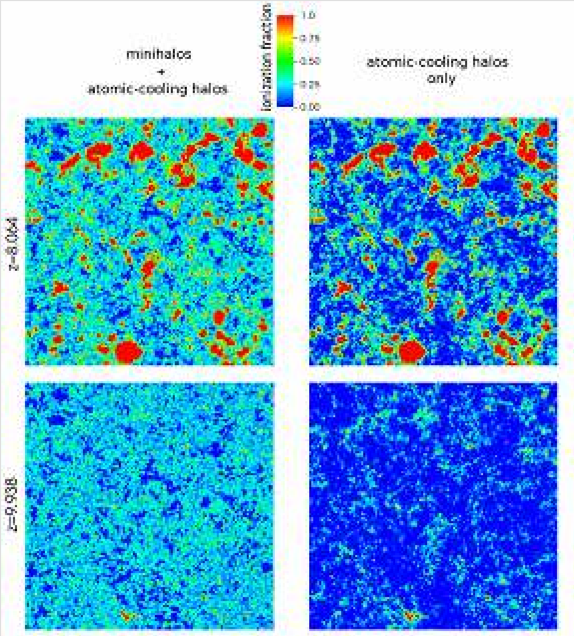
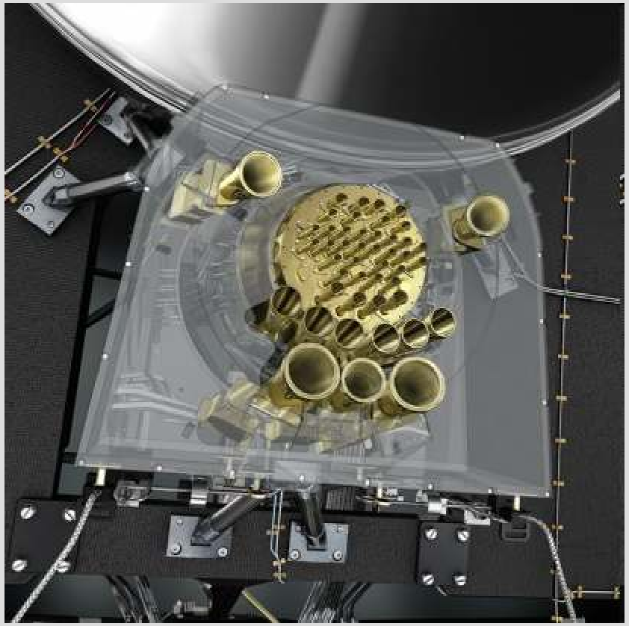
Impact of Minihalos on Cosmic Reionization and Numerical Schemes behind It





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Cosmic Radiative Transfer Comparison Project IV, Austin

Dec 2012

w/ Paul Shapiro, Ilian Iliev, Garrelt Mellema, Ue-Li Pen, Yi Mao, Jun Koda, Hyunbae Park

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 et al. 2011), LAE in LBGs(Pentericci et al. 2011), LAEs(Ota et al. 2010) → all indicating neutral fraction > 10% at z=7 !!!!!! (albeit warning from Dayal)

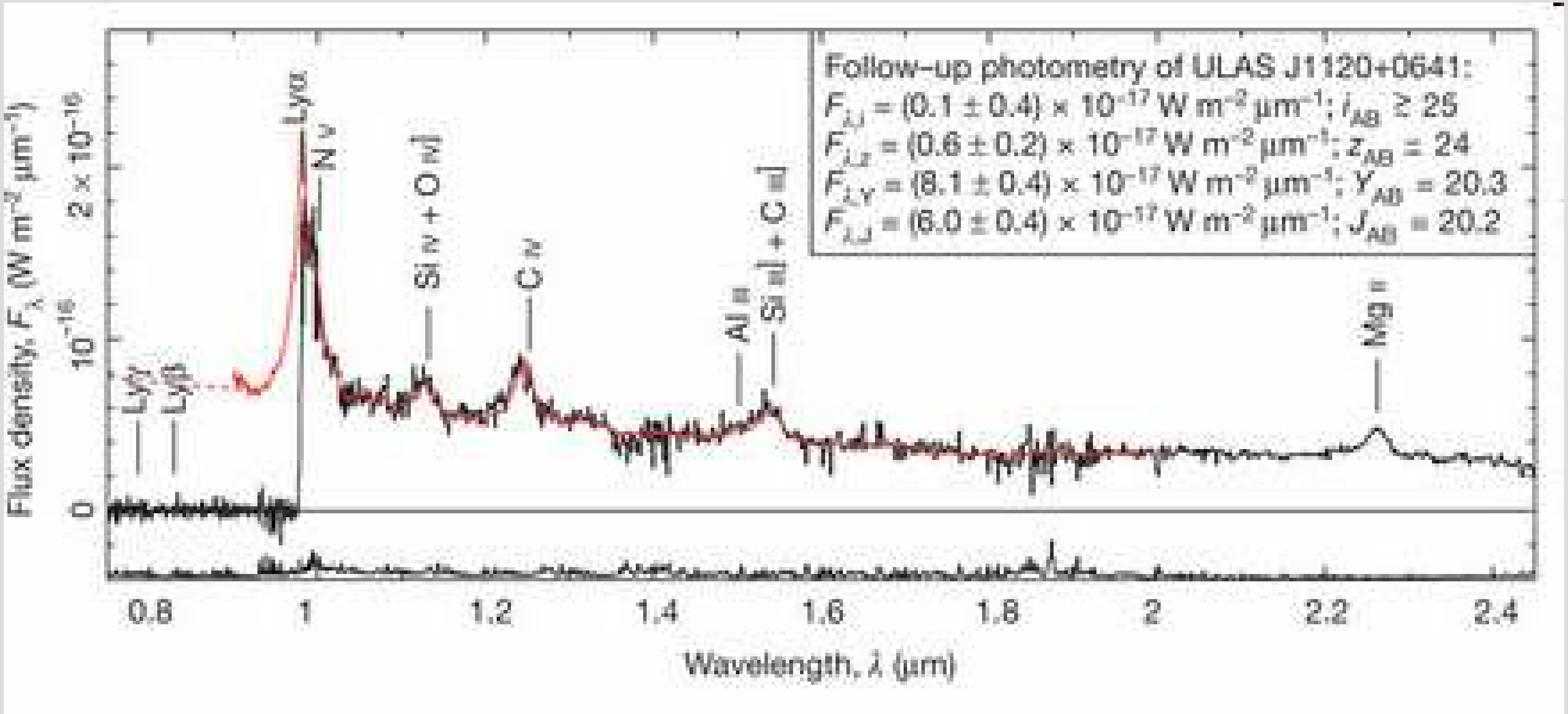
- Electron content
  - kinetic Sunyaev- Zeldovich effect on CMB
  - SPT: z(x=99%)- z(x=20%) ~ 4.4 – 7.9 (2σ level, Zahn et al. 2011; c.f. see Mesinger, McQuinn, Spergel 2012)

- Electron content, in terms of Thomson scattering optical depth of CMB
  - $\tau = 0.085 \pm 0.015$ (WMAP7, 1σ level)

$$\tau = \int n_e \sigma_T \, dl$$

Current observational constraints on Reionization

z=7.085 QSO (Mortlock et al. 2011)



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

Current observational constraints on Reionization

SPECTROSCOPIC CONFIRMATION OF Z~ 7 LBGS: PROBING THE EARLIEST GALAXIES AND THE EPOCH OF REIONIZATION

L.Pentericci[1] A. Fontana [1] E. Vanzella[2] M. Castellano [1] A. Grazian [1] M. Dijkstra [3] K. Boutsia [1] S. Cristiani [2] M. Dickinson[4] E. Giallongo [1] M. Giavalisco [5] R. Maiolino [1] A. Moorwood[6*] P. Santini [1]

Out of the 20 z-dropouts observed we confirm 5 galaxies at $6.7 < z < 7.1$. This is systematically below the expectations drawn on the basis of lower redshift observations: in particular there is a significant lack of objects with intermediate Lyα EWs (between 20 and 55 Å). We conclude that the trend for the fraction of Lyα emission in LBGs that is constantly increasing from z~3 to z~6 is most probably reversed from $z \sim 6$ to z~7. Explaining the observed rapid change in the LAE fraction among the drop-out population with reionization requires a fast evolution of the neutral fraction of hydrogen in the Universe. Assuming that the Universe is completely ionized at z=6 and adopting the semi-analytical models of Dijkstra et al. (2011), we find that our data require a change of the neutral hydrogen fraction of the order $\Delta\chi_{HI} \sim 0.6$ in a time $\Delta z \sim 1$, provided that the escape fraction does not increase dramatically over the same redshift interval.

James Bolton upgrading on this (Bolton & Haehnelt 2012), but still n_{HI}>0.1 at z~ 7

Motivation / Puzzle / Our answer

- Lost photon budget
  - first stars in minihalos
- Late reionization(z_{ov}<7) & high τ conditions: hard to match simultaneously
  - hard w/ observed luminosity function
  - hard in numerical simulations (Iliev et al.; Zahn et al.; Trac & Cen; …)
- Photon starvation (Bolton & Haehnelt 2007) and high optical depth
- 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!!

Reionization simulation with all stellar sources (KA, Iliev, Shapiro, Mellema, Koda, Mao 2012)

- lowest- mass host: Minihalos (<~ 10^8 $M_\odot$)
  - hosting First Stars
  - regulation of only coolant, H_2, by Lyman- Werner radiation

- middle - high- mass host: atomic- cooling halos (>~ 10^8 $M_\odot$)
  - immune to Lyman- Werner radiation (high column density)
  - sub- categorized (feedback from photoheating; Iliev et al.)
    - immune to Jeans mass filtering: >~ 10^9 $M_\odot$
    - vulnerable to Jeans mass filtering: <~ 10^9 $M_\odot$

- Can we achieve full dynamic range on big box?
  - subgrid treatment on minihalos
  - Lyman- Werner band radiative transfer needed

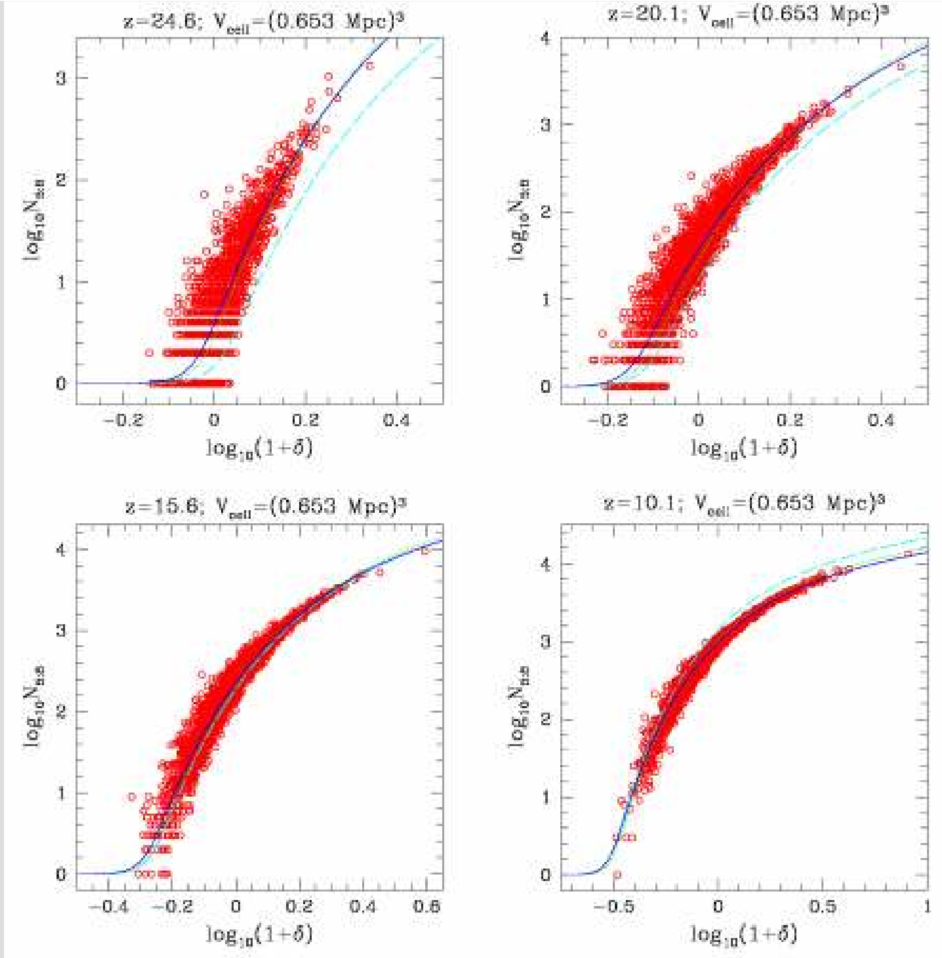
- Done! (N- body → source, density → radiative transfer)
  - 114/h Mpc box
  - N- body halo resolution: 10^8 $M_\odot$
  - minihalos (one 100- 300 $M_\odot$ Pop III star/minihalo, M>=10^5 $M_\odot$)
  - LW feedback ($J_{LW,th}$=0.01- 0.1x10^{-21} erg cm^{-2} s^{-1} sr^{-1})

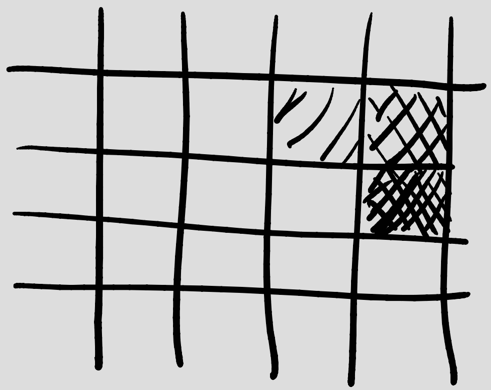
- minihalos as sinks: e.g. Ciardi et al. 2006, McQuinn et al. 2007

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, Iliev, Shapiro & Koda in preparation)
  - put one Pop III star per minihalo

- Considering photo- dissociation of coolant, H_2
  - calculate transfer of Lyman- Werner Background (KA, Shapiro, Iliev, Mellema, Pen 2009)
  - remove first star from minihalos, if LW intensity over- critical





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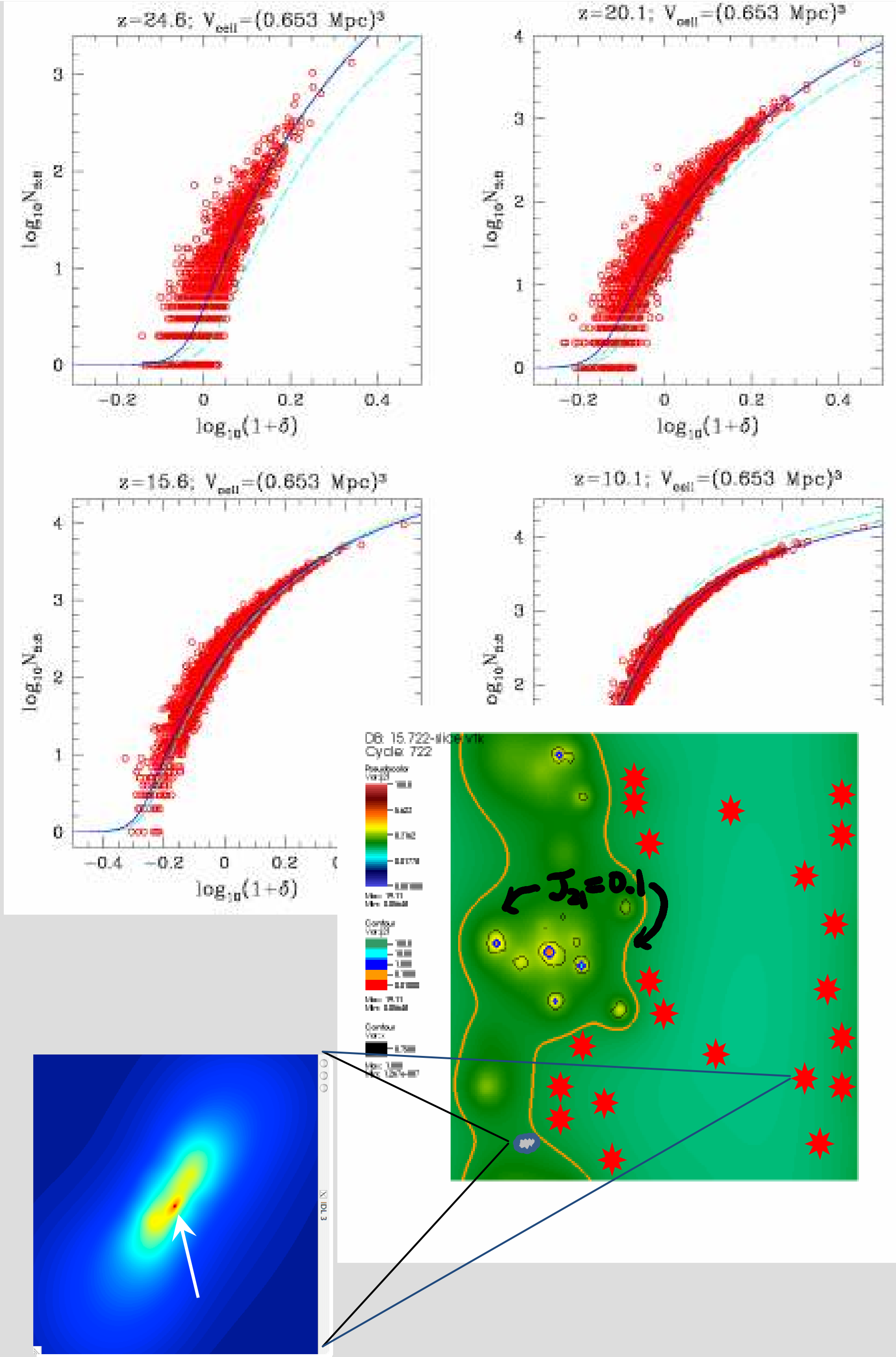
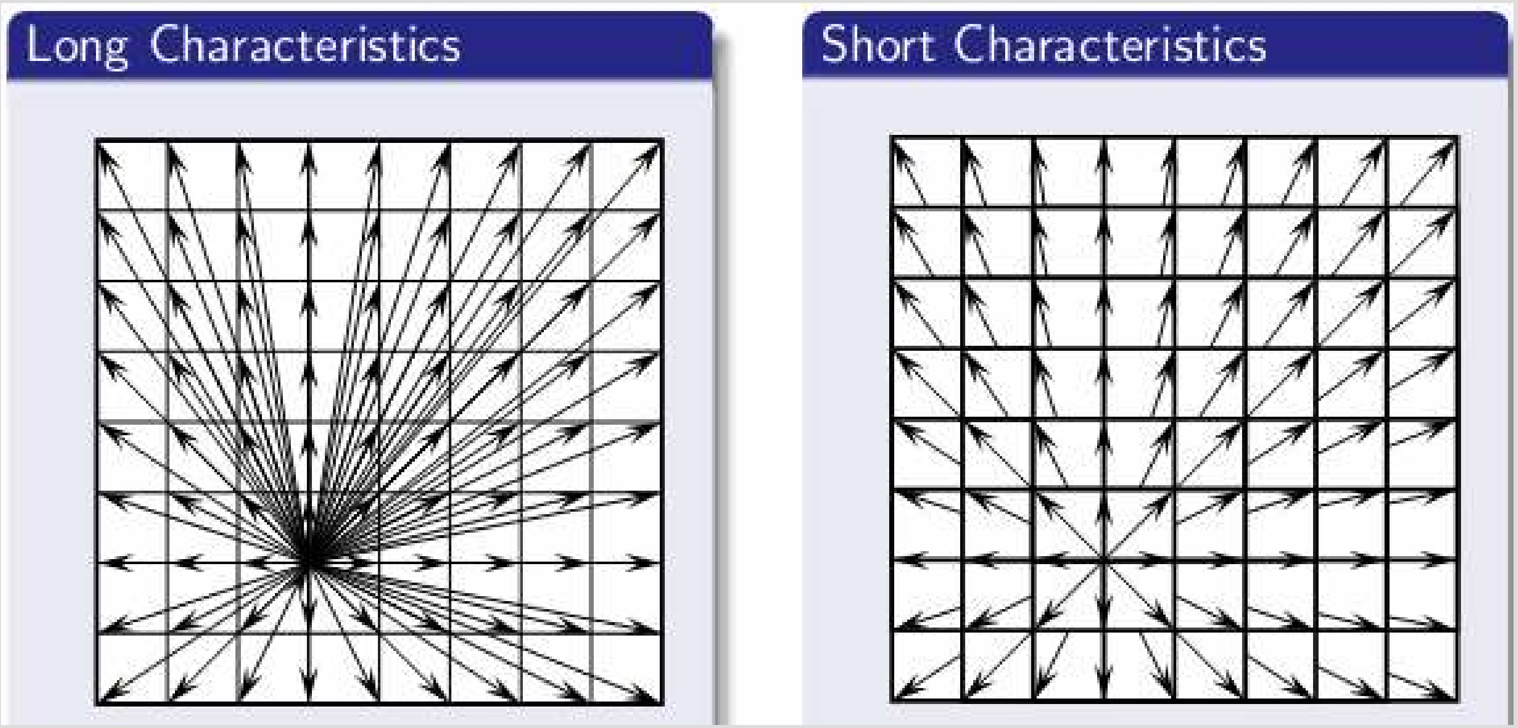


How ionizing radiation transfer done: C^2Ray (Mellema, Iliev, Alvarez, Shapiro 2006)

- Photon-**C**onserving
  - photon-absorption rate = hydrogen-ionization rate
- **C**ausal
  - from source to cell
- Short-characteristics for ray-tracing (O~N_source * N_cell)
  - from source to cell (fig from Thomas Peters)



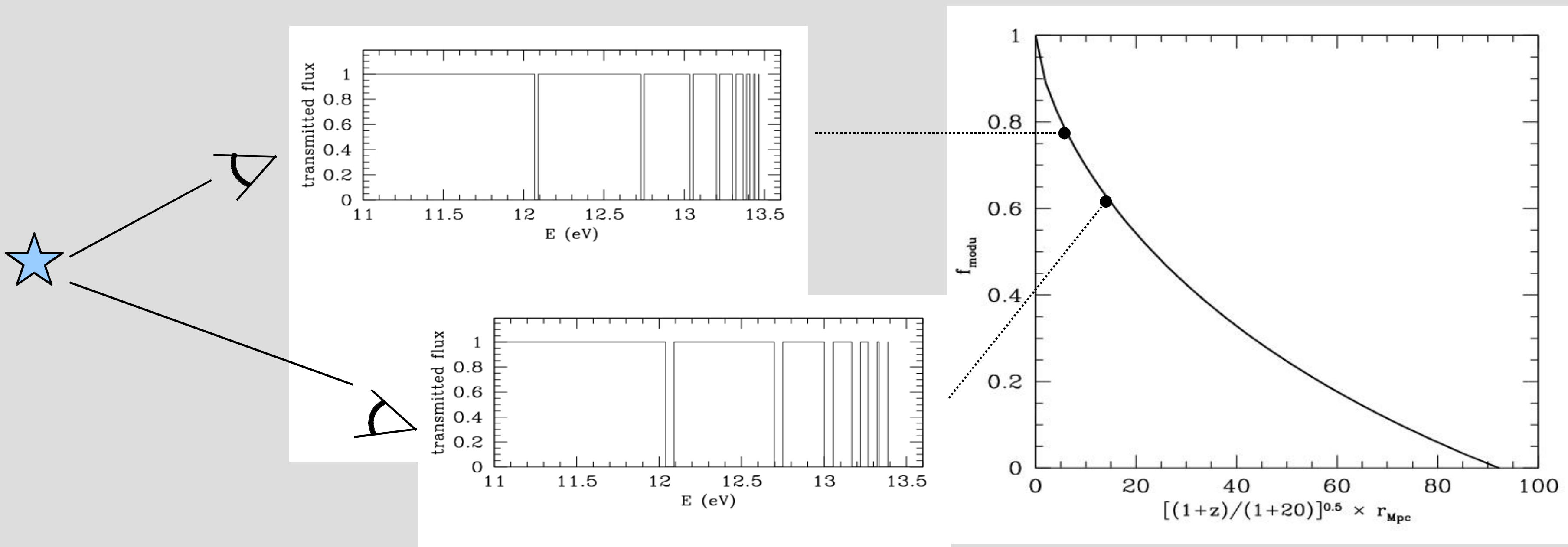
- Hear more from Garrelt Mellema on Friday (if available)

How LW transfer done: Picket-Fence Modulation Factor (KA, Shapiro, Iliev, Mellema, Pen 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.

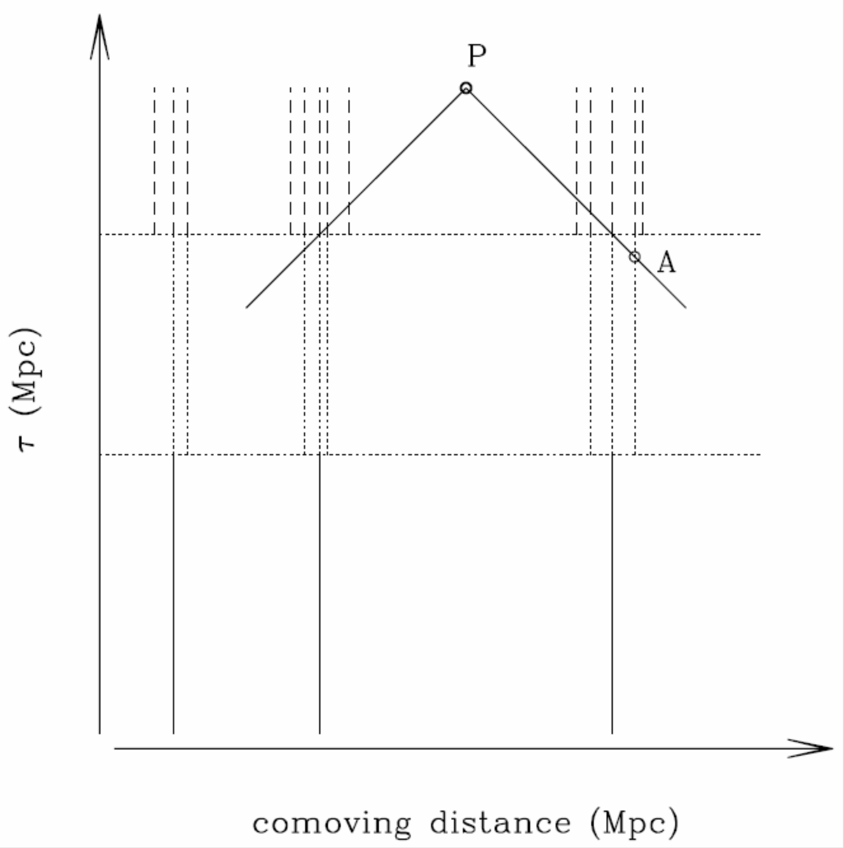
  - Relative flux averaged over E=[11.5 – 13.6] eV

  - multi-frequency phenomenon → single-frequency calculation with pre-calculated factor → Huge alleviation computationally.



How LW transfer done: Retarded-time emissivity/FFT

- Numerical techniques (continued)
  - Retarded time emissivity
- New development
  - Too many sources contributing to UV background
  - Before: brute-force summation of intensities from all sources
  - Now: Fast Fourier Transformation (N*logN operation)



How LW transfer done: Retarded-time emissivity/FFT

$$J_{LW}(t,\vec{x}) = G(t-t', \vec{x}-\vec{x}')\, L_{LW}(t', \vec{x}')$$

FFT ↕

G : Green's function for J_{LW}. $\sim \frac{1}{(\vec{x}-\vec{x}')^2} f_{mod}(|\vec{x}-\vec{x}'|)$

L_{LW} : LW luminosity of a source

$$\tilde{J}_{LW}(t,\vec{k}) = \tilde{G}(t-t', \vec{k})\, \tilde{L}_{LW}(t', \vec{k})$$

① Compute G (one $L_{LW}=1$ source in the box)

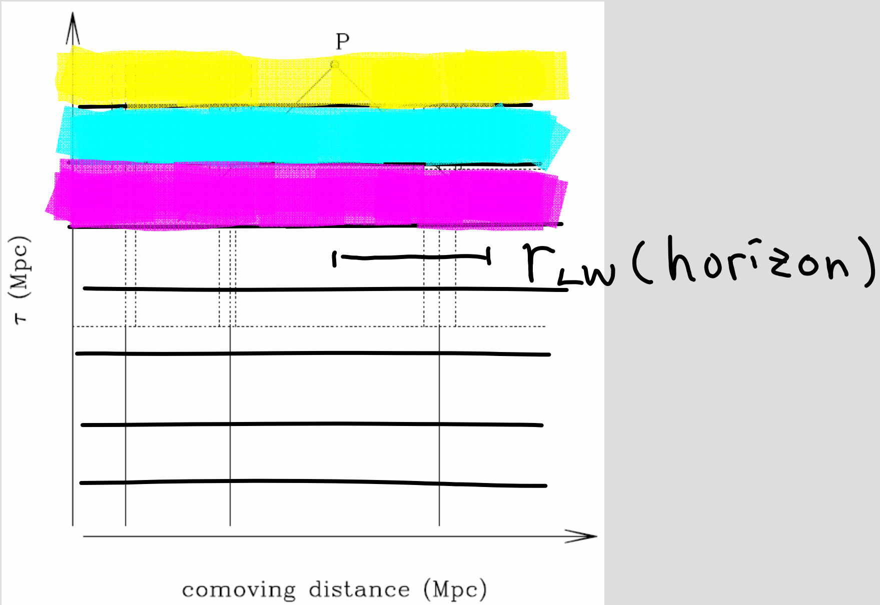
② FFT(G) → $\tilde{G}$, store $\tilde{G}$ ↑ (pre-computation)

- - - - - - - - - - - - - - - - - - -

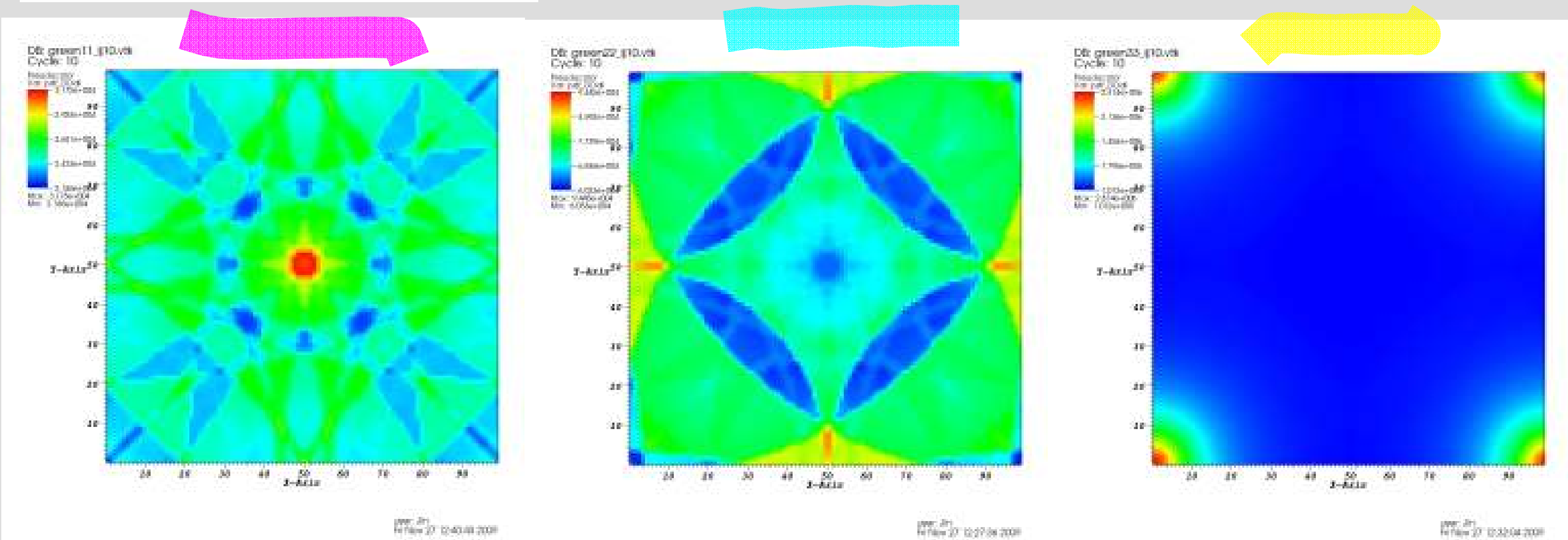
③ FFT(L_{LW}) → $\tilde{L}_{LW}$ ↓ (during simulation)

④ FFT($\tilde{G}\tilde{L}_{LW}$) → J_{LW} → Suppress Pop III formation accordingly.

How LW transfer done: Retarded-time emissivity/FFT



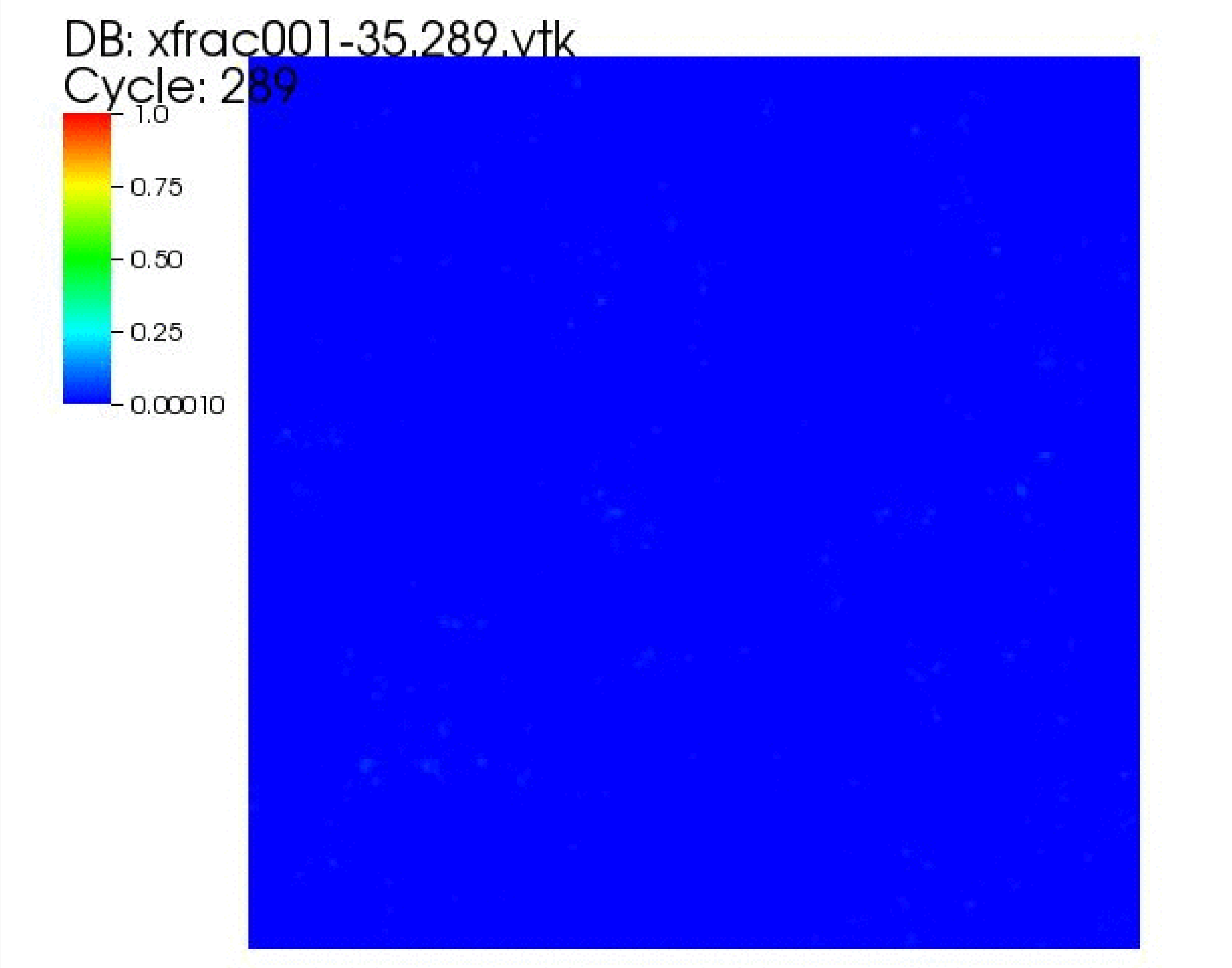
what $\tilde{G}(t-t', \vec{k})$ looks like



What do we expect

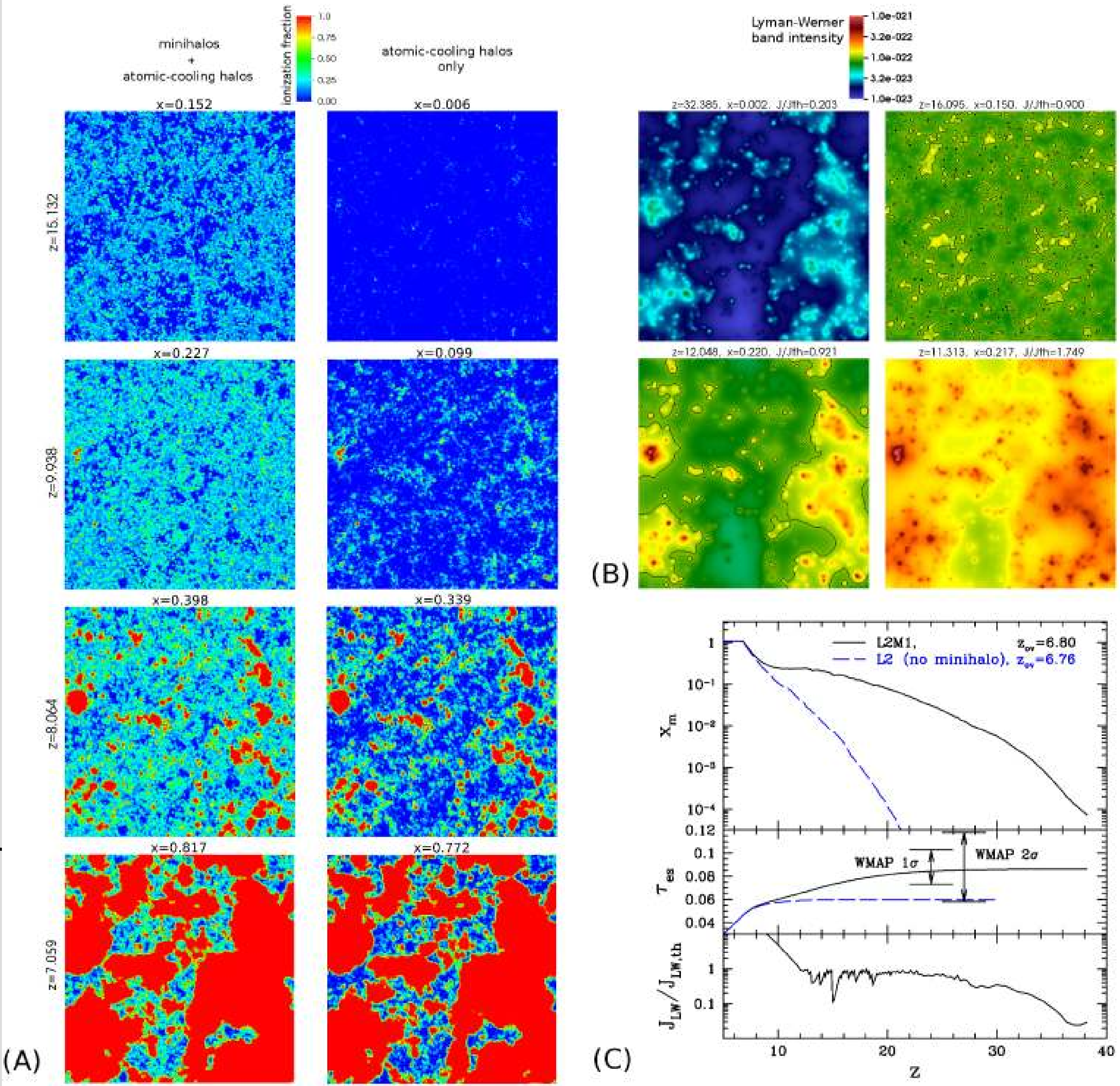
- More extended reionization
- Same x_e but different morphology, with and without minihalos (c.f. McQuinn et al. 2007)
- More electron content → stronger polarization of CMB
- Earlier heating of intergalactic medium
- Earlier Lyα pumping on 21cm
- Earlier whatever…

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

114/h Mpc



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

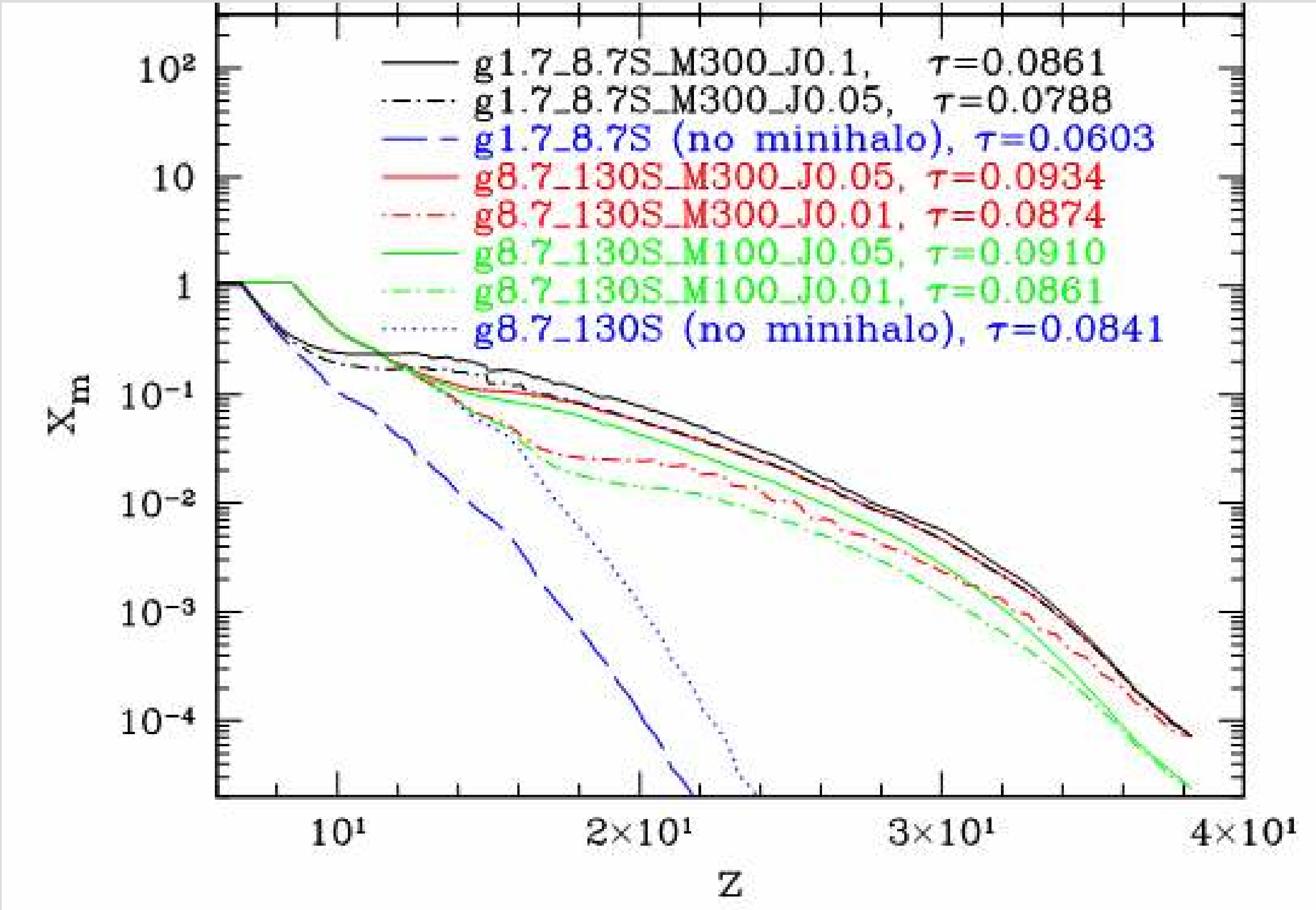
- Late- reionization- completion prior (z<~ 7)
  - small emissivity in massive halo sources required
  - not large enough optical depth ONLY with massive halo sources

- 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

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

amplitude (model)

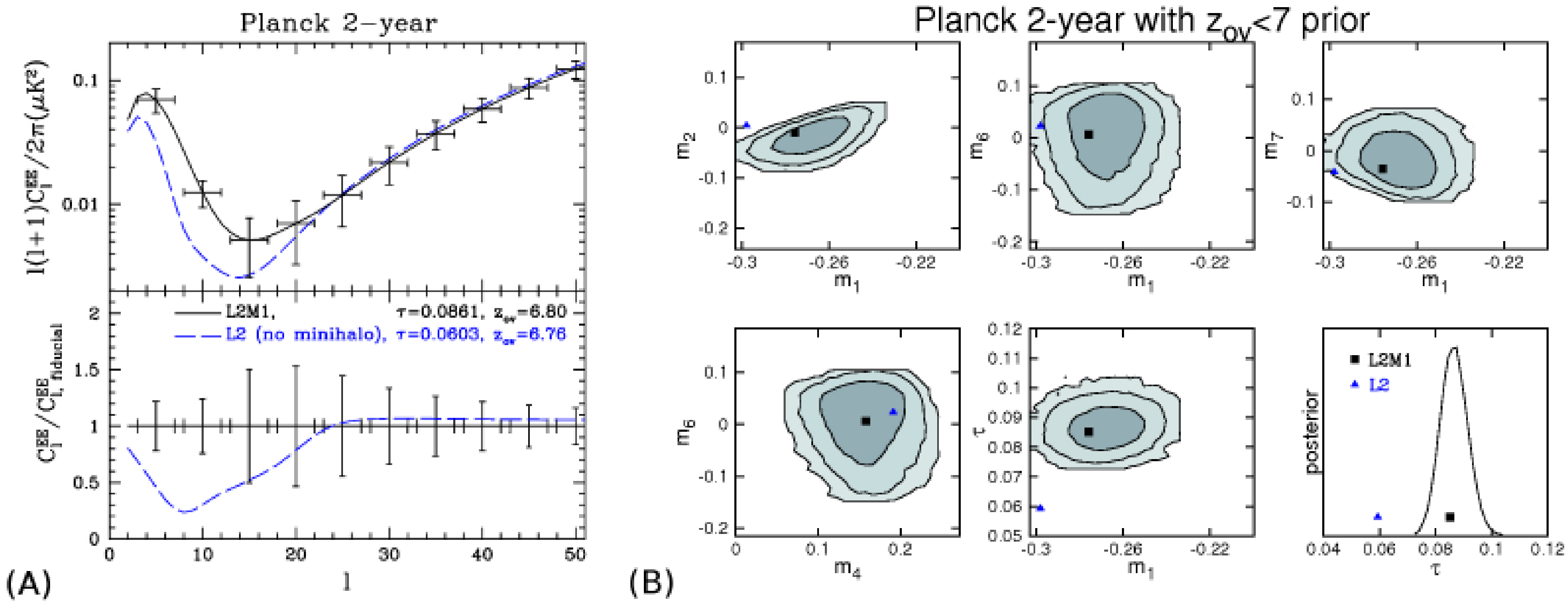
model-independent

principal component (basis)

Planck Forecast

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

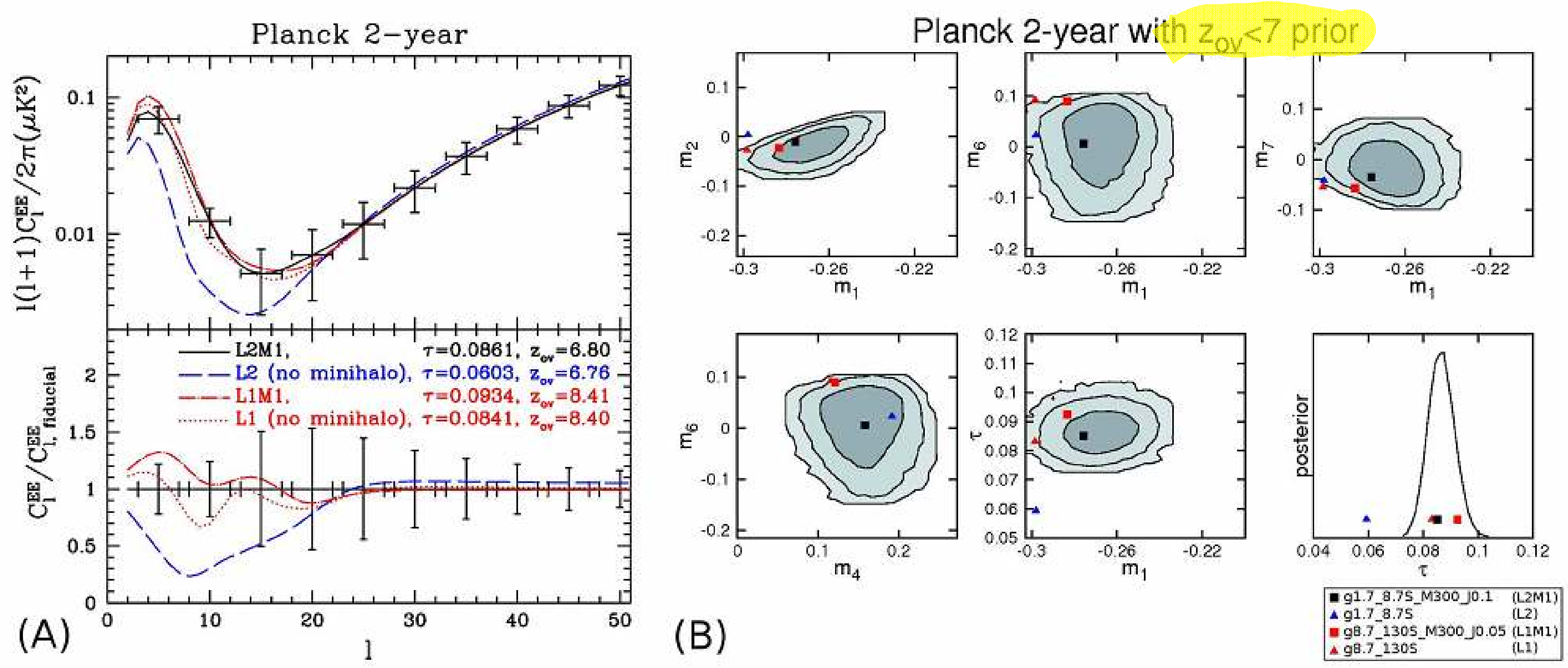
high-τ	vs.	low-τ
(w/ minihalo)		(wo/ minihalo)
(w/ first star)		(wo/ first star)



Hu & Holder; Motonson & Hu: PCA for reionization

Planck Forecast

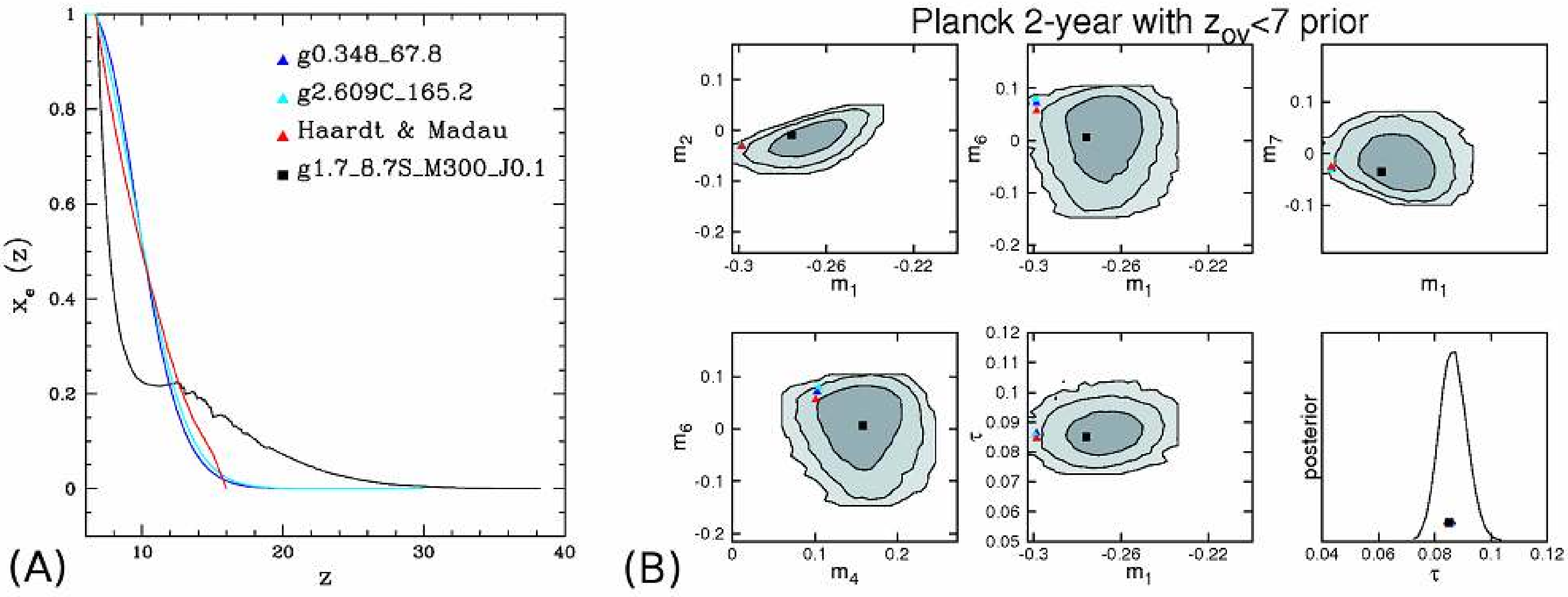
$\tau \sim 0.085$ (common), late ($z_{ov}<7$) (black) (w/ first star) vs. early ($z_{ov}>7$) (red) (w/ or wo/ first star)



Planck Forecast

$\tau \sim 0.085$ (common) w/ first star (black) vs. w/o first star (red, blue, cyan)

$z_{ov} < 7$

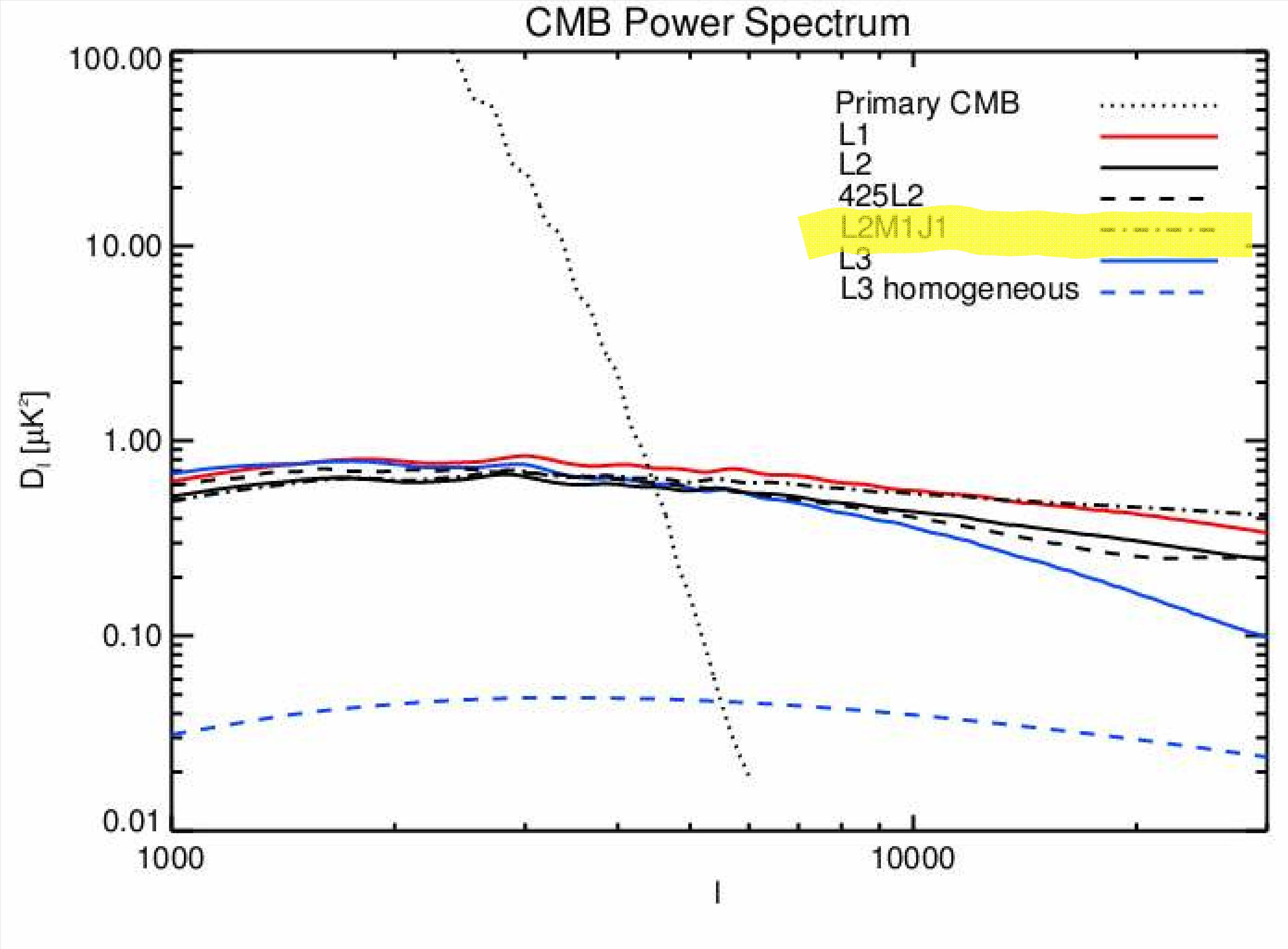


Summary/ prospects

- Minihalos (first stars)
  - can satisfy late reionization, high- optical depth conditions simultaneously: puzzle solved
  - very extended reionization, with plateau in x(z)
  - Planck can smell the first stars no matter what!
- Chores
  - 21cm (absorption, emission, cosmology (Mao), ...)
  - tSZ, kSZ (related to SPT observation)
  - NIRB
  - cosmic archeology / local universe metallicity
- 0^{th} order done, 1^{st} order need be further pursued
  - mass of Pop III star, x- ray binary, baryon offset
- Observational constraints needed more (LAE hunters, QSO hunters, GRB hunters)
- Theoretical constrains needed more (e.g. critical LW intensity: Norman, Wise, Hasegawa, Susa, ...)

Post-Planck language (if interested in EoR)

- WMAP
  - reionization parameterized by two (dependent) variables: τ_{es}, z_{reion}
  - was OK with WMAP sensitivity
- Planck
  - reionization SHOULD BE parameterized by many (dependent) variables: τ_{es}, m_1, m_2, m_3, …
  - probing astrophysics at cosmological scale! (detecting first star era)
- Hasty conclusion from South Pole Telescope (small-scale CMB aniostropy)
  - Zahn et al. 2012: reionization duration dz < 4.4-7.9
  - being debunked by Hyunbae Park et al. in preparation


CMB Power Spectrum
Primary CMB
L1
L2
425L2
L2M1J1
L3
L3 homogeneous
100.00
10.00
1.00
0.10
0.01
D_l [μK^2]
1000
10000
l