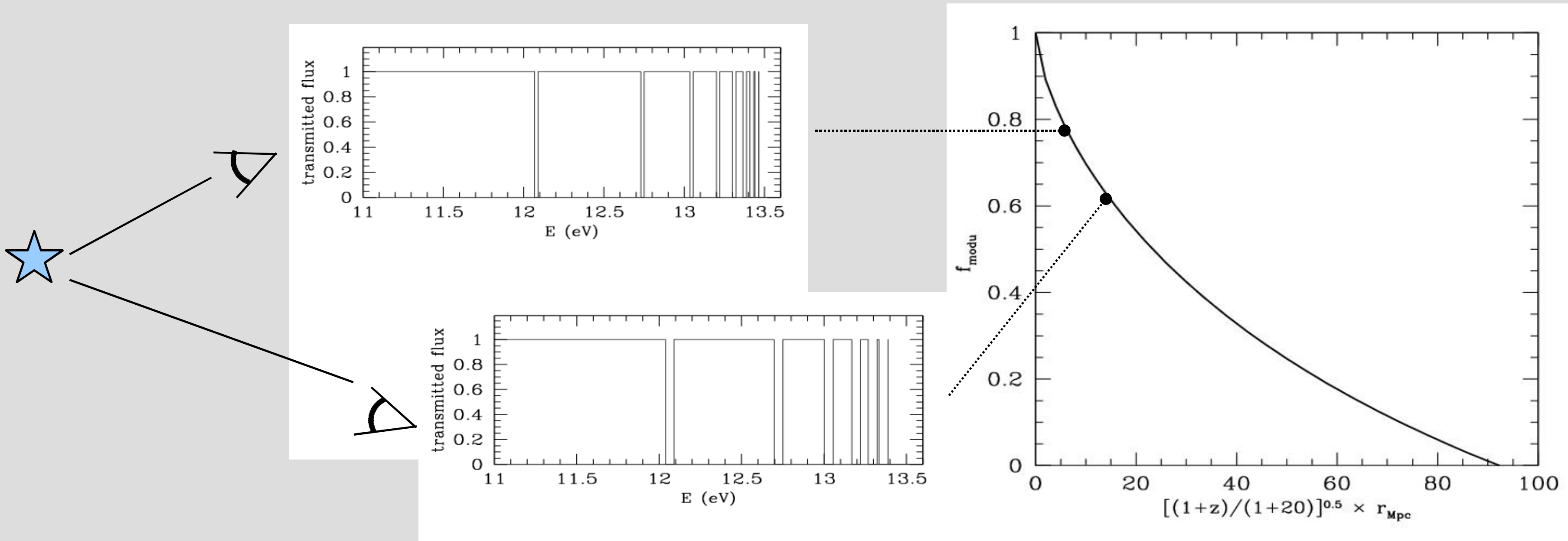
- Considering photo-dissociation of coolant
  - calculate transfer of Lyman-Werner Background (KA, Shapiro, Iliev, Mellema, Pen 2009)
  - remove first star from minihalos, if LW intensity over-critical



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

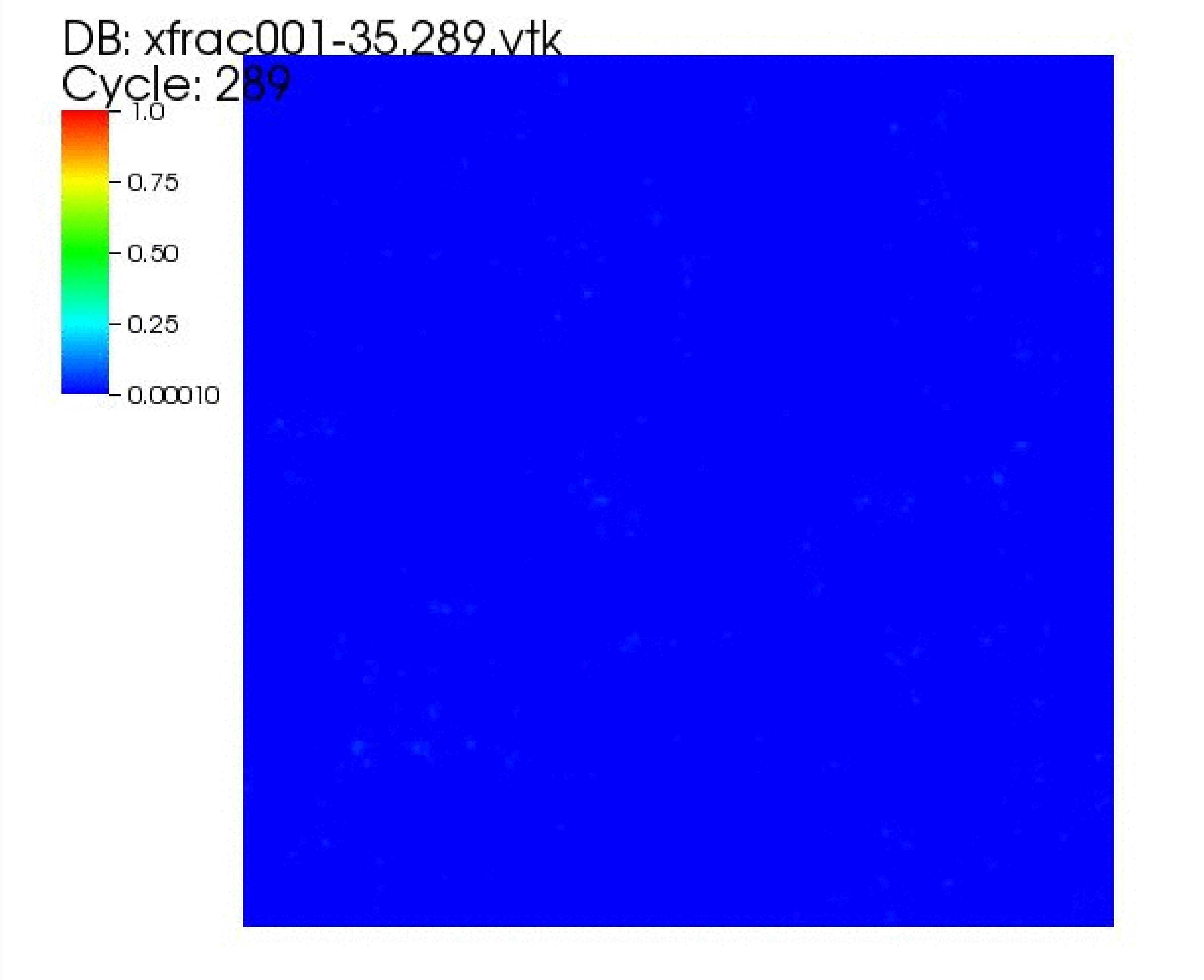
- Sources distributed inhomogeneously: Need to sum individual contribution
- One single source is observed as a picket-fence in spectrum
- Obtain pre-calculated "picket-fence modulation" factor and multiply it to L/D_L^2. This becomes mean intensity to be distributed among H_2 ro-vibrational lines.
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



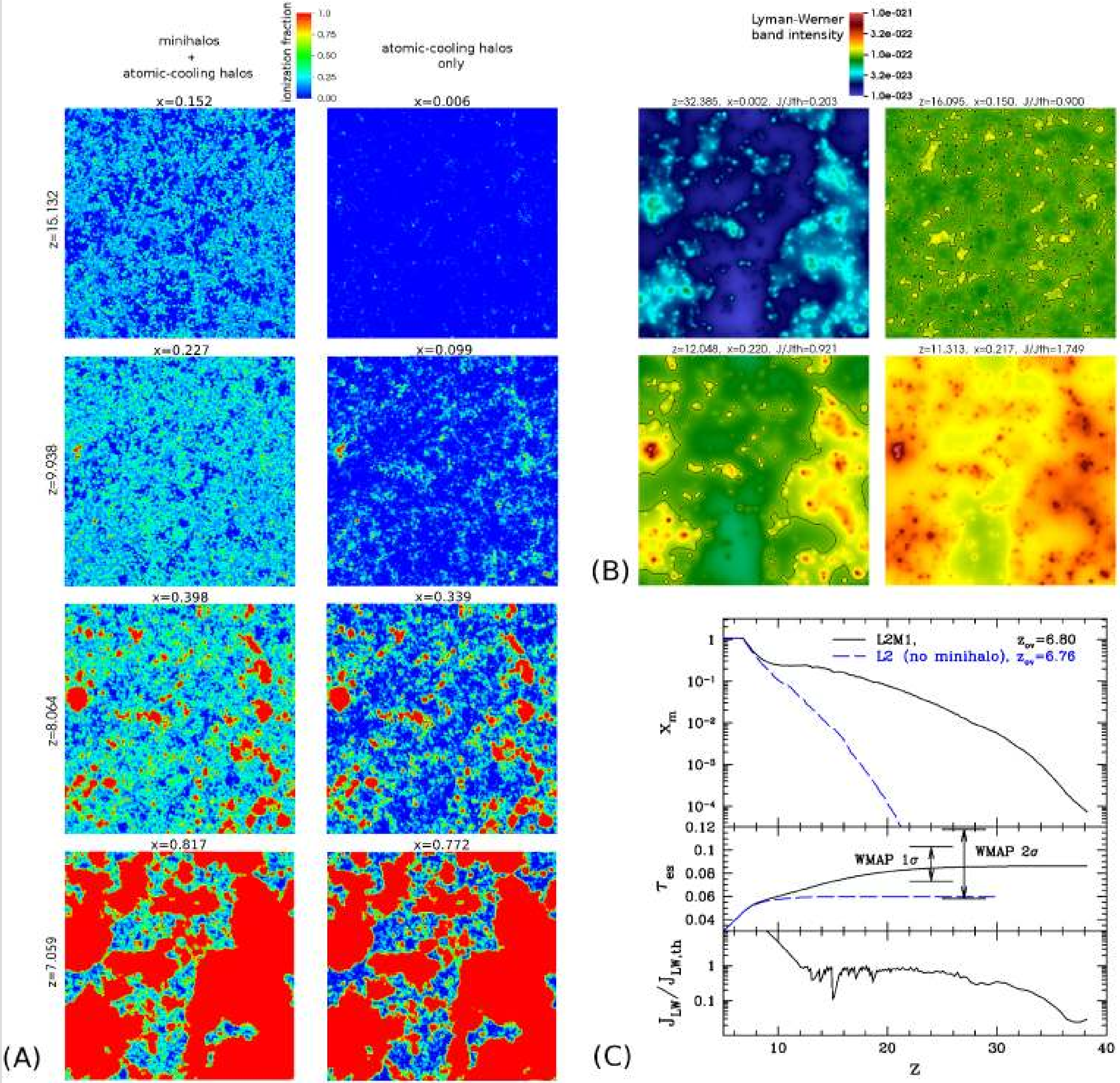
What do we expect

- 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 Lyα pumping on 21cm
- result in KA+ 2012

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



Storyline

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

Observation –

large-scale CMB

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)

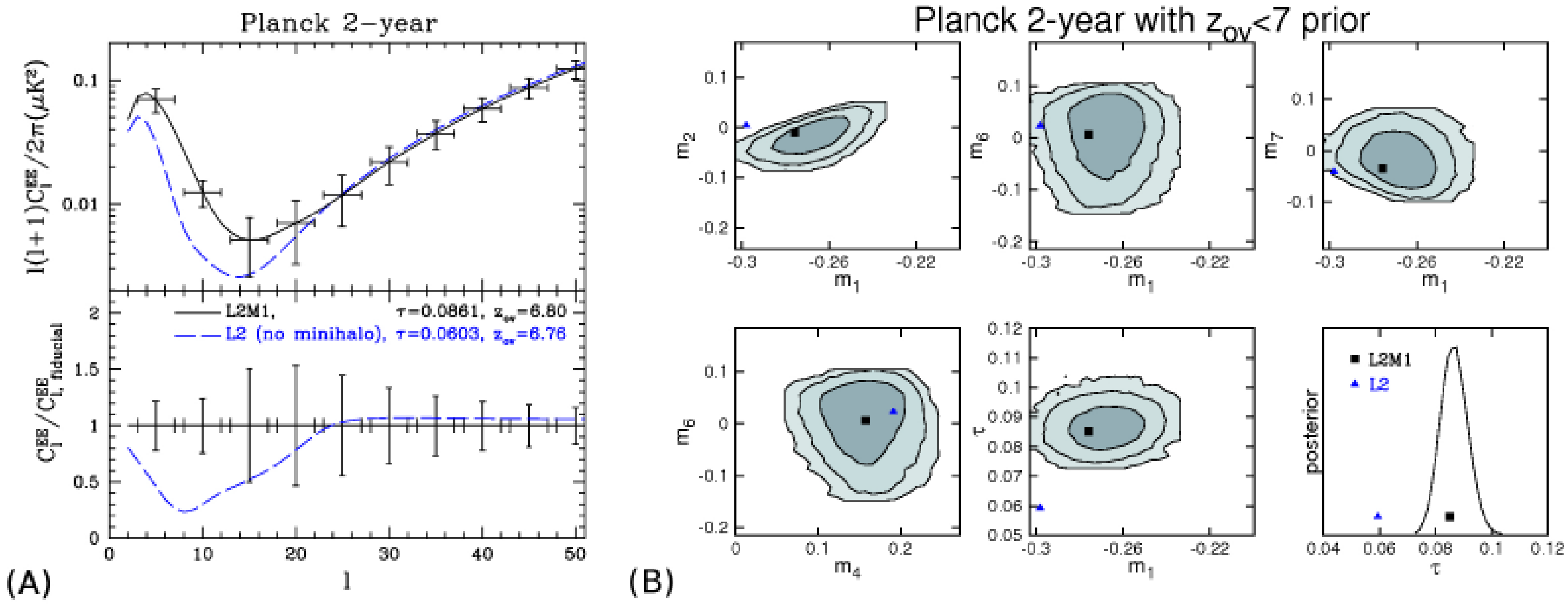
model-independent

principal component (basis)

Planck Forecast

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

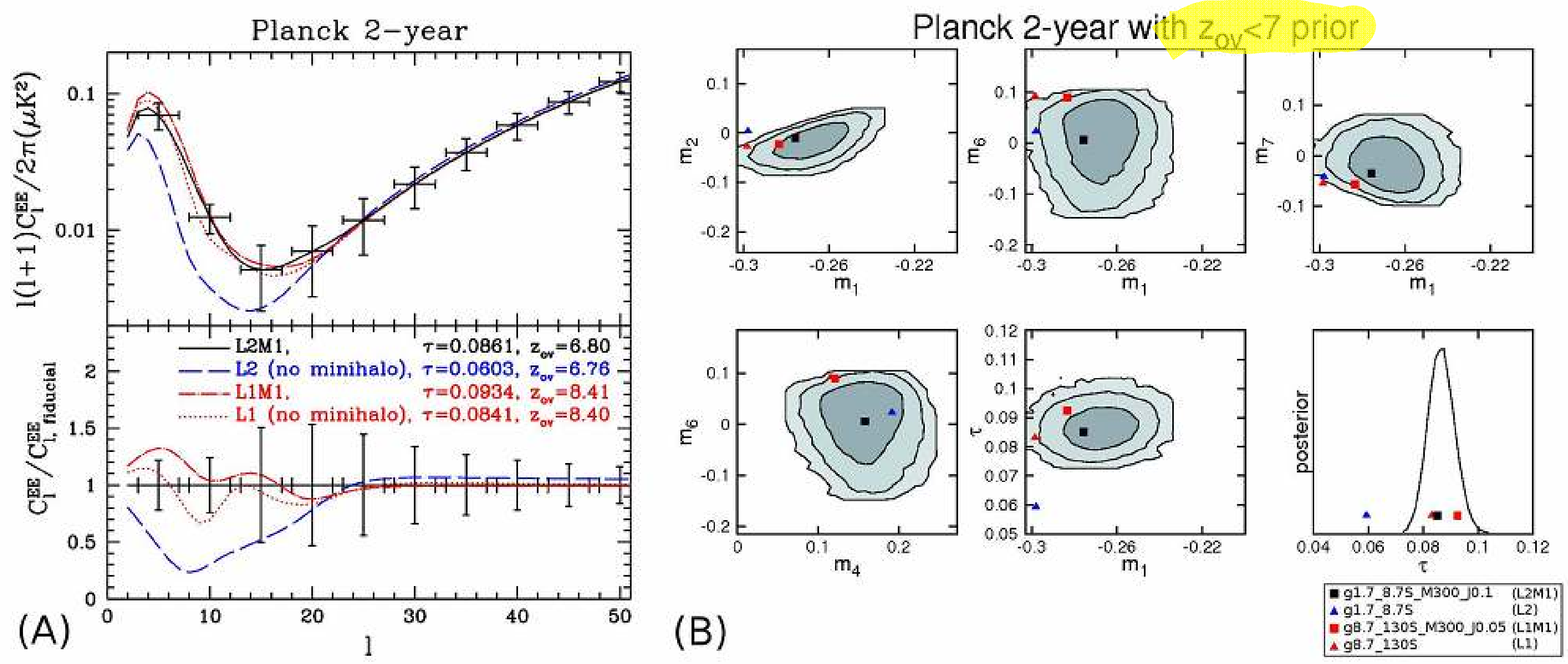
high-τ (w/ minihalo) (w/ first star) vs. low-τ (w/o minihalo) (w/o first star)



Hu & Holder; Motonson & Hu: PCA for reionization

Planck Forecast

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

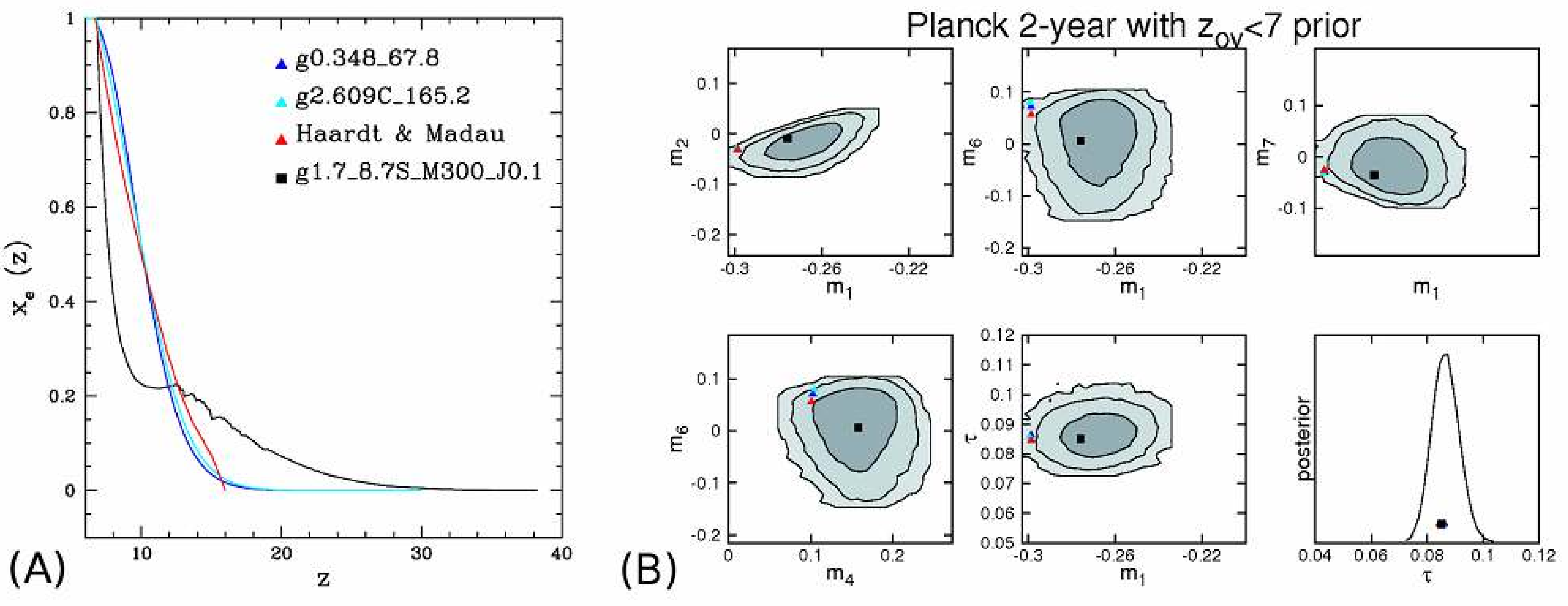


Planck Forecast

$\tau \sim 0.085$ — common

$z_{ov} < 7$

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

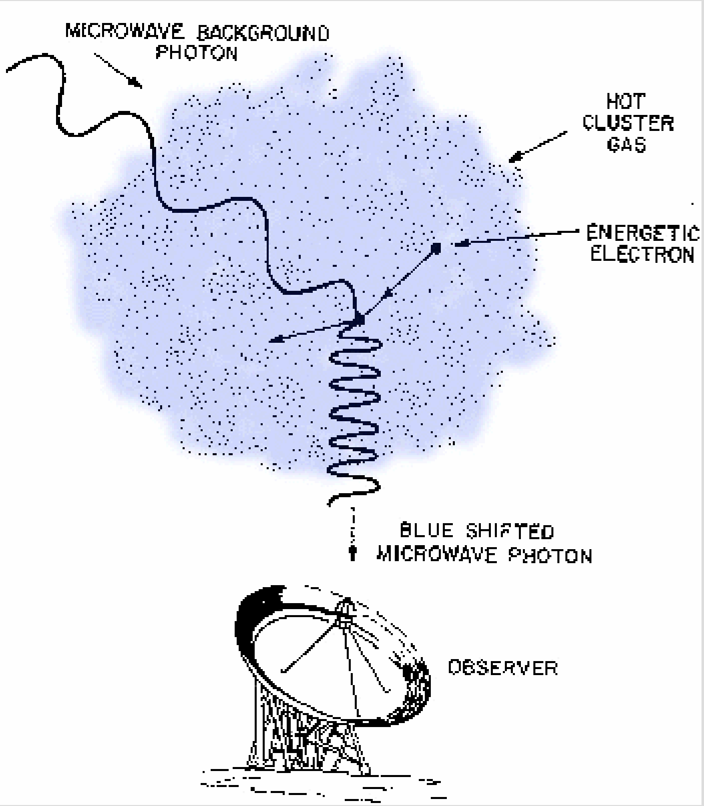


Observation –
small-scale CMB

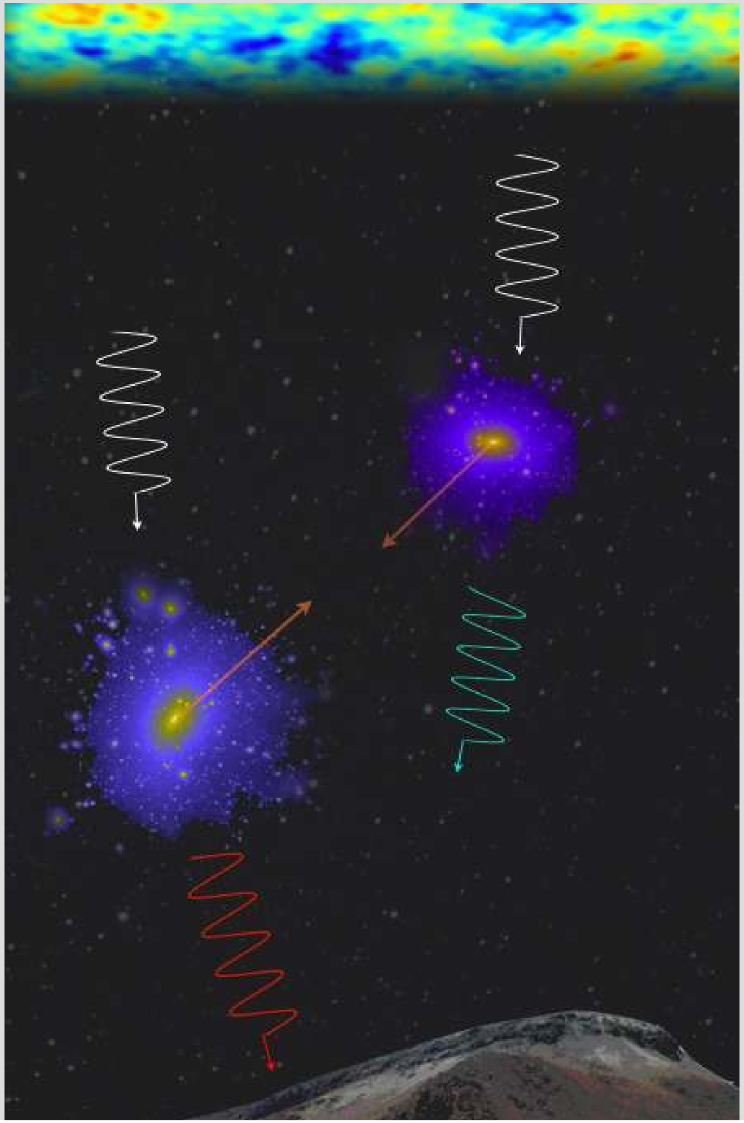
Dominant process

Sunyaev- Z'eldovich effect

thermal

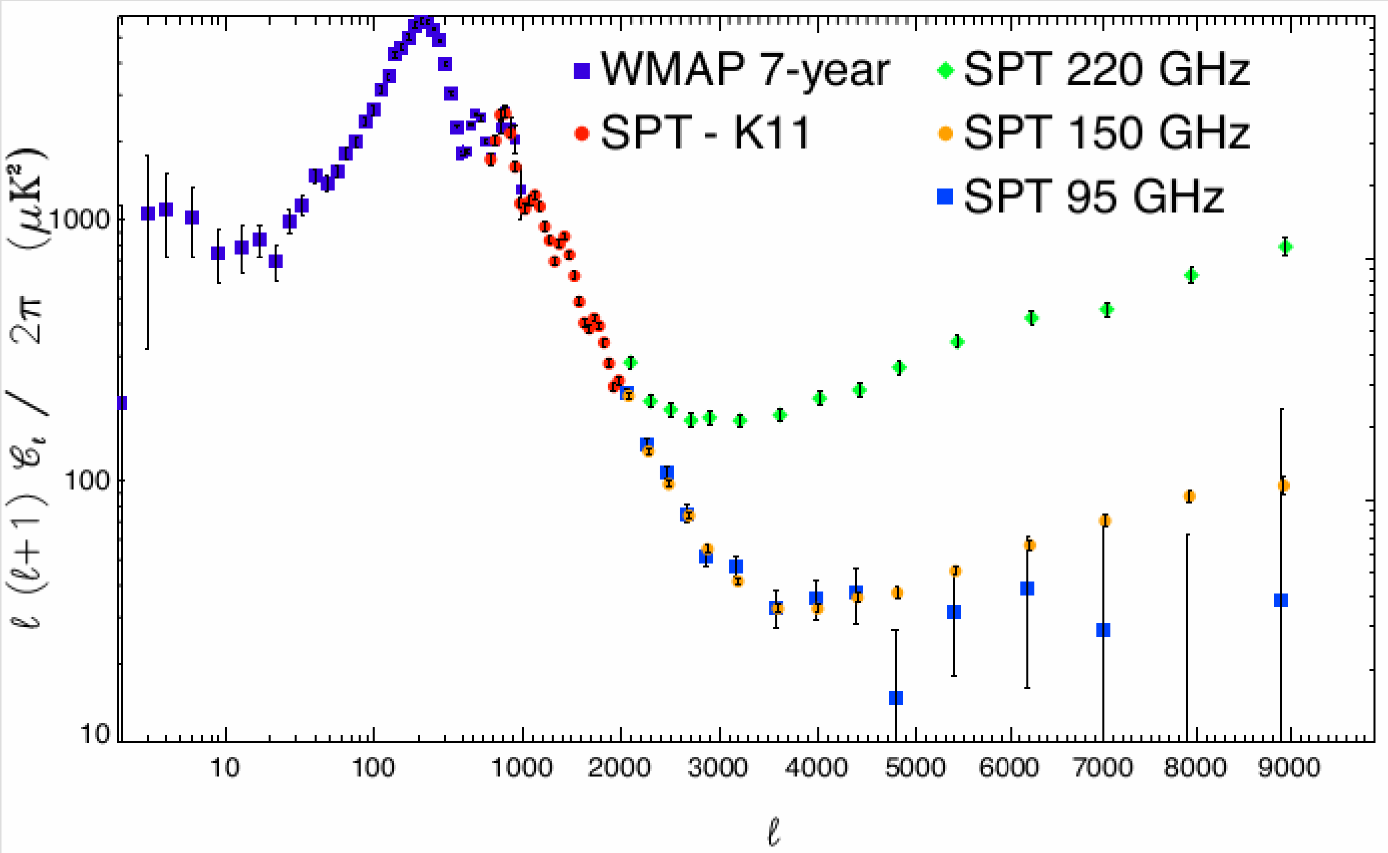


kinetic

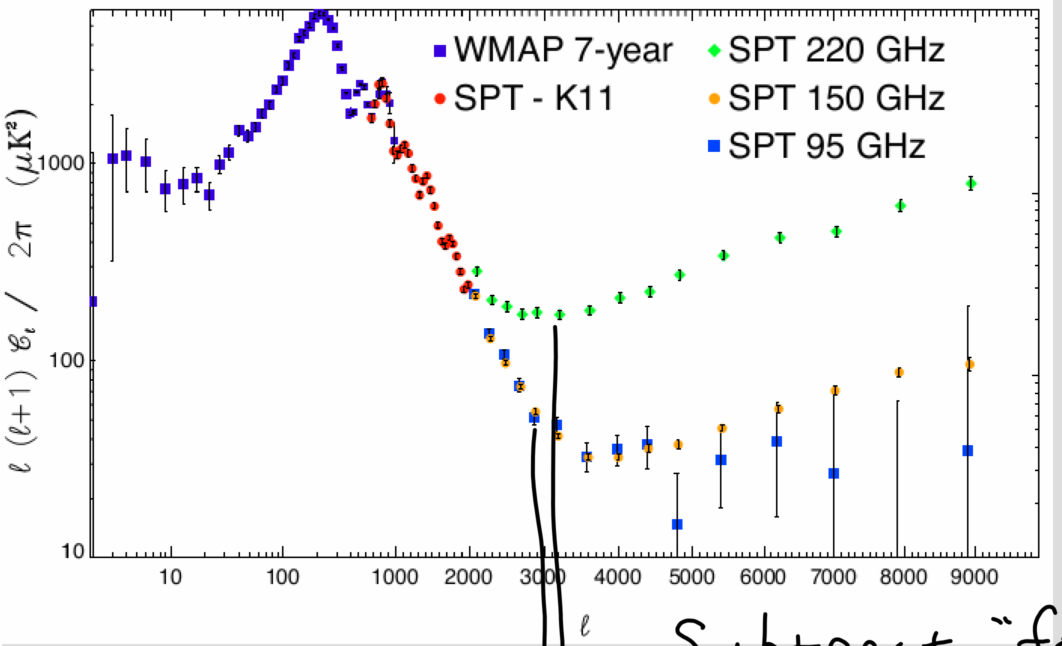


CMB temperature anisotropy at small scale

Reichardt+ 2012
South Pole Telescope (SPT)



CMB temperature anisotropy at small scale



Reichardt+ 2012
South Pole Telescope (SPT)

Subtract "foreground" by modeling

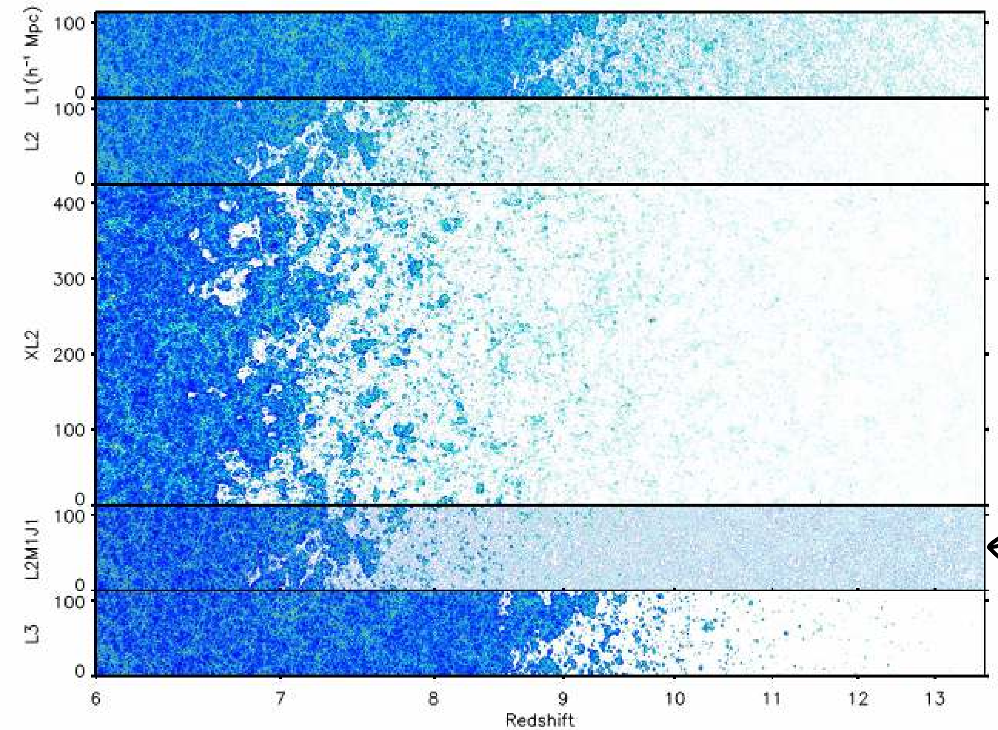
~ 2.1 μK^2 for kinetic SZ from EoR HII bubbles

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

Zahn+ 2012

model-dependent.

CMB temperature anisotropy at small scale

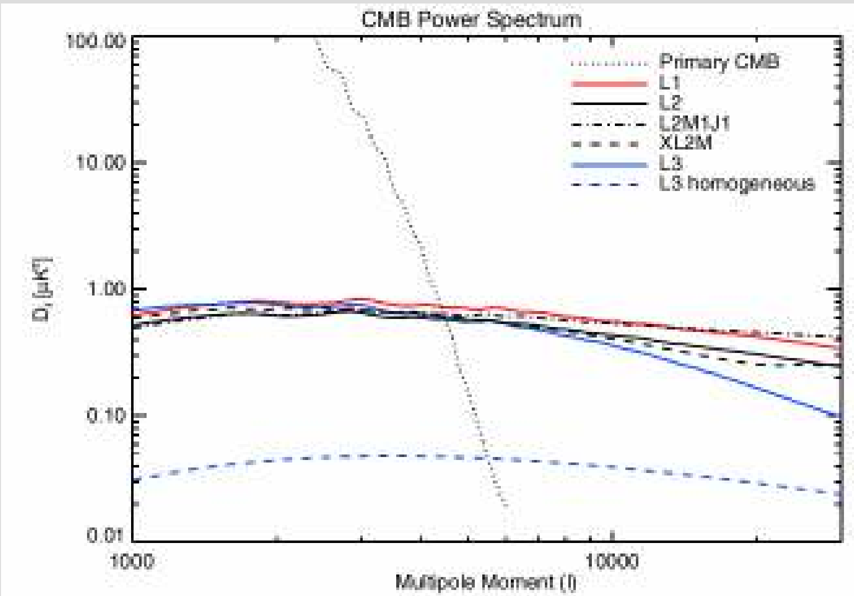


Park, Shapiro, Komatsu, Iliev, KA, Mellema 2013

← First-Star included sim.

$\Delta z = 6.5$

OK!



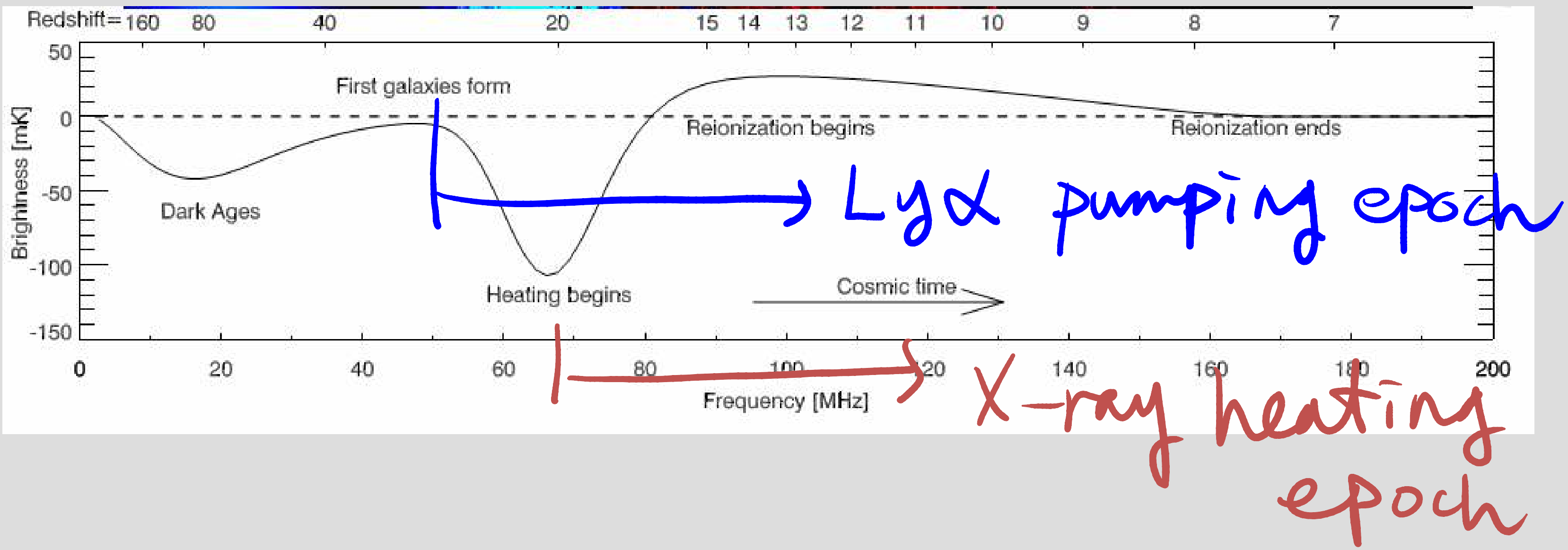
SPT upper limit by Zahn + (2012)

Observation –

21 cm signal

Global 21cm (cosmic mean) evolution

- 21cm observation
  - Lya pumping epoch: Deep absorption(~ -100 mK)
  - X- ray heating epoch: changing to weak (saturated) emission (~ 30 mK)
  - EoR: patchy H II bubbles are created



21cm power spectrum evolution

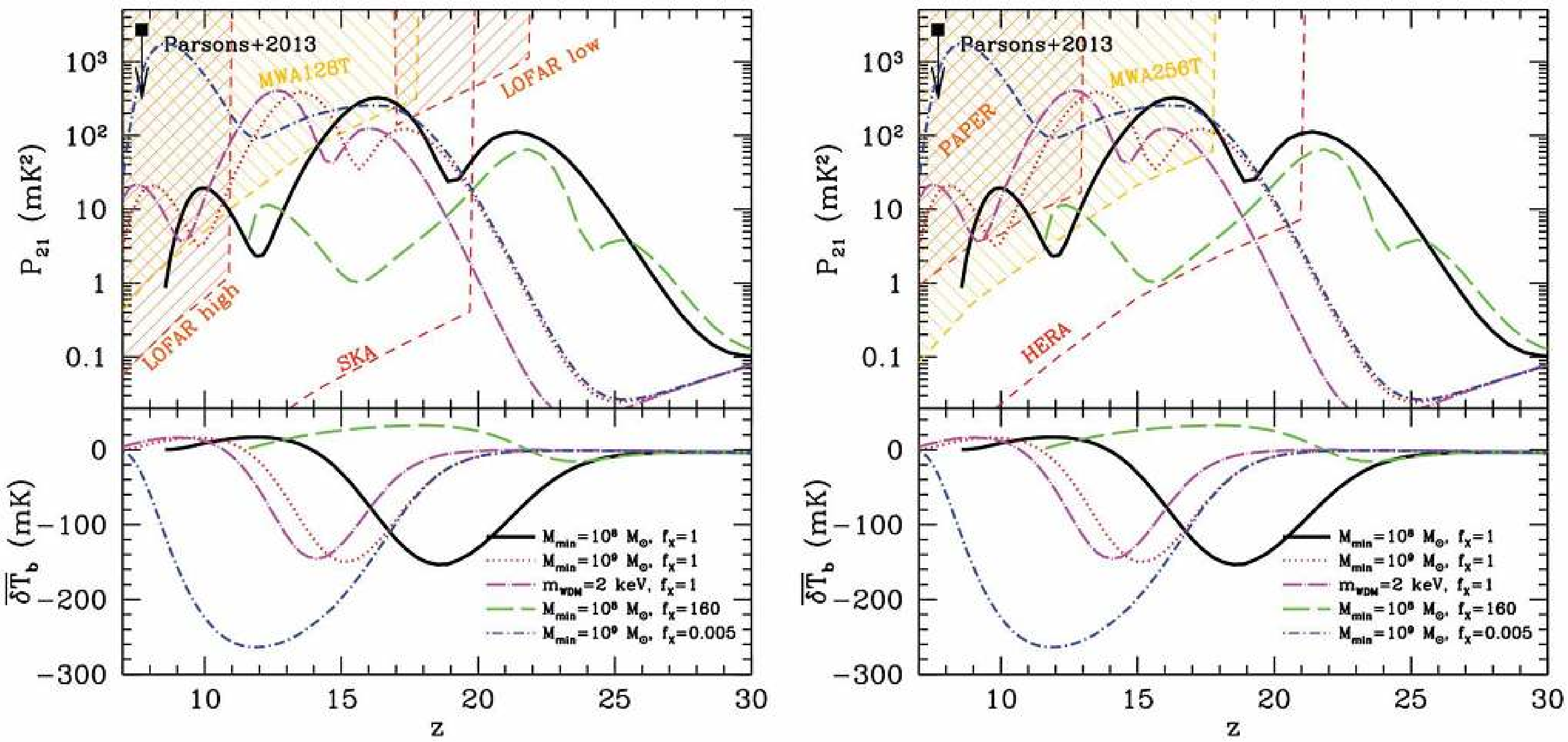
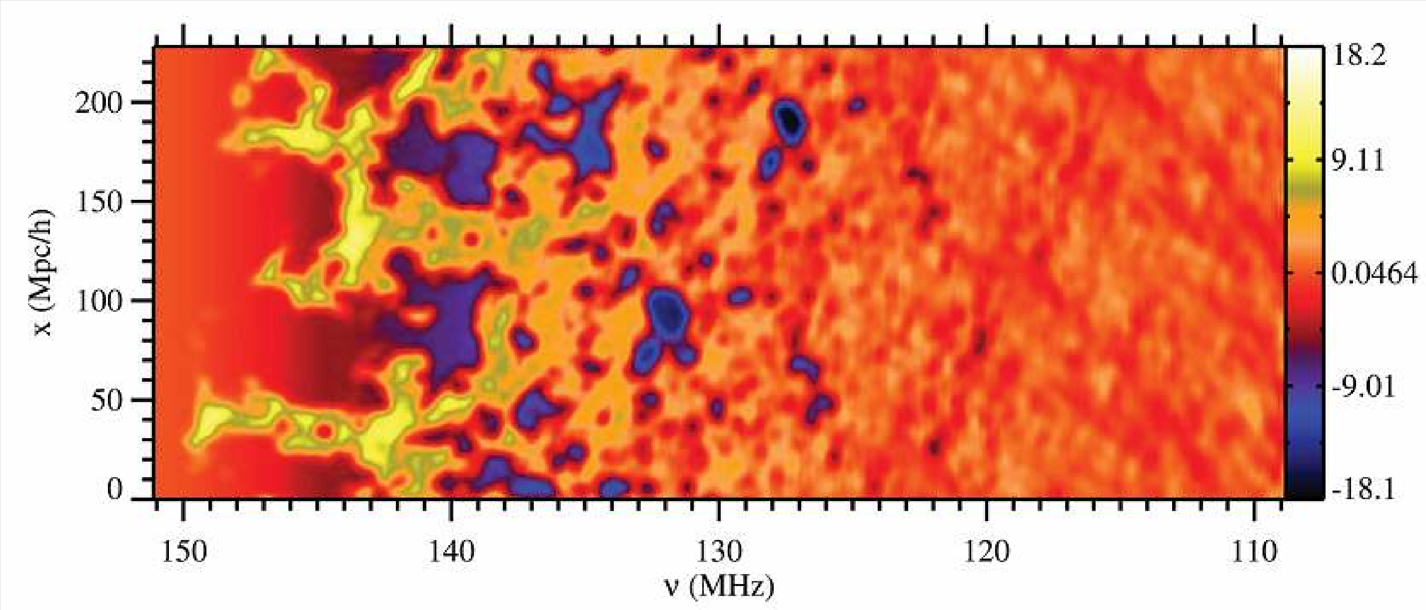
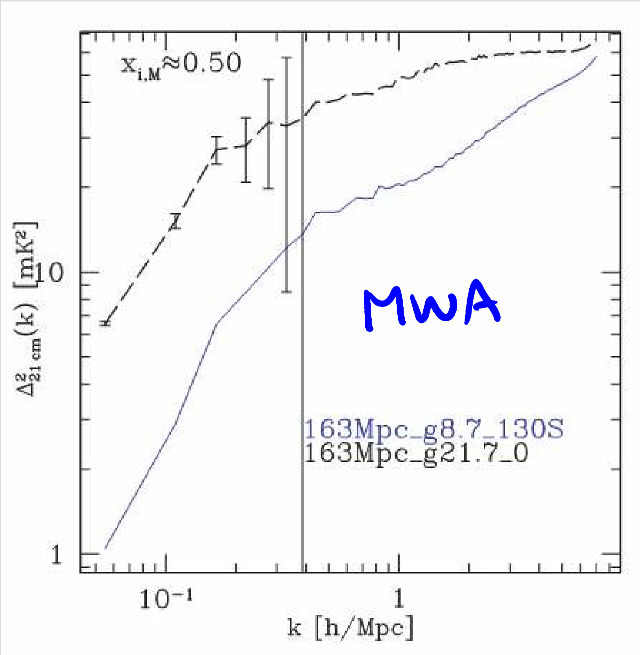


Figure 1: (top subpanels) Evolution of $D^2(k)$ at $k = 0.1/\mathrm{Mpc}$ and sensitivity of various apparatuses including SKA. Three peaks appear when fluctuations in δT_b are boosted due to efficient Lyα-pumping, X-ray heating and patchy reionization, subsequently from high to low redshifts (Mesinger et al. 2014).

Of course big-H II bubble easier to probe





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

What to do with 21cm observation

- cosmology
  - probing matter distribution at high- z (z>7)

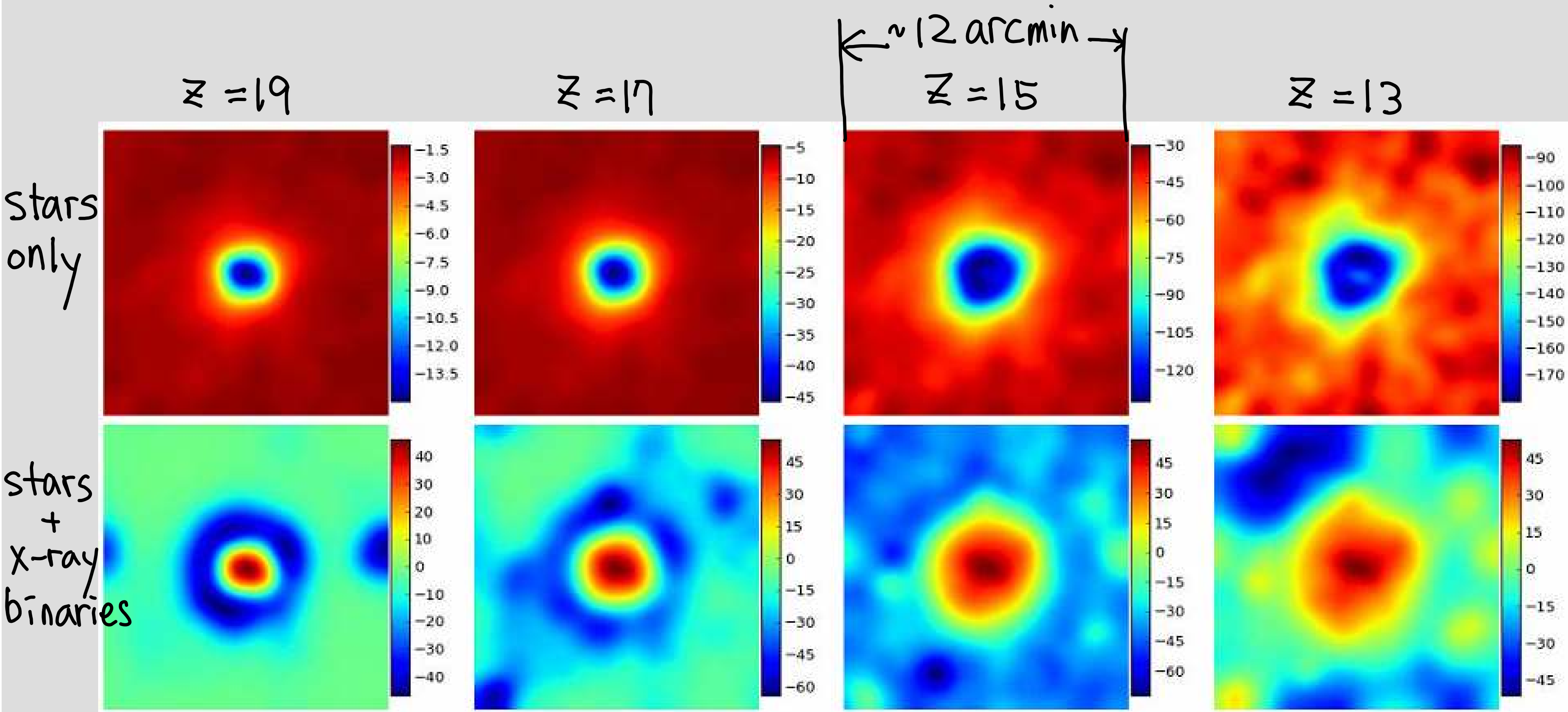
- astrophysics
  - probing radiation source properties at high- z (z>7)

- Astrophysics spoils cosmology if x>~ 0.2 (Shapiro+2013)

- Future radio astonomy
  - pathfinders to SKA: MWA, LOFAR, PAPER, DARE, 21CMA, …
  - SKA (Square Kilometre Array)
  - I joined SKA EoR science team

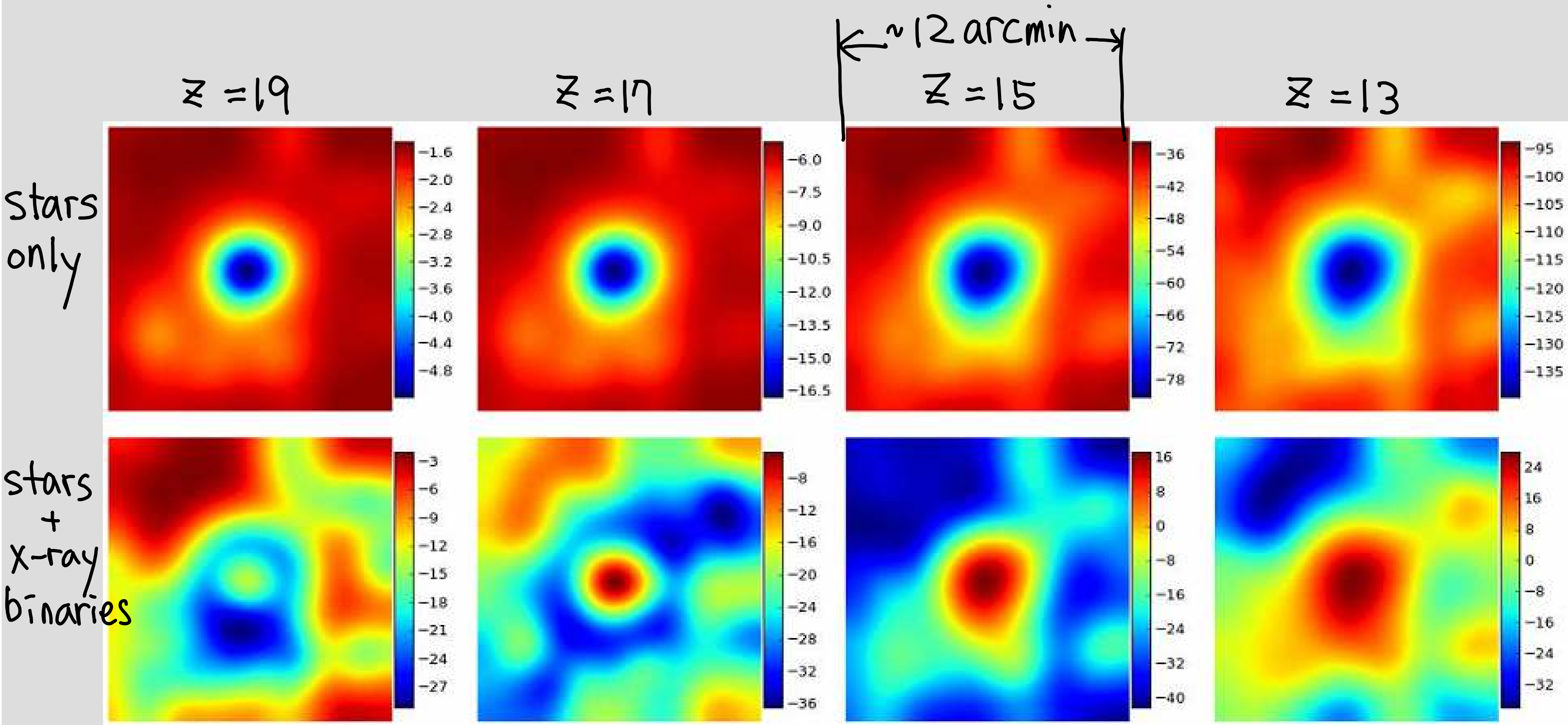
Lyα sphere + X-ray heated sphere (clustered source: "Rarepeak": KA, Xu, Norman, Alvarez, Wise 2014)

- Good image with Θ=1', Δν=0.2 MHz

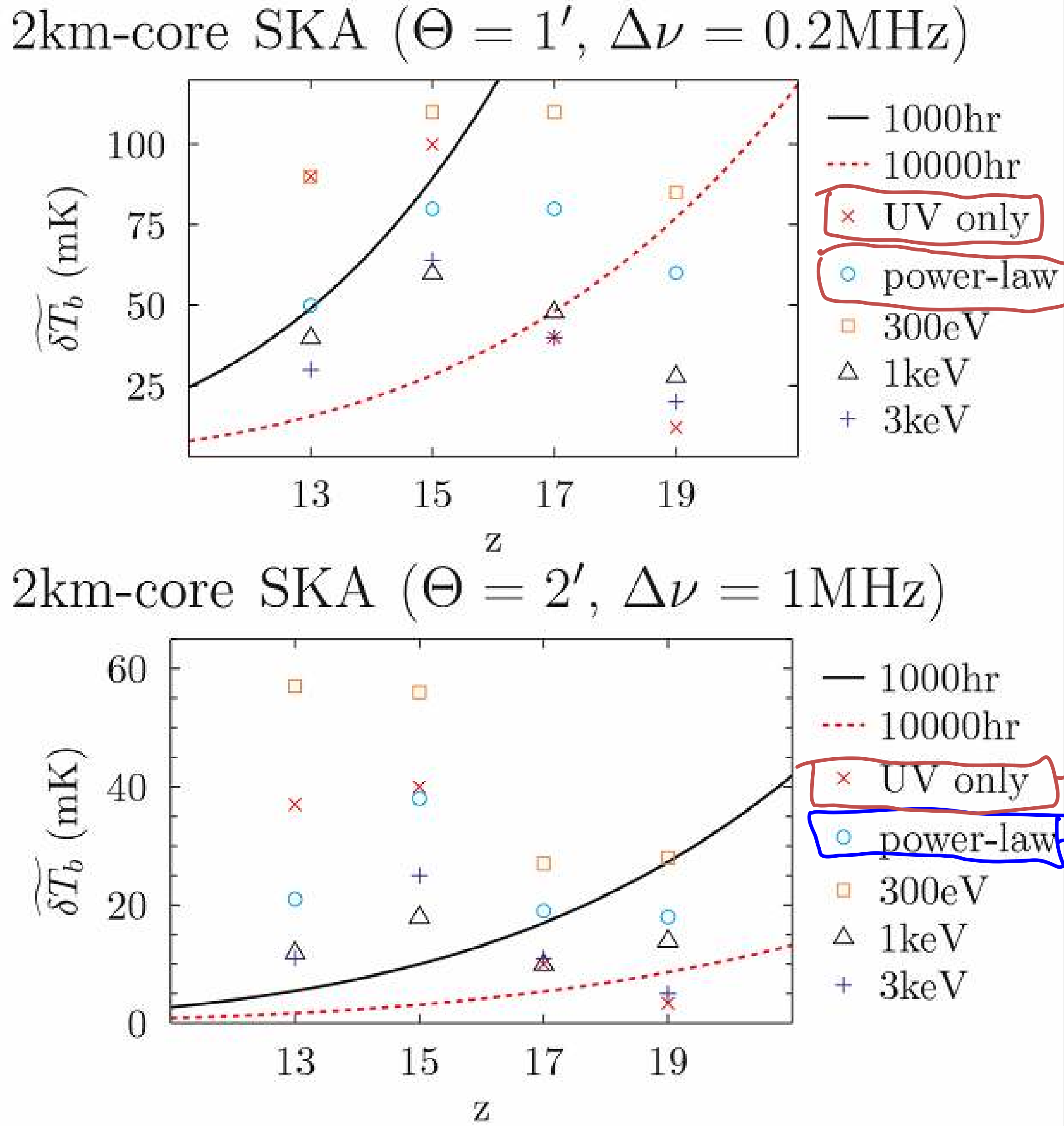


Lyα sphere + X-ray heated sphere (clustered source: "Rarepeak": KA, Xu, Norman, Alvarez, Wise 2014)

- OK image with Θ=2', Δν=1 MHz
  - promising with SKA1 & 2
- suggestion
  - optimal baseline for at least 2'
  - z=12- 17 (700 Mpc along l.o.s.), 100 Mpc × 100 Mpc dedicated- field
  - ~30MHz × 2° × 2° dedicated volume (~100 objects), ~1000- 4000 hrs
  - ~30MHz × FOV dedicated volume(?)



Lyα sphere + X-ray heated sphere (clustered source: "Rarepeak": KA, Xu, Norman, Alvarez, Wise 2014)

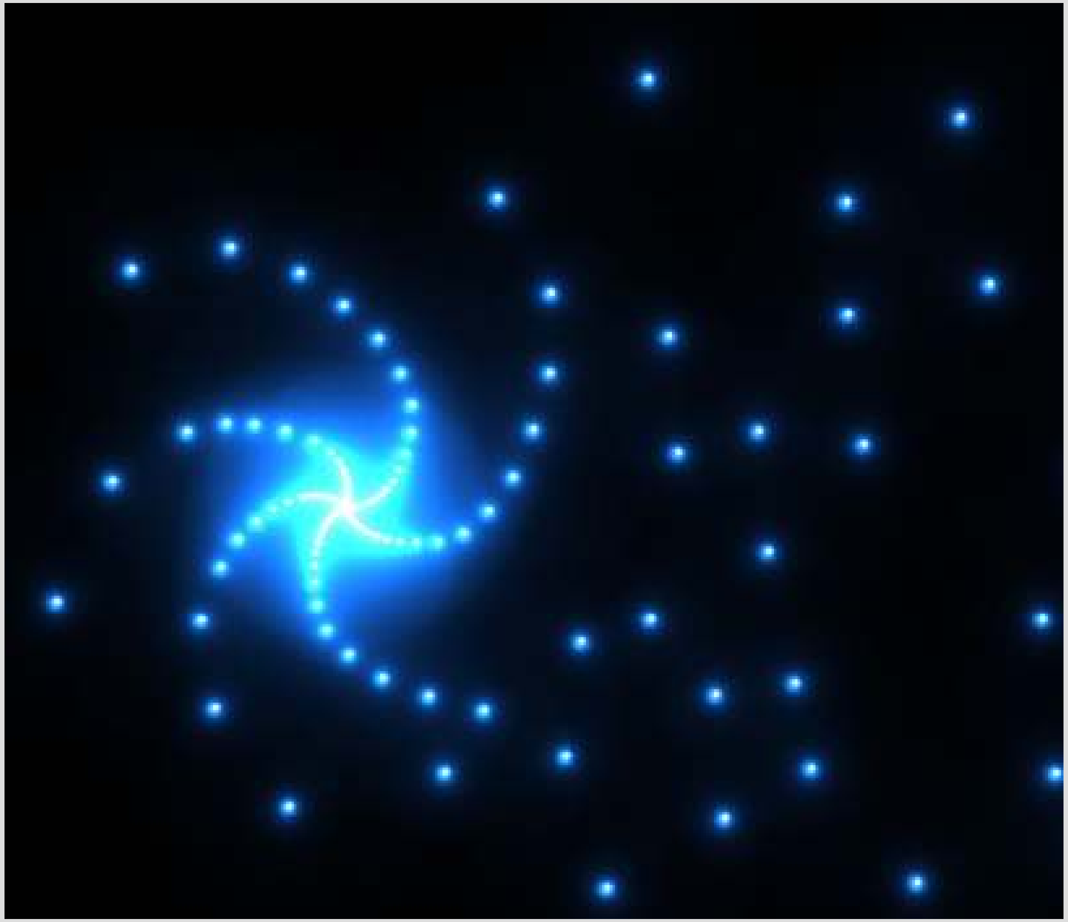


- model points
- sensitivity curves
  - SKA (2-km core) with 1km^2 collecting area
  - multiply by 1km^2/(collecting area), roughly

stars only

fiducial X-ray + UV

SKA & its precursors



Low-frequency targeted down to z=28 !!! (EoR science group)

Low-frequency in Australia

Sensitivity targeted at 1-10 mK, both for imaging and power spectrum analysis

Korea's role?

Summary

- bias useful for creating fast mock catalogue for cosmology
  - Care needs with stochasticity (super-Poissonian)

- High- z astrophysics is frontier field

- High- z cosmology is interesting…