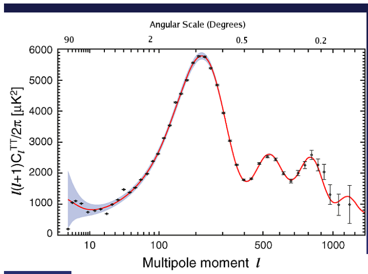
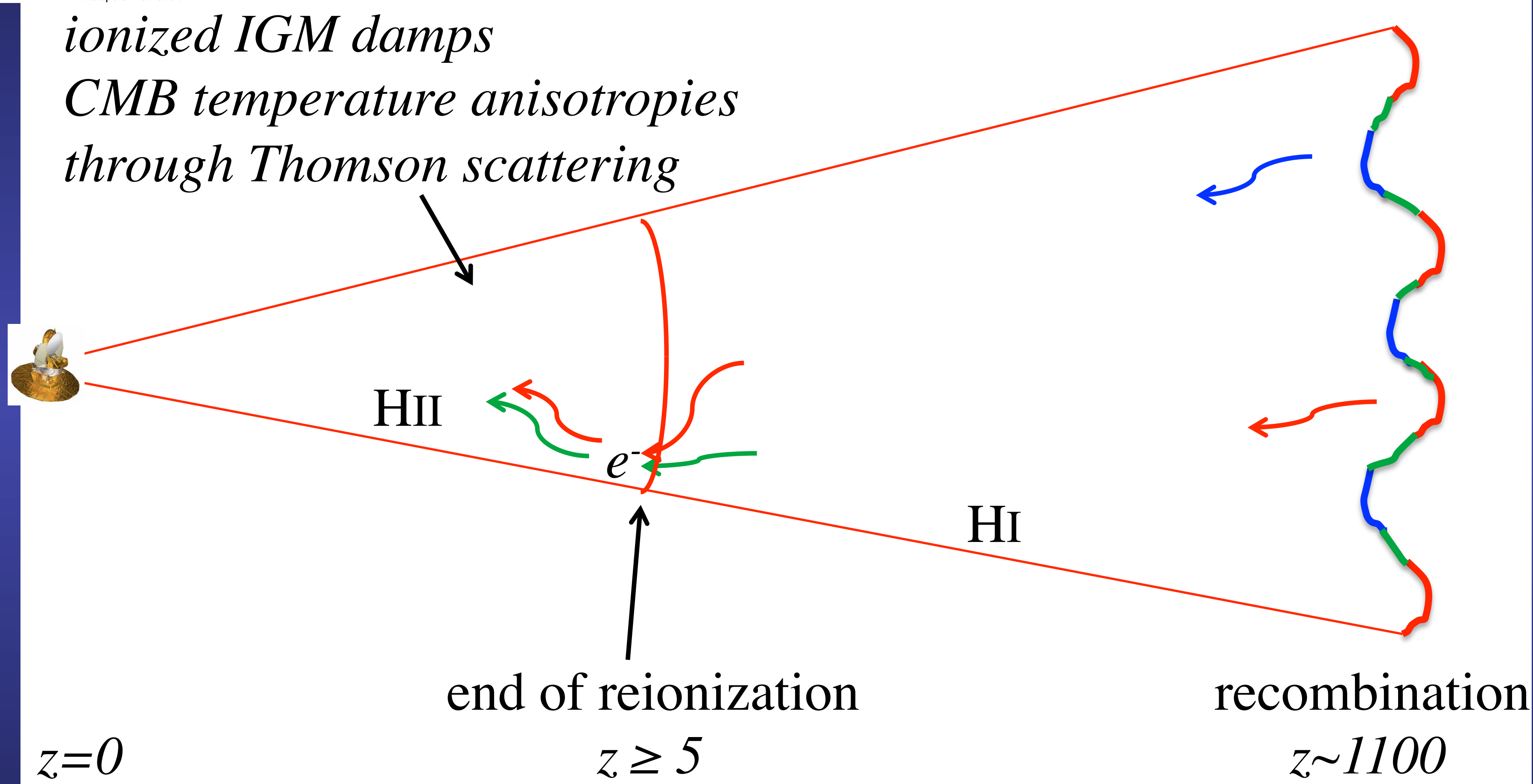
What can we learn about reionization from the kSZ

Andrei Mesinger

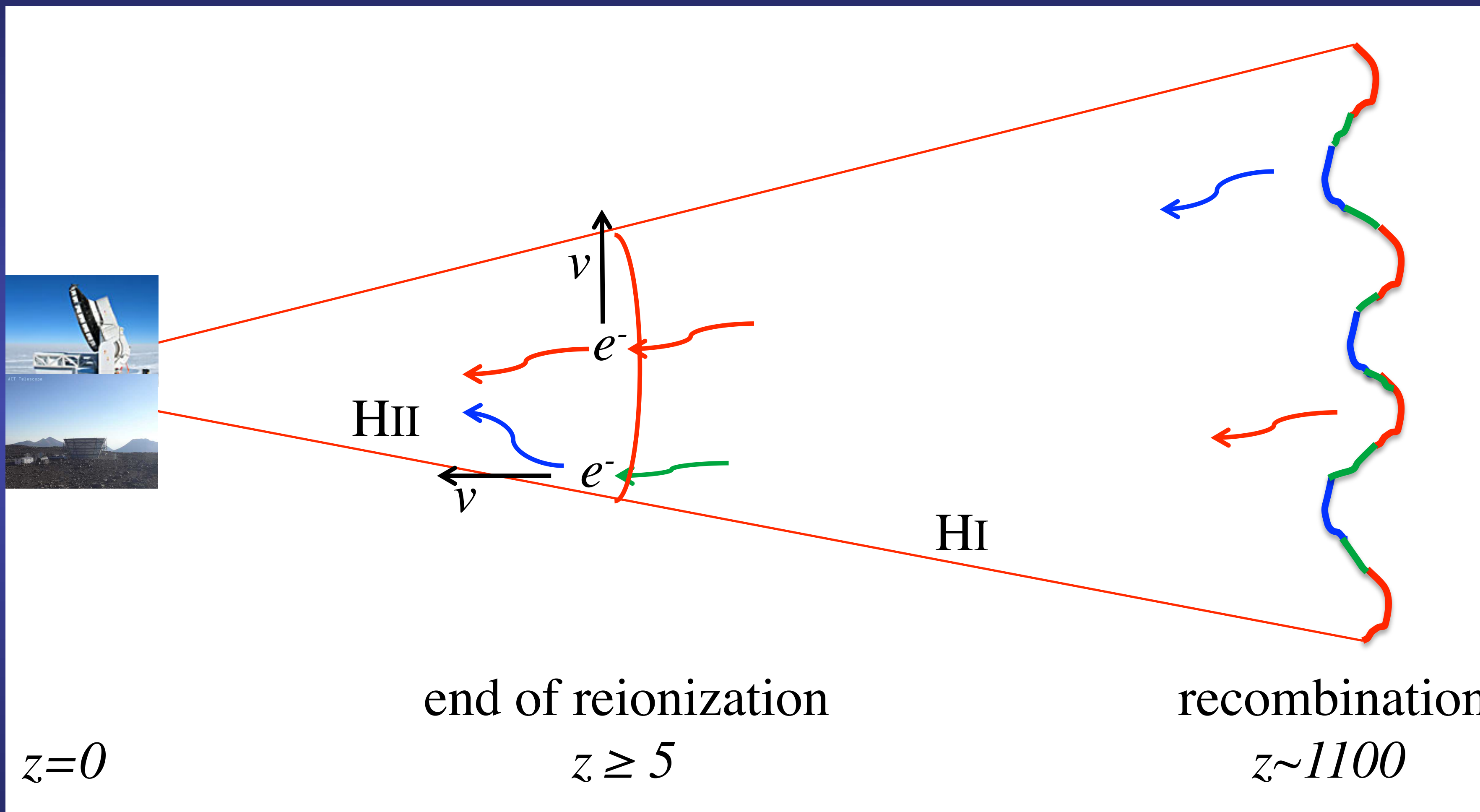
Scuola Normale Superiore, Pisa

IGM effect on CMB primary temperature anisotropies





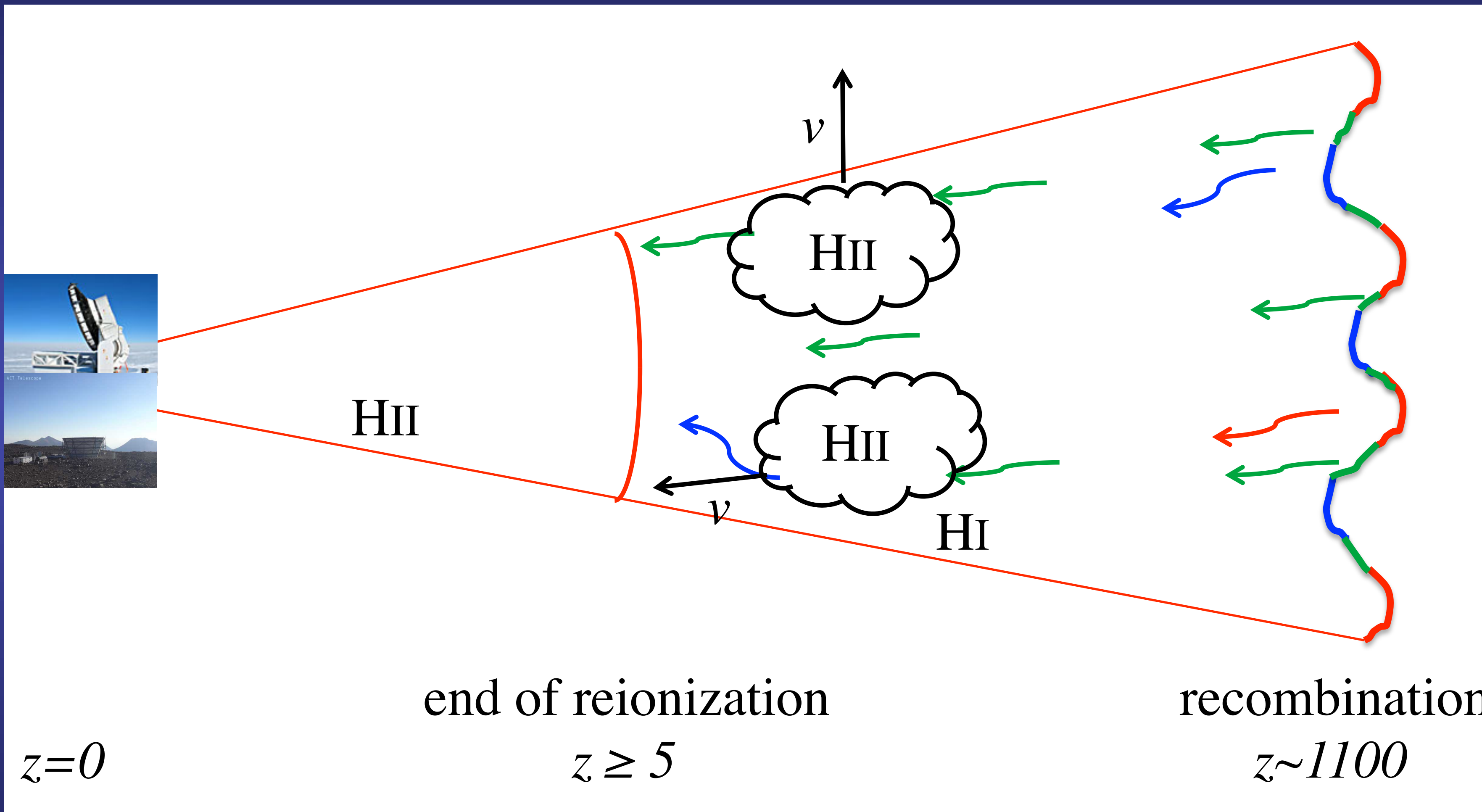
CMB secondary temperature anisotropies:
kSZ post-reionization (~OV signal)



Velocity field modulates anisotropies

$$\frac{\Delta T}{T}(\hat{\mathbf{u}}) = \sigma_{\mathrm{T}} \int dz\, c\,(dt/dz)\, e^{-\tau_e(z)} n_e \hat{\mathbf{u}} \cdot \mathbf{v}$$

CMB secondary temperature anisotropies:
kSZ patchy reionization

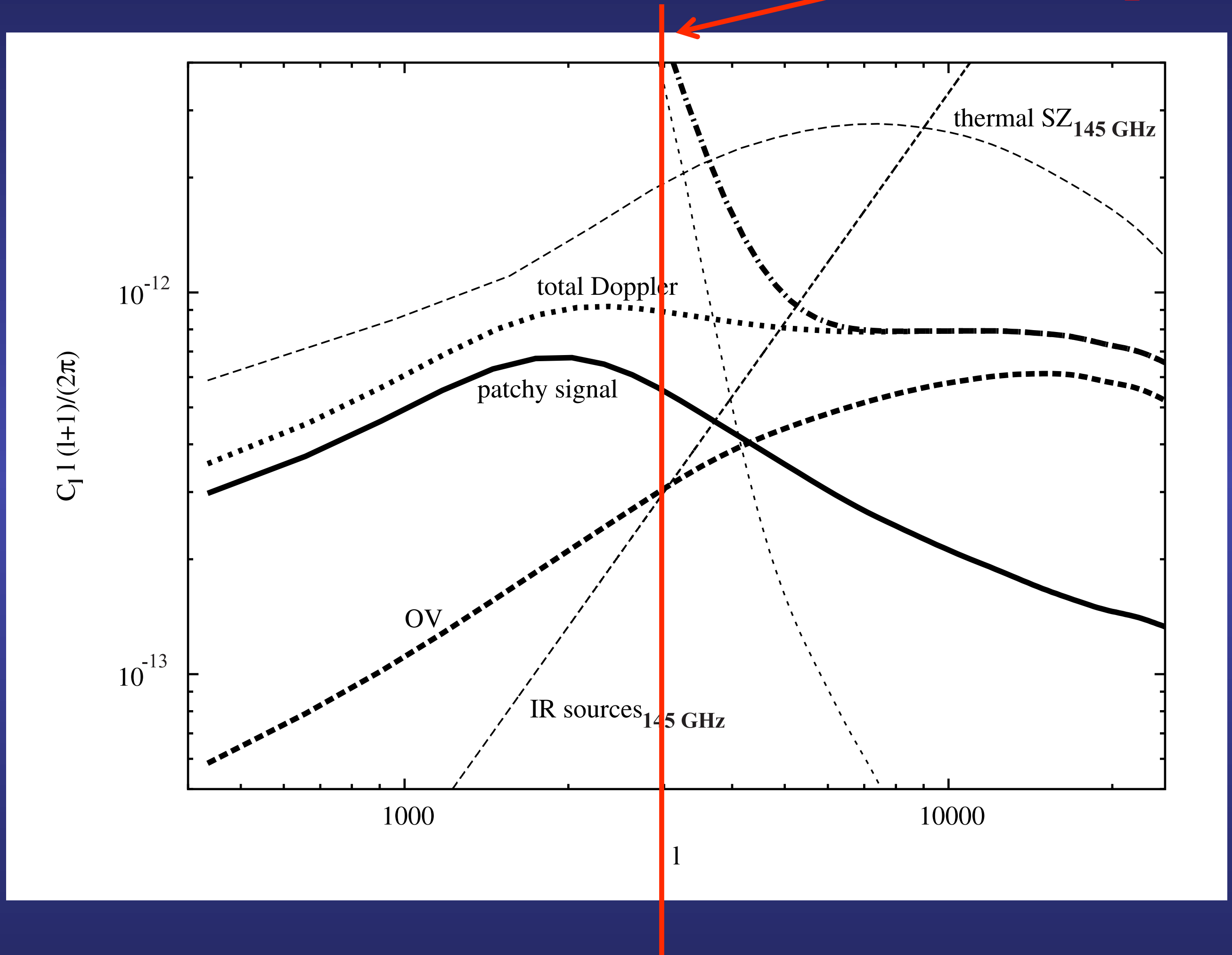


Velocity field + HII morphology
modulates anisotropies

$$\frac{\Delta T}{T}(\hat{\mathbf{u}}) = \sigma_{\mathrm{T}} \int dz\, c\,(dt/dz)\, e^{-\tau_e(z)} n_e \hat{\mathbf{u}} \cdot \mathbf{v}$$

CMB power

l~3000 is best shot
~20 cMpc at high-z



Zahn+2005

tSZ has different frequency dependence

Extract out OV component of kSZ

Paper	$\mathcal{D}_{3000}$ [μK^2]		
	Unnorm.	Cosm Cor.	Box Cor.
WHS02	3.00	1.57	3.91
H09	7.40	8.50	9.45
B10, NR	2.50	2.42	4.03
B10, AGN	1.50	1.45	2.42
TBO11, adiabatic	2.50	2.70	2.70
TBO11, standard	2.10	2.27	2.27
This work, DM	⋯	⋯	3.44
This work, NR	⋯	⋯	3.24
This work, CSF	⋯	⋯	2.19

NOTE. — The amplitude of the kSZ power predicted by hydrodynamical simulations in previous work. We show the results from the SPH simulations of White et al. (2002, WHS02), the ENZO simulations of Hallman et al. (2009, H09), both the non-radiative (NR) simulations and those including cooling, star-formation and AGN feedback from Battaglia et al. (2010, B10) and the 'adiabatic' and 'standard' models from the N-body plus semi-analytic approach of Trac et al. (2011, TBO11).

Shaw+2011

$P_{kSZ}^{OV} \sim 2\text{-}3\mu K^2$

STP and ACT

Large diameter (fine resolution) telescopes:

- Atacama Cosmology Telescope (ACT)
- South Pole Telescope (STP)

Constraints on reionization kSZ power at l~3000 from SPT (Reichardt + 2012)*:*

- P_{kSZ}^{patchy} <~ 1 μK^2 (95% CL) assuming no tSZ-CIB correlation
- P_{kSZ}^{patchy} <~ 4 μK^2 (95% CL) allowing tSZ-CIB correlation

*A (marginal) detection (*Crawford+2013*):*

- $P_{kSZ}^{patchy} = 0.9 \pm 1.5\ \mu K^2$

Limits include a conservatively small contribution from OV of 2 μK^2

Caution: constraints are sensitive to the choice of prior

Interpreting the patchy reionization signal

Challenges:

- Large-dynamic range: need to capture small ionization structure (~Mpc) and go out to large scales to capture the velocity field (~Gpc)
- Very little is known about reionization -> large parameter space to explore

Can construct empirical models (e.g. Zahn+2012, Battaglia+2013) →

- fast, adaptable to MCMC
- however unclear physical insight
- must be careful not to over-interpret results from unphysical models

Interpreting the patchy reionization signal

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- Very little is known about reionization -> large parameter space to explore

Or: use 21cmFAST (Mesinger & Furlanetto 2007; Mesinger+2011) to do astrophysical parameter exploration

- Combination of Lagrangian perturbation theory and excursion-set formalism
- Generates realizations of reionization in minutes, allowing true parameter space studies of physical models
- Tested extensively against cosmo sims
- Publicly available

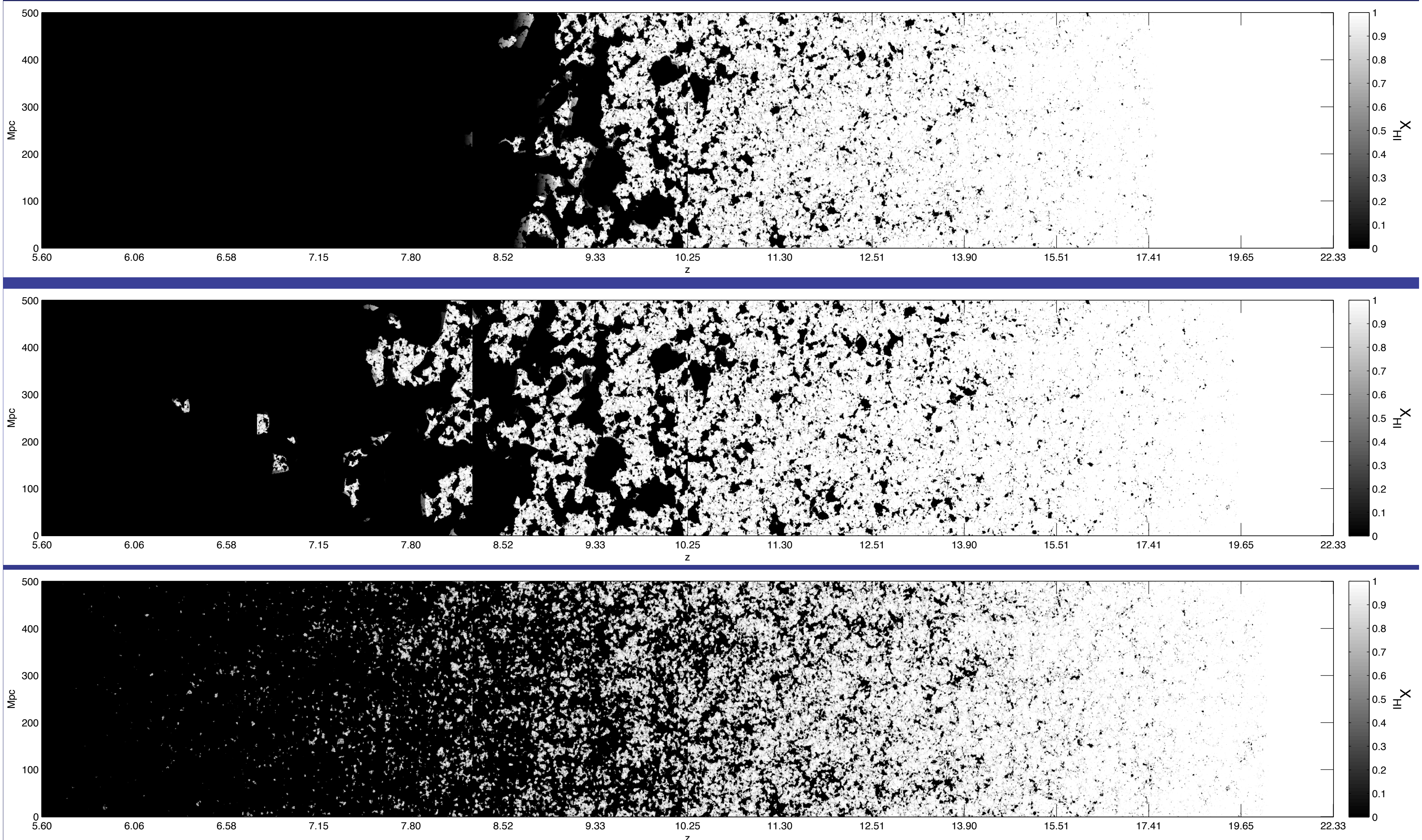
Interpreting the patchy reionization signal

(Mesinger, McQuinn, Spergel 2012)

3 free parameters:

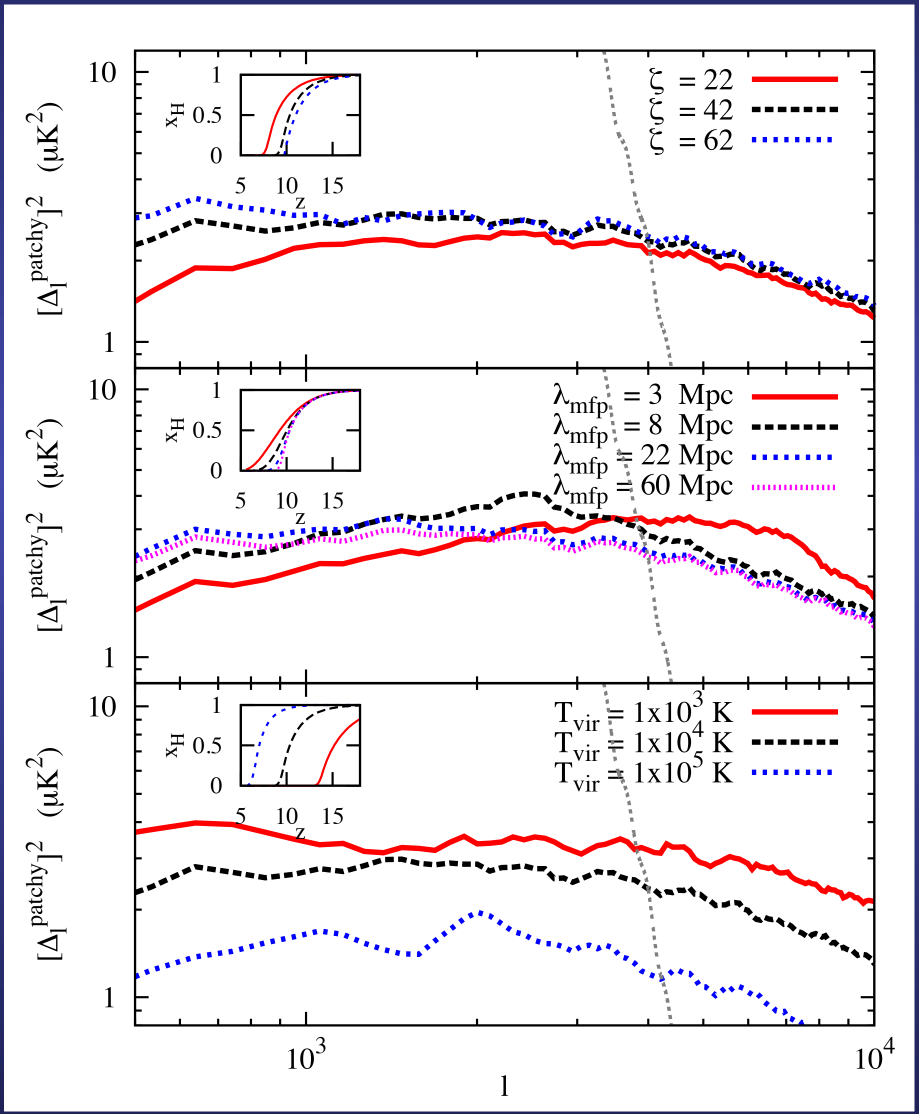
- ζ - ionizing efficiency of high-redshift galaxies. for example: $\zeta = f_{esc}\, f_{*}\, N_{\gamma}/(1+n_{rec})$
- T_{vir} – minimum virial temperature of halos which can host stars
- R_{mfp} – mean free path of ionizing photons inside ionized IGM (set, e.g. by LLSs). R_{mfp}~30-50Mpc at z~6

Modeling reionization (~>100 realizations)



$z \rightarrow$

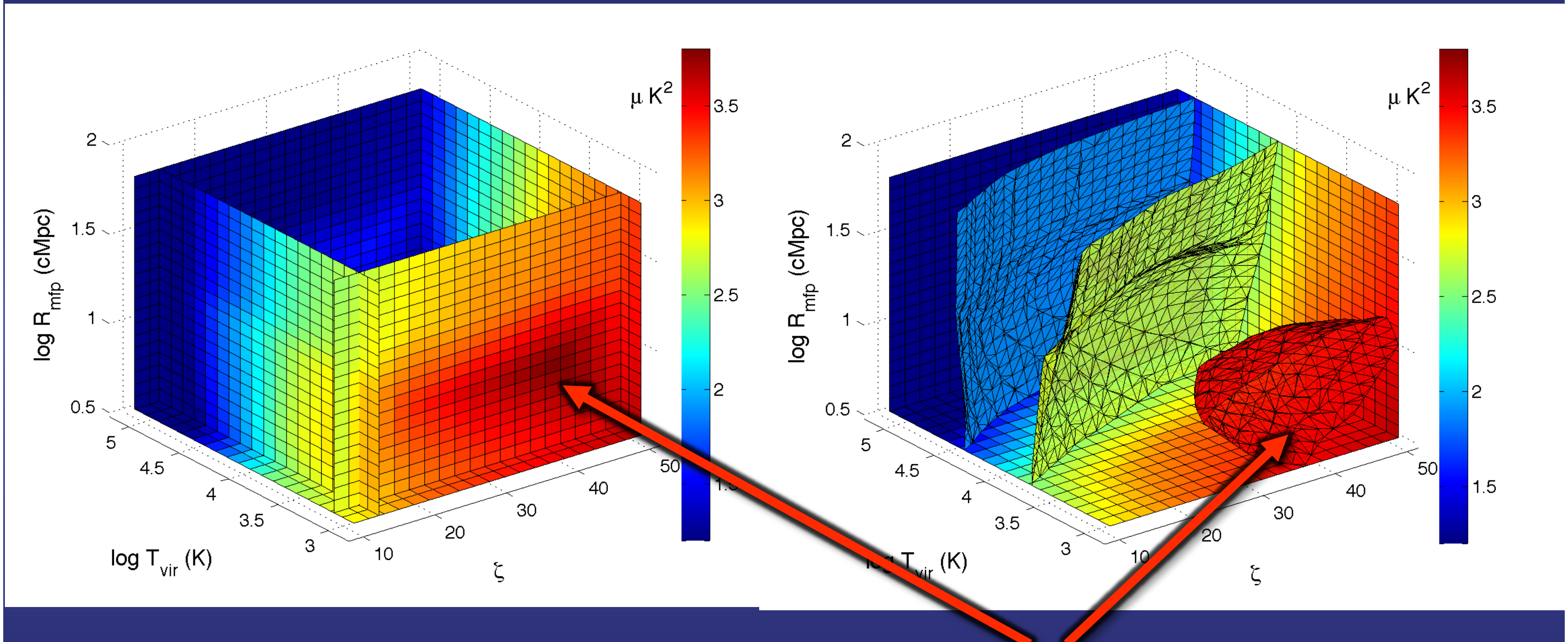
Spectra as one varies parameters



Mesinger, McQuinn, Spergel (2012)

Compute the power at l~3000

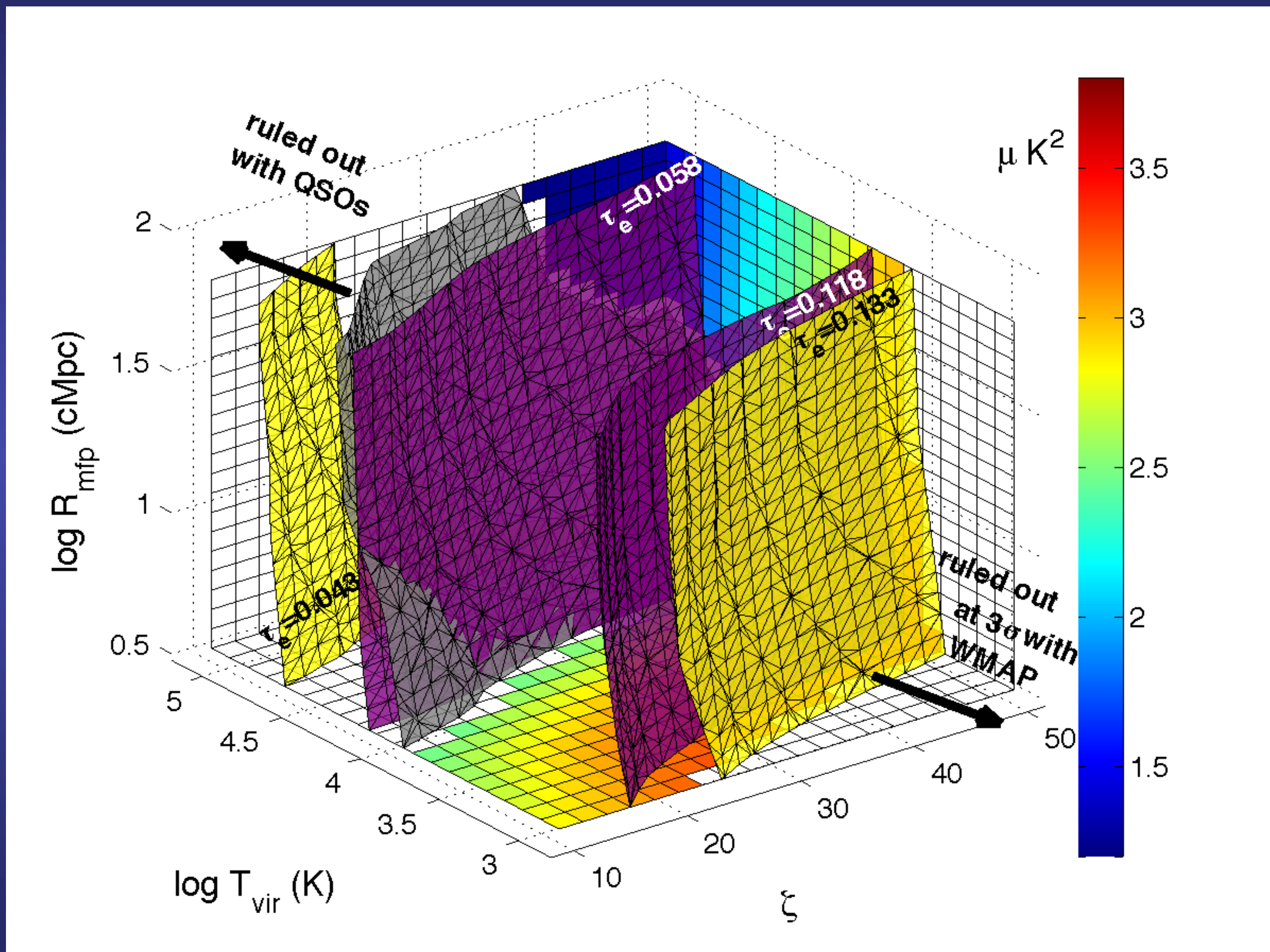
Mesinger, McQuinn, Spergel (2012)



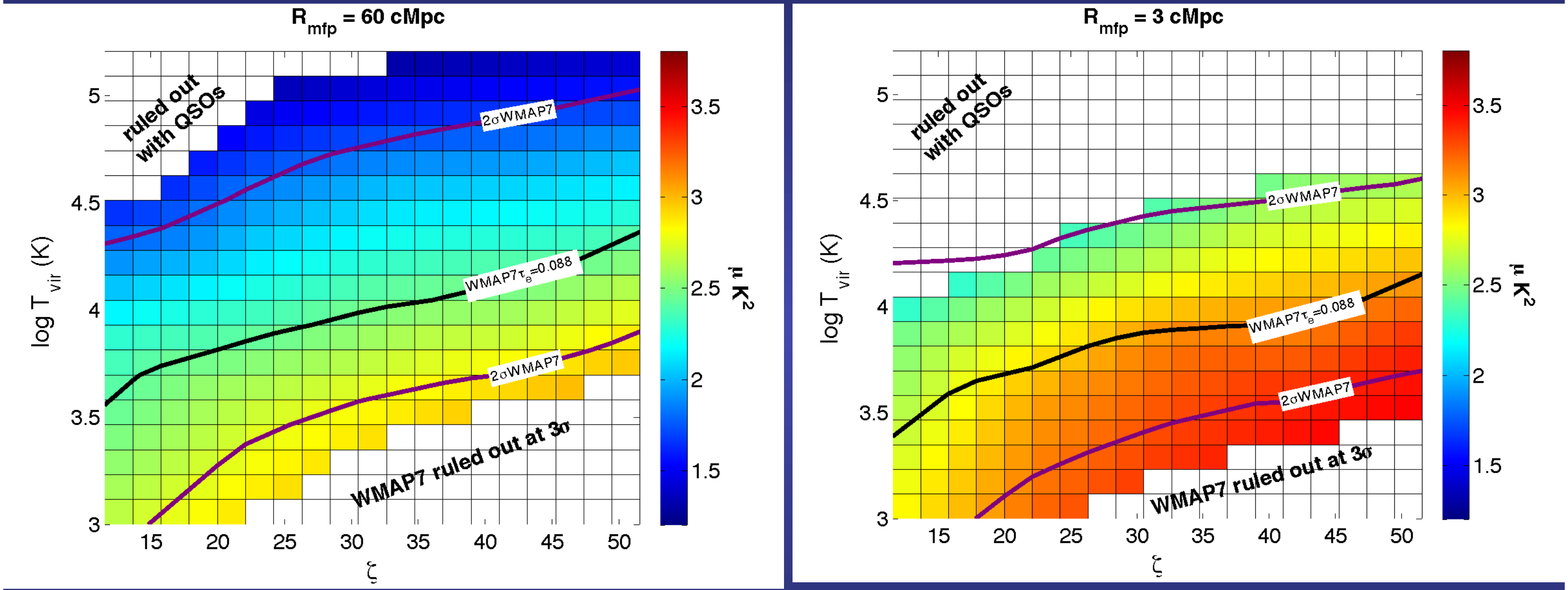
Easiest to detect or rule out (i.e. largest signal):

models driven by small galaxies which form early, evolve slowly, and where ionization is retarded by abundant absorption systems

Including constraints from WMAP and QSOs

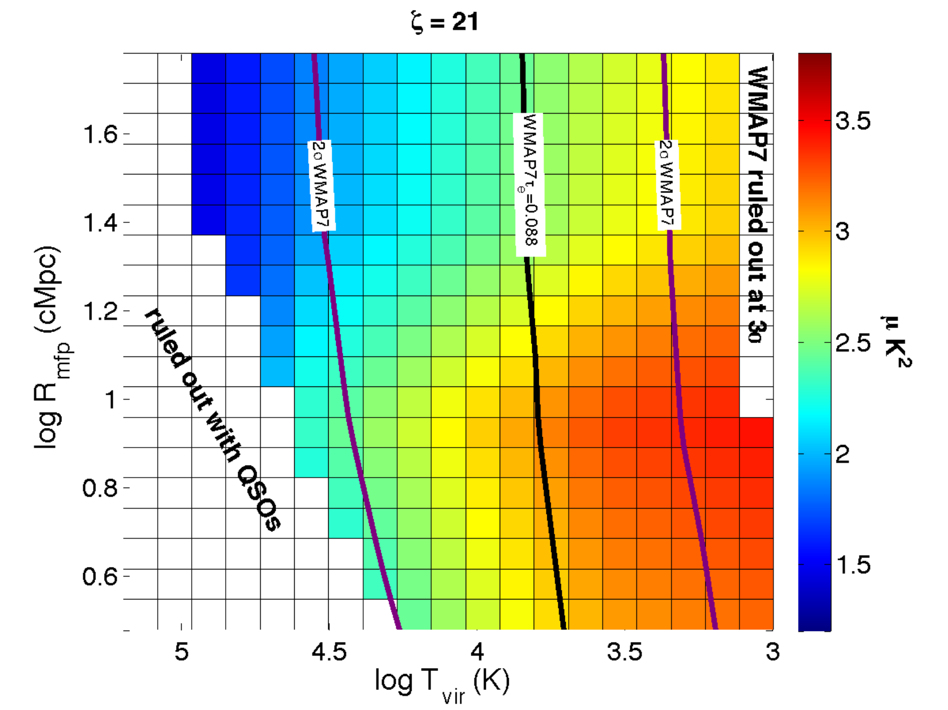


Mfp slices

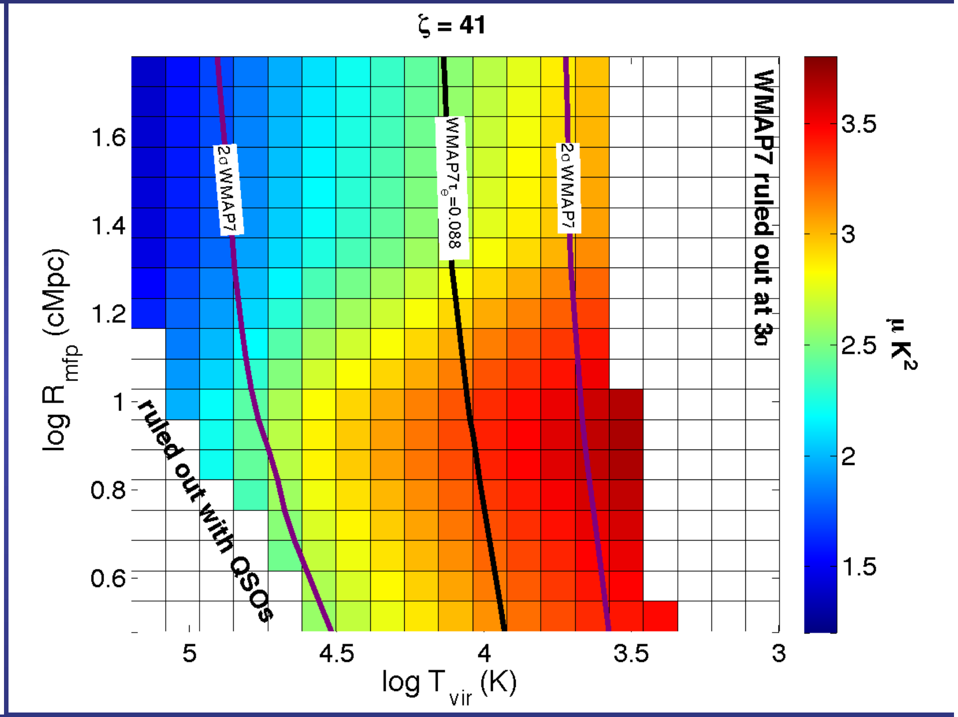


R_{mfp} = 60 cMpc
ruled out with QSOs
2σWMAP7
WMAP7τ_e=0.088
2σWMAP7
WMAP7 ruled out at 3σ
log T_{vir} (K)
ζ
μK²
R_{mfp} = 3 cMpc
ruled out with QSOs
2σWMAP7
WMAP7τ_e=0.088
2σWMAP7
WMAP7 ruled out at 3σ
log T_{vir} (K)
ζ
μK²

Zeta slices

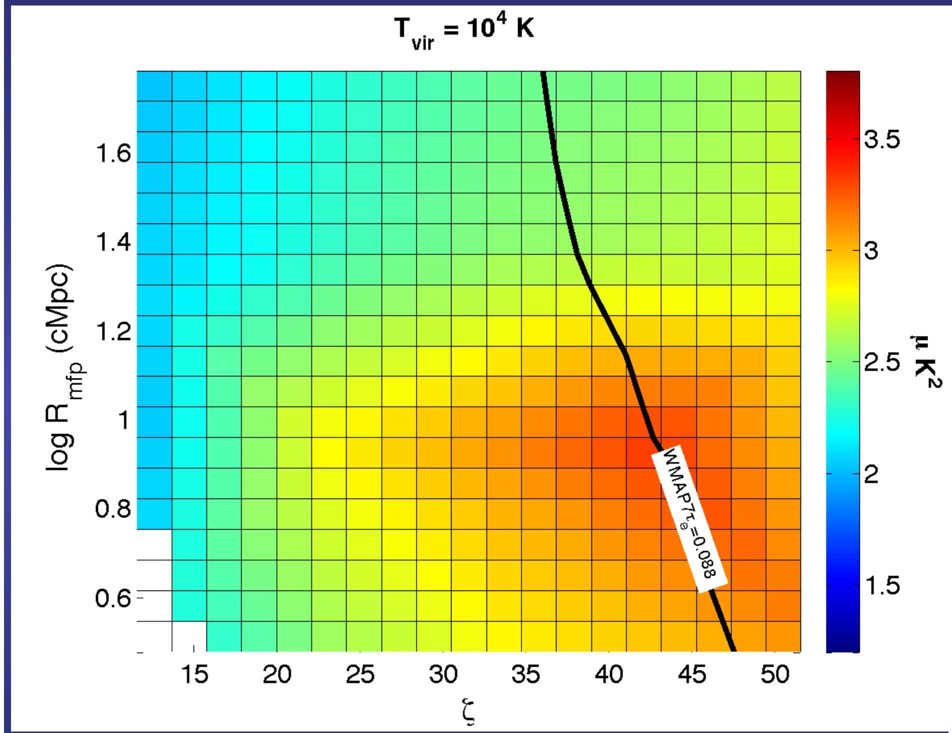


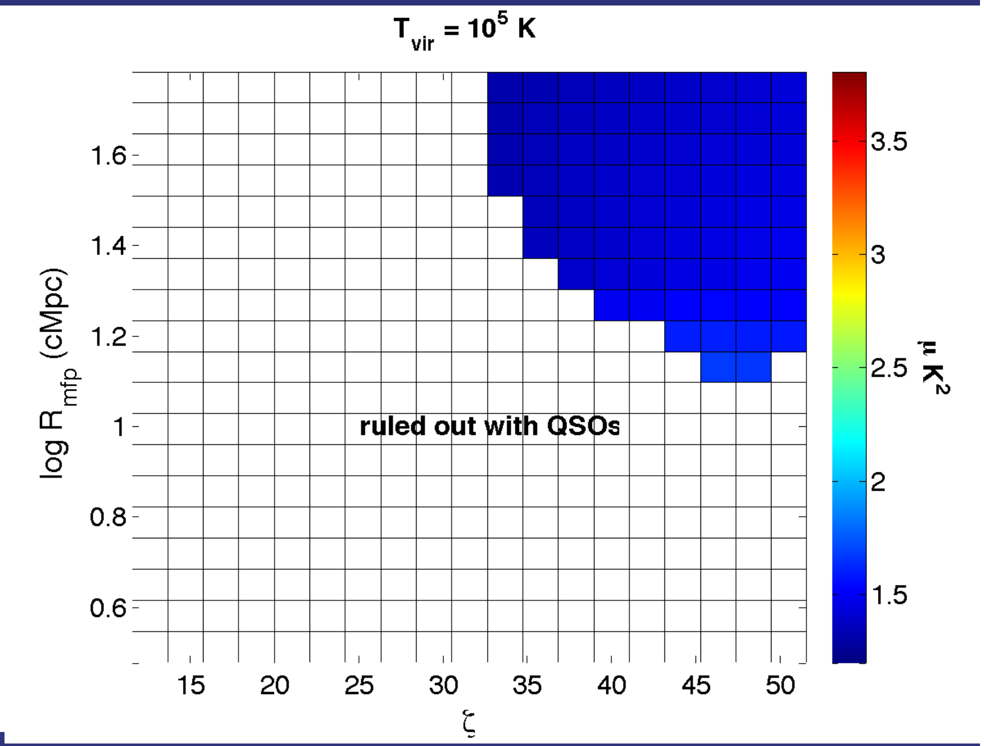
ζ = 21
1.6
1.4
1.2
1
0.8
0.6
log R mfp (cMpc)
5
4.5
4
3.5
3
log T vir (K)
ruled out with QSOs
2σ WMAP7
WMAP7 τe=0.088
2σ WMAP7
WMAP7 ruled out at 3σ
3.5
3
2.5
2
1.5
μ K²



ζ = 41
1.6
1.4
1.2
1
0.8
0.6
log R mfp (cMpc)
5
4.5
4
3.5
3
log T vir (K)
ruled out with QSOs
2σ WMAP7
WMAP7 τe=0.088
2σ WMAP7
WMAP7 ruled out at 3σ
3.5
3
2.5
2
1.5
μ K²

Tvir slices

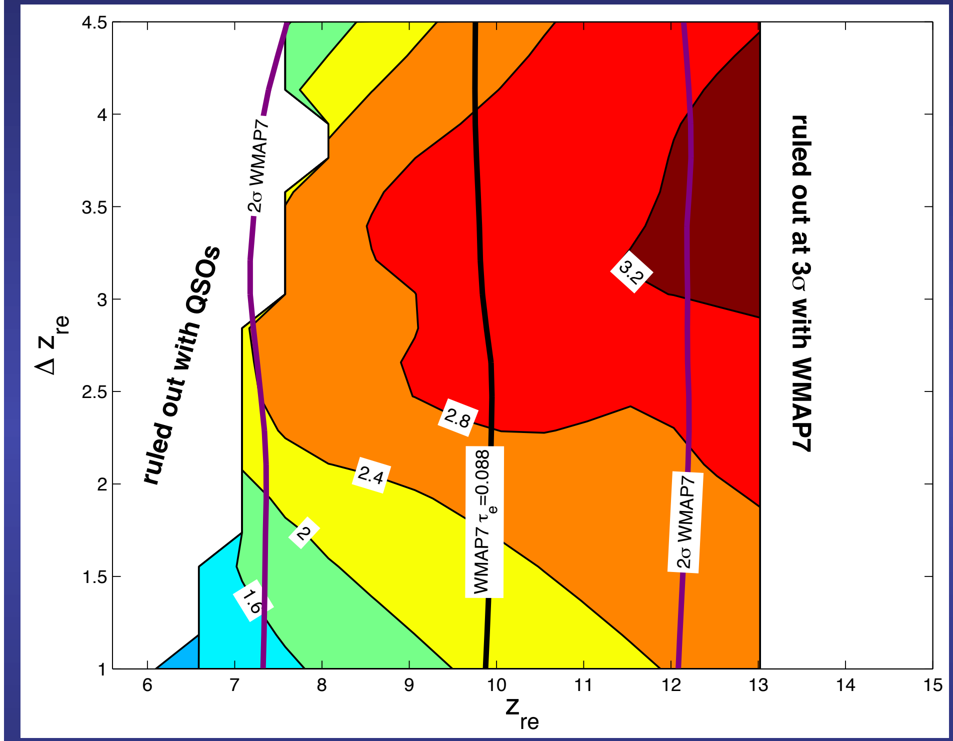

$T_{vir} = 10^4$ K
log R_{mfp} (cMpc)
1.6
1.4
1.2
1
0.8
0.6
15 20 25 30 35 40 45 50
ζ
WMAP7 τ_e=0.088
3.5
3
2.5
2
1.5
μ K²


$T_{vir} = 10^5$ K
log R_{mfp} (cMpc)
1.6
1.4
1.2
1
0.8
0.6
15 20 25 30 35 40 45 50
ζ
ruled out with QSOs
3.5
3
2.5
2
1.5
μ K²

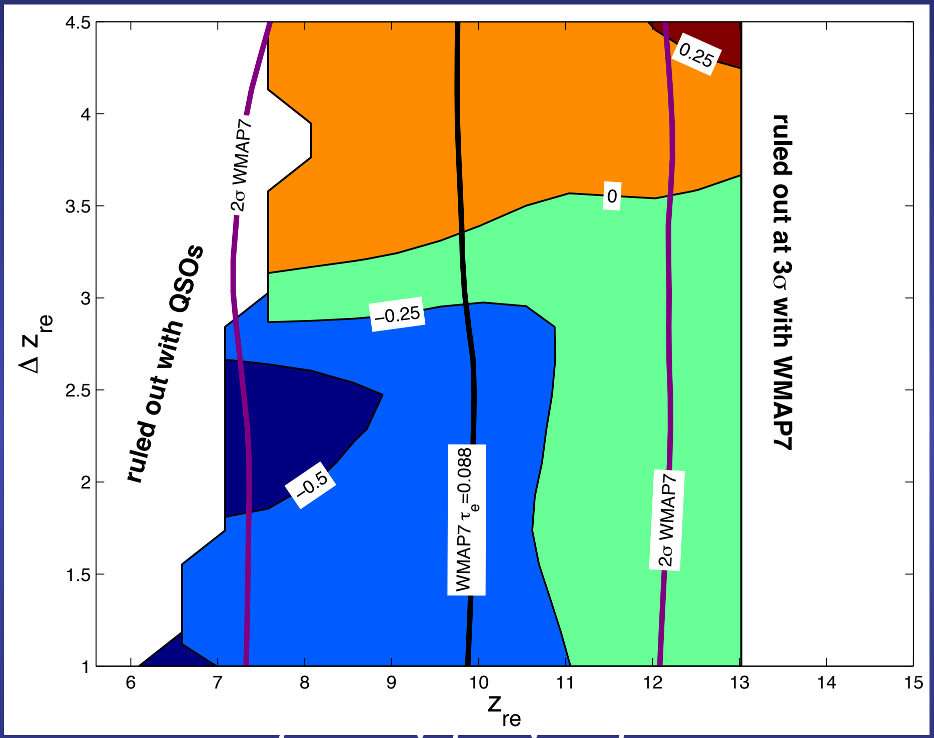
Empirical parameters, Δz_{re} and z_{re}

z_{re} – redshift when $\langle x_{HI} \rangle = 0.5$

Δz_{re} – redshift duration from $\langle x_{HI} \rangle = 0.75$ to $\langle x_{HI} \rangle = 0.25$



power

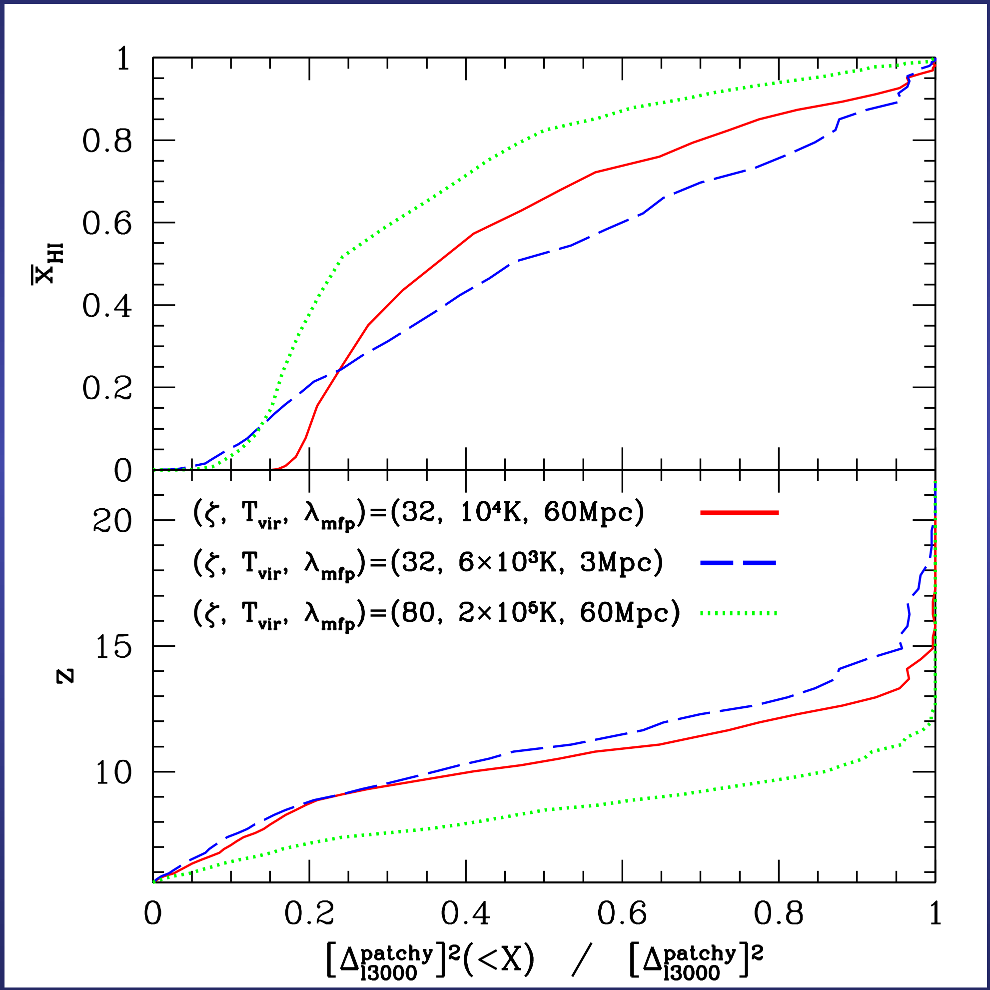


logarithmic slope

caution: the kSZ power is not a singly defined function of Δz_{re} and z_{re}

What is sourcing the signal?

- Early to mid stages source the bulk of the l~3000 power.



- *A "fiducial" model has half of patchy power imprinted already when x_{HI} >0.75.*
- *By x_{HI} >0.5, 85% of the kSZ power is in place*

caution: the end of reionization cannot be directly constrained by kSZ (e.g. Zahn+2012)

What about X-ray reionization?

- Due to their long mean free paths X-rays can have a dramatic impact on reionization morphology:

$$\lambda_{\rm X} \approx 20\, \bar{x}_{\rm HI}^{-1} \left(\frac{E_{\rm X}}{300{\rm eV}}\right)^{2.6} \left(\frac{1+z}{10}\right)^{-2} \;{\rm cMpc}$$

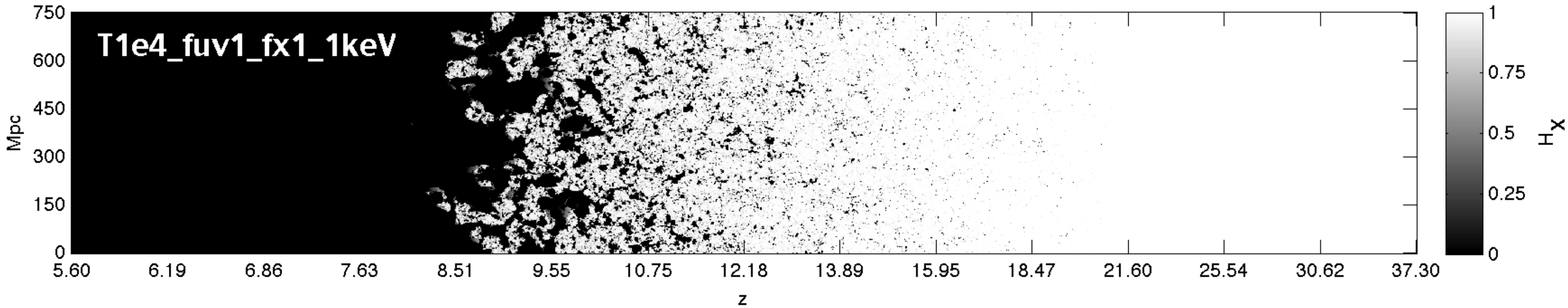
no fiducial “swiss cheese” morphology?

?

Cream cheese morphology?

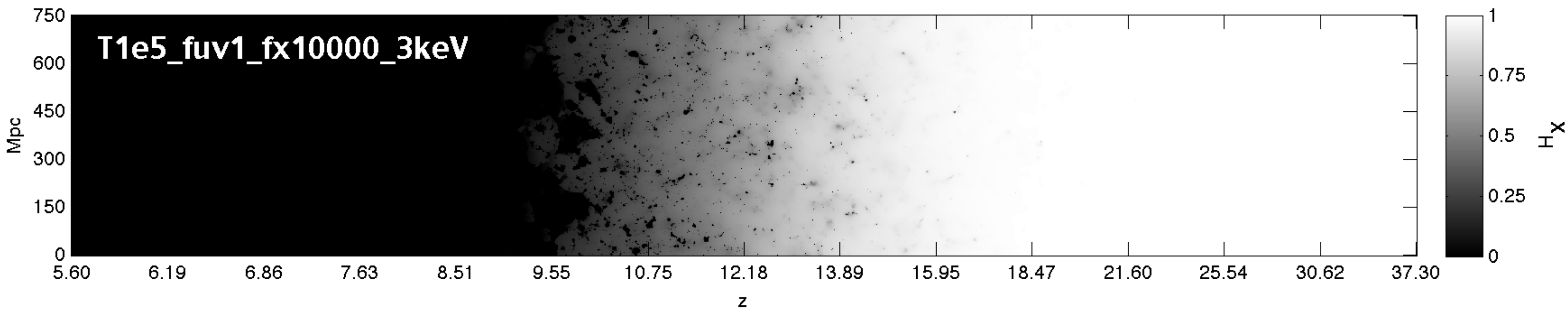
X-ray reionization

"fiducial" model (UV driven reionization)



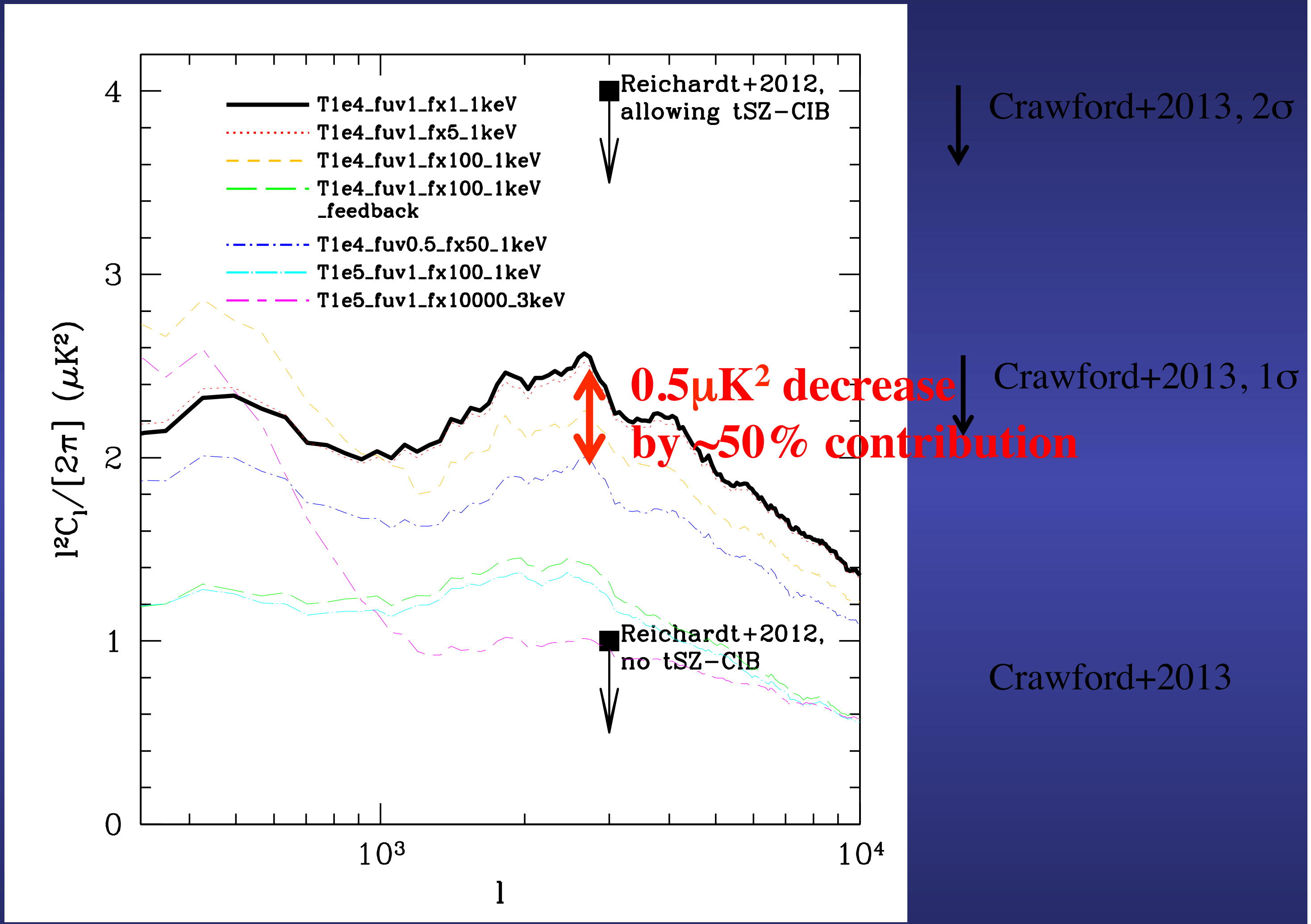
vs

"extreme" model (X-ray driven reionization)



Mesinger, Ferrara, Spiegel (2013)

Reasonable X-ray models have only a mild impact on kSZ



Conclusions

- Despite wide parameter space exploration, the patchy kSZ signal at l=3000 only ranges from 1.5—3.5 μK^2 (when including WMAP and QSO constraints)
- Observed SPT limits (2 σ) are just at this border, under conservative assumptions
- Largest power (first to be ruled out) comes from early/extended reionization scenarios (minihalos + abundant sinks)
- Bulk of the signal is sourced from early to mid stages of reionization → kSZ does not tell us about the end of reionization
- X-rays can decrease the kSZ power by <~0.5 μK^2
- Slope is useful in breaking the degeneracy between different ionization morphologies with the same l~3000 kSZ power
- kSZ might be the only near-term indirect probe of z >~ 10