Kinetic Sunyaev-Zel’dovich Effect as a Probe of the Reionization Epoch

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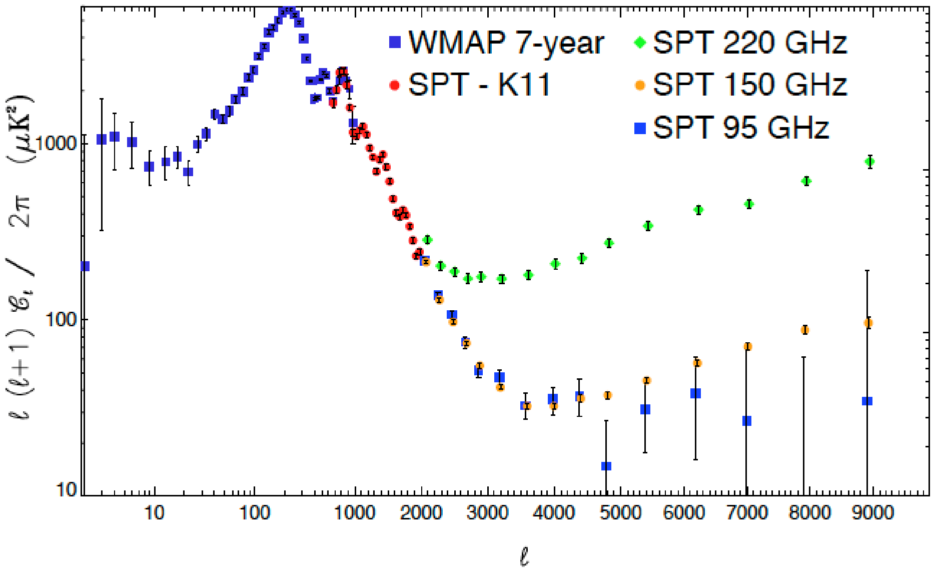
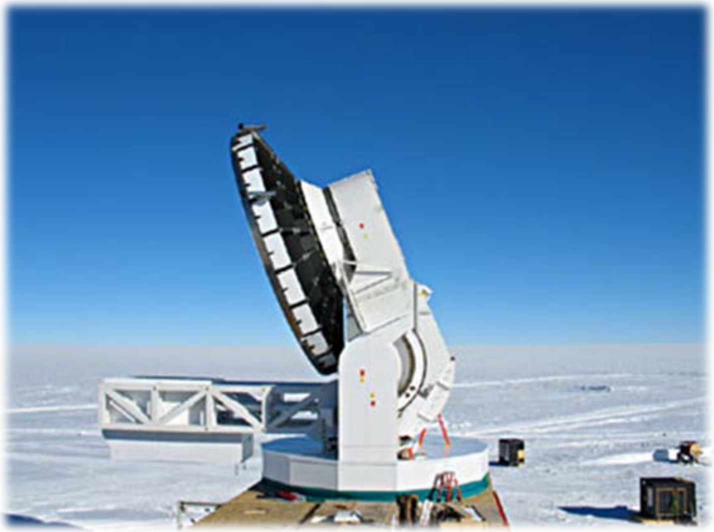
Introduction
Secondary CMB Fluctuations on small scales

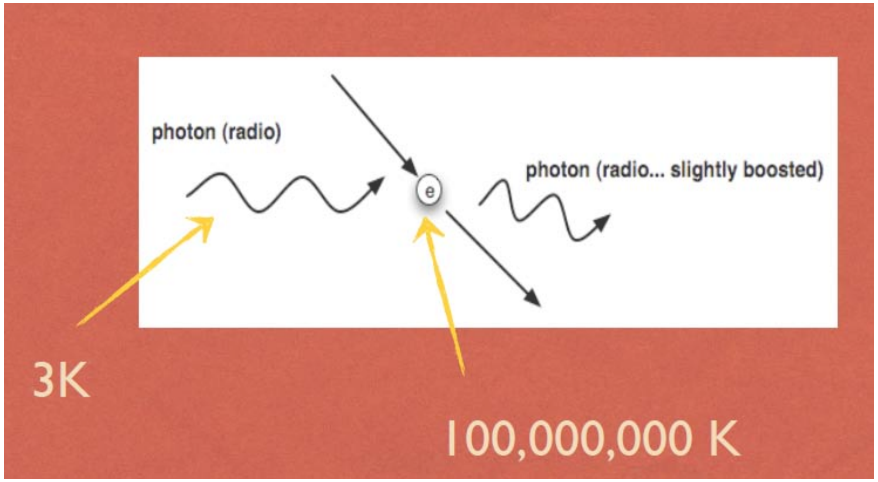
South Pole Telescope

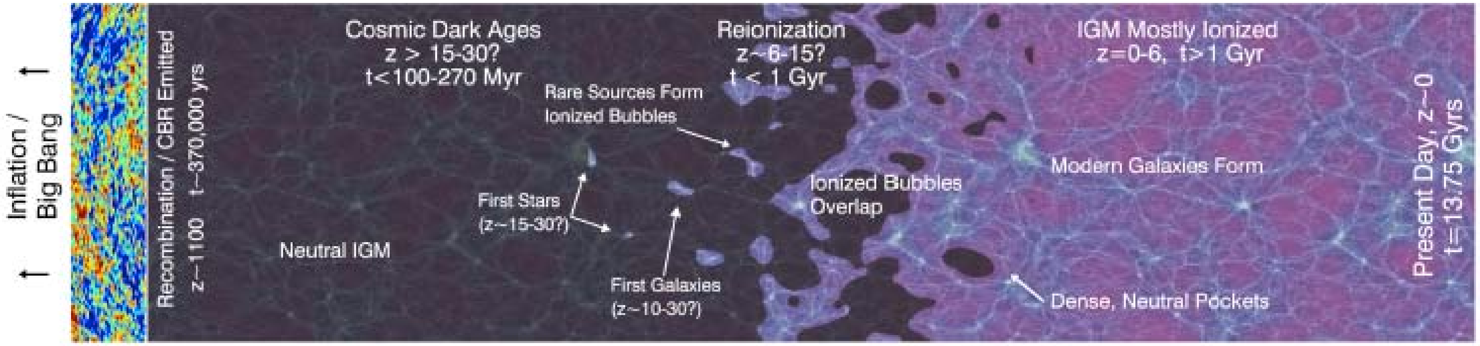


Reichardt et al. (2011)



Introduction
Sunyaev-Zel'dovich effect



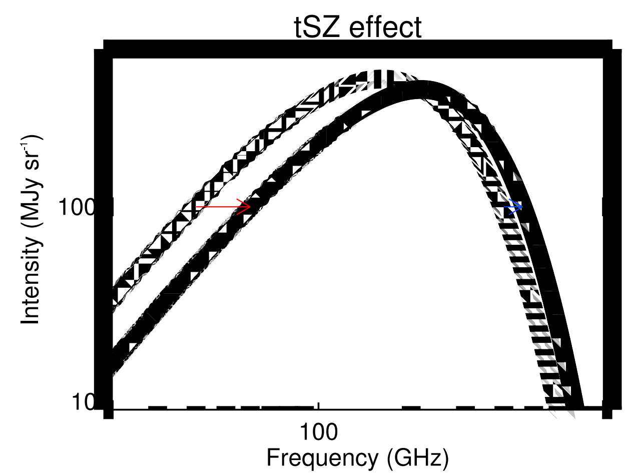


(Robertson et al. 2010)

Introduction
tSZ and kSZ effect

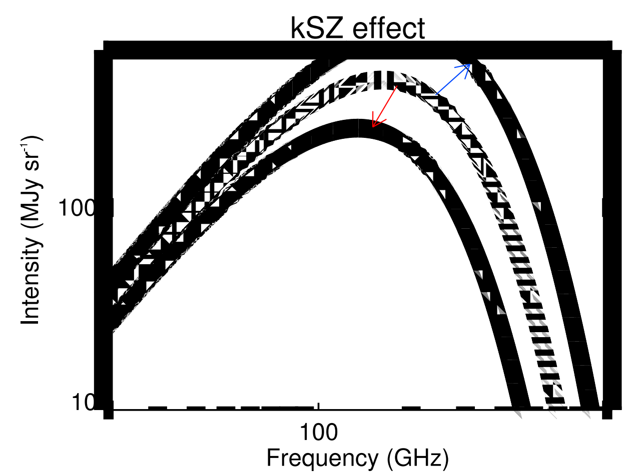
- Thermal SZ Effect (tSZ)

$$\frac{\Delta T}{T}(\hat{\gamma}) \propto \int d\tau \frac{kT_e}{m_e c^2}$$



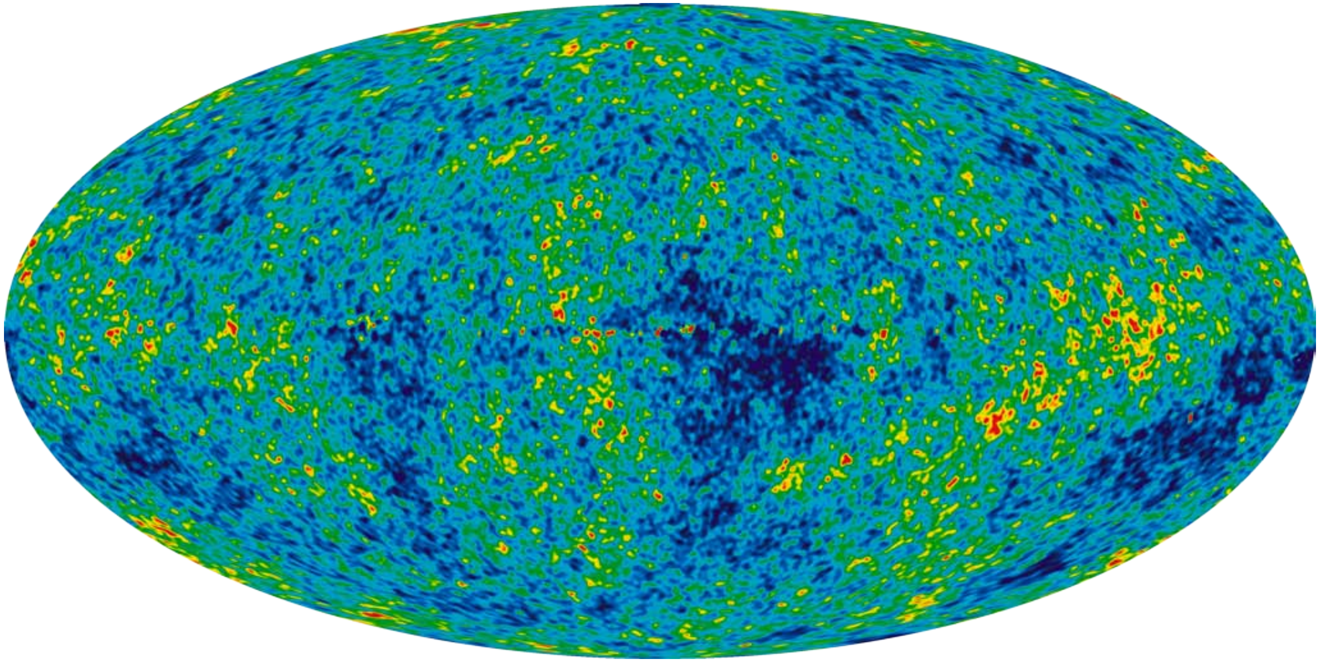
- Kinetic SZ Effect (kSZ)

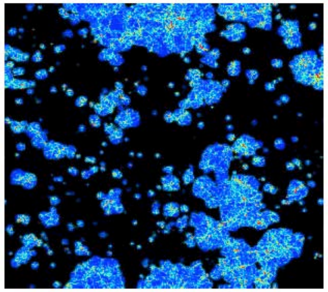
$$\frac{\Delta T}{T}(\hat{\gamma}) = \int d\tau \hat{\gamma} \cdot \frac{\mathbf{v}}{c}$$

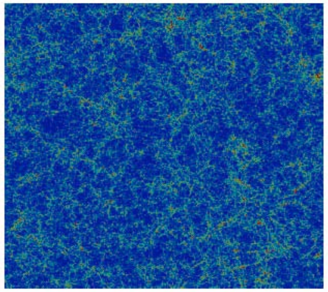


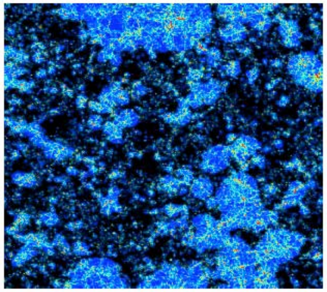
Introduction

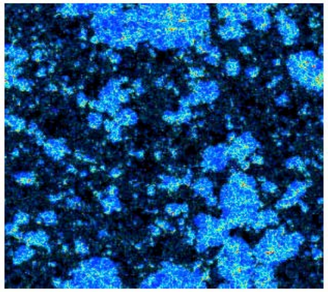
Imprint of reionization on the CMB



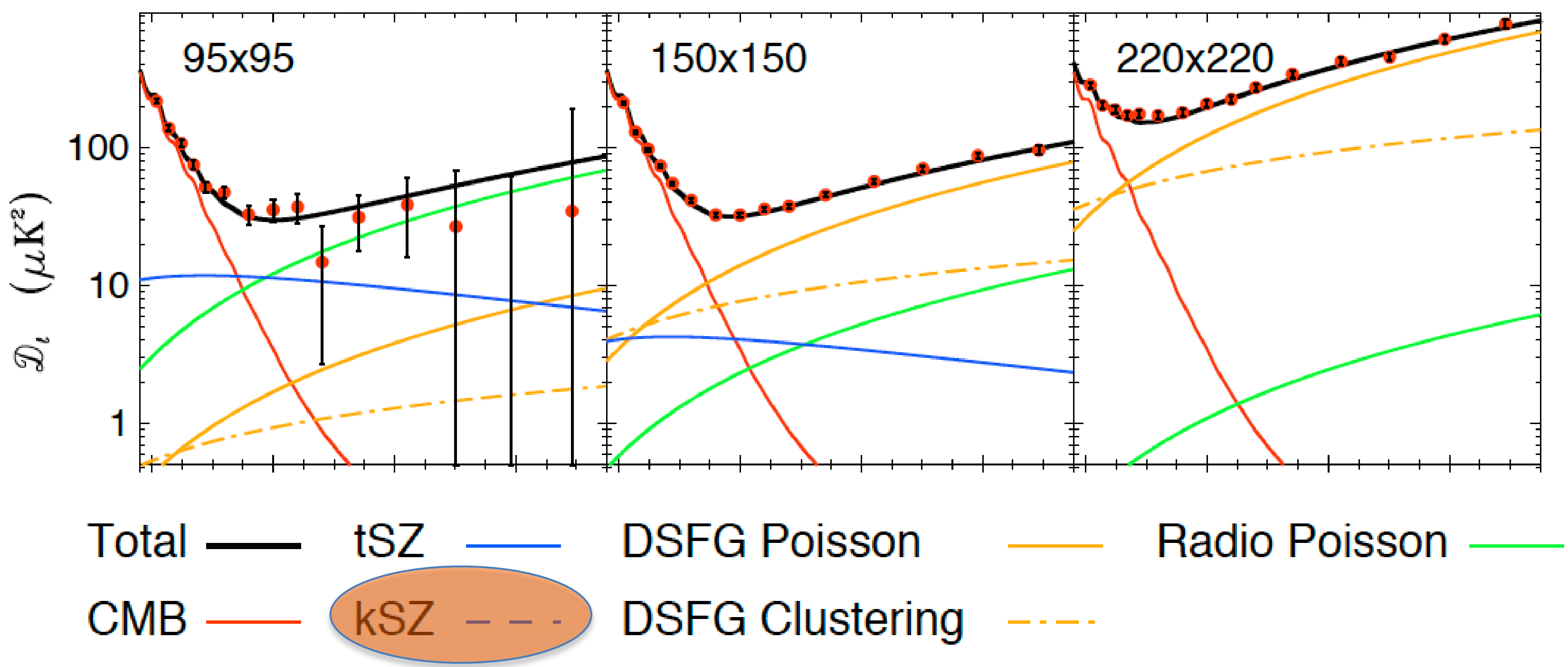








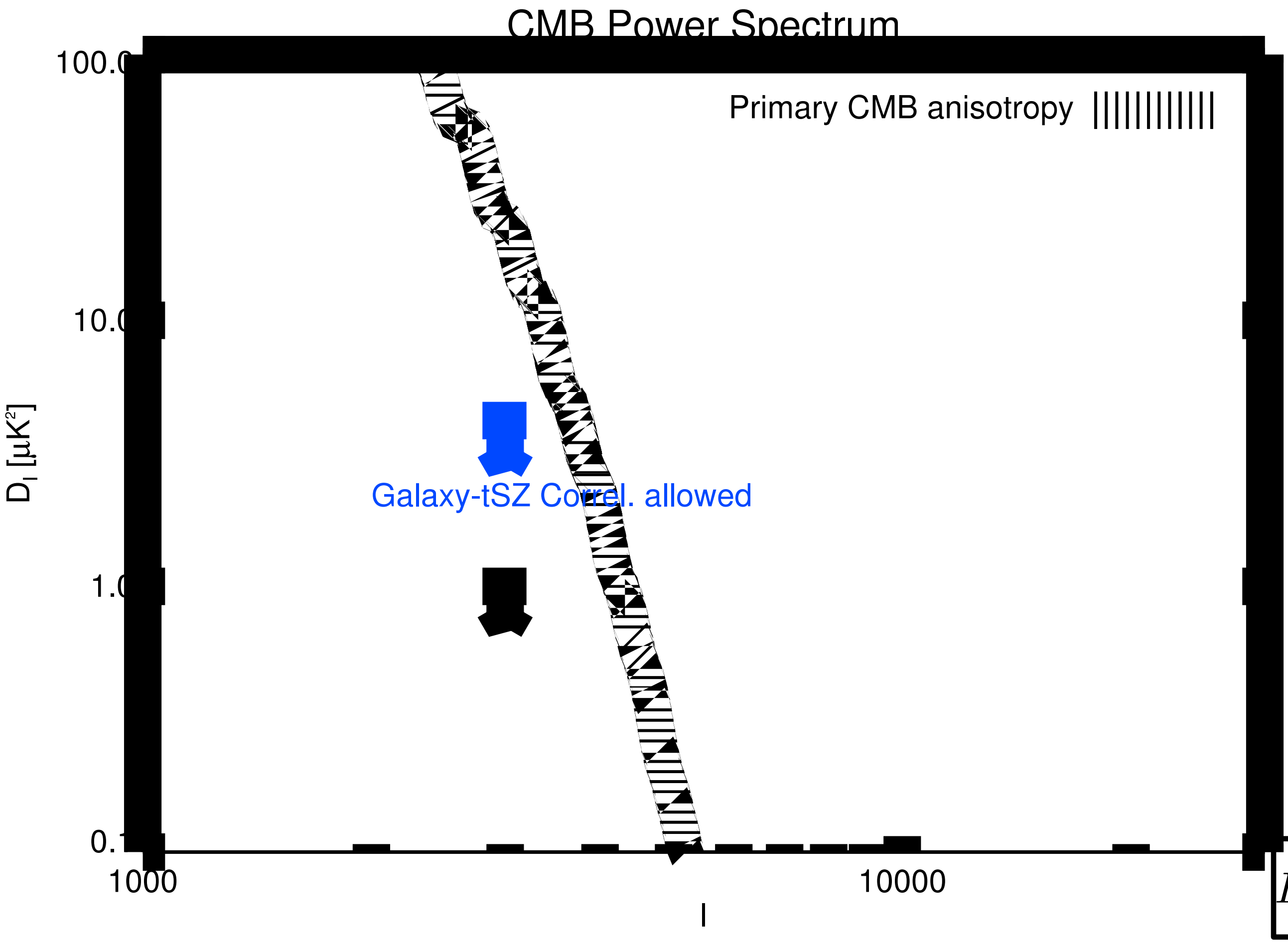
Introduction
kSZ signal from observation



Reichardt et al. (2011)

kSZ signal has not been detected yet but, has an upper bound.

Introduction
Observational constraint on the reionization kSZ signal

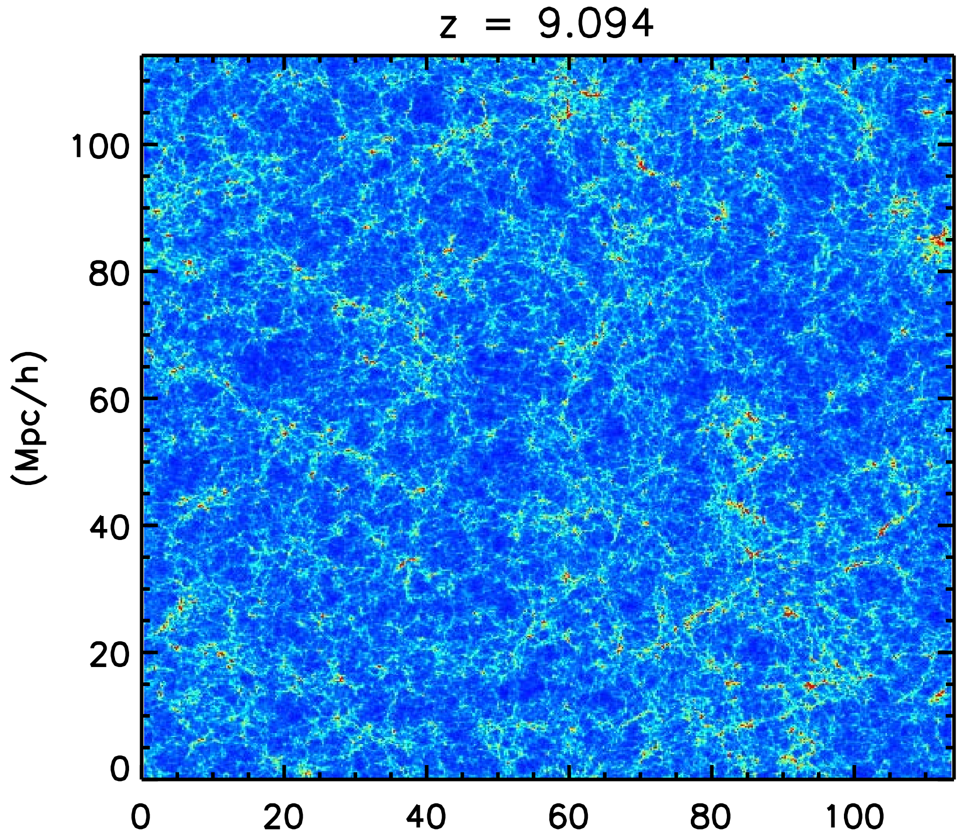


$$D_l \equiv \frac{l(l+1)C_l}{2\pi}$$

$$D_{l=3000}^{\mathrm{kSZ},z>6} < 1\ \mu K^2 \text{ or } 4.2\ \mu K^2 \text{ with maximum possible galaxy-tSZ correlation}$$

Method
Simulating the Reionization Epoch

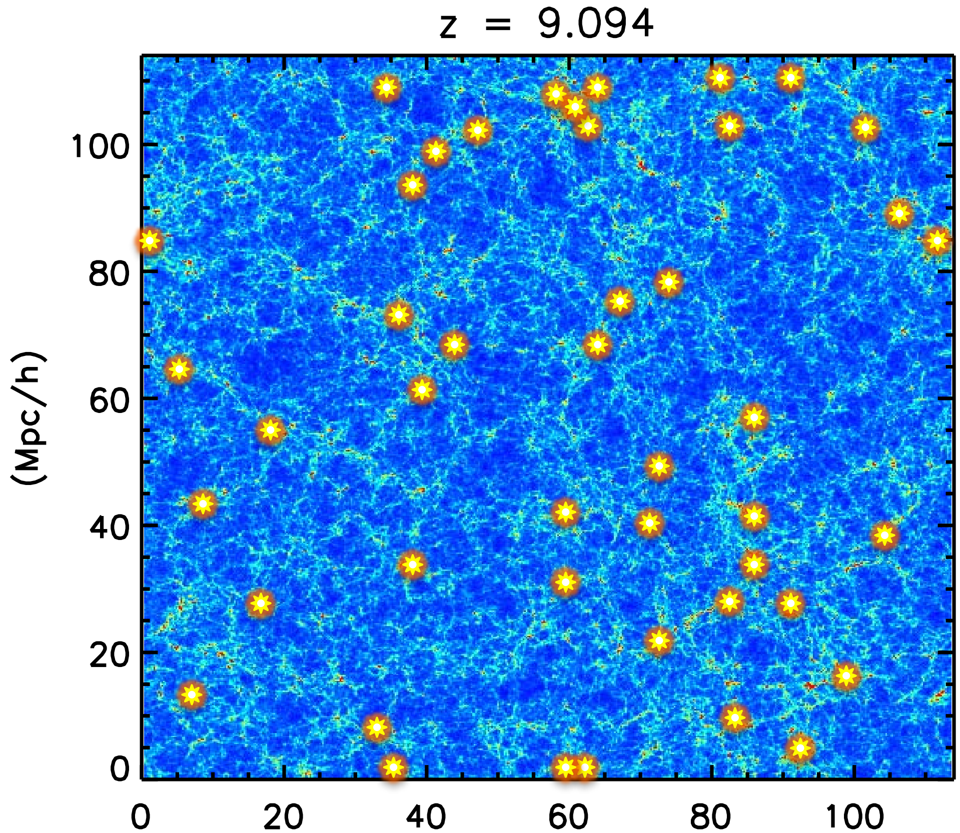
- Run N-body simulation.

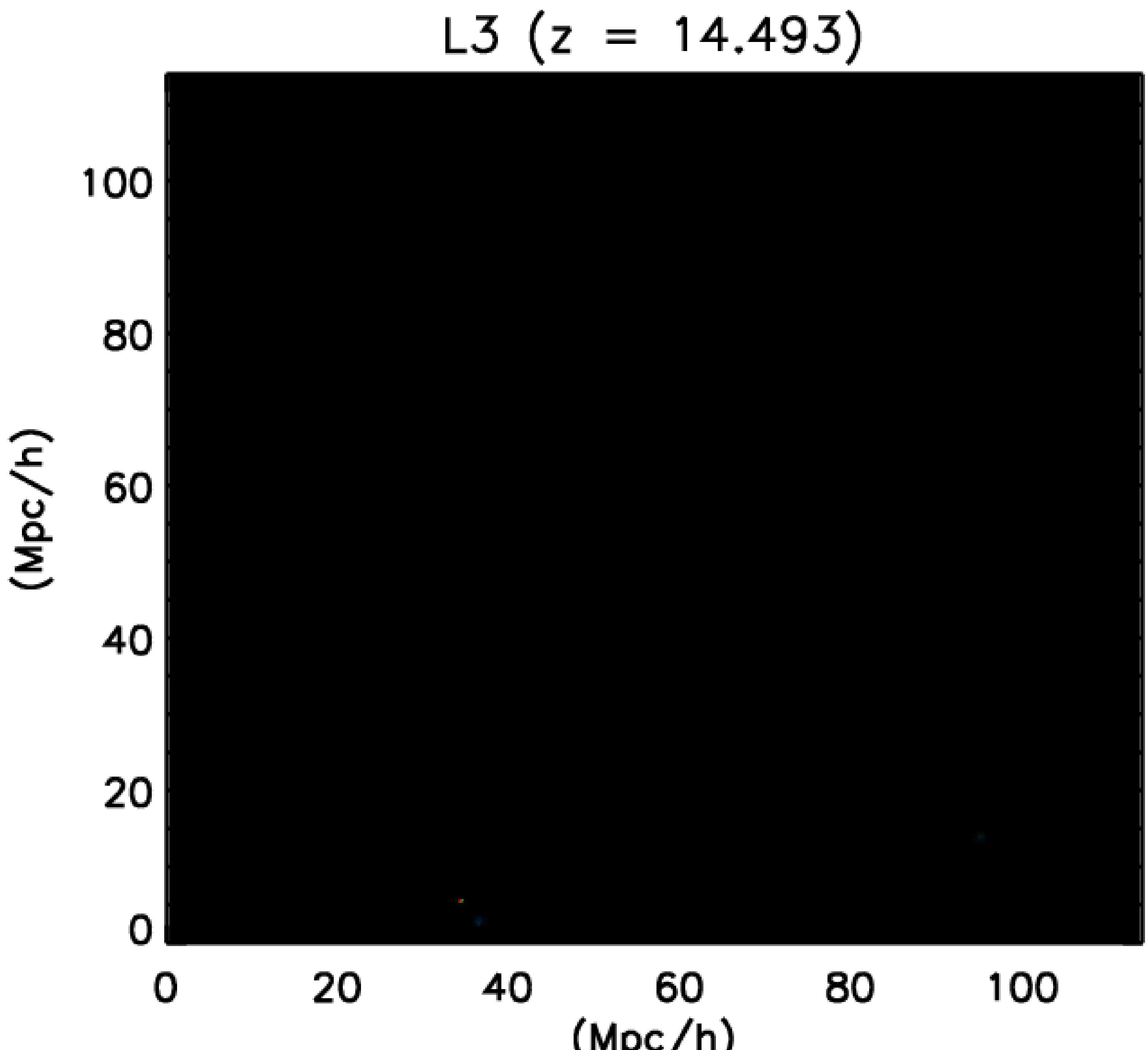


Method

Simulating the Reionization Epoch

- Run N-body simulation.
- Identify halos and assign ionizing efficiencies to them.

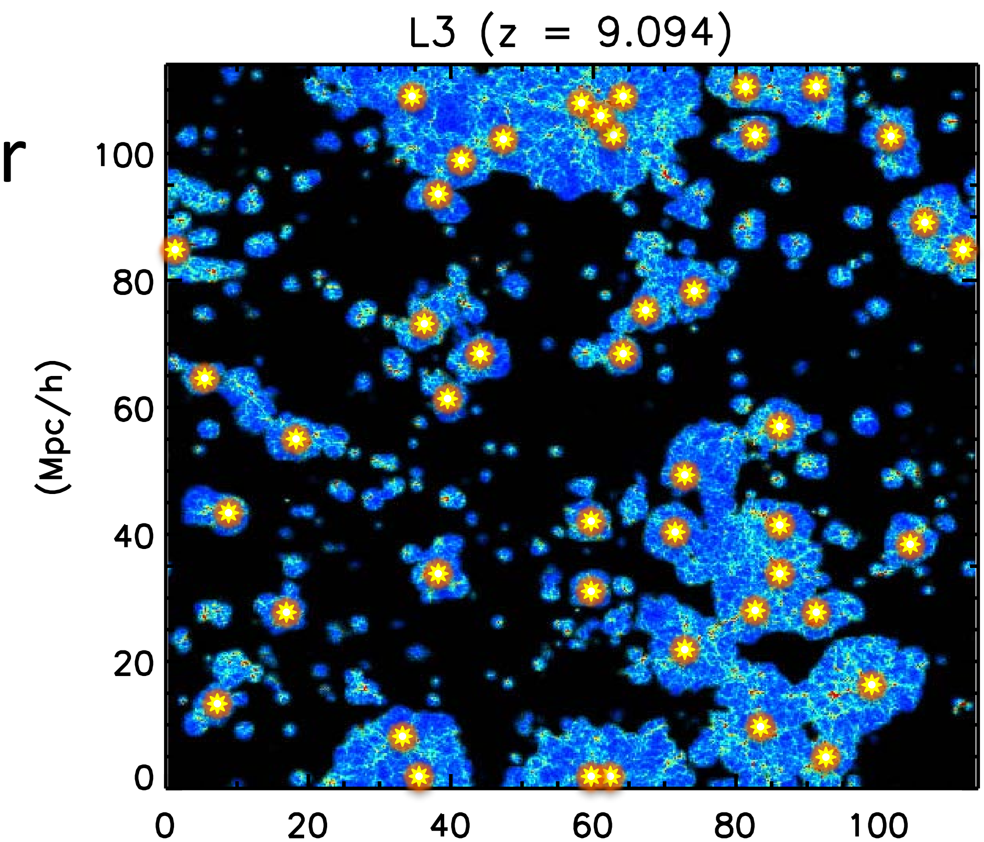



L3 (z = 14.493)
100
80
60
40
20
0
(Mpc/h)
0
20
40
60
80
100
(Mpc/h)

Method

Simulating the Reionization Epoch

- Run N-body simulation.
- Identify halos and assign ionizing efficiencies to them.
- Run radiative-transfer simulation.



Method

Computing the kSZ signal

$$\frac{\Delta T}{T}(\hat{\gamma}) = \int d\tau \hat{\gamma} \cdot \frac{\mathbf{v}}{c}$$

Method

Computing the kSZ signal

$$\frac{\Delta T}{T}(\hat{\gamma}) = \int d\tau \hat{\gamma} \cdot \frac{\mathbf{v}}{c}$$

$$\frac{\Delta T}{T}(\hat{\gamma}) = (\frac{\bar{n}_{H,0}\sigma_T}{c}) \int \frac{ds}{a^2} \, (X\mathbf{v}(1+\delta)) \cdot \hat{\gamma}$$

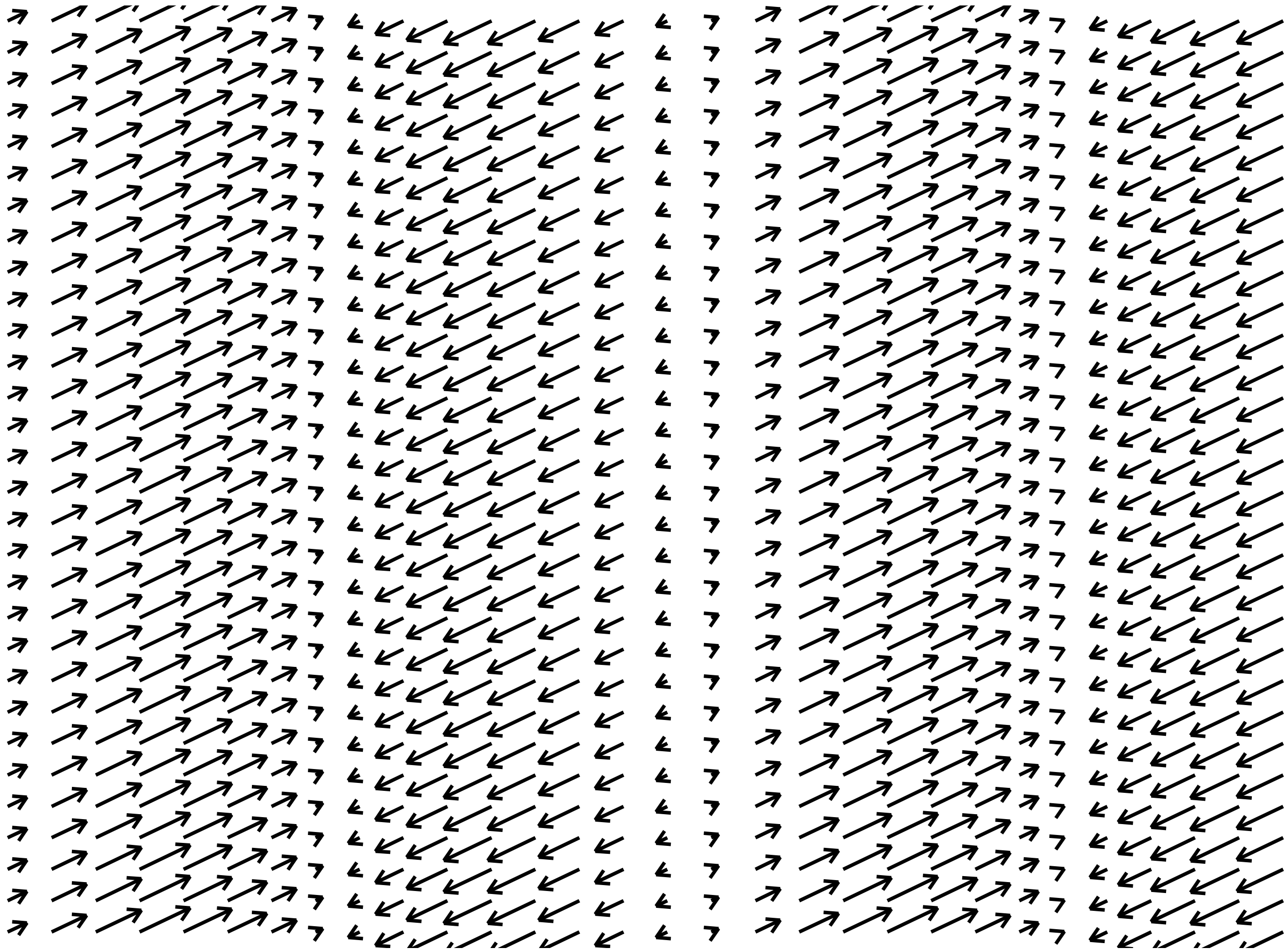
Method
Computing the kSZ signal

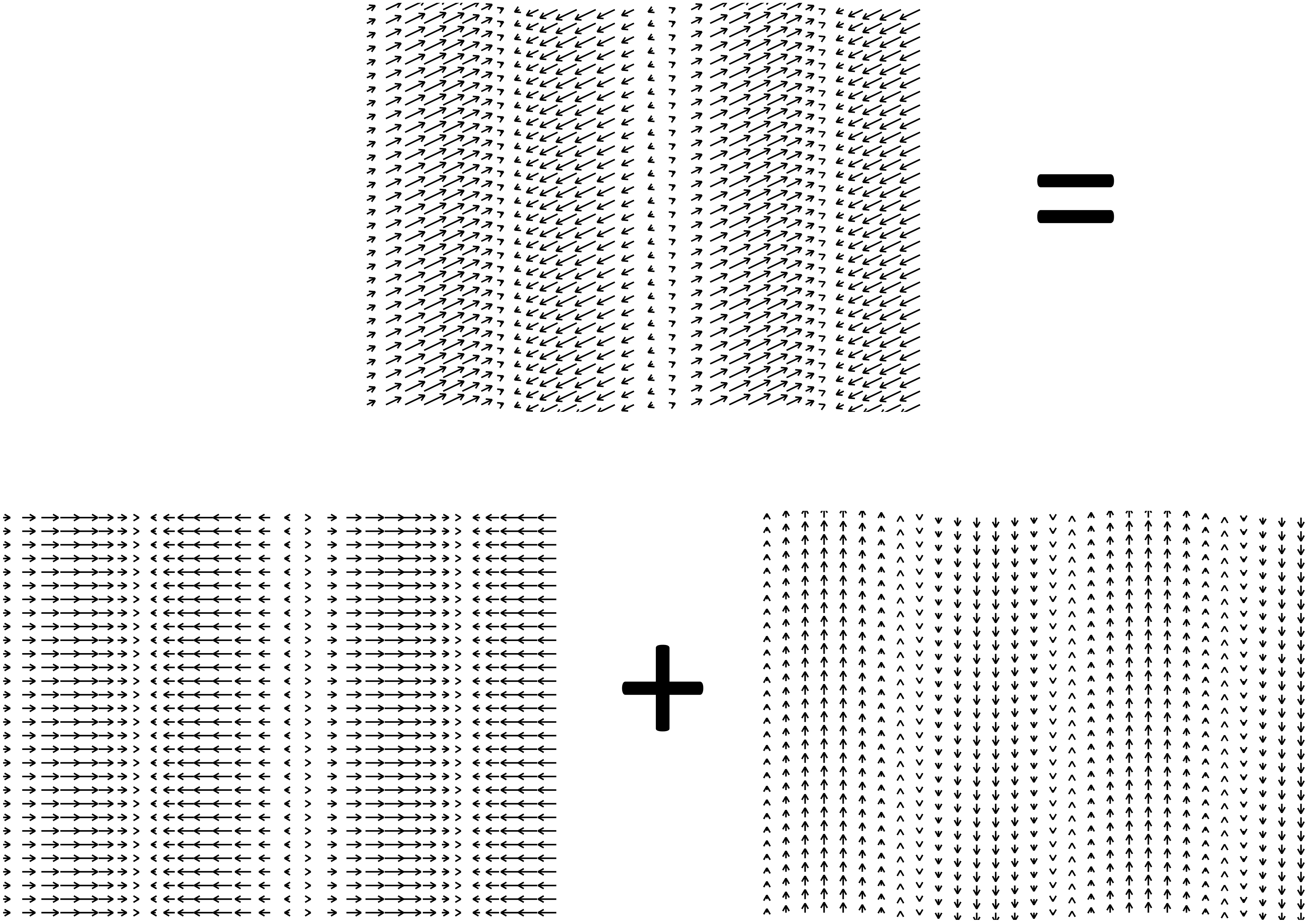
$$\frac{\Delta T}{T}(\hat{\gamma}) = \int d\tau \hat{\gamma} \cdot \frac{\mathbf{v}}{c}$$

$$\frac{\Delta T}{T}(\hat{\gamma}) = (\frac{\bar{n}_{H,0}\sigma_T}{c}) \int \frac{ds}{a^2} (X\mathbf{q}) \cdot \hat{\gamma}$$

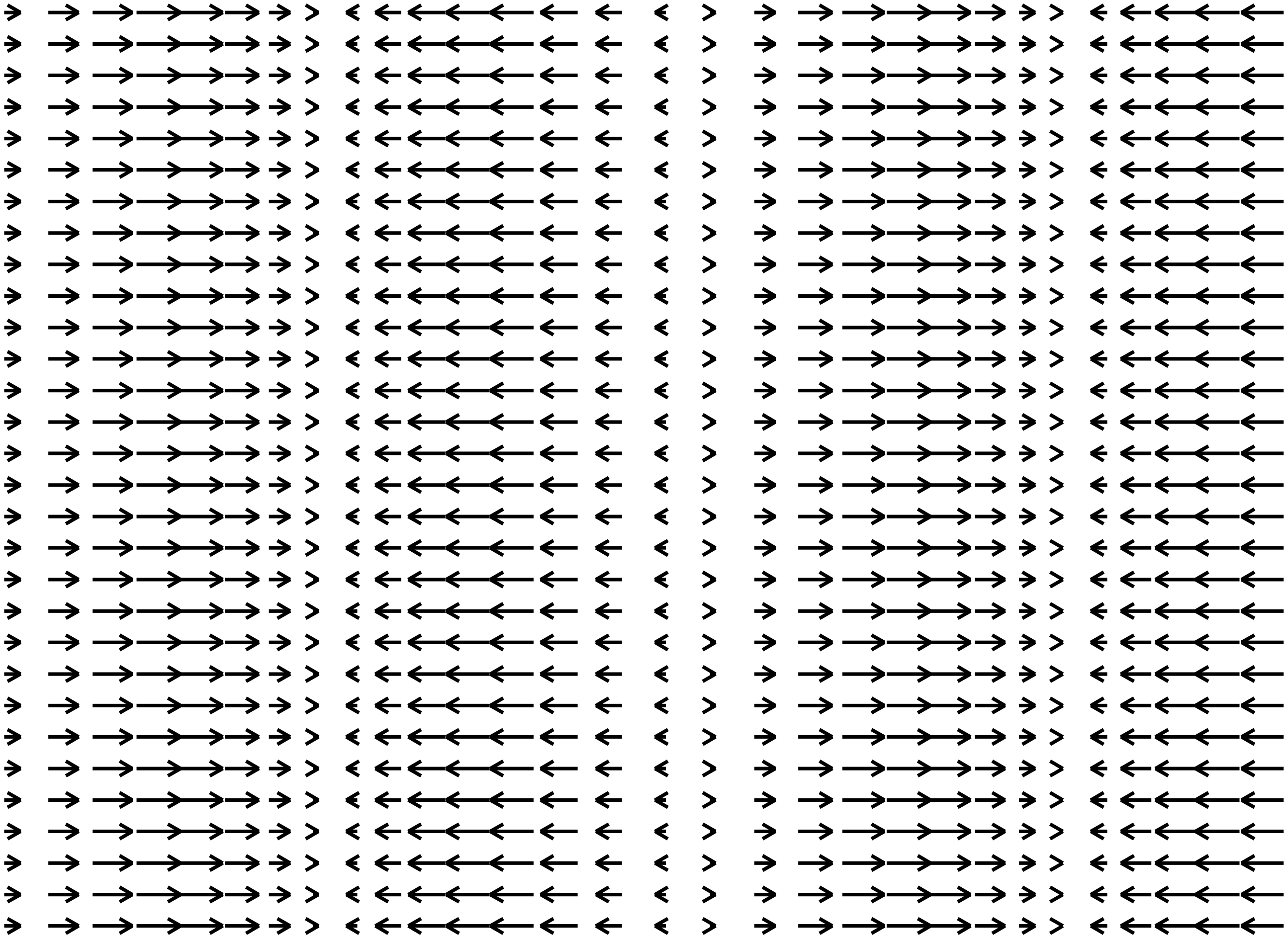
$$\mathbf{q} \equiv (1+\delta)\mathbf{v}$$

A vector plain wave



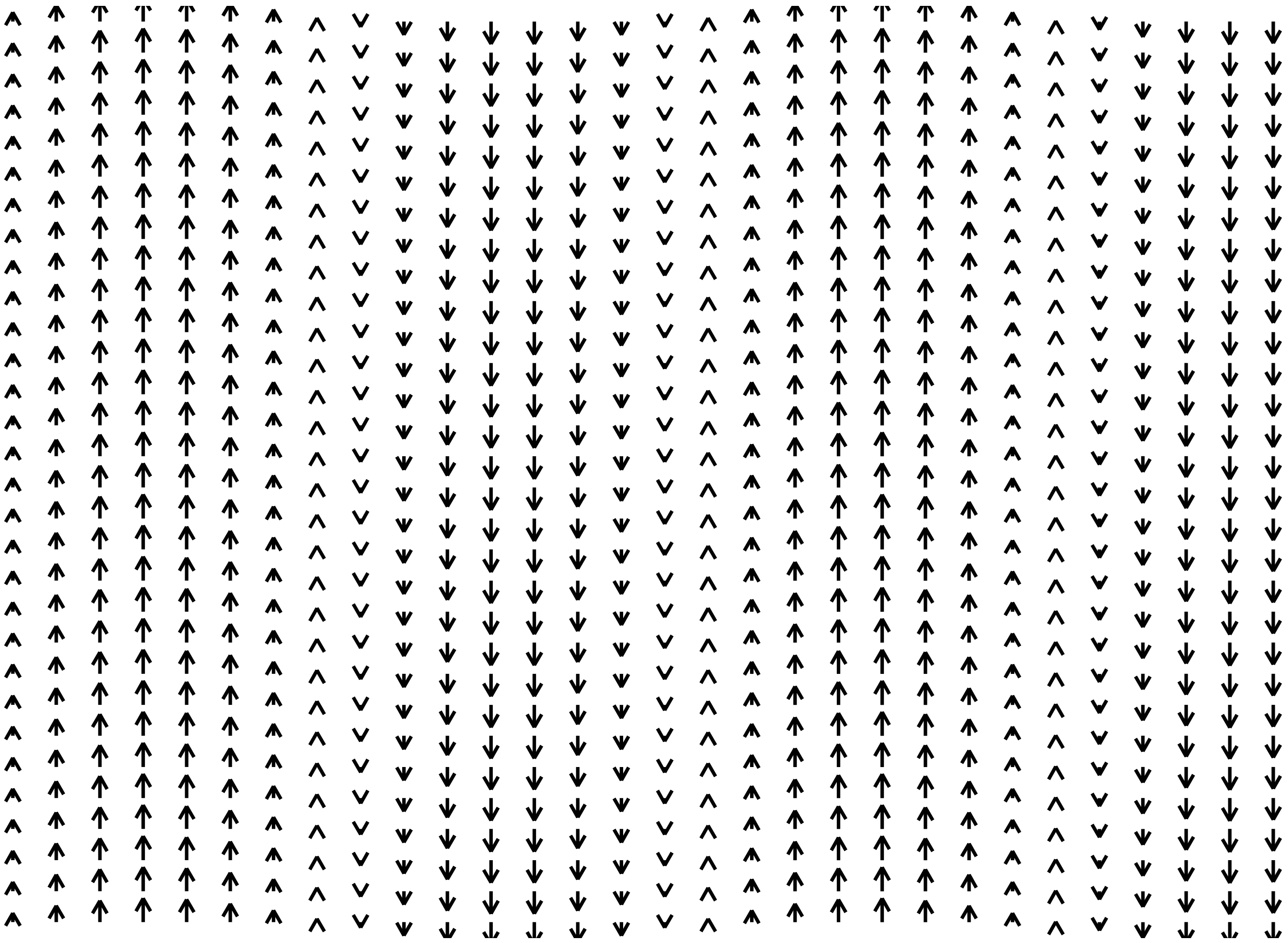


Curl-free mode



No kSZ contribution from the curl-free mode.

Curl Mode (Divergence Free Mode)



kSZ contribution when looking from ↑

Method
Computing the kSZ signal

$$\frac{\Delta T}{T}(\hat{\gamma}) = \int d\tau \hat{\gamma} \cdot \frac{\mathbf{v}}{c}$$

$$\frac{\Delta T}{T}(\hat{\gamma}) = (\frac{\bar{n}_{H,0}\sigma_T}{c}) \int \frac{ds}{a^2} \ (X\mathbf{q}) \cdot \hat{\gamma}$$

$$\mathbf{q} \equiv (1+\delta)\mathbf{v}$$

$$C_l = (\frac{\bar{n}_{H,0}\sigma_T}{c})^2 \int \frac{ds}{s^2 a^4} \ \frac{P_{(X\mathbf{q})_\perp}(k = l/s, s)}{2}$$

$\rightarrow$ Model $P_{(X\mathbf{q})_\perp}$!

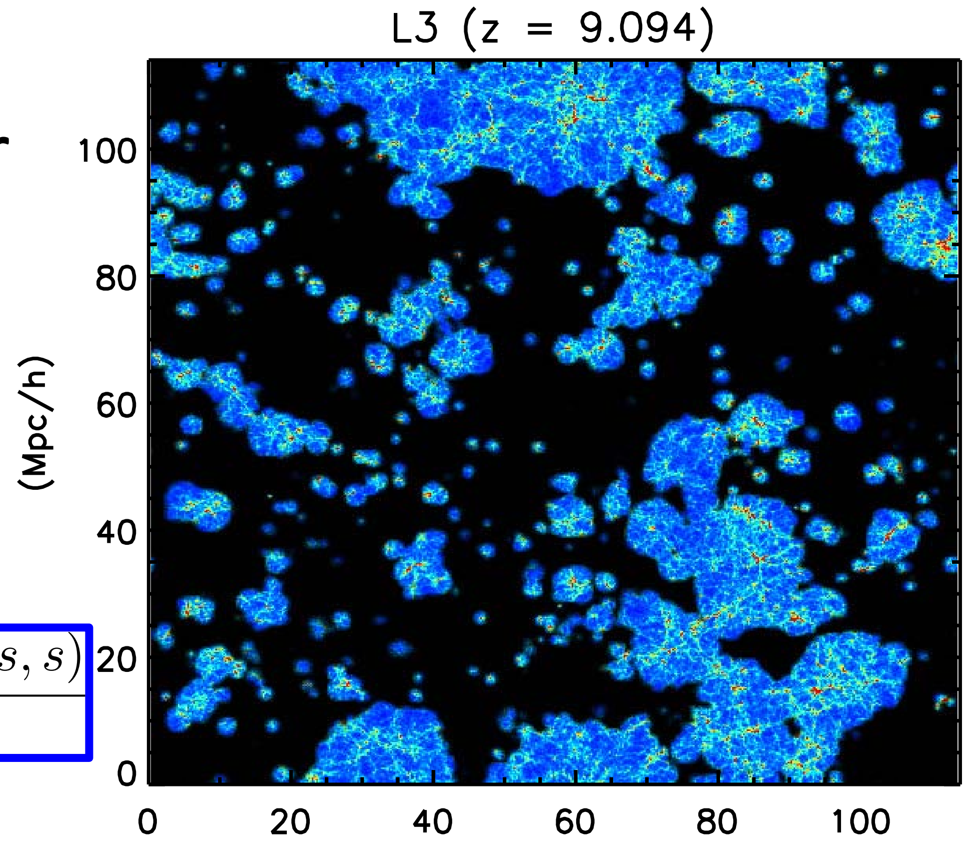
Method
Computing the kSZ signal

- Run N-body simulation.
- Identify halos and assign ionizing efficiencies to them.
- Run radiative-transfer simulation.

$\rightarrow$ Extract $P_{(X\mathbf{q})_\perp}$.

$\rightarrow$ Evaluate

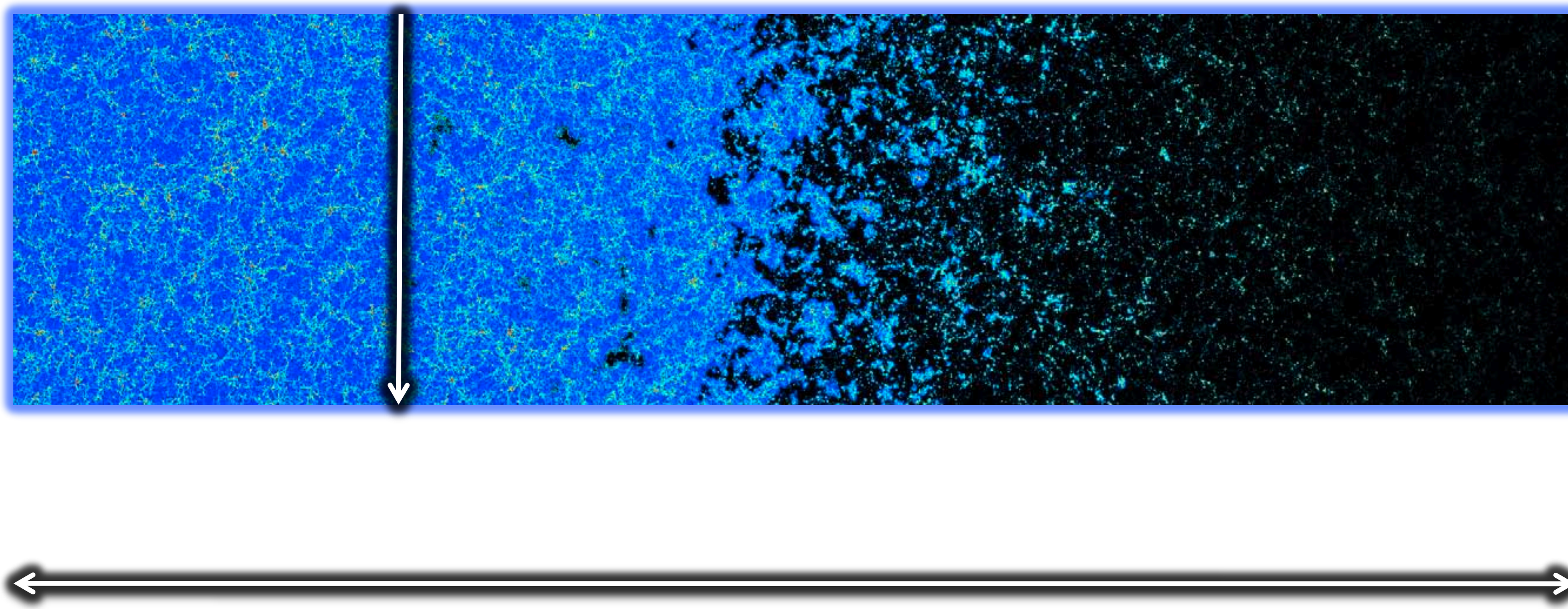
$$C_l = (\frac{\bar{n}_{H,0}\sigma_T}{c})^2 \int \frac{ds}{s^2 a^4} \; \frac{P_{(X\mathbf{q})_\perp}(k = l/s, s)}{2}$$



Model

Constraints on the Reionization Epoch

$z_{\rm ov} > 6$

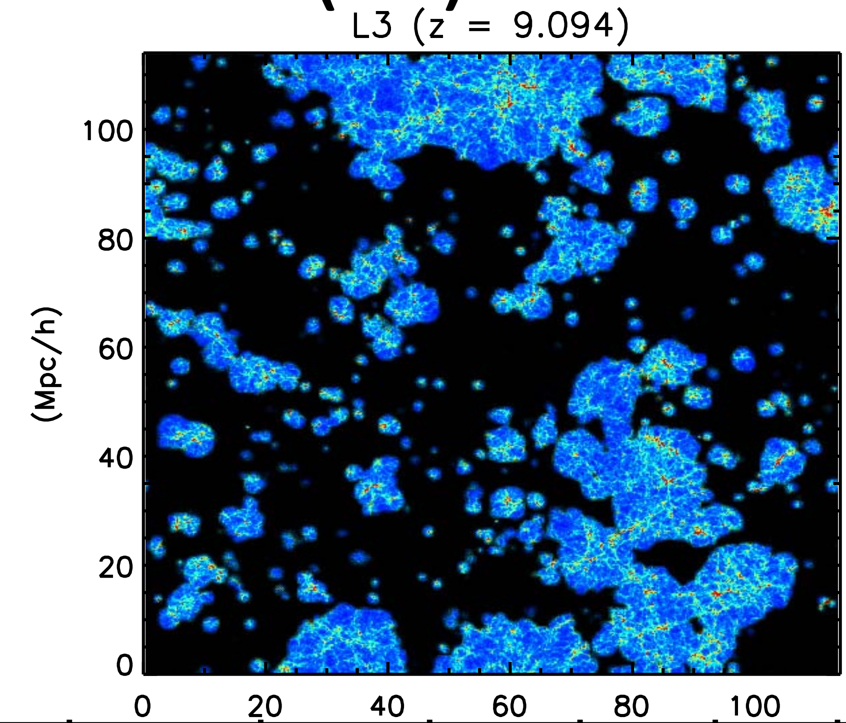


$\tau_{\rm es} = 0.088 \pm 0.015$

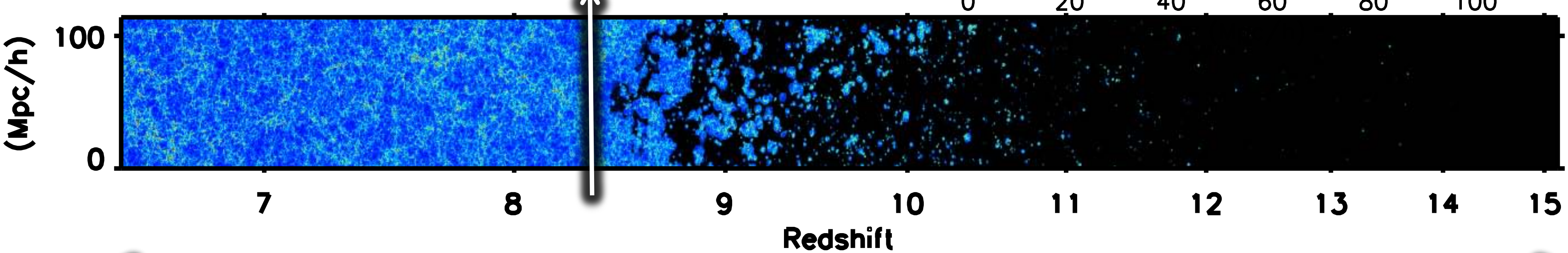
Model

Single kind of Source (L3)

$$M_{\rm halo} > 2.2 \times 10^9 M_\odot$$



$$z_{\rm ov} = 8.3$$



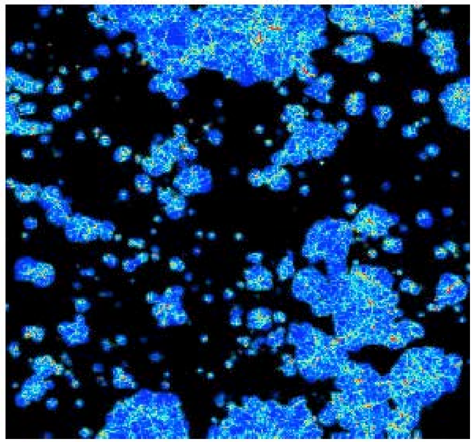
$$\tau_{\rm es} = 0.07$$

$(\tau_{\rm es,WMAP} = 0.088 \pm 0.015$

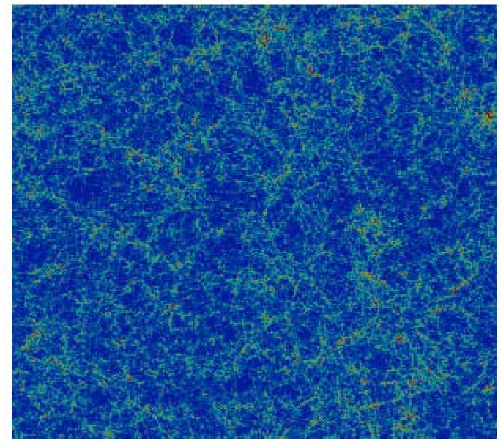
Model

Inhomogeneous vs Homogeneous

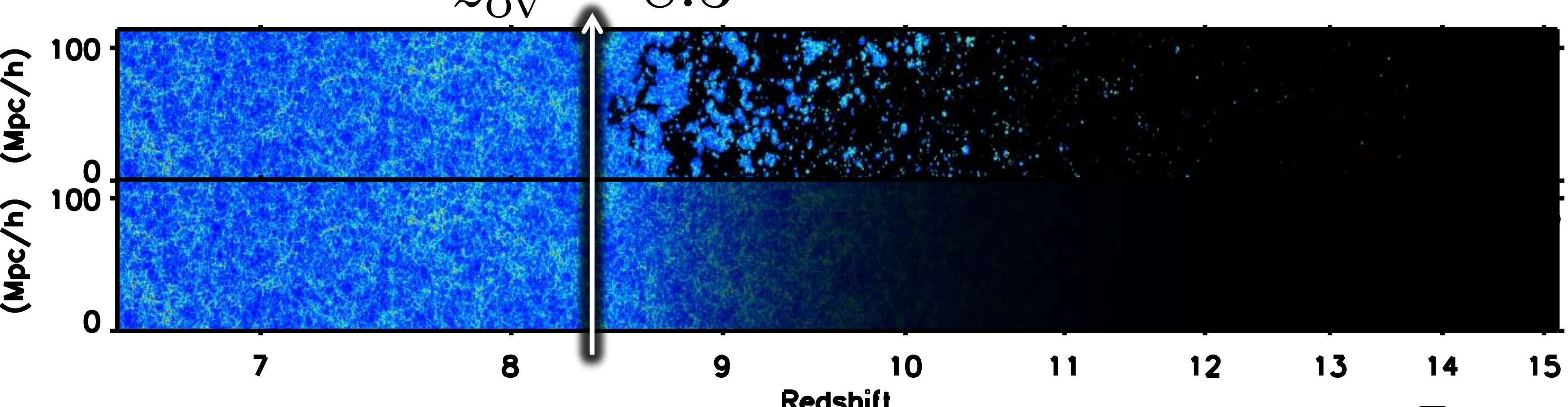
L3



L3 homogeneous



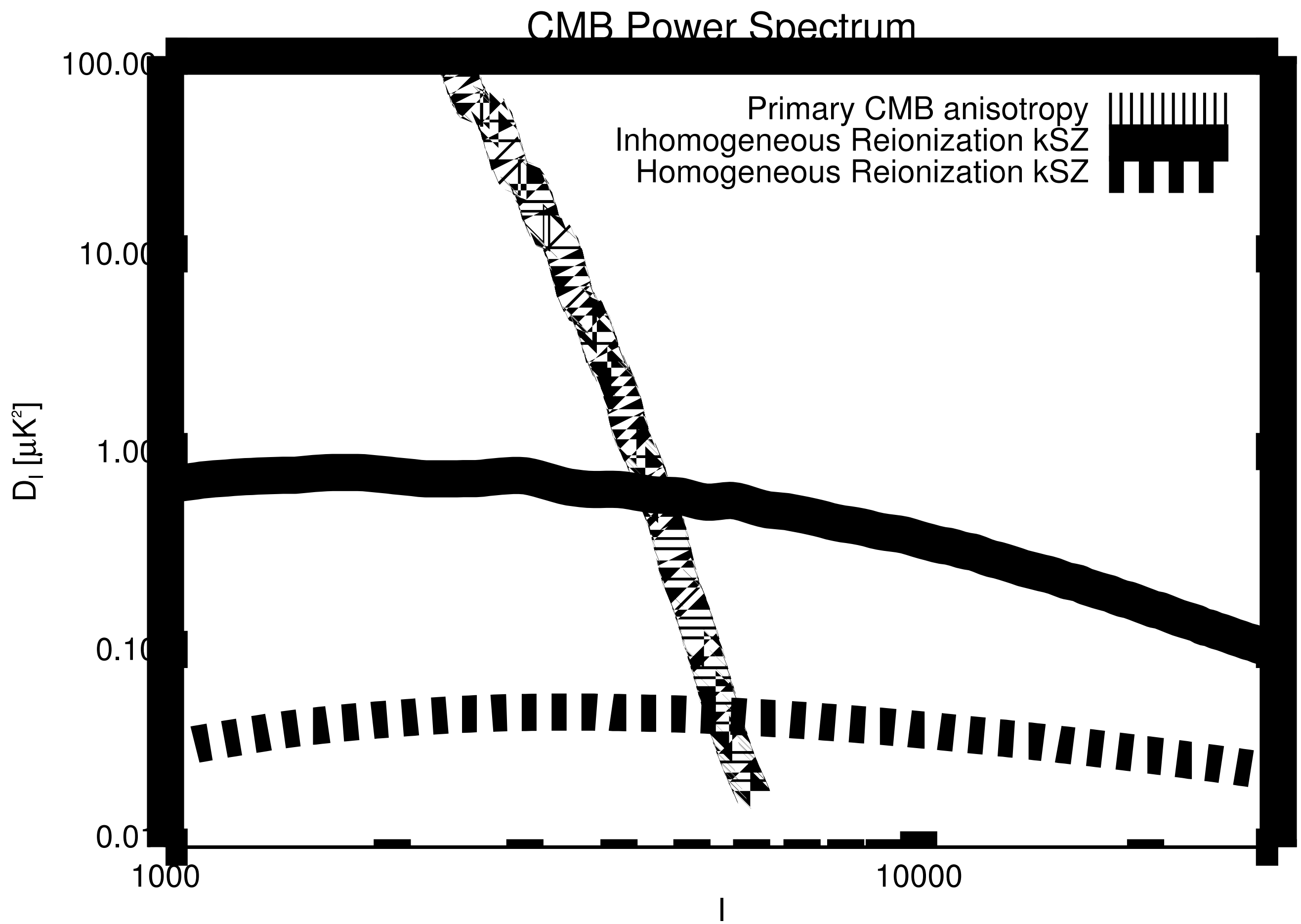
$z_{\mathrm{ov}} = 8.3$



$\tau_{\mathrm{es}} = 0.07$

Result

Homo. vs. Inhomo. : Total signal

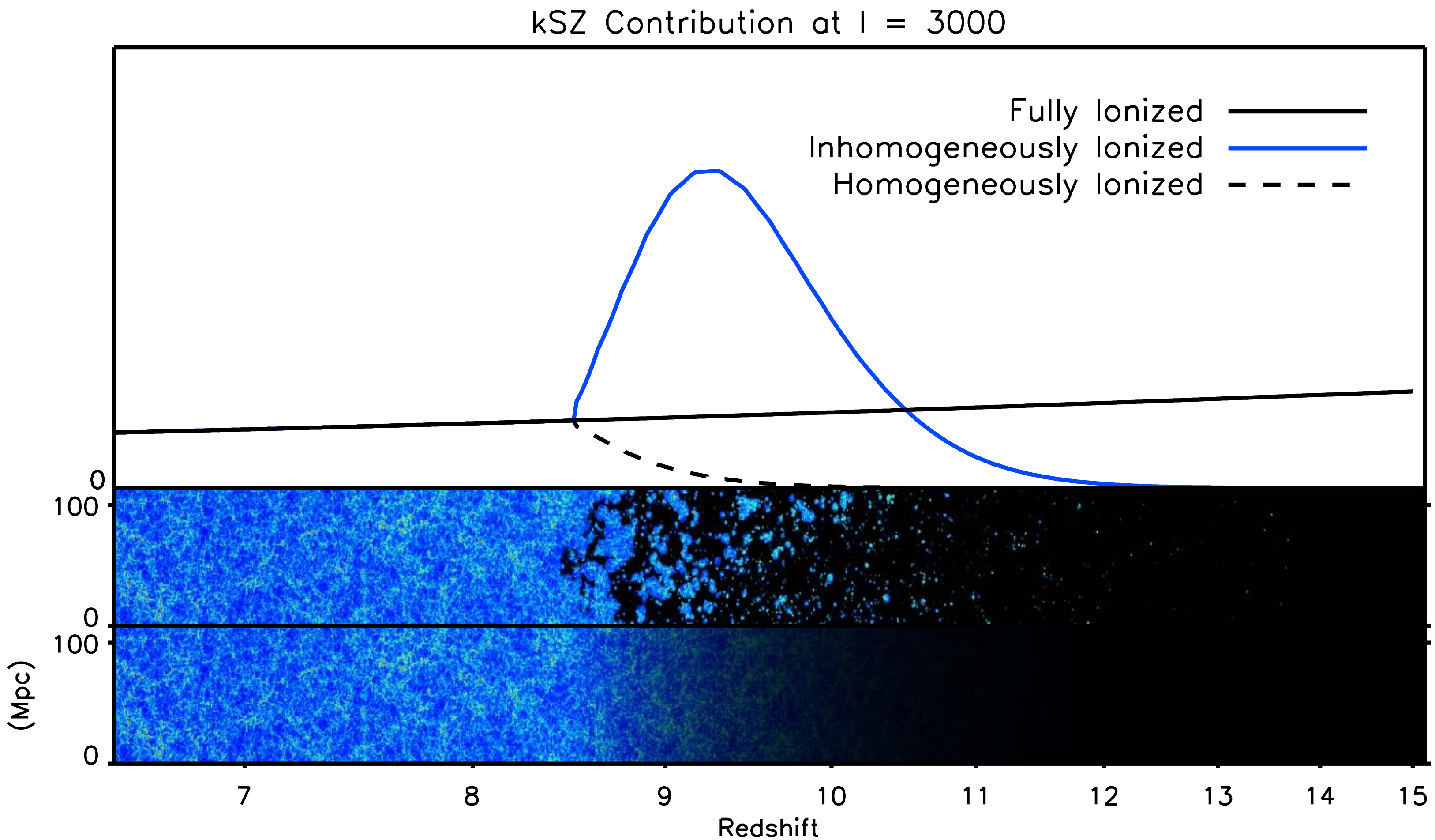


Inhomogeneity of the reionization boosts the kSZ signal significantly!

$$C_l = (\frac{\bar{n}_{H,0}\sigma_T}{c})^2 \int \frac{ds}{s^2 a^4} \frac{P_{(X\mathbf{q})_\perp}(k = l/s, s)}{2}$$

Result

Contribution Over Time

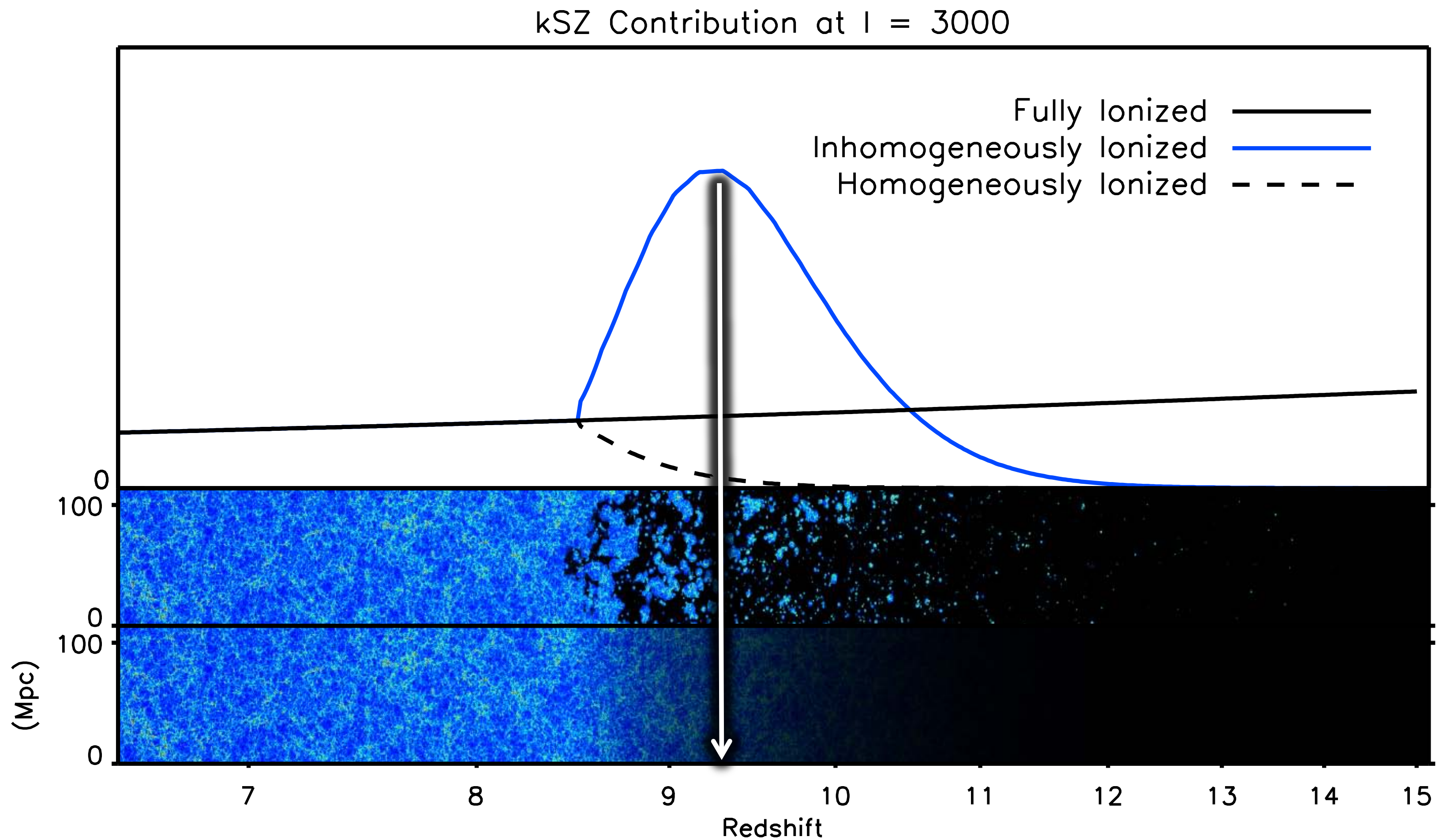


<u>Inhomogeneity of the reionization boosts the kSZ signal significantly!</u>

$$C_l = \left(\frac{\bar{n}_{H,0}\sigma_T}{c}\right)^2 \int \frac{ds}{s^2 a^4} \frac{P_{(X\mathbf{q})_\perp}(k = l/s, s)}{2}$$

Result

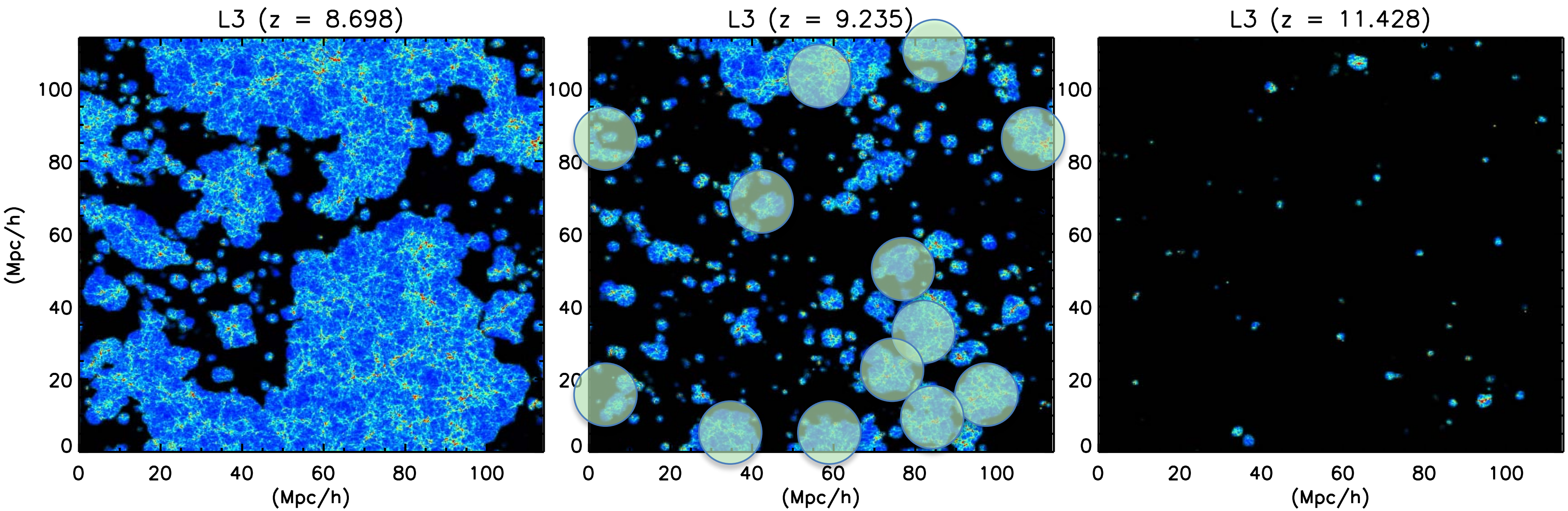
Peak of contribution



Result

Where the most of the signal comes from

Bubbles too large ! Lack of ions !



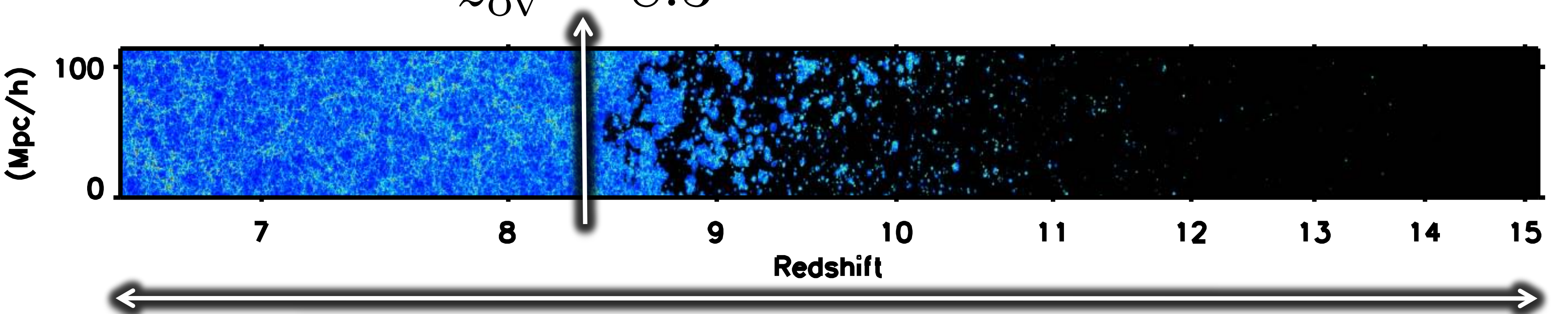
Most of the kSZ signal comes from when the typical size of bubbles matches the angular scale we are look at.

Modeling

Motivation for the self-regulated reionization

Using a single kind of sources can not meet the two constraints on reionization, $\tau_{\rm es}$ and $z_{\rm ov}$ at the same time

$z_{\rm ov} = 8.3$



$\tau_{\rm es} = 0.07$ $(\tau_{\rm es,WMAP} = 0.088 \pm 0.015)$

Modeling
Introduction of Self-regulated Sources

Low mass atomic cooling halo (LMACH) : $10^8 M_\odot < M < 10^9 M_\odot$

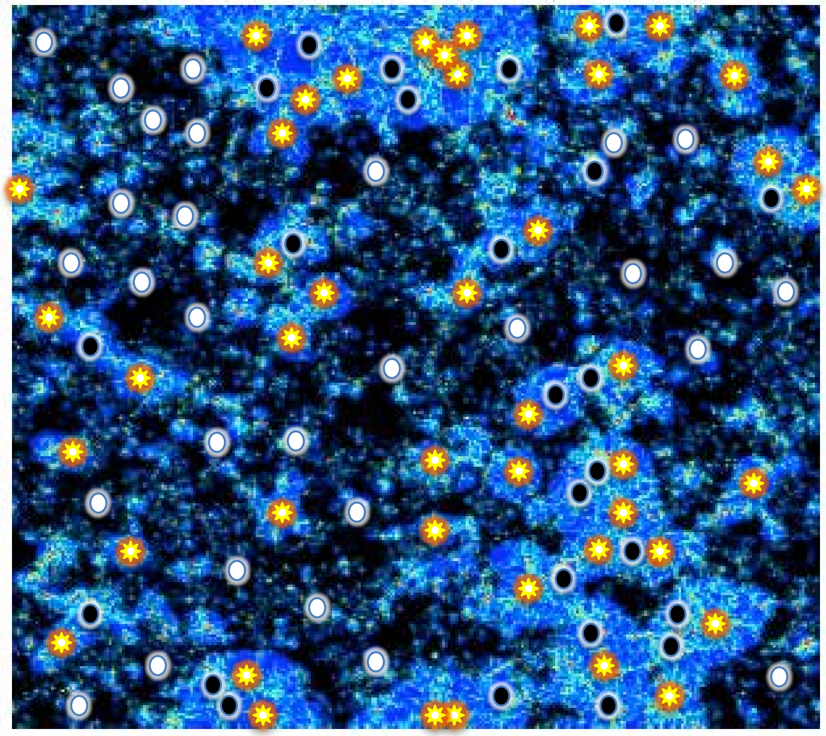
- Can form stars in neutral regions, but can not shield itself from ionizing radiation. Active as ionizing sources until surrounding IGM ionizes.

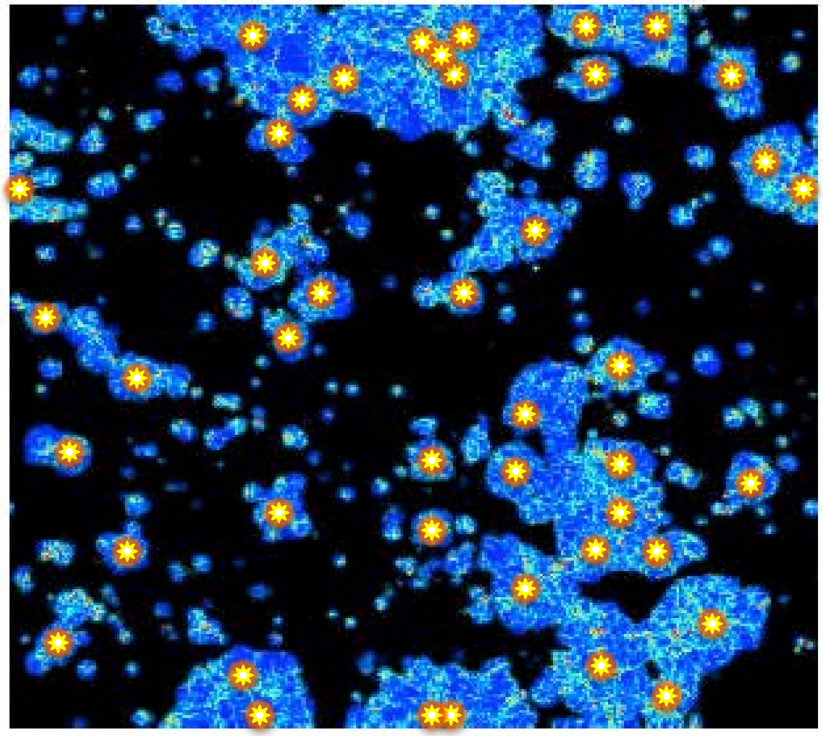
Mini halo (MH) : $10^4 M_\odot < M < 10^8 M_\odot$

- Cools itself with molecular hydrogens created by residual free electrons after the recombination. Active until Lyman-Werner radiation from neighbors dissociates its molecular hydrogens.

Modeling

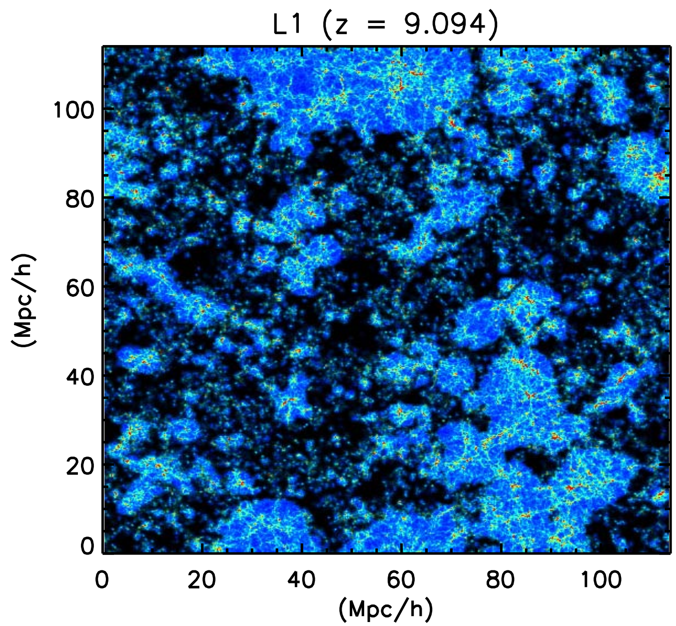
Simulating LMACHs

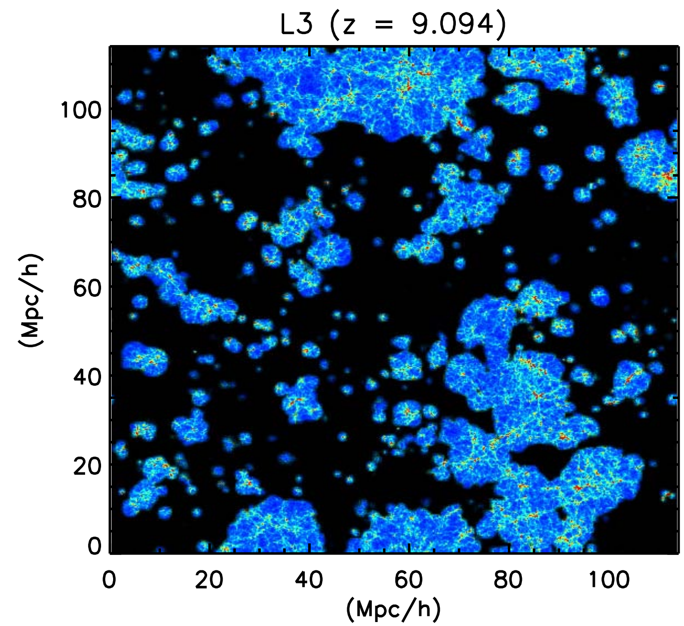




Modeling

Impact of LMACHs on reionization





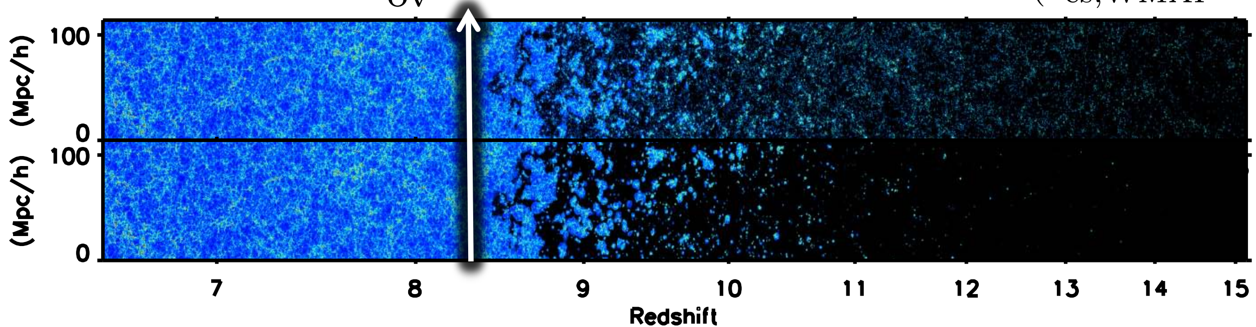
L1	L3
$M_{\rm HMACH} > 10^9 M_\odot$ $10^9 M_\odot > M_{\rm LMACH} > 10^8 M_\odot$	$M_{\rm HMACH} > 2.2 \times 10^9 M_\odot$

$z_{\rm ov} = 8.3$

$(\tau_{\rm es,WMAP} = 0.088 \pm 0.015)$

L1

L3

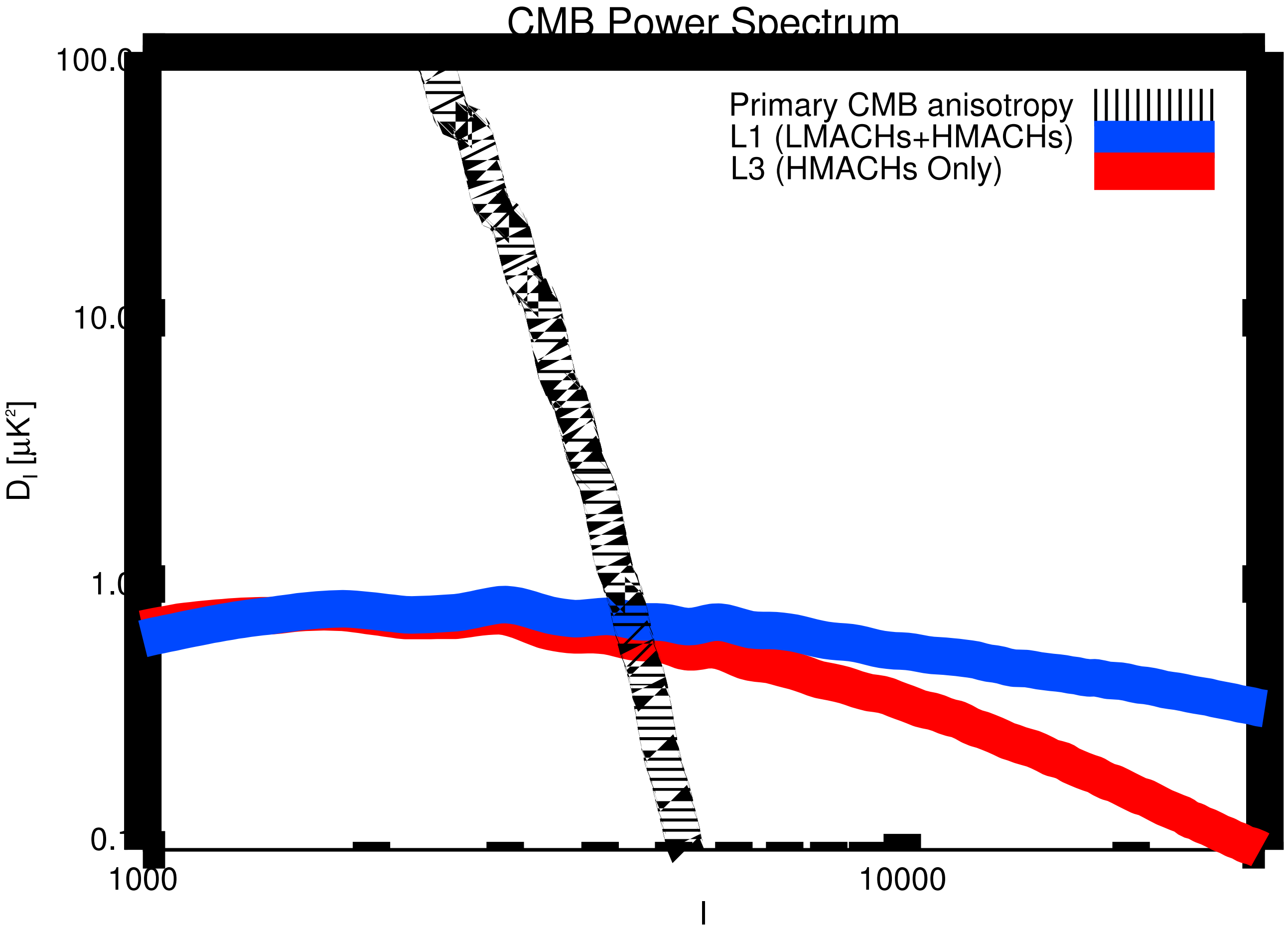


$\tau_{\rm es} = 0.080$

$\tau_{\rm es} = 0.070$

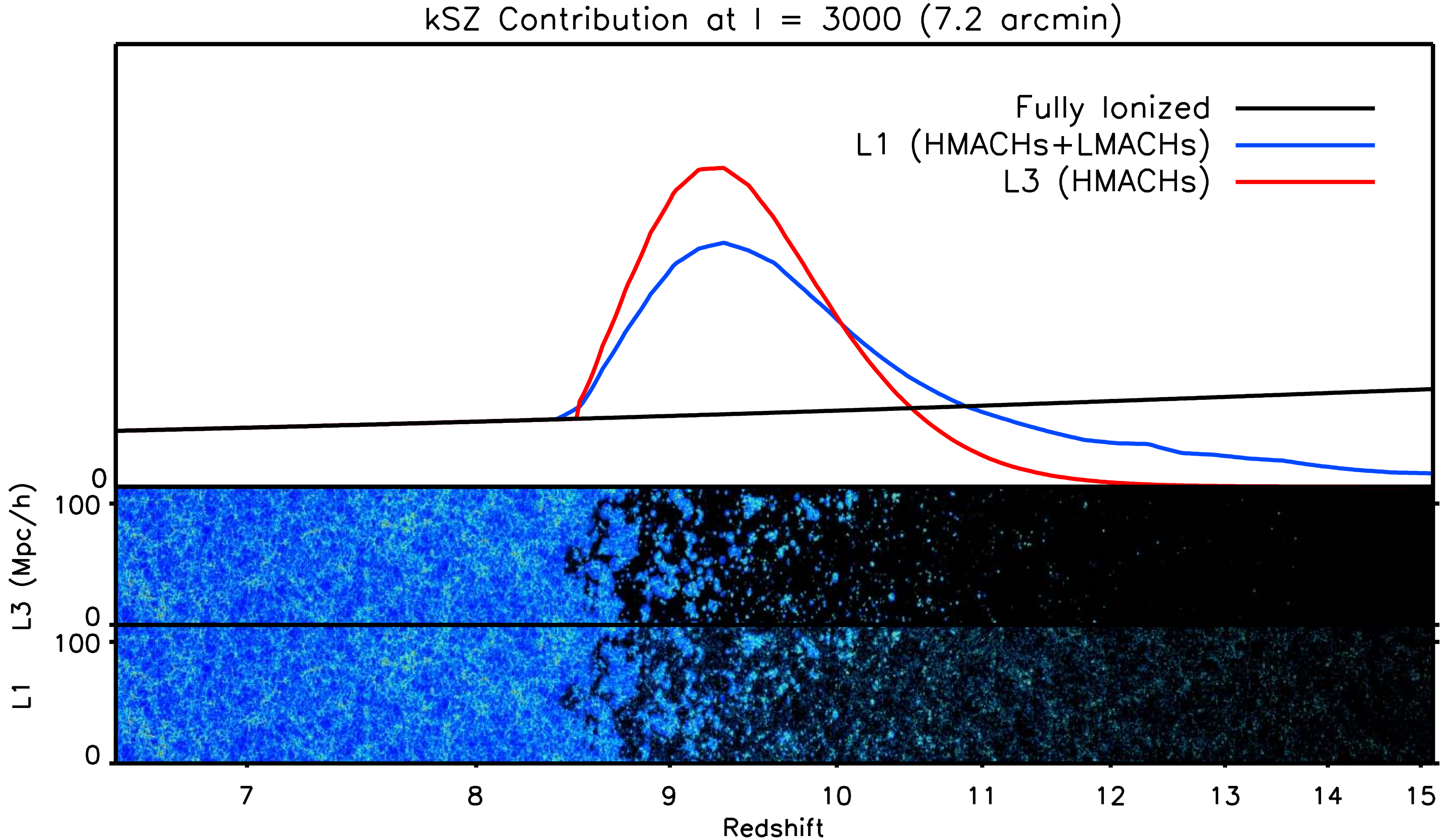
Result

Impact of LMACHs : Total kSZ signal



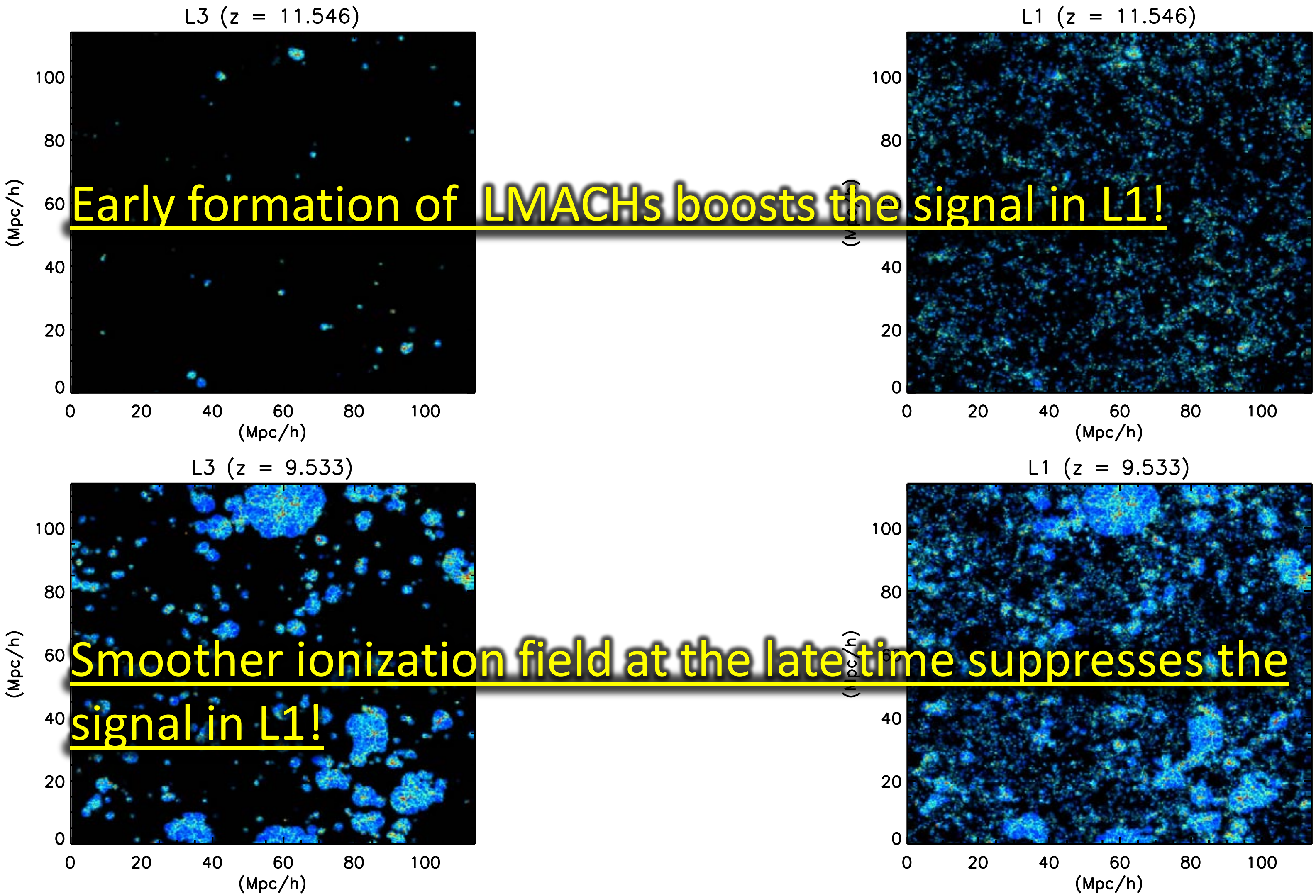
Result

Impact of LMACHs : Contribution over time



Result

Impact of LMACHs : Contribution over time

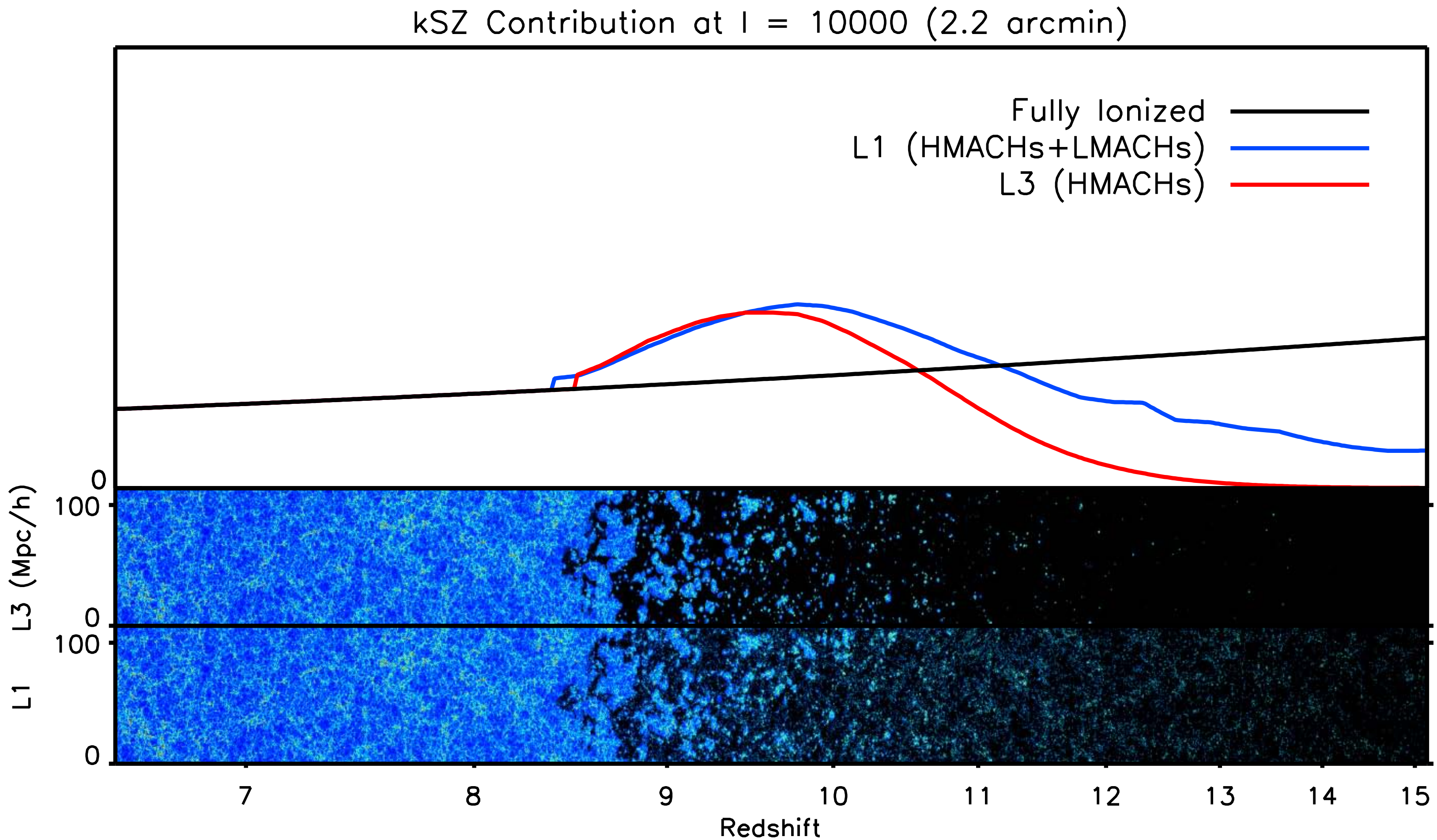


Early formation of LMACHs boosts the signal in L1!

Smoother ionization field at the late time suppresses the signal in L1!

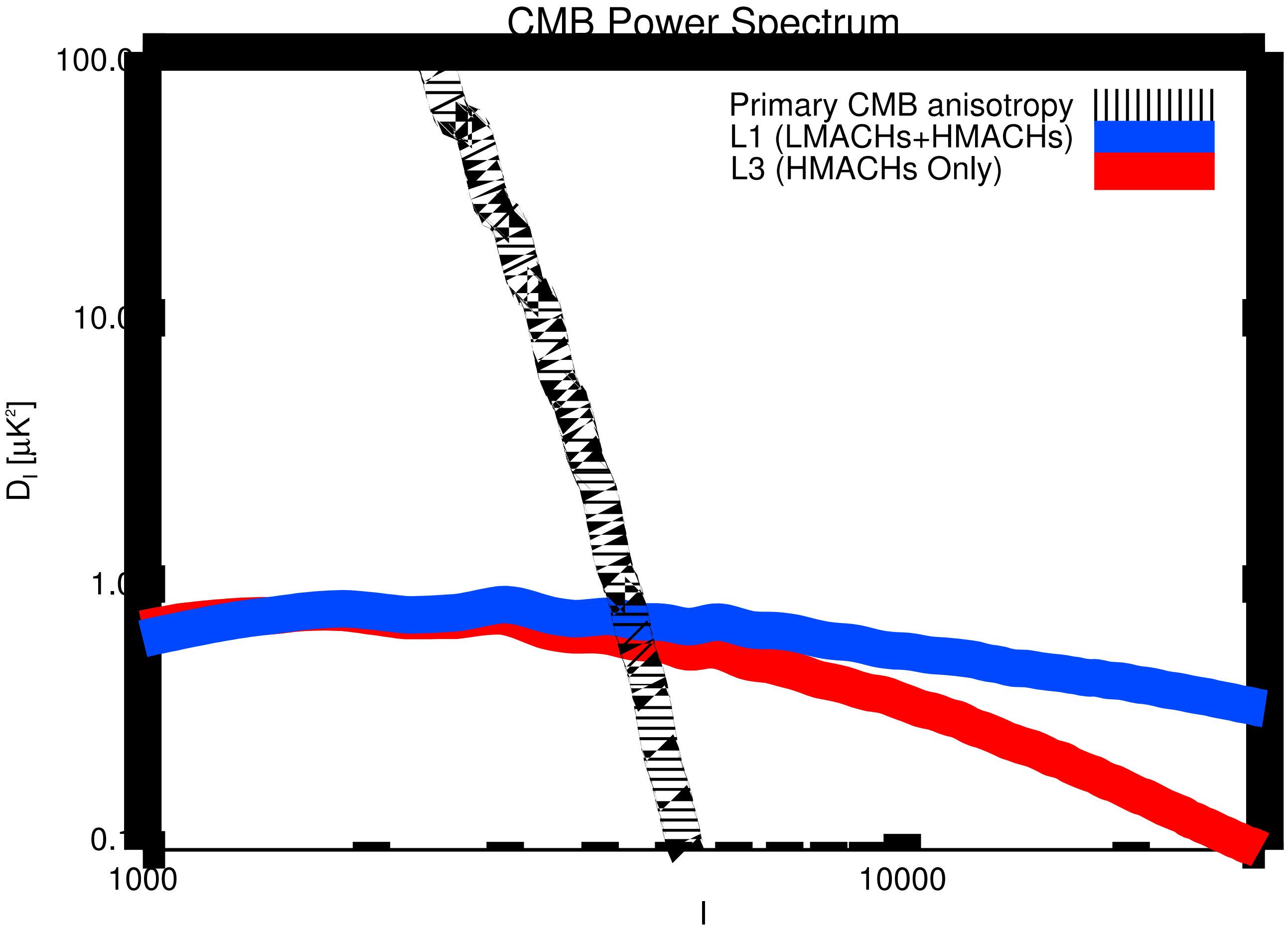
Result

Impact of LMACHs : Smaller Scales



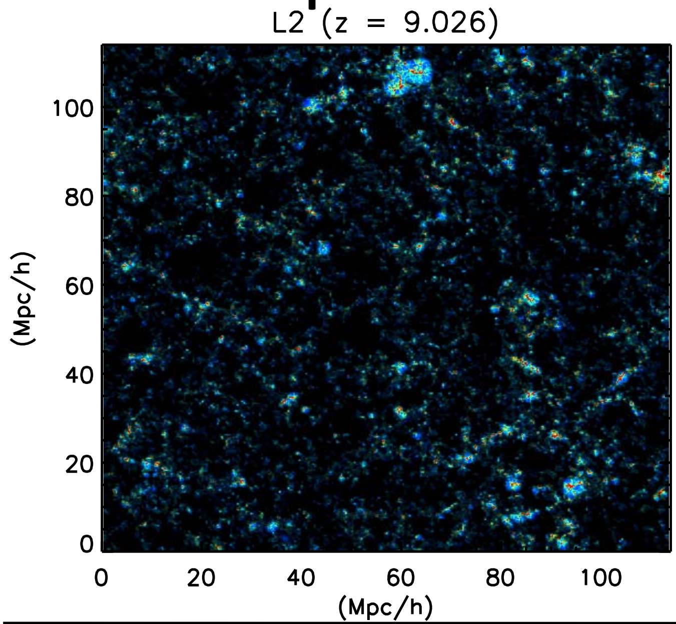
Result

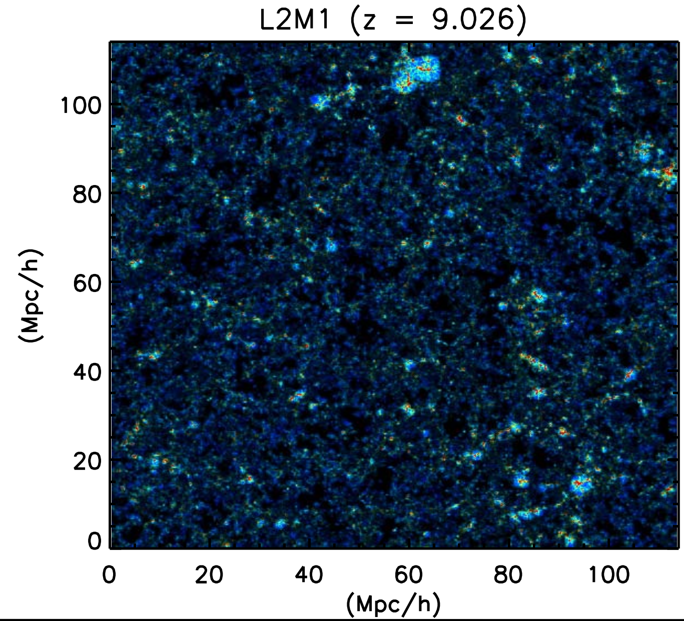
Impact of LMACHs : Total kSZ signal



Modeling

Impact of MHs on reionization





L2	L2M1
$M_{\rm HMACH} > 10^9 M_\odot$ $10^8 M_\odot < M_{\rm LMACH} < 10^9 M_\odot$	$M_{\rm HMACH} > 10^9 M_\odot$ $10^8 M_\odot < M_{\rm LMACH} < 10^9 M_\odot$ $10^5 M_\odot < M_{\rm MH} < 10^8 M_\odot$

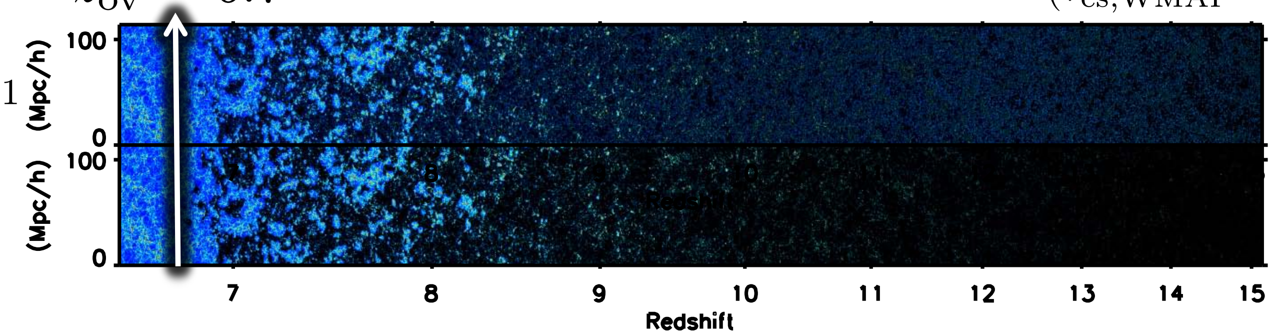
(Ahn et al. 2012)

$z_{\rm ov} = 6.7$

$(\tau_{\rm es,WMAP} = 0.088 \pm 0.015)$

L2M1

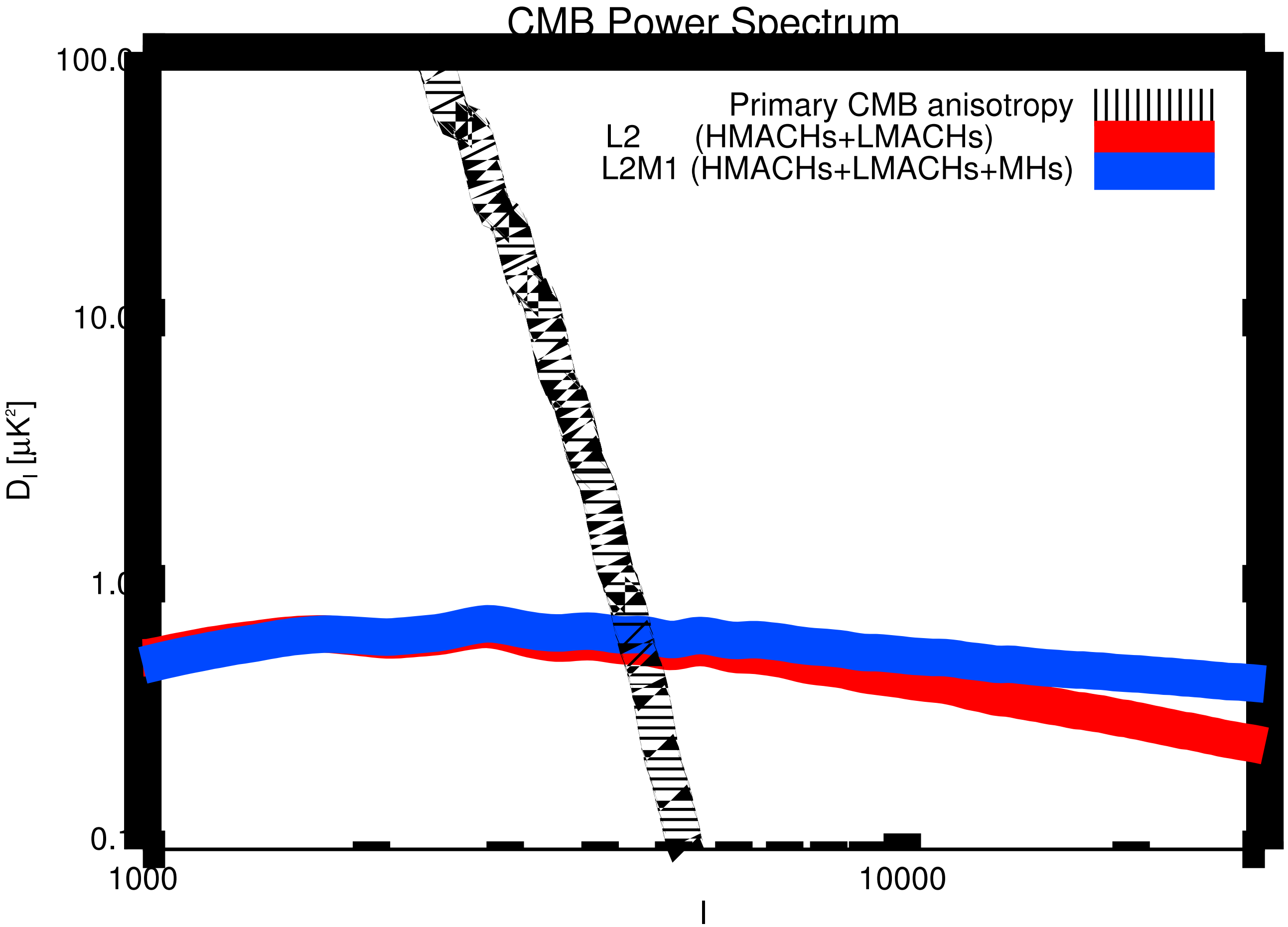
L2



$\tau_{\rm es} = 0.086$

$\tau_{\rm es} = 0.058$

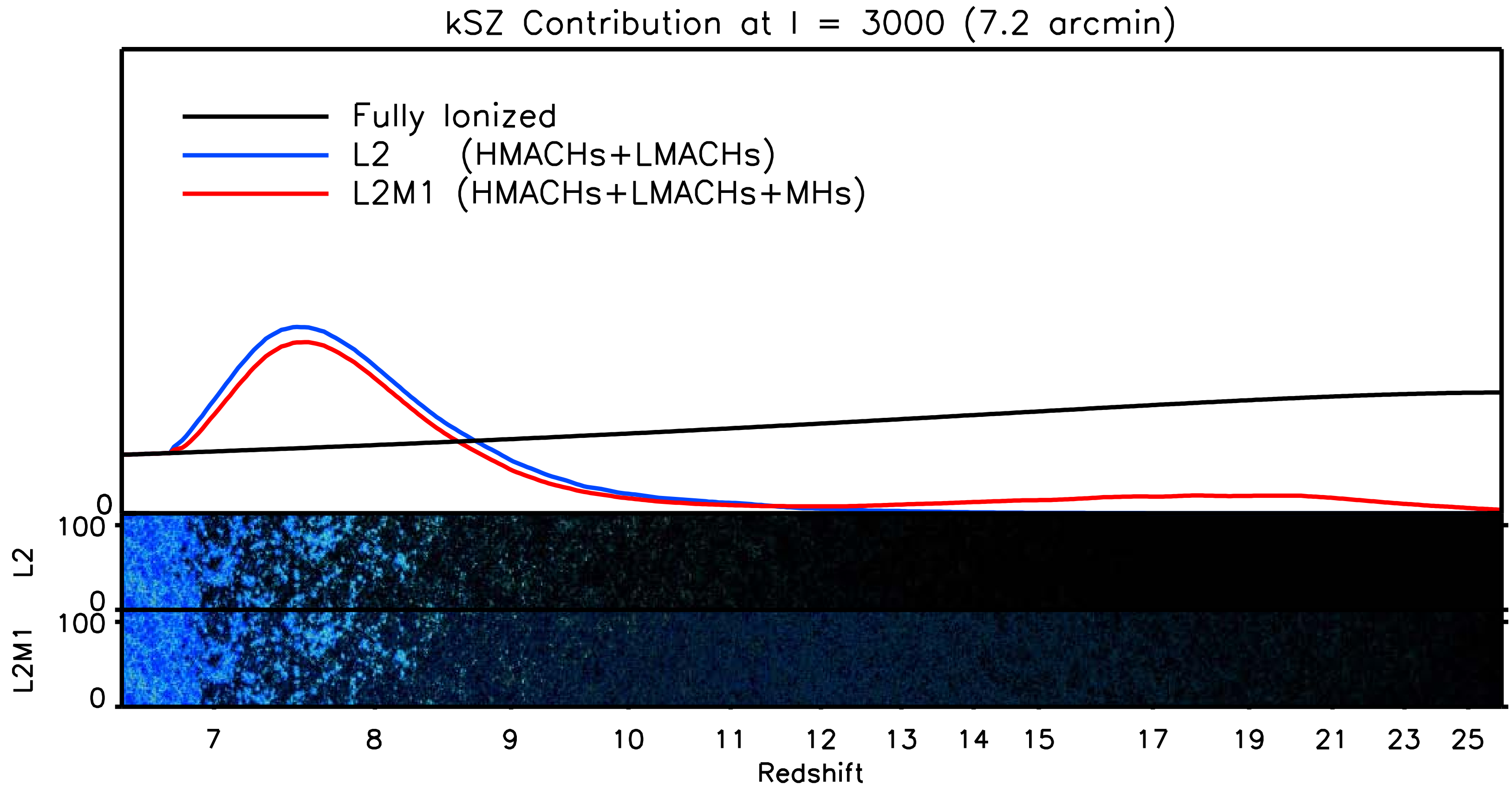
Modeling
Impact of MHs : Total kSZ signal



Mini halos mainly boosts small-scale fluctuations !

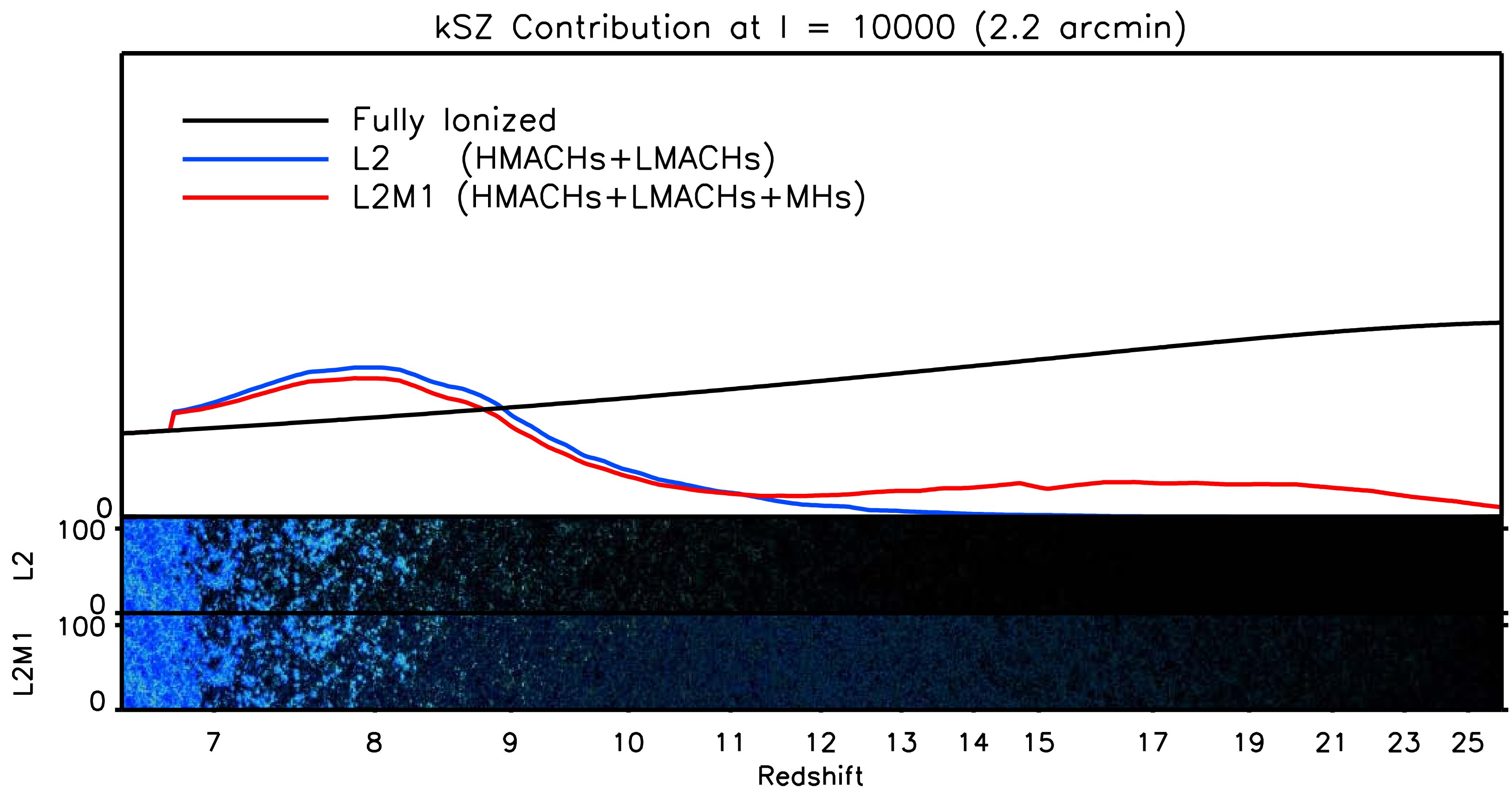
Modeling

Impact of MHs : Contribution over time



Modeling

Impact of MHs : Smaller scale



Interpretation

Testing recent semi-analytical works

$$D_{l=3000}^{\mathrm{kSZ}} = D_{l=3000}^{\mathrm{kSZ}}(\Delta z)$$

$$(\Delta z \equiv z_{75\%} - z_{25\%} \text{ or } z_{99\%} - z_{20\%})$$

Mesinger, McQuinn, Spergal (2011); Zahn et al. (2011)

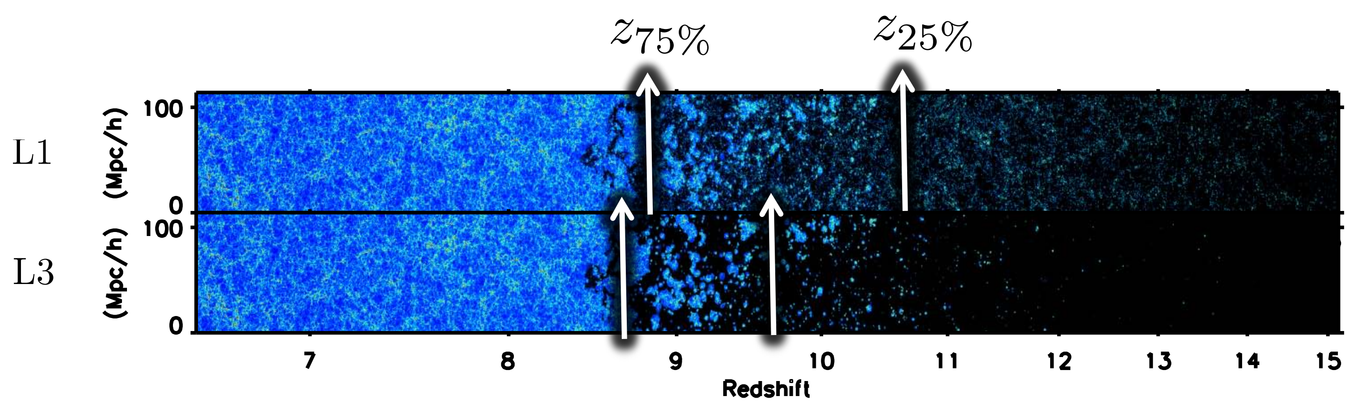
$$D_{l=3000}^{\mathrm{kSZ}} < 2.8\ \mu K^2 \rightarrow \Delta z < 4.4$$

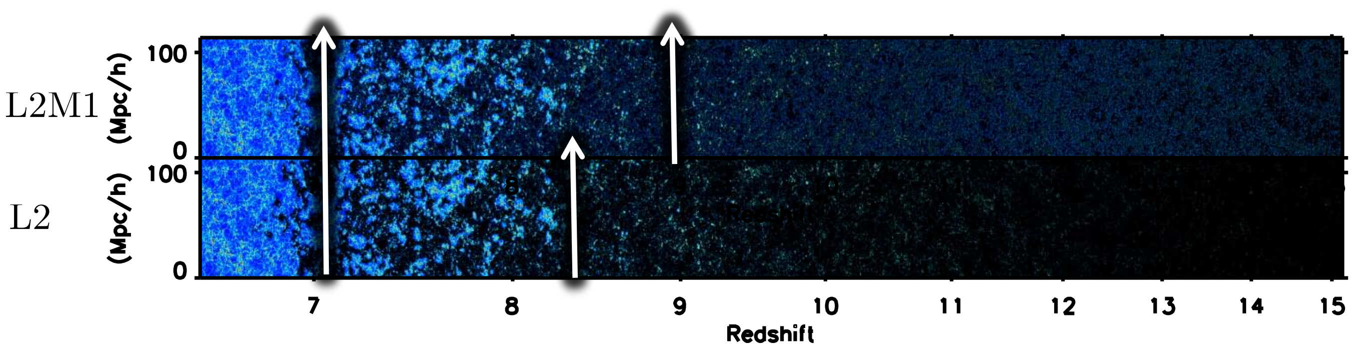
Zahn et al. (2011)

Is the kSZ signal (at l =3000) a function only of the DURATION of reionization?

Interpretation

Testing recent semi-analytical works

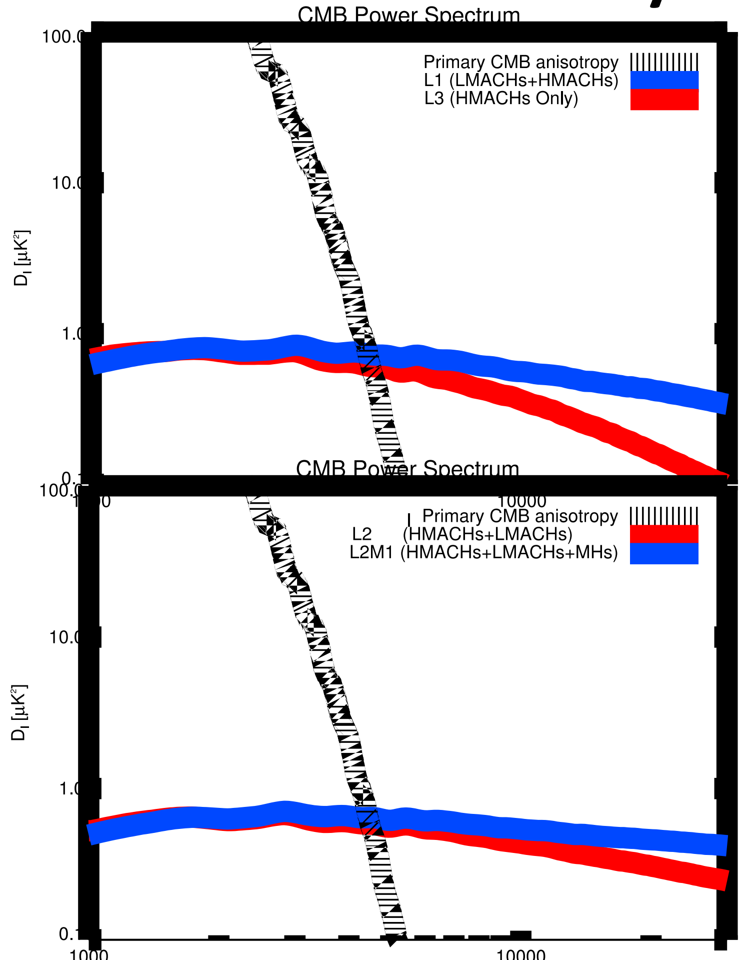




Is the kSZ signal (at l =3000) a function only of the DURATION of reionization?

Interpretation

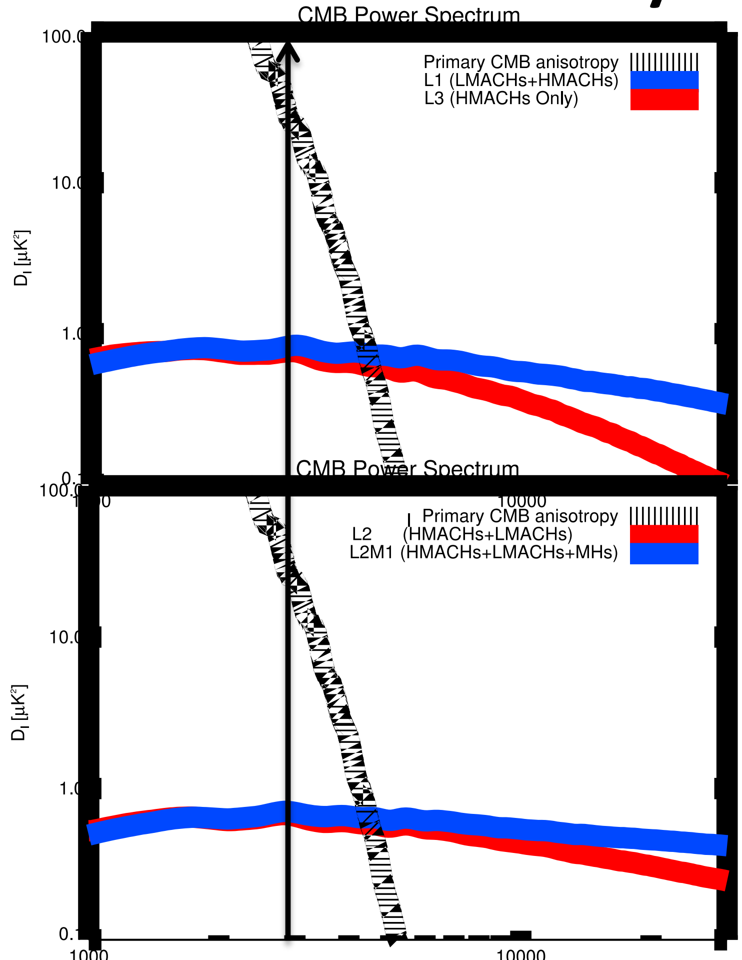
Testing recent semi-analytical works



Is the kSZ signal (at l =3000) a function only of the DURATION of reionization?

Interpretation

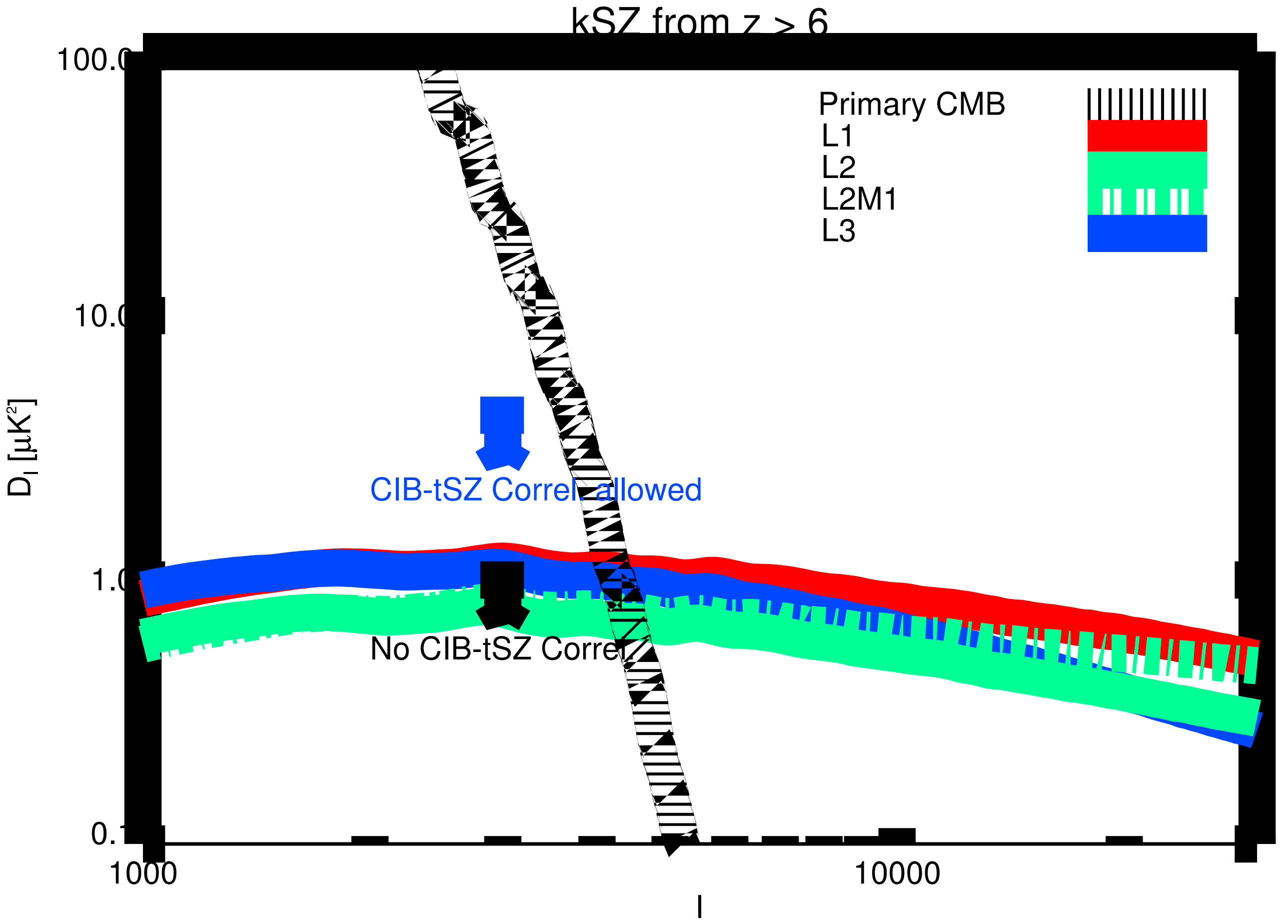
Testing recent semi-analytical works



Is the kSZ signal (at l =3000) a function only of the DURATION of reionization?

NO!

Interpretation
Comparison to the SPT constraint



Conclusion

- kSZ signal is an effective probe of late time inhomogeneity of reionization.
- Signal at l=3000 is not sensitive to LMACHs or MHs, but higher l signal will be able to tell their presence.
- D_l^{kSZ} is not just $D_l^{\mathrm{kSZ}}(\Delta z)$
- Current observation of the kSZ signal is on the edge of ruling out reionization models. We will be able to constrain the reionization with kSZ signal shortly.