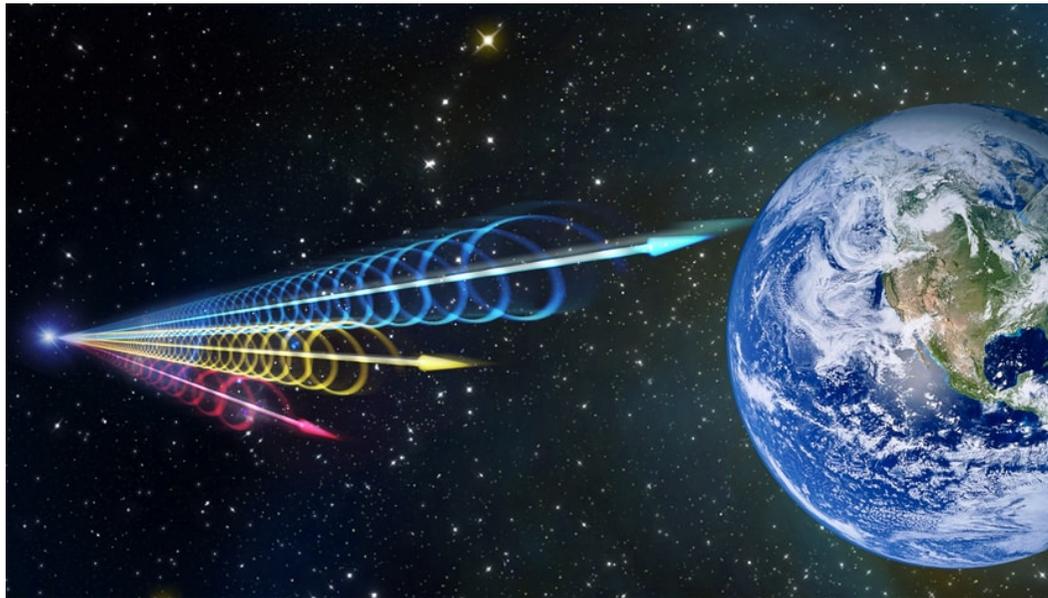


# Fast Radio Bursts as Potential Cosmological Probes

Susumu Inoue (RIKEN)

K. Ichiki, H. Shimabukuro

Papers in prep.

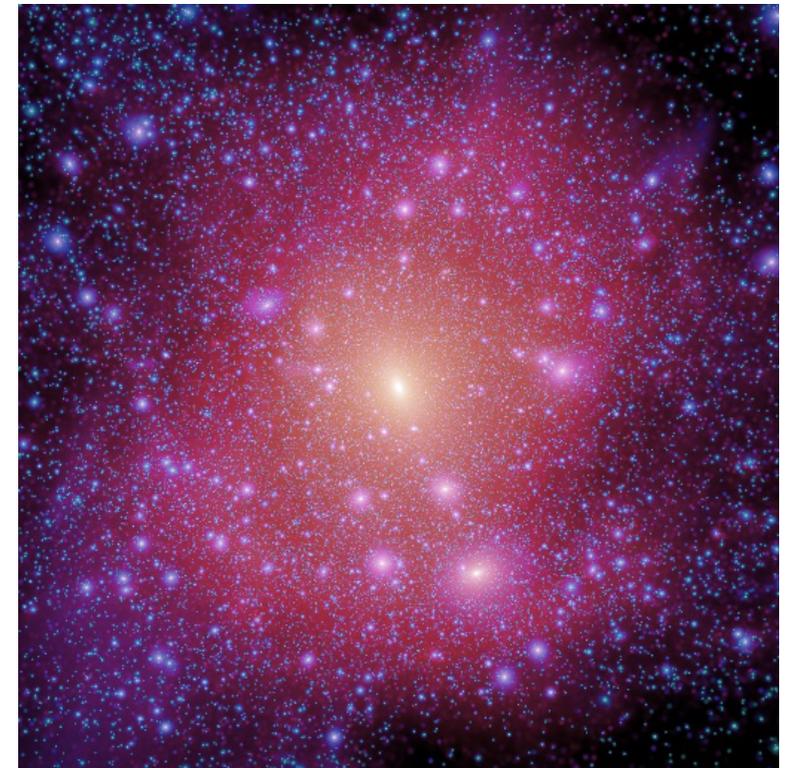
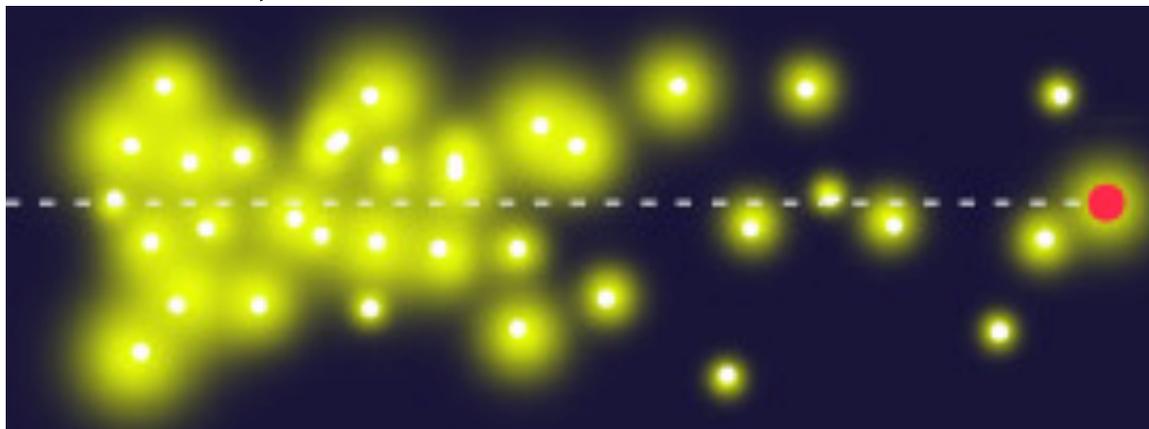


## Small-Scale Power Spectrum

galaxy formation,  
warm dark matter

## Cosmic Reionization

H+He, evolution of faint AGN



*In an intergalactic burst I'm back to reveal the Universe...*

# cosmic dark ages -> cosmic dawn

$z \sim 3600$

$z \sim 1000$

$z > \sim 30$

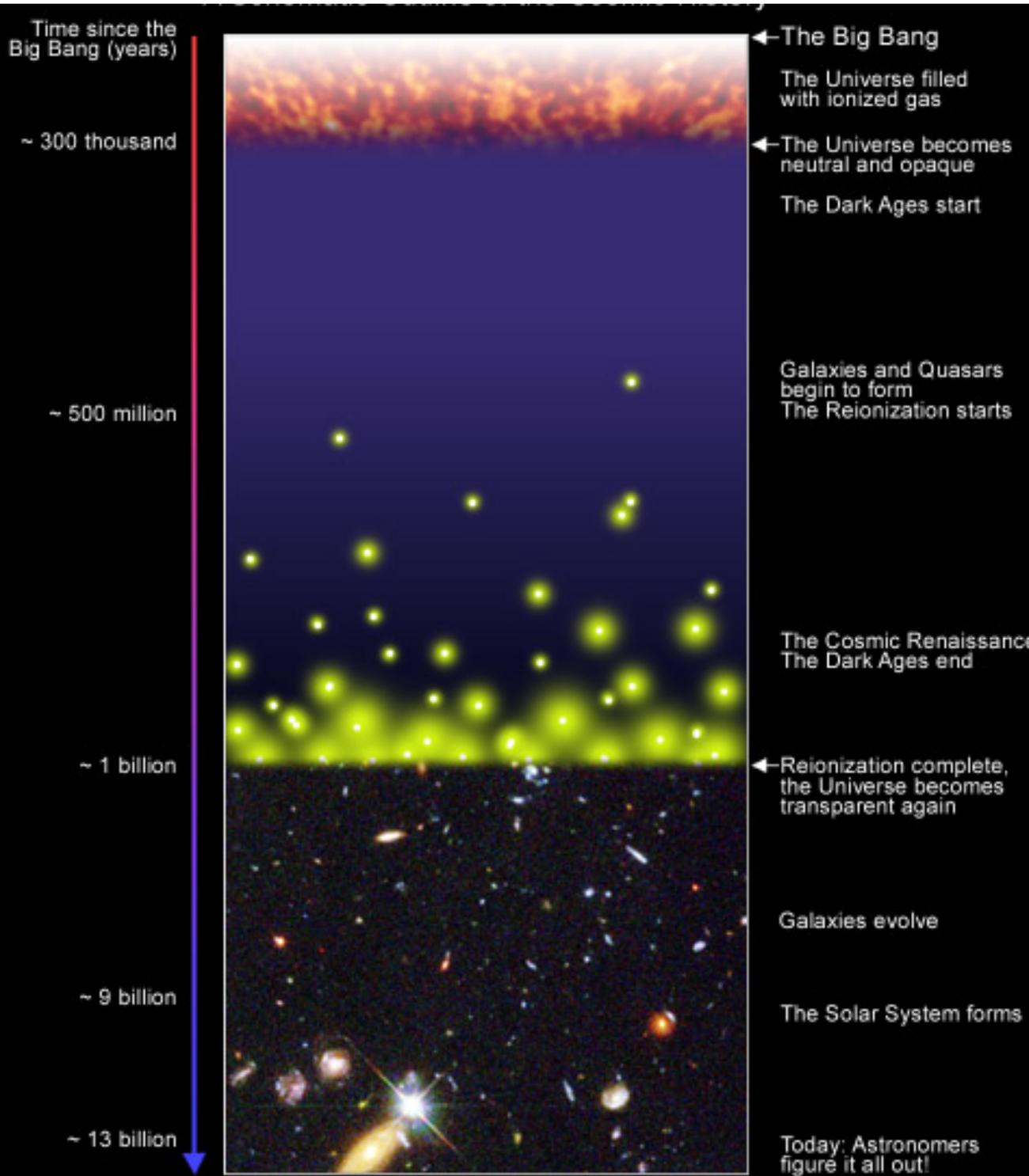
$z \sim 8-10$

$z \sim 6$

$z \sim 3$

$z \sim 1-2$

$z \sim 0$



- big bang
- matter-rad. eq.
- recombination

- first stars, galaxies, black holes...  
-> reionization

- HI reion. end (+HeI->HeII)
- HeII reion. end

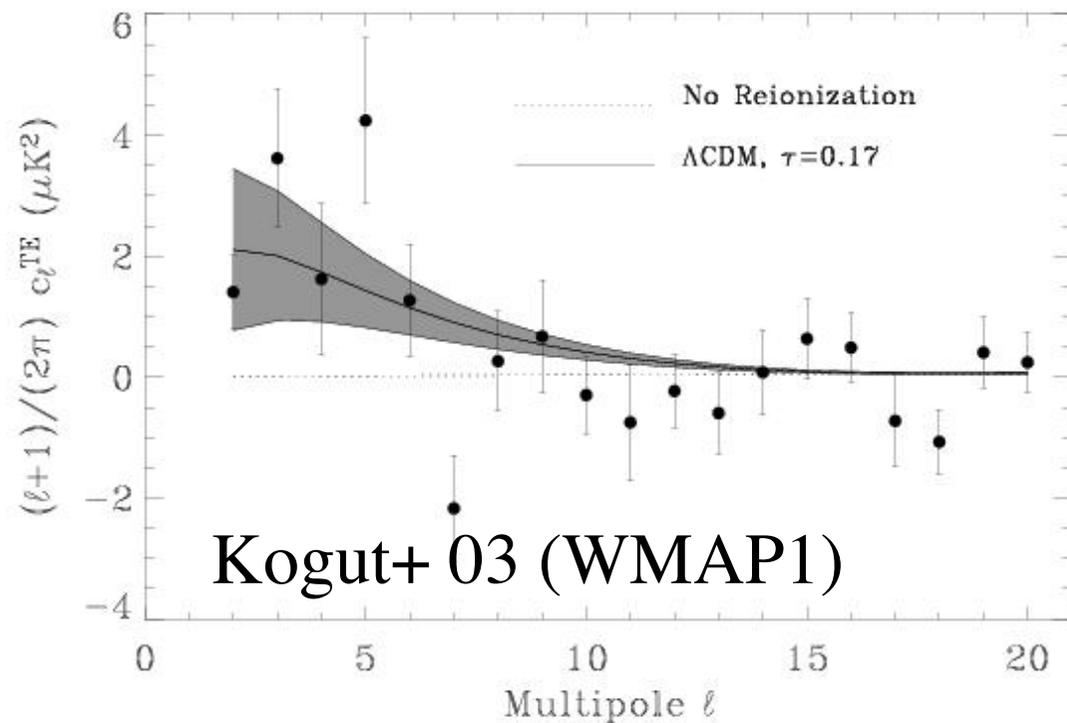
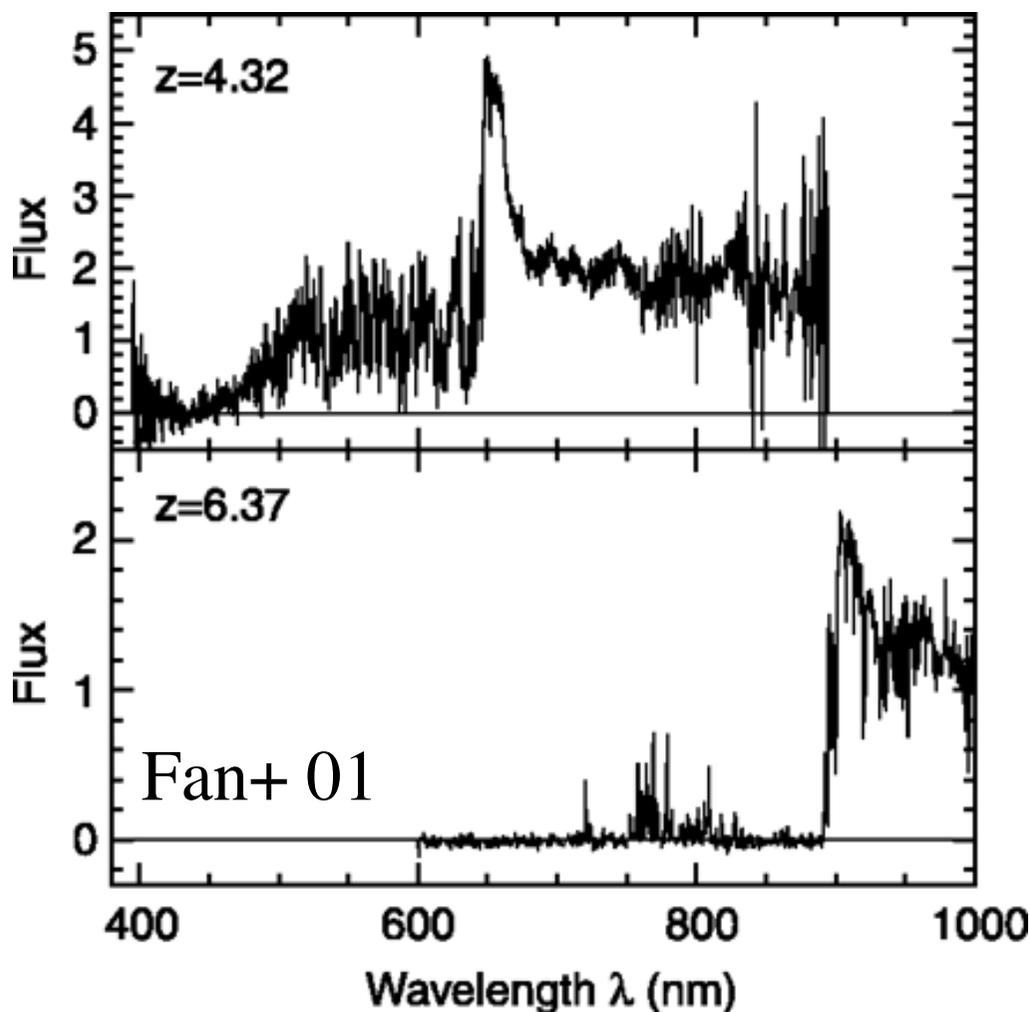
- star formation  
AGN activity  
peak

adapted from Djorgovski

# observational constraints on cosmic HI reionization

quasar Ly $\alpha$  absorption troughs:  
neutral IGM at  $z \sim 6$

CMB polarization anisotropy:  
ionized IGM at  $z \sim < 17? \rightarrow 6-10$



# HeII Ly $\alpha$ absorption troughs: end of He reionization at $z \sim 3$

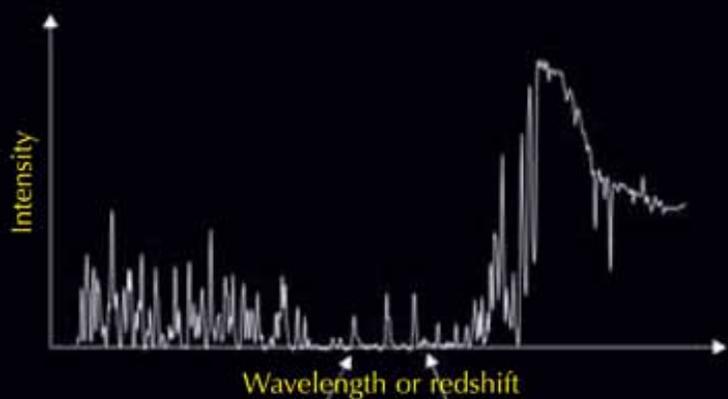
ionization energy:

HeI – 24.6 eV

near-simultaneous with  
H reionization (massive stars?)

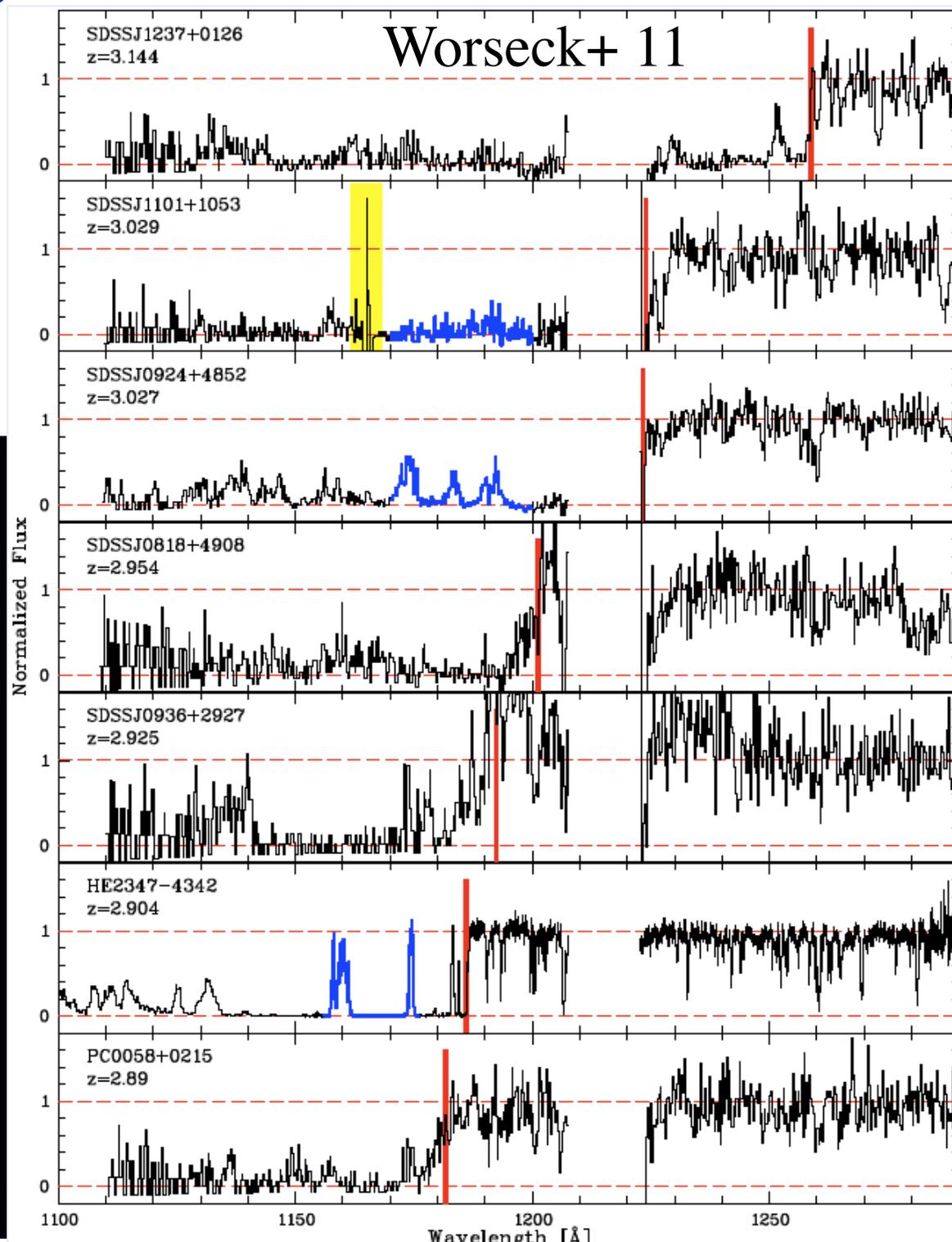
HeII – 54.4 eV    quasars only!

## The effect of reionisation on quasar spectra



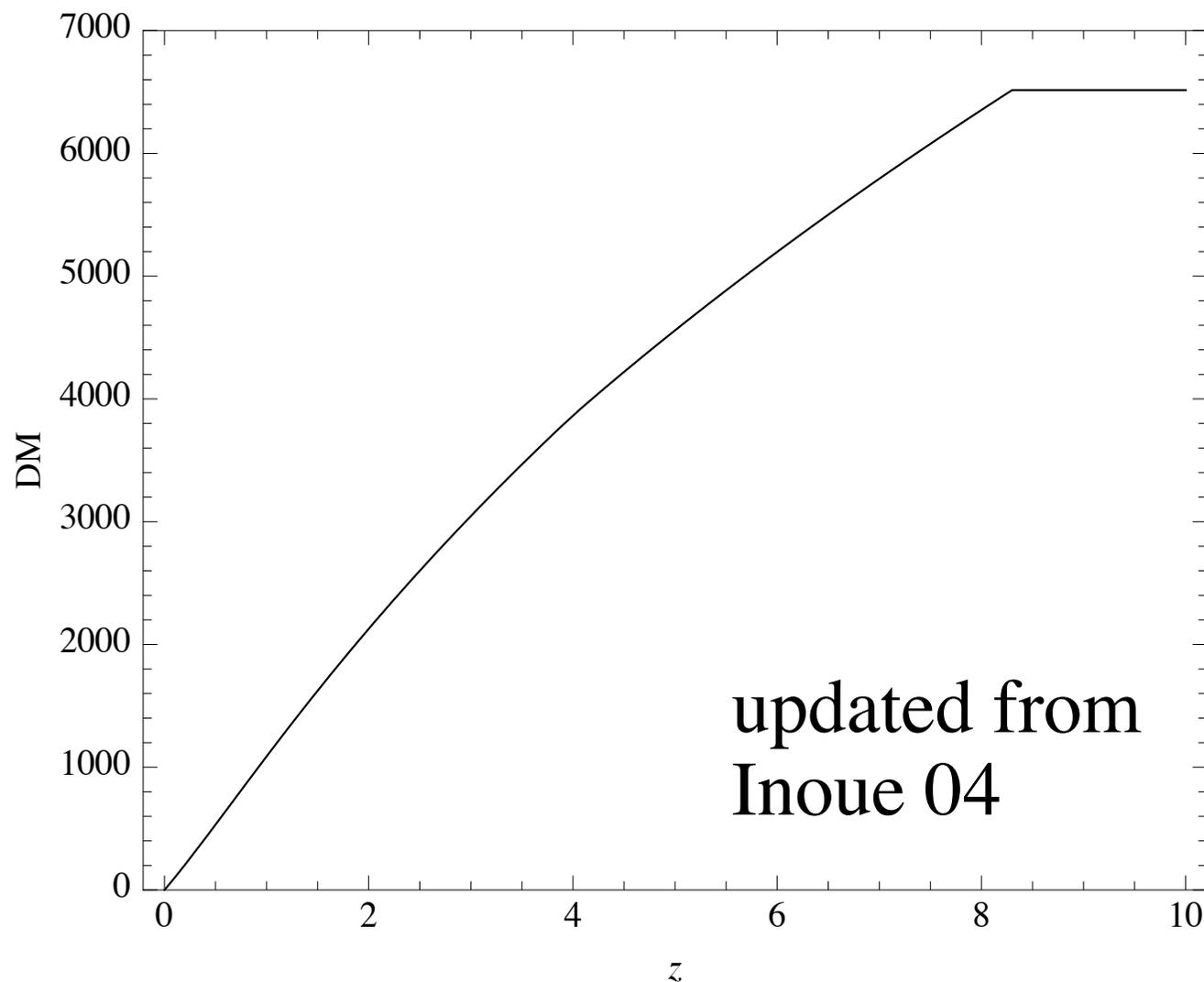
Isolated transmission spikes correspond to the ionised bubbles along the line of sight

Dark regions correspond to the still opaque, neutral gas along the line of sight



# dispersion measure for IGM with H+He

assuming instantaneous reionization of HI at  $z=8.3$ , HeII at  $z=4$



NB

Ioka 03: H only, no He

Inoue 04: H+HeII,  
but no HeIII

updated from  
Inoue 04

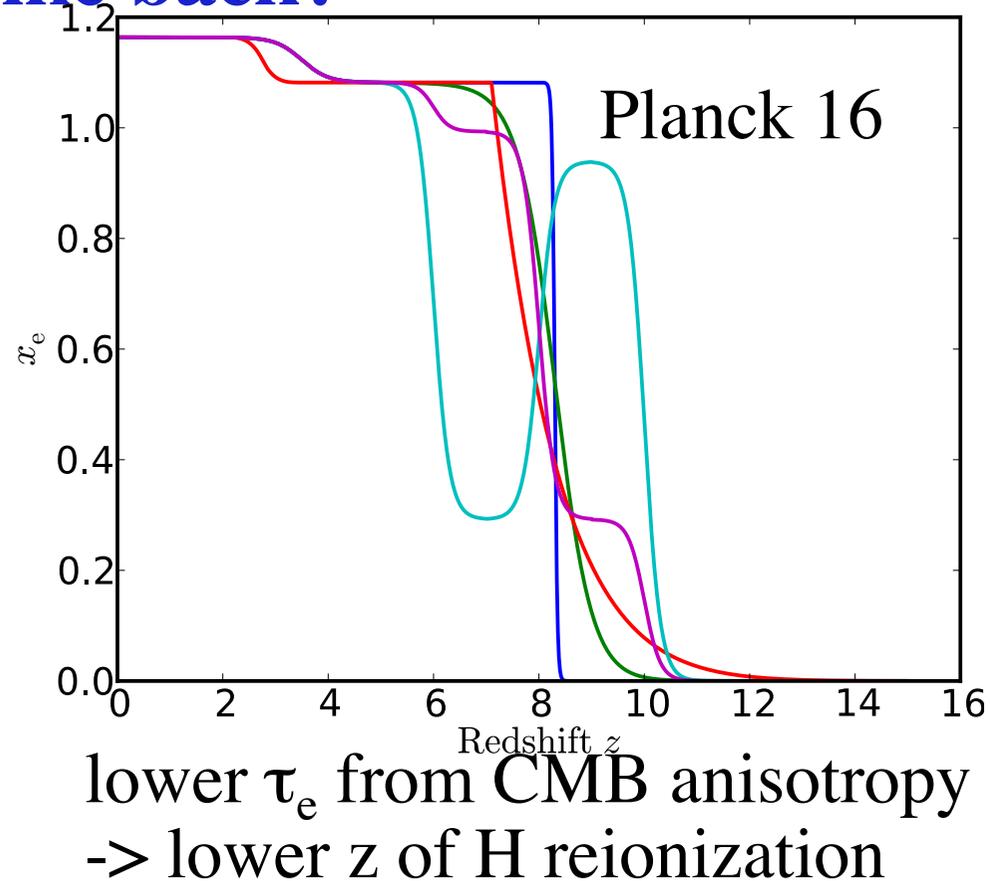
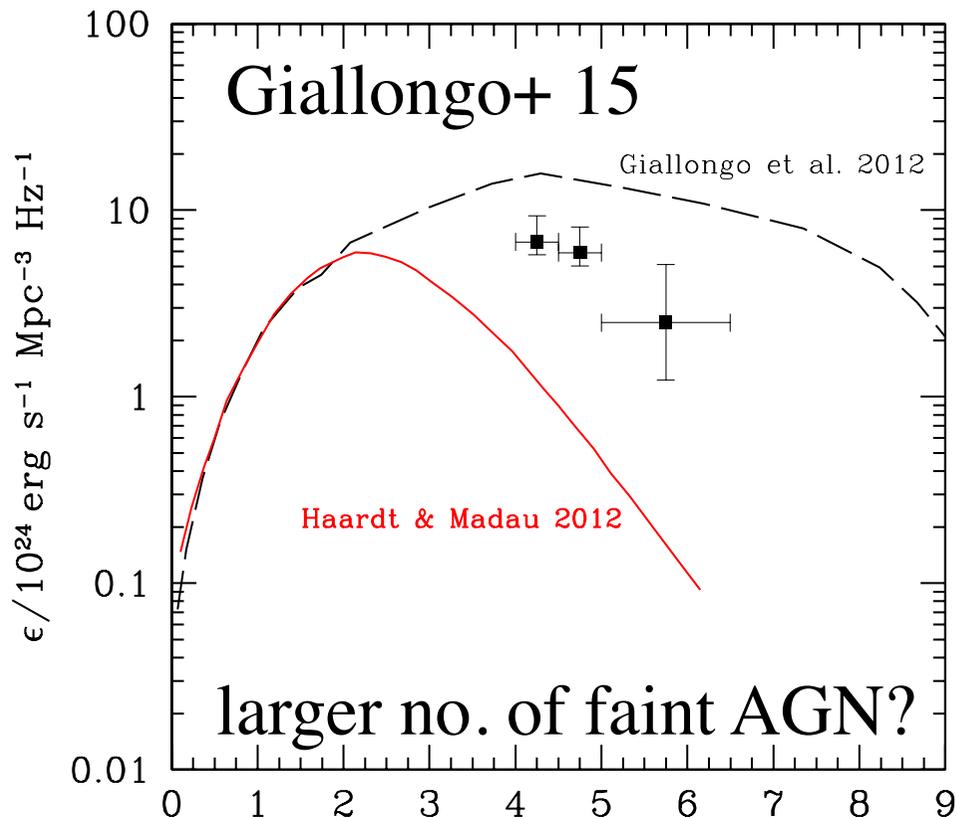
see also Zheng+ 14  
Deng & Zhang 14

FRB 160102:  $DM=2596 \text{ pc cm}^{-3}$   $\rightarrow z=2.5$  (not  $z=2.1$ !)

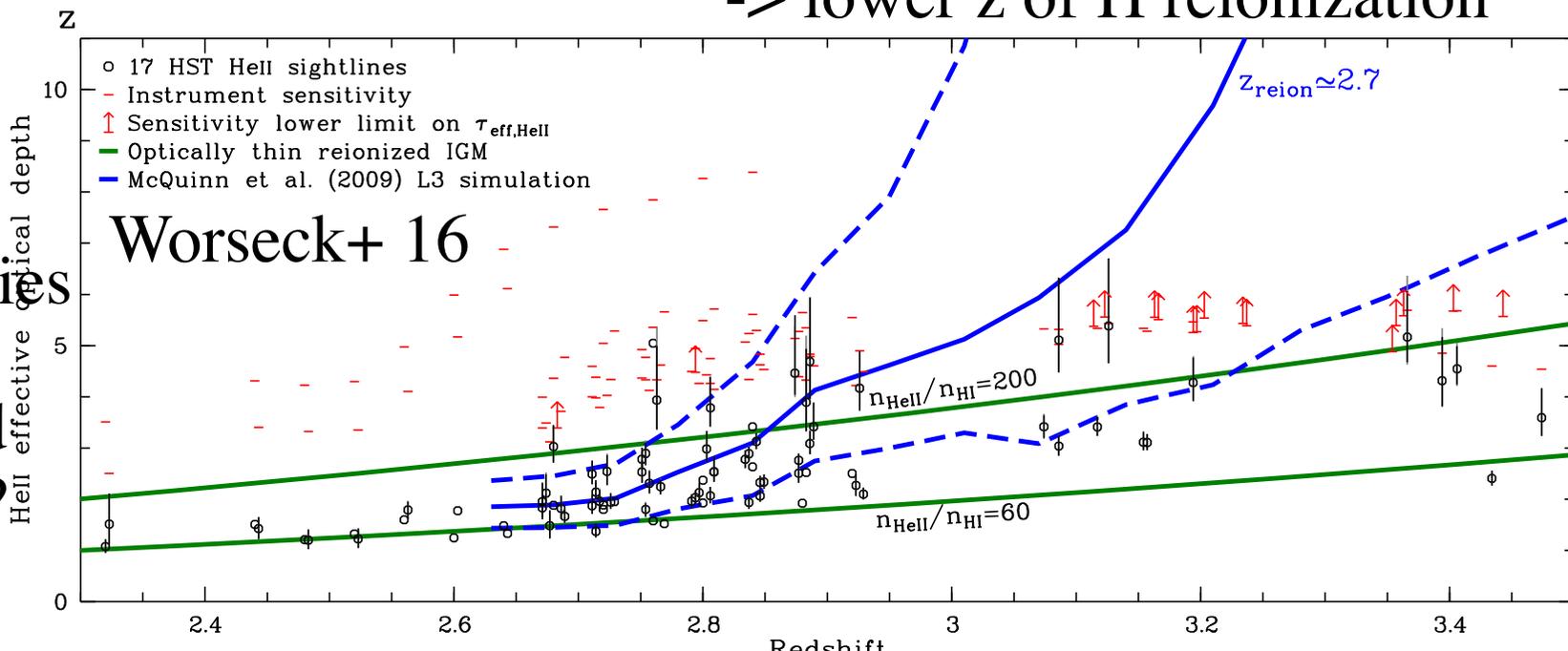
assuming  $DM_{\text{local}} \sim 100-200$ ,  $z \sim 2.3-2.4$

approaching epoch of HeII reionization

# cosmic reionization: quasars strike back?



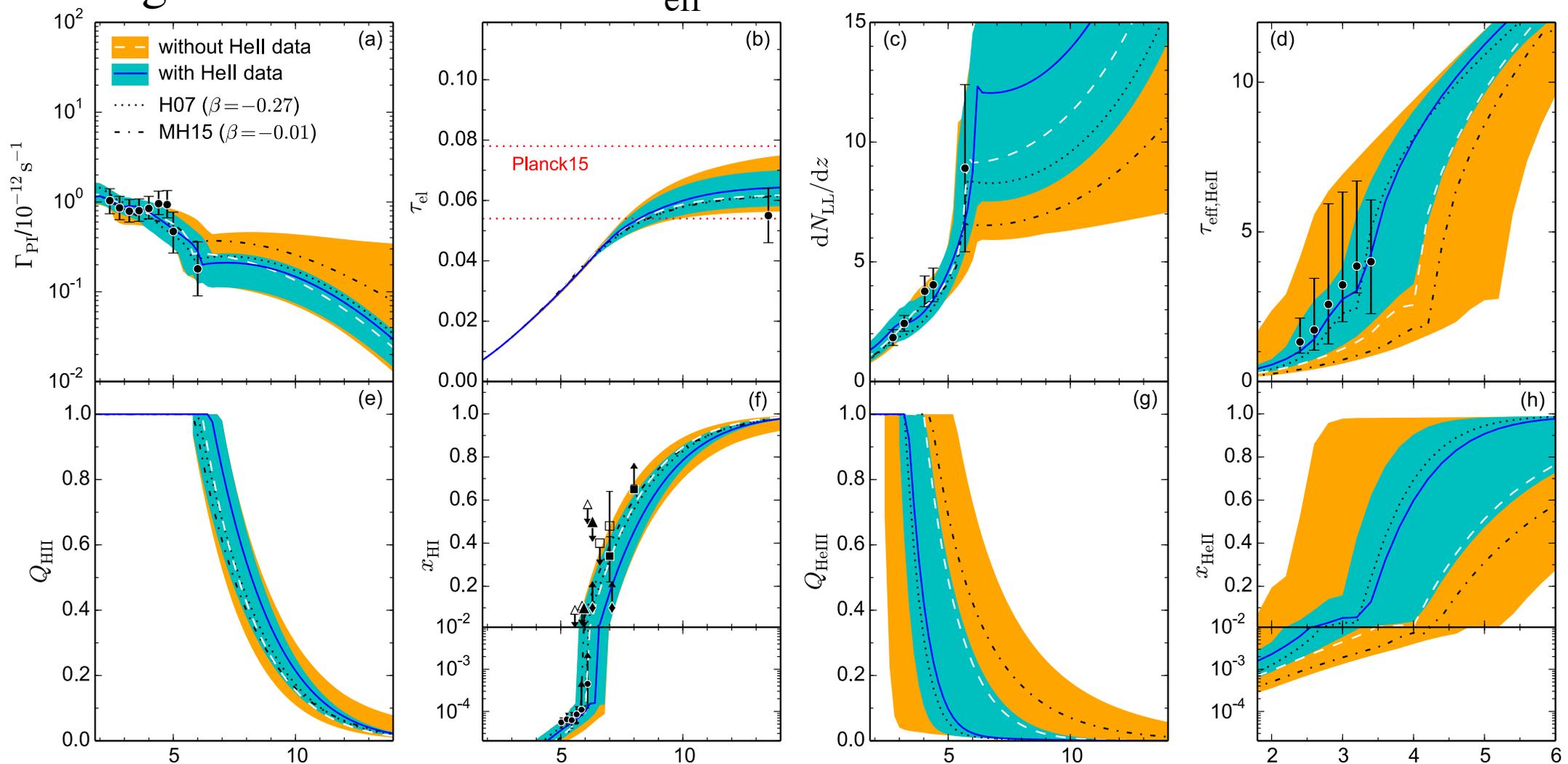
HeII Ly $\alpha$  opacities  
->  
earlier, extended  
He reionization?



# quasar contribution to H+He reionization

Madau & Haardt 15, Khaire+ 16,  
Yoshiura+ 16, D'Aloisio+ 16...

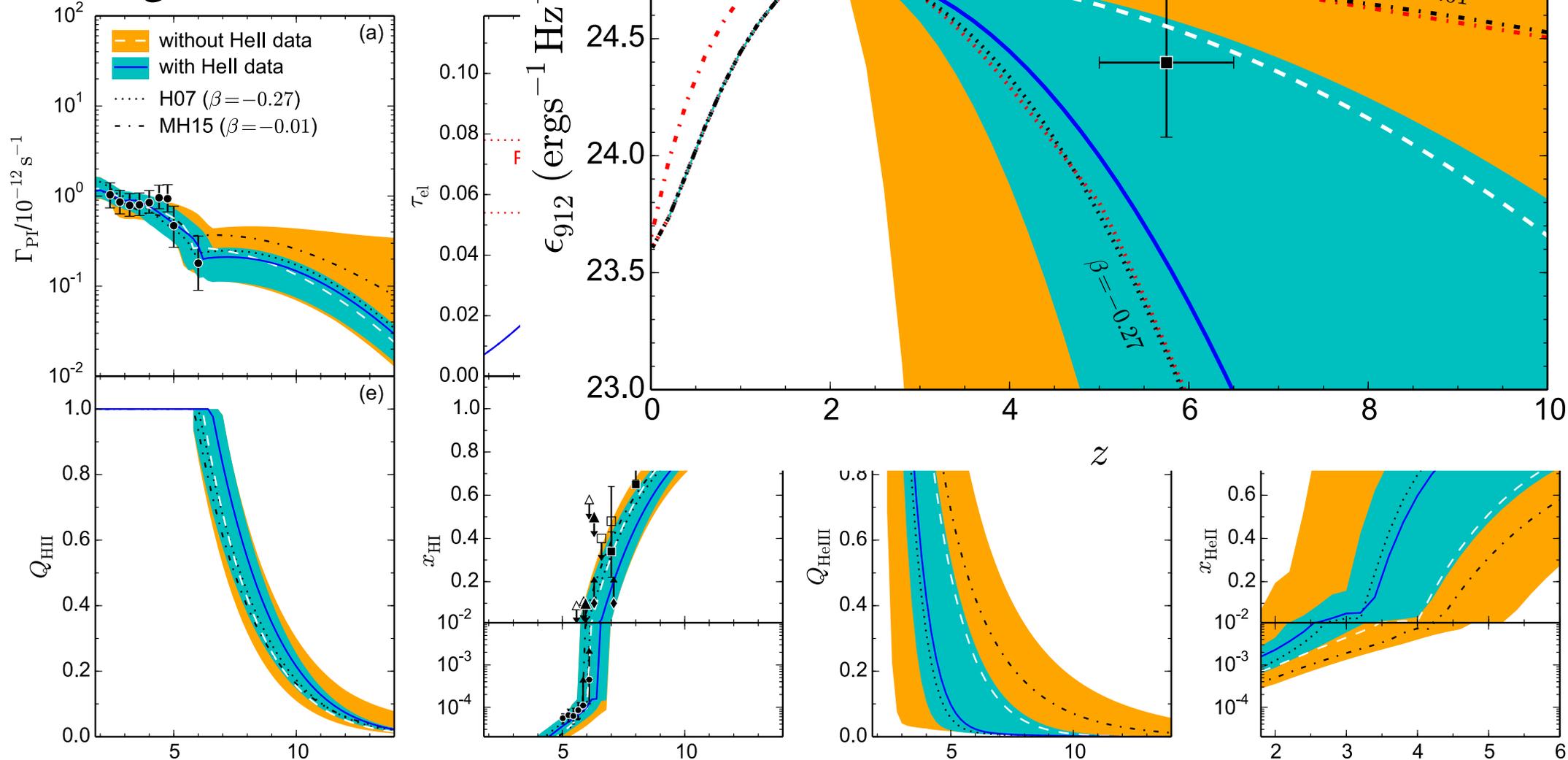
Mitra, Choudhury & Ferrara 16  
semi-analytic model with stars+QSOs  
strong constraints from HeII  $\tau_{\text{eff}}$  inferred



# quasar contribution to H+He reionization

Madau & Haardt 15, K  
Yoshiura+ 16, D'Aloisi

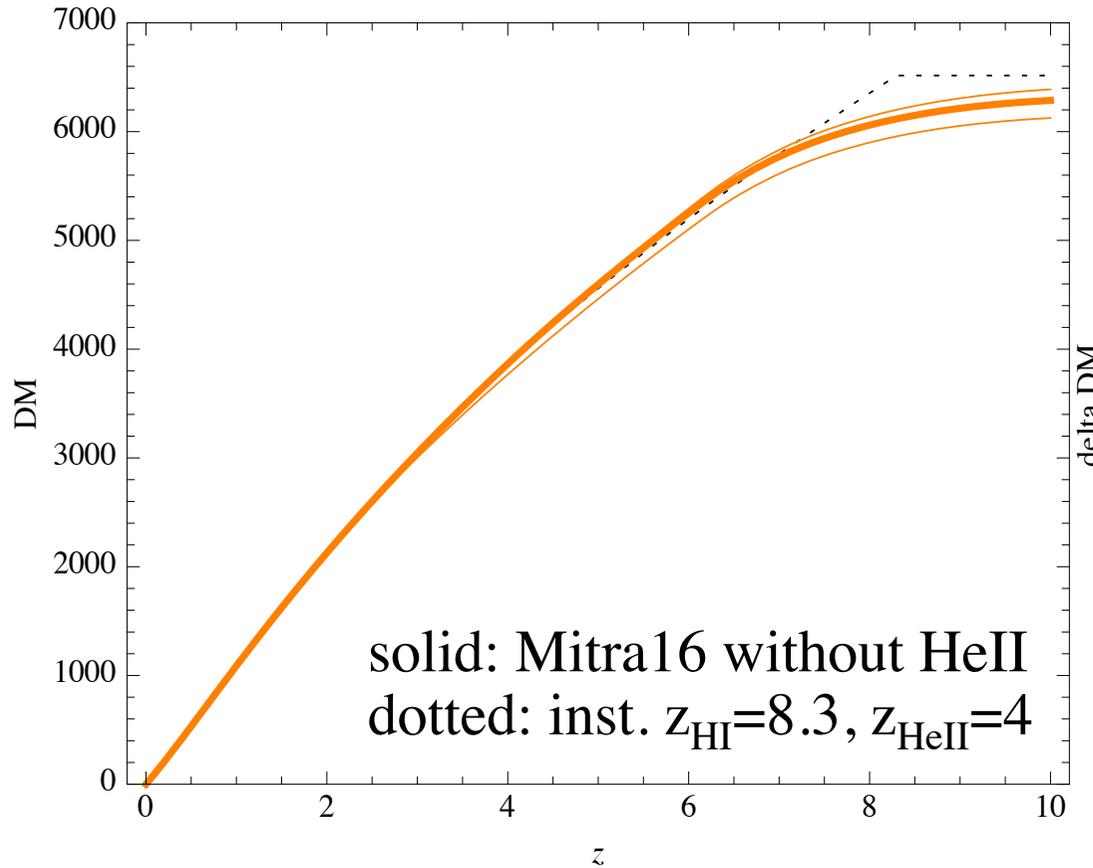
Mitra, Choudhury & Ferrara  
semi-analytic model with  
strong constraints from



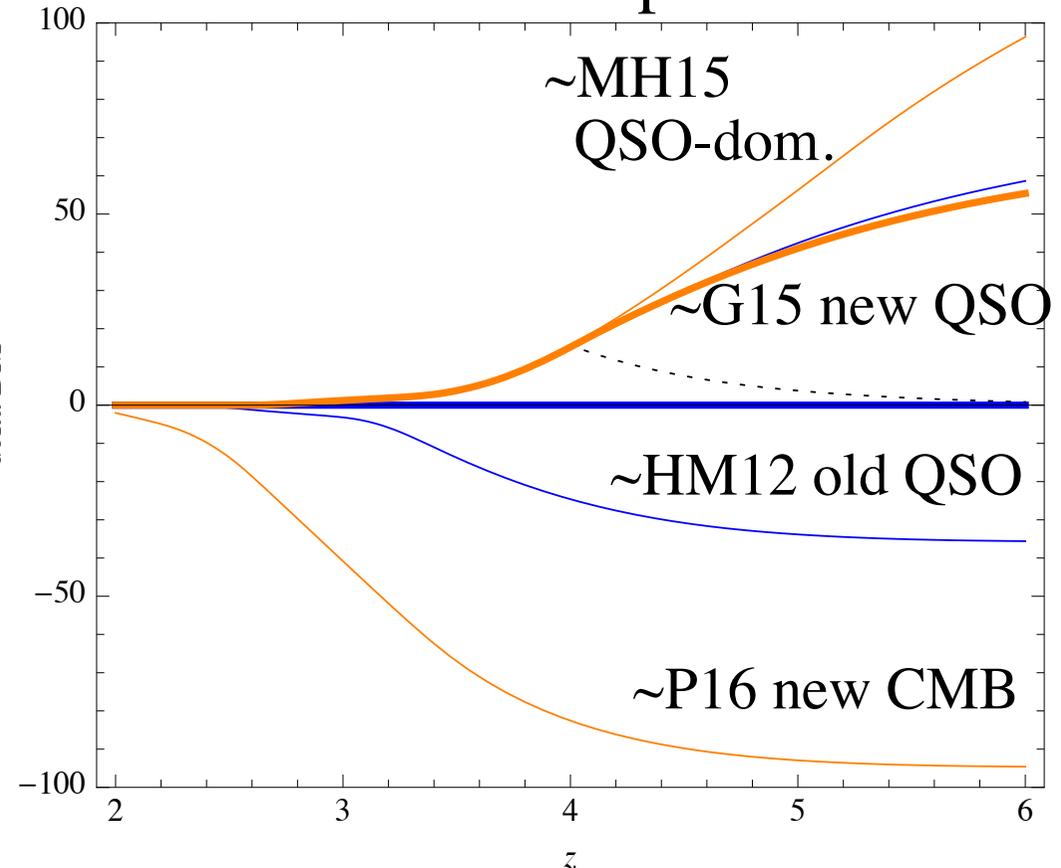
# IGM dispersion measure with reionization by stars+quasars

Mitra+16 model

DM of mean IGM

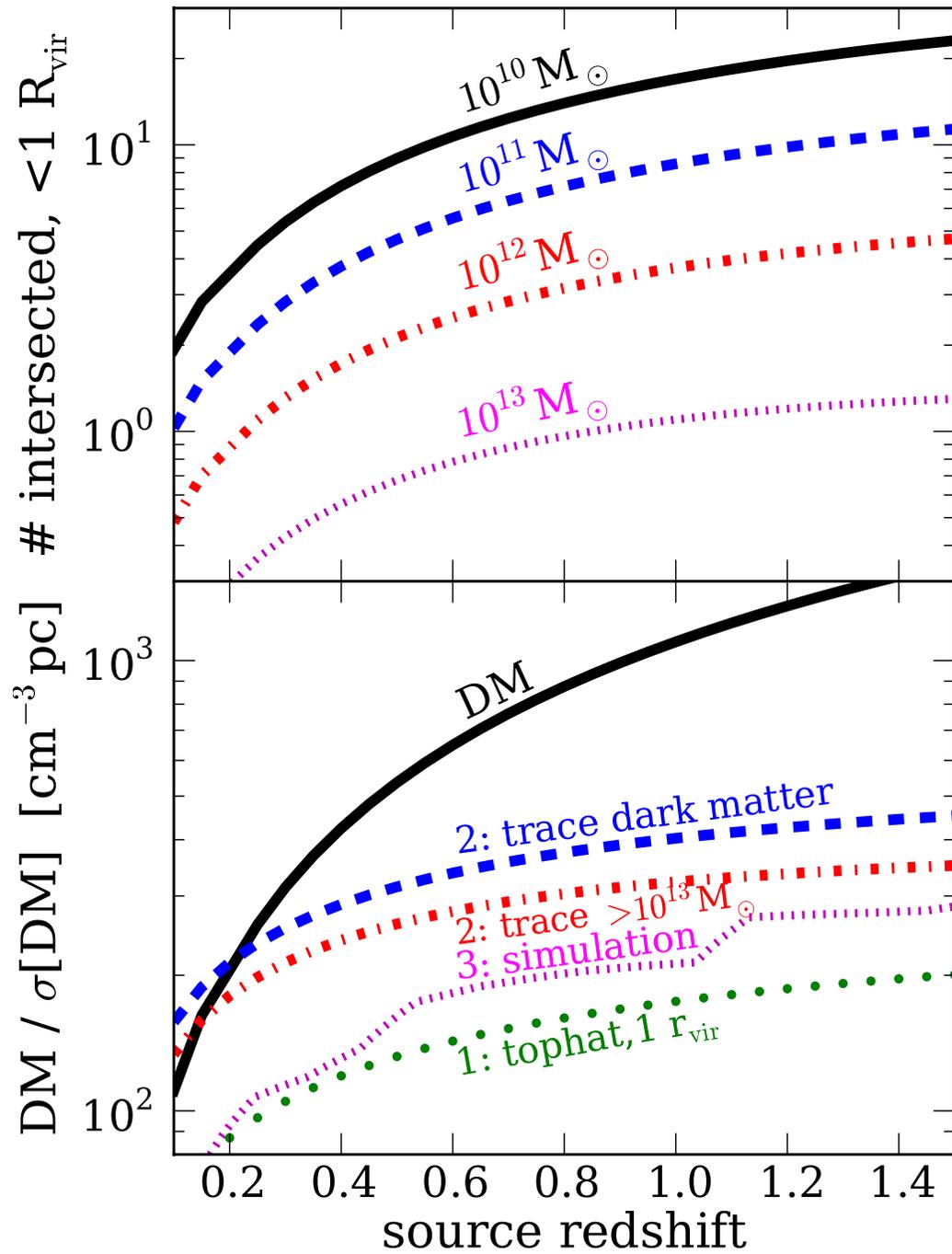


difference with respect to best fit



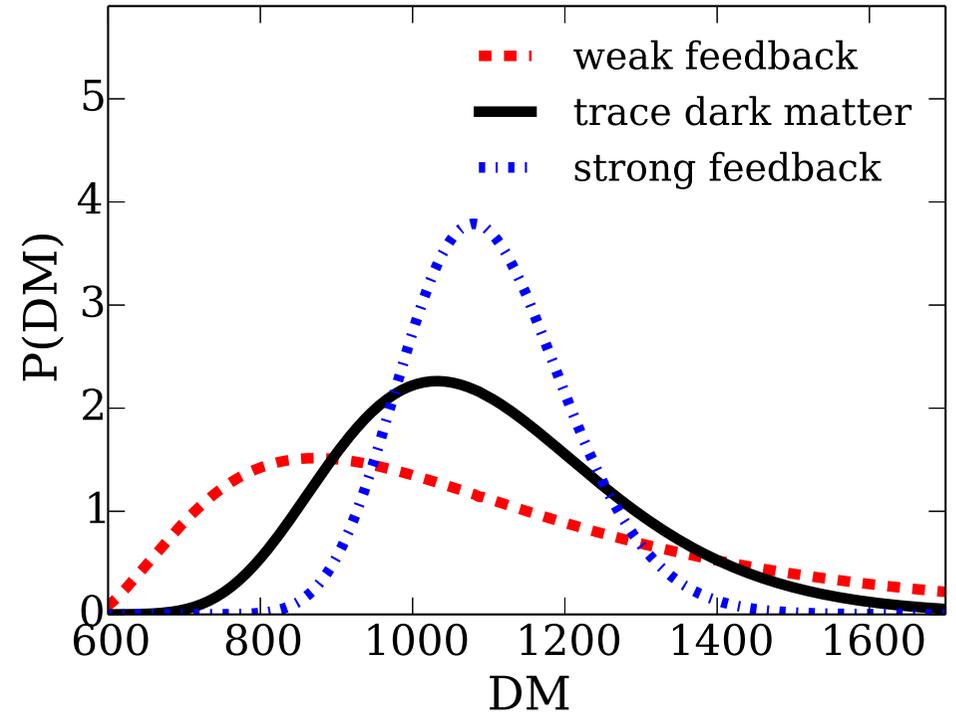
- model differences not large ( $\delta\text{DM} \sim \pm 100$  at  $z \sim 2-6$ ) but measurable
- unique info on H+He reionization, evolution of faint AGN
- variance from LSS averaged out in sufficiently large sample
- local DM main uncertainty  $\rightarrow$  can it be sufficiently constrained?
- uncertainties in reionization history important for  $\text{DM} > \sim 3000$

# FRB DM as probe of missing baryons $\rightarrow$ abundance of small halos



McQuinn 14

sizable variance expected due to LSS  
 $\rightarrow$  probe distribution of ionized circumgalactic gas



lines of sight out to  $z \sim 1$  intersect  
 sizable number of  $\sim 10^{10} M_{\text{sun}}$  halos  
 $\rightarrow \sigma(\text{DM})$  sensitive to abundance  
 and baryon distribution of such halos  
 $\rightarrow$  connection to small-scale issues  
 in galaxy formation, e.g. WDM

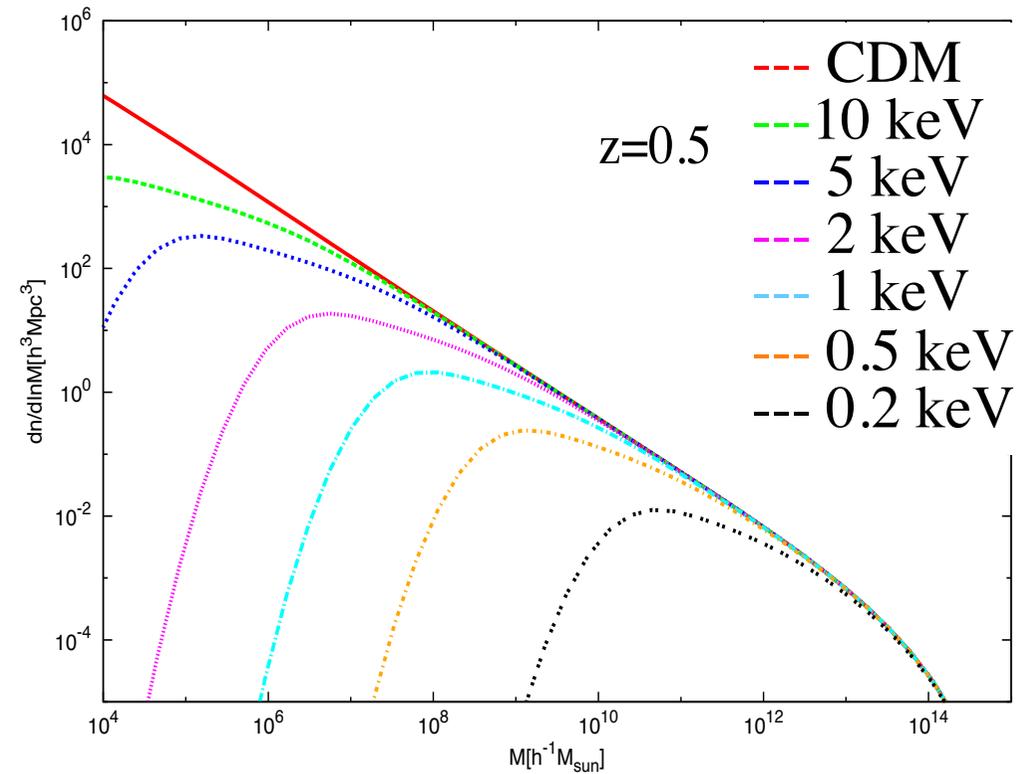
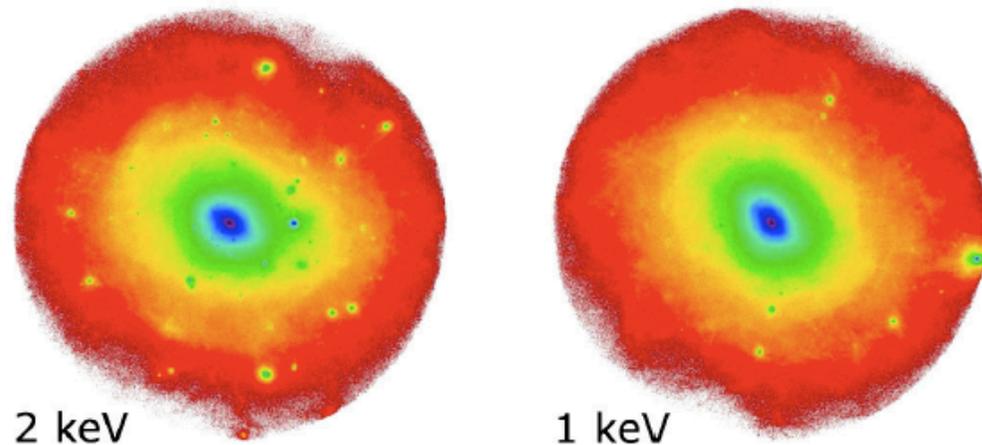
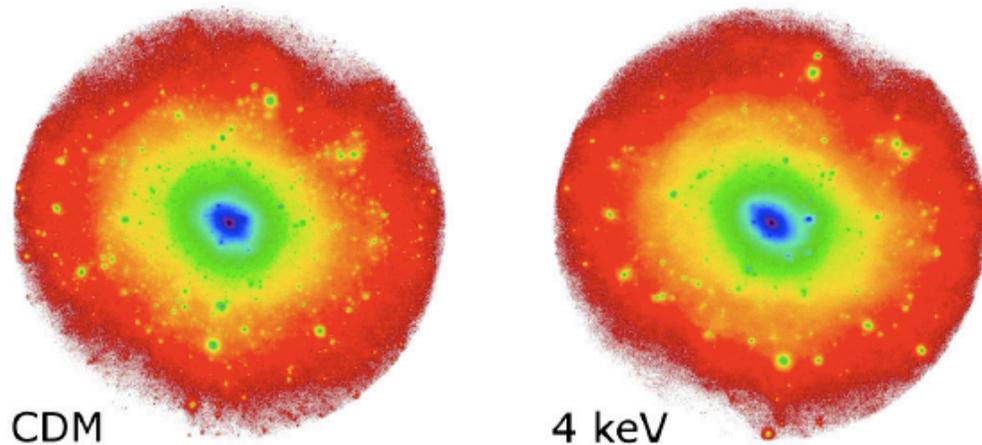
# cold dark matter (CDM): small-scale problems

e.g. “missing satellites” compared to simple CDM predictions

- astrophysical feedback?

- modification to CDM: warm dark matter (WDM)?

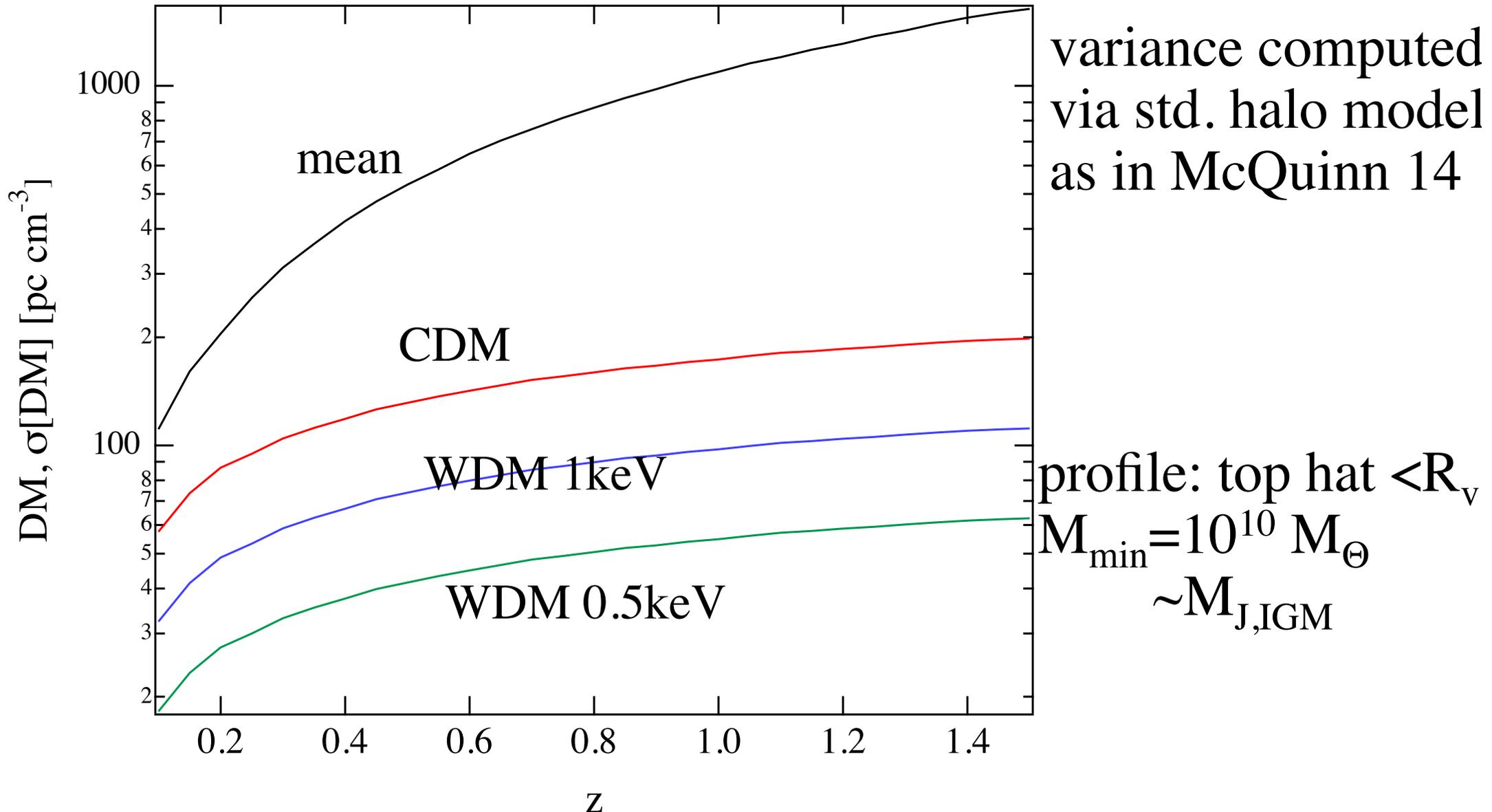
WDM halo MF



WDM simulation Polisensky & Ricotti 11



# dispersion measure: mean and variance with WDM



- further considerations necessary for variance in  $f_b$ , different profiles, etc
  - measurable differences expected for  $m_{\text{WDM}} \sim < 1 \text{ keV}$ 
    - > perhaps weaker compared to other probes e.g. Ly $\alpha$  forest
- nevertheless valuable independent probe from structure of ionized IGM

## summary

- crucial to include He for quantitative estimates of IGM DM
- FRB DMs: potentially unique, new probe of ionized intergalactic baryons
  - > cosmic reionization of H+He by stars+quasars  
evolution of faint AGN
  - > small scale power-spectrum (warm dark matter)
- need to distinguish  $\delta\text{DM}_{\text{IGM}} \sim 100\text{-}200$   
Q: can local DM be constrained to sufficient accuracy?

*Everything I had to know, I heard it on the radio...*