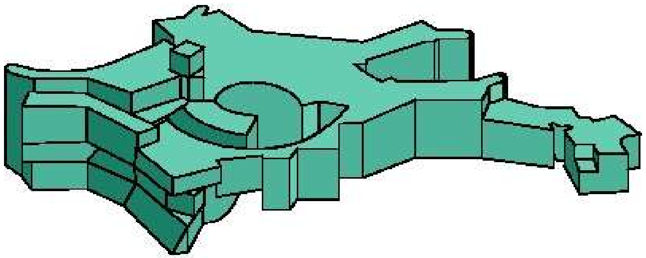
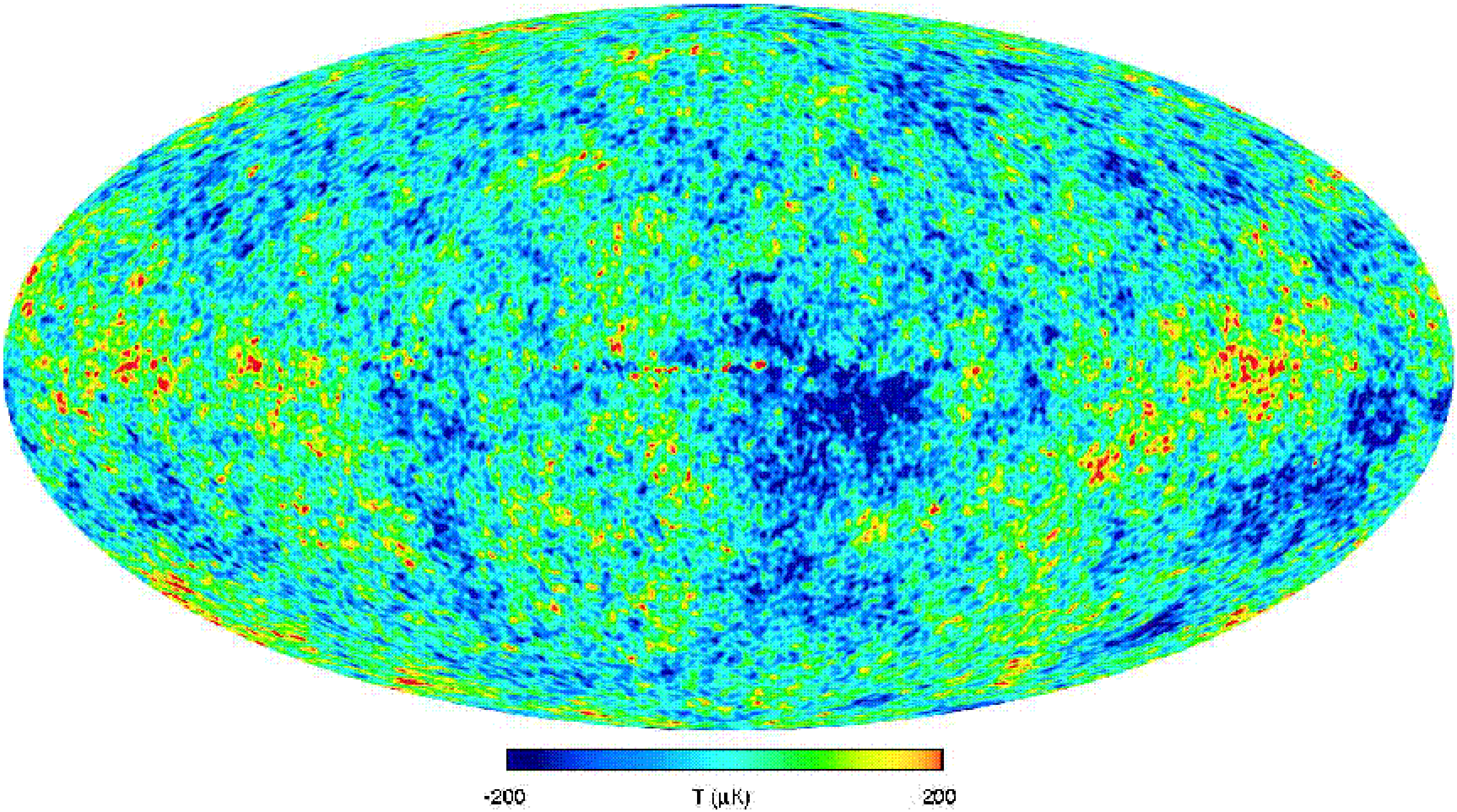


Paris, January 2004

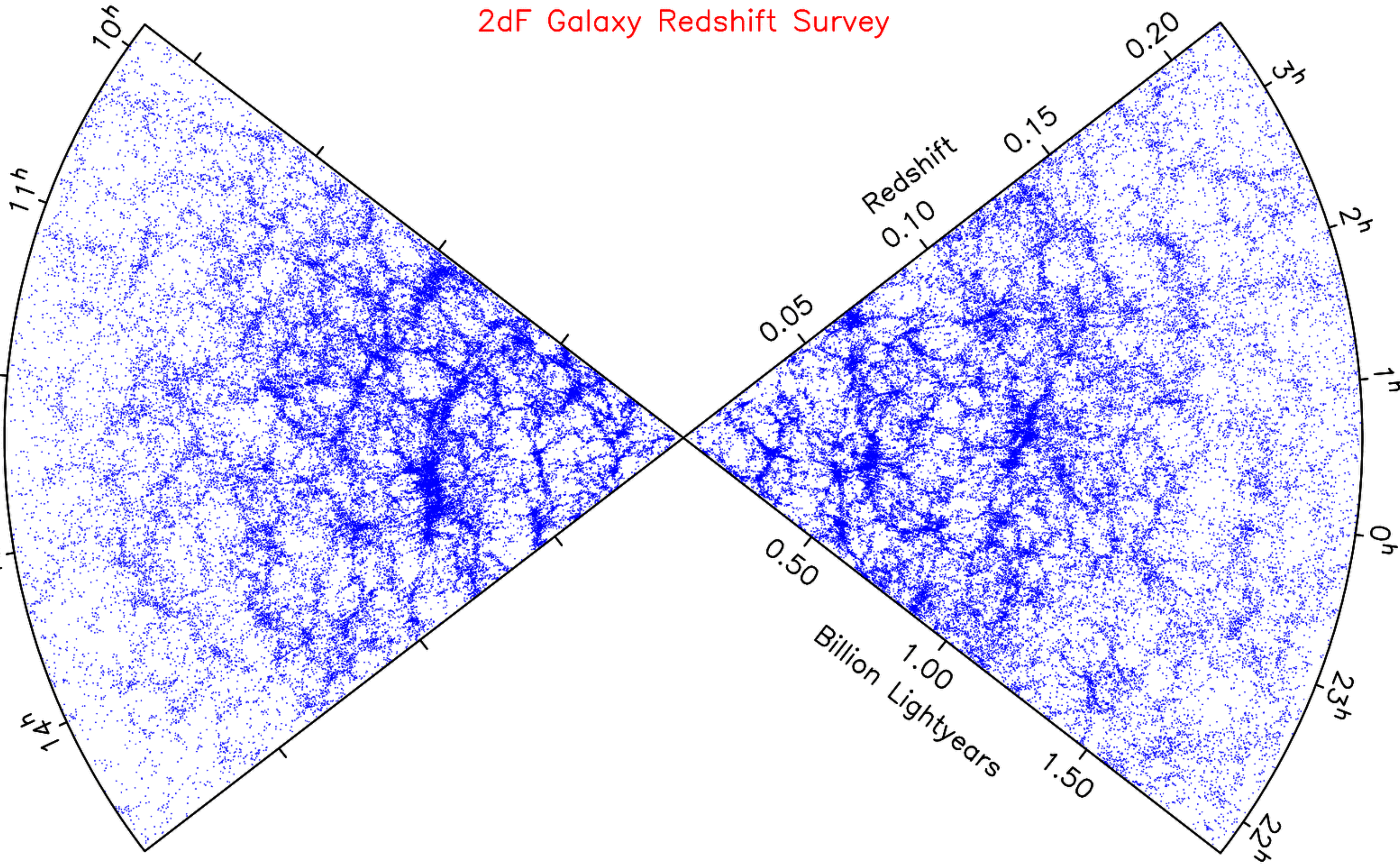
Structure formation and its impact on the CMB

Simon D.M. White
Max Planck Institute for Astrophysics

The *WMAP* of the whole CMB sky

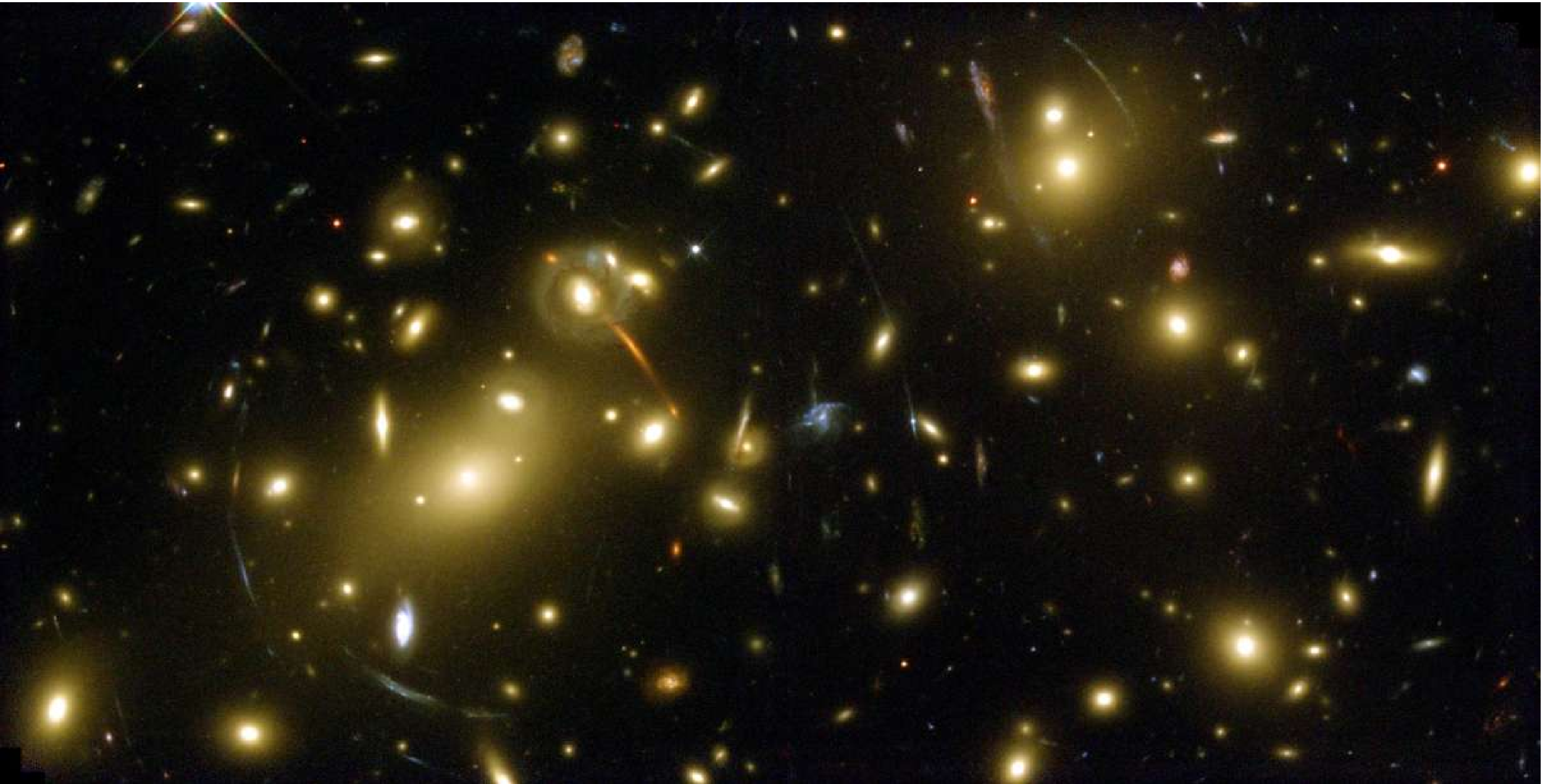


Bennett et al 2003


2dF Galaxy Redshift Survey
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h

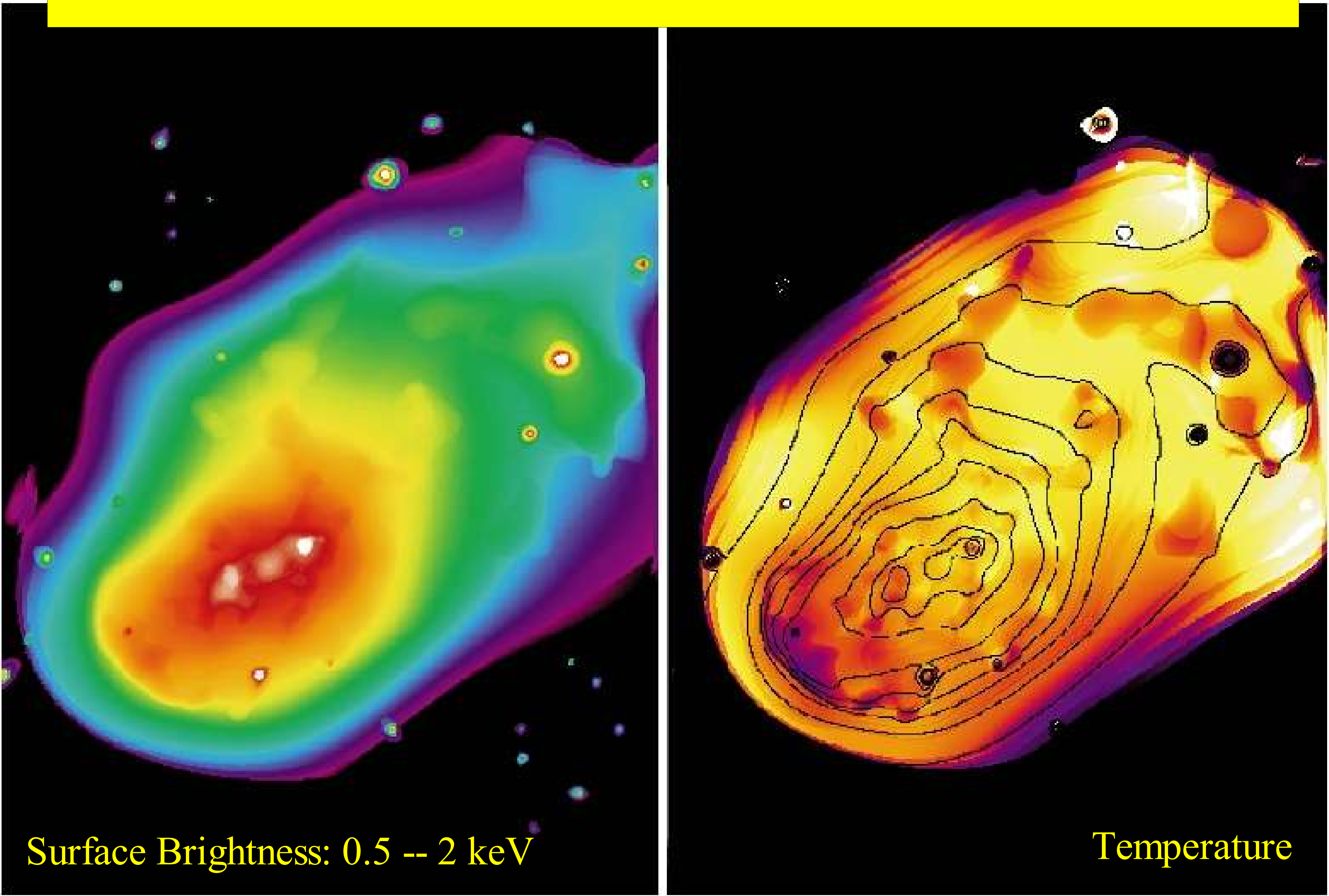
Hubble Space Telescope image of a galaxy cluster

Abell 2218   z=0.17

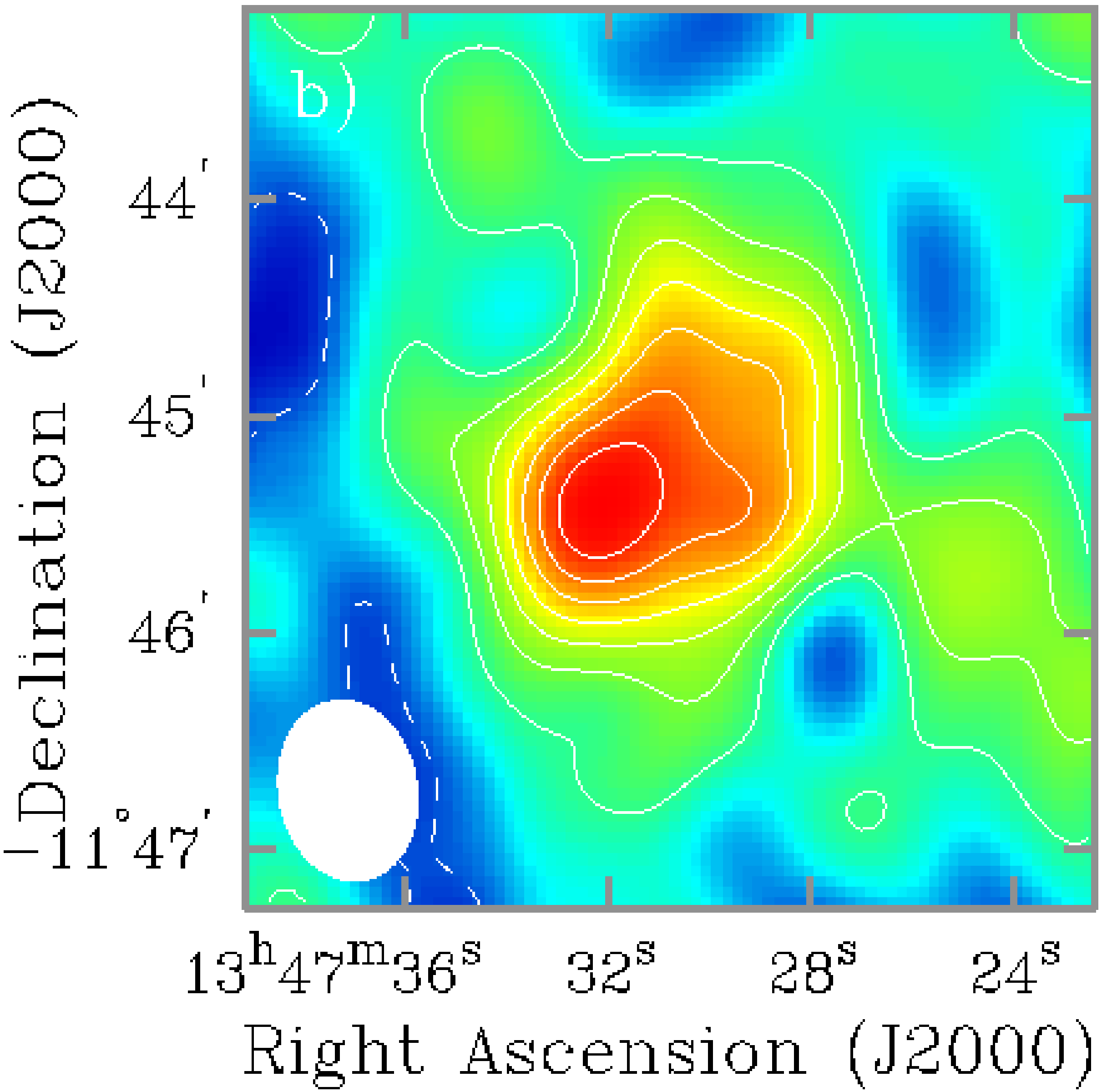



SDSS
M101

Rosat X-ray image of the cluster Abell 3667



Cluster shadows on the microwave background



- Compton upscattering of CMB photons by e^{-} in the hot intracluster gas leaves a deficit in the background

  Sunyaev-Zeldovich effect

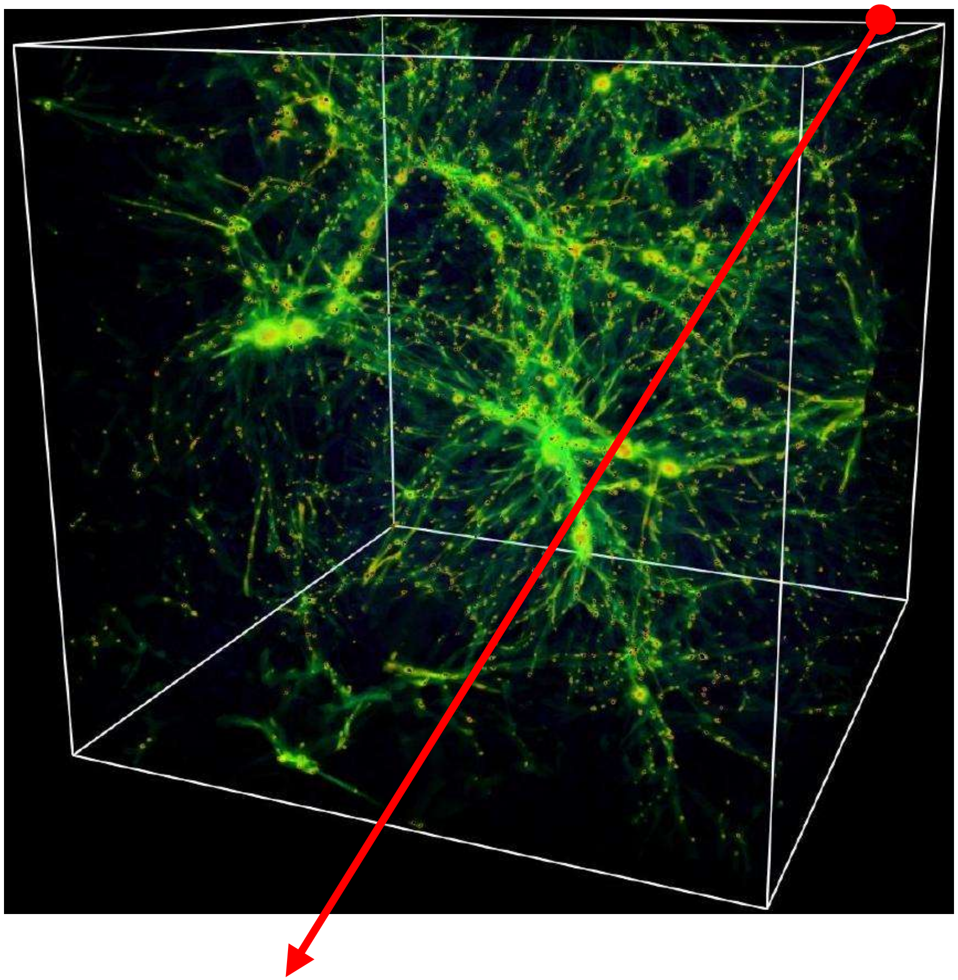
- Map made using the BIMA interferometer

  Carlstrom et al 2001

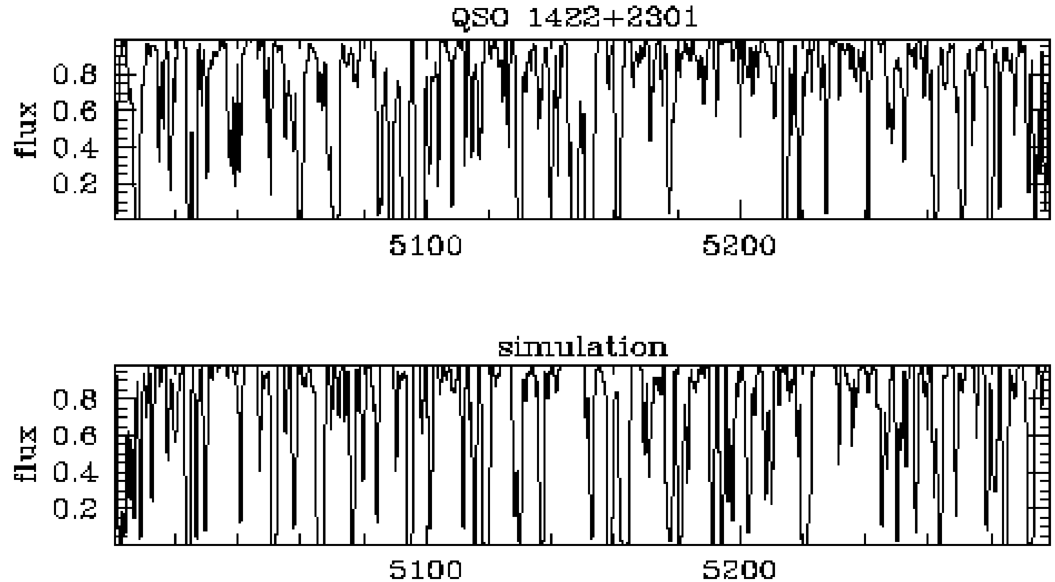
Structure in the intergalactic medium

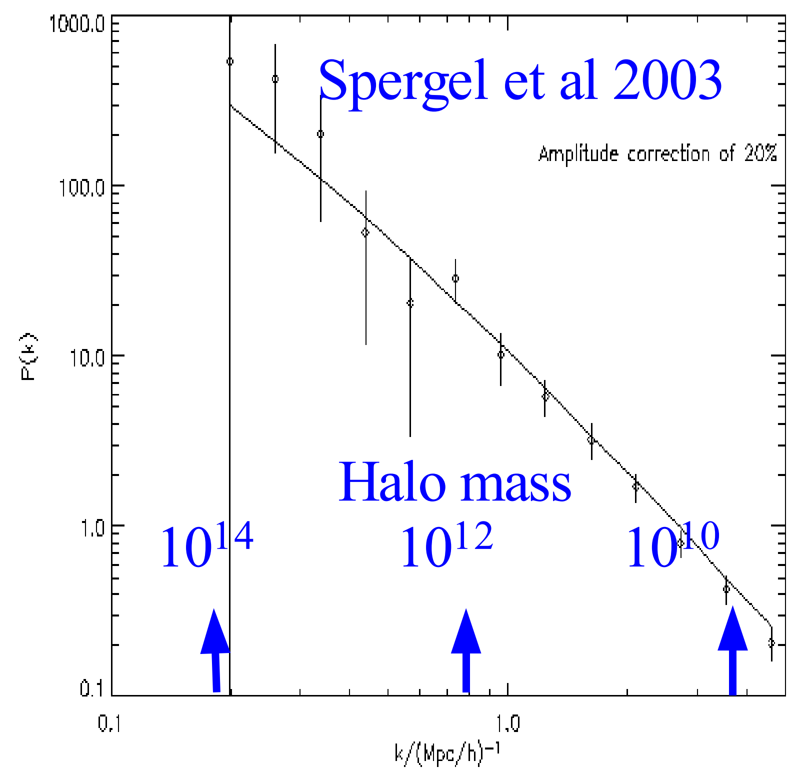
Cen et al 2001

Quasar



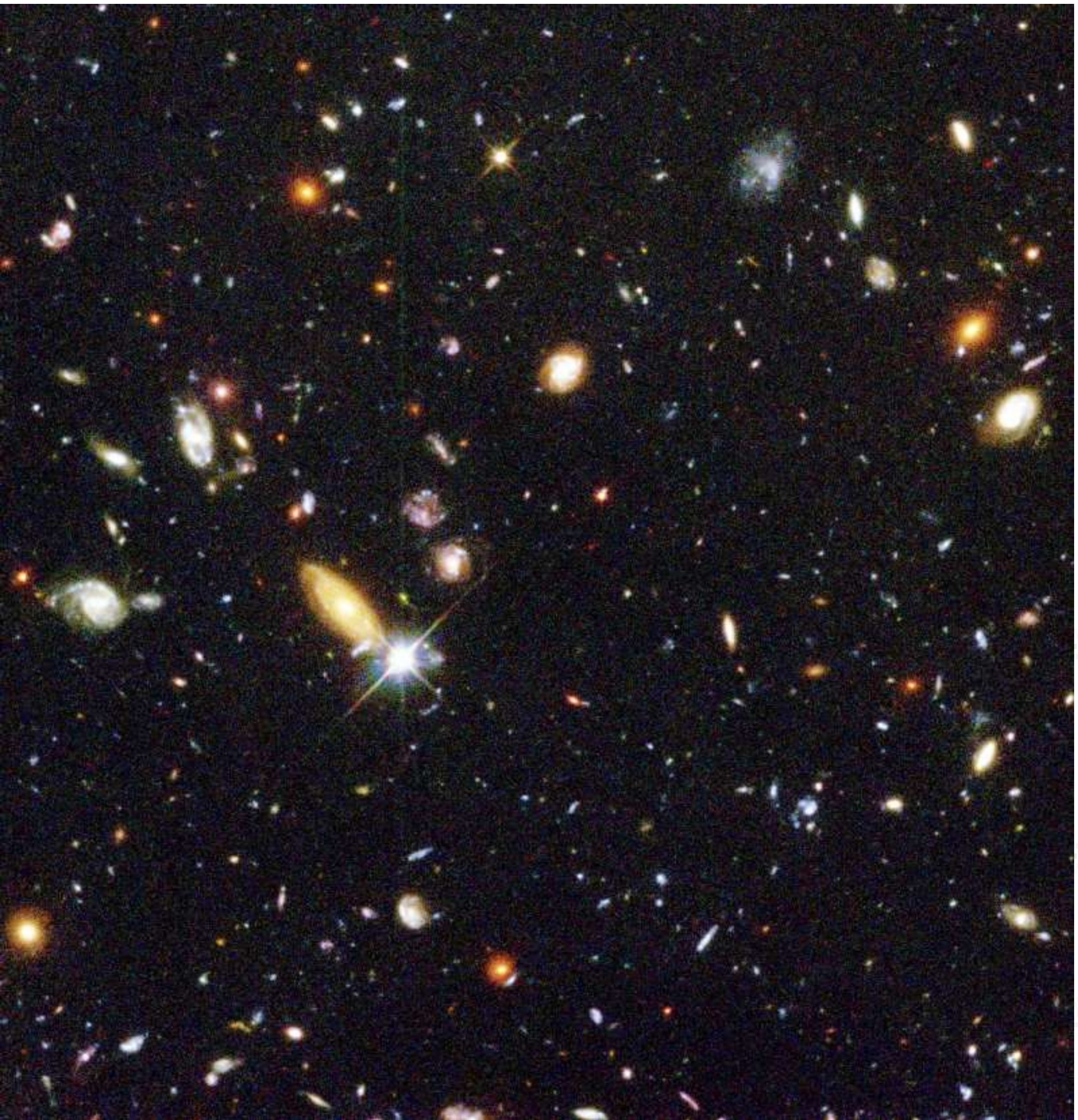
To observer

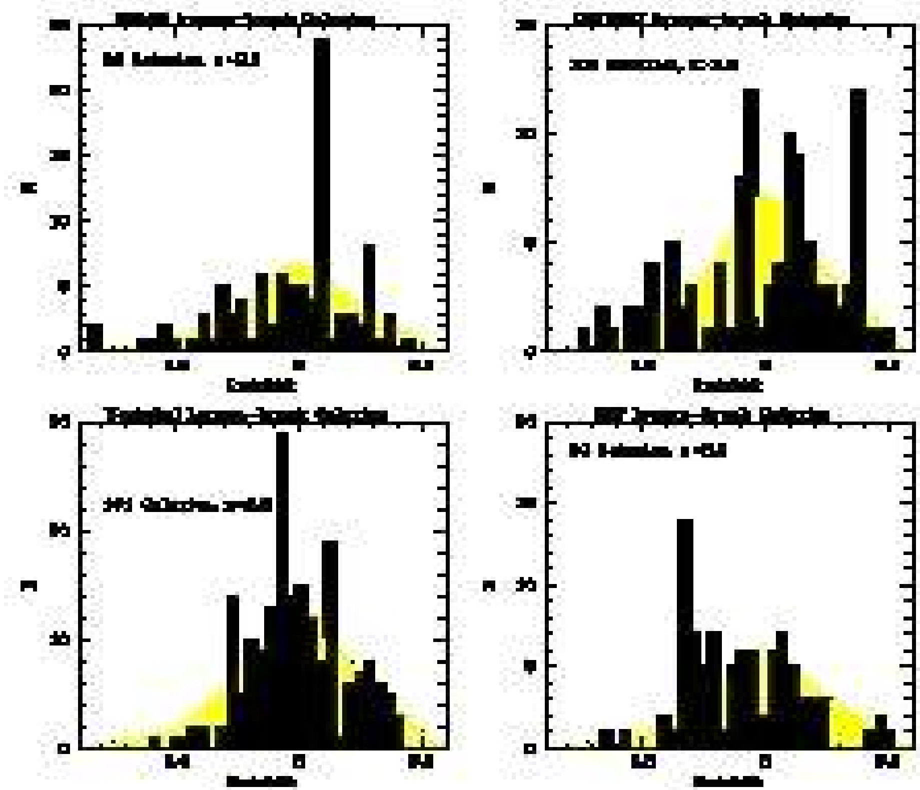


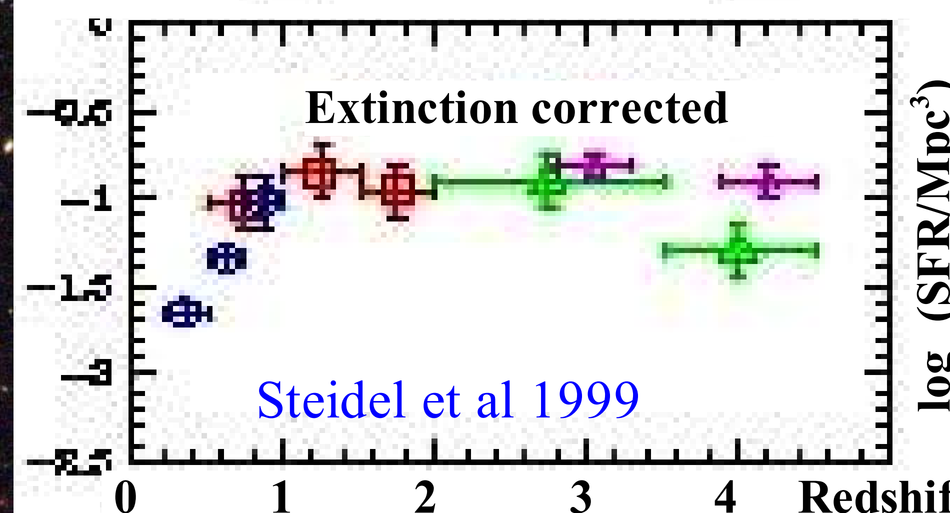


Young galaxies and the cosmic star formation history

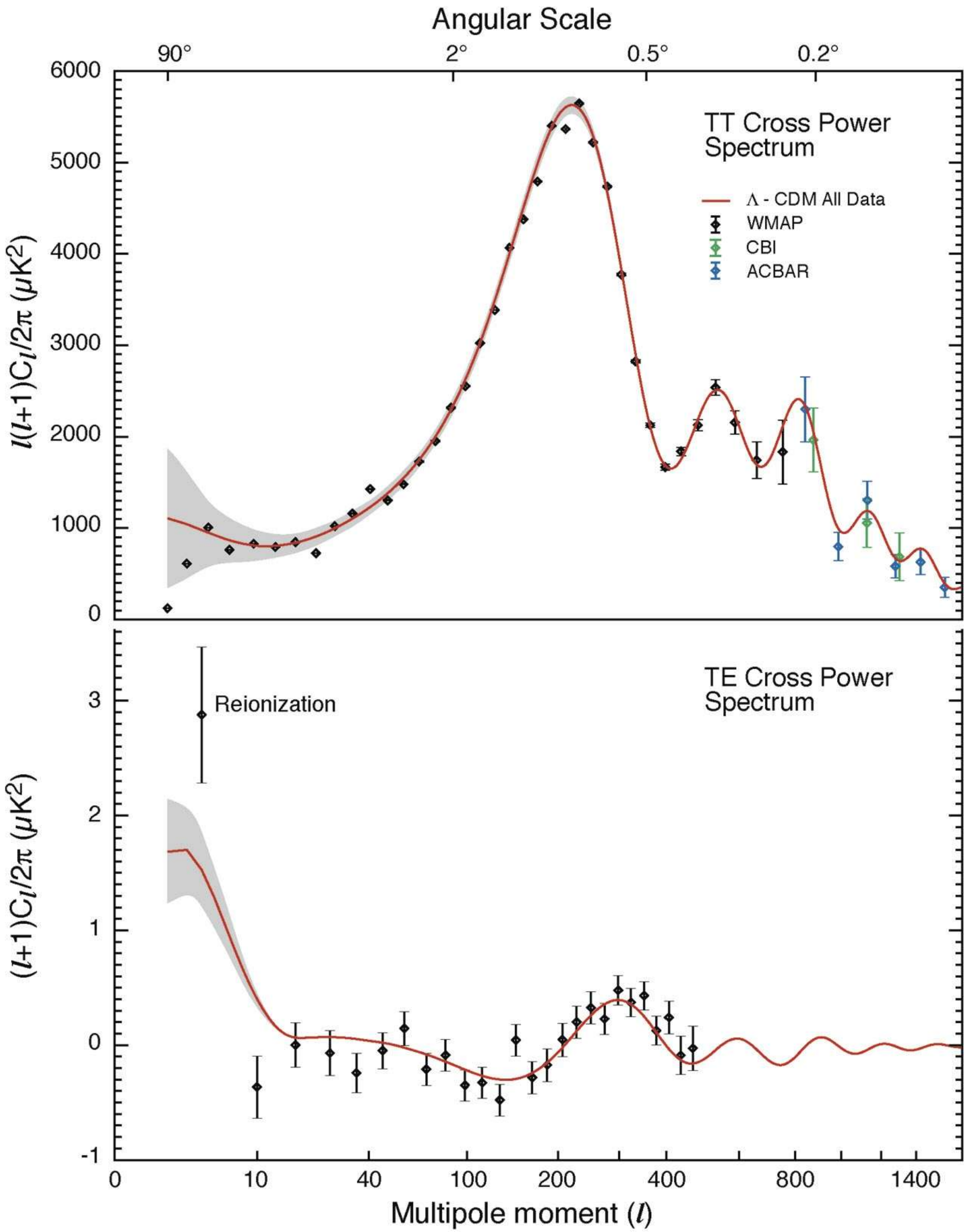
The Hubble Deep Field







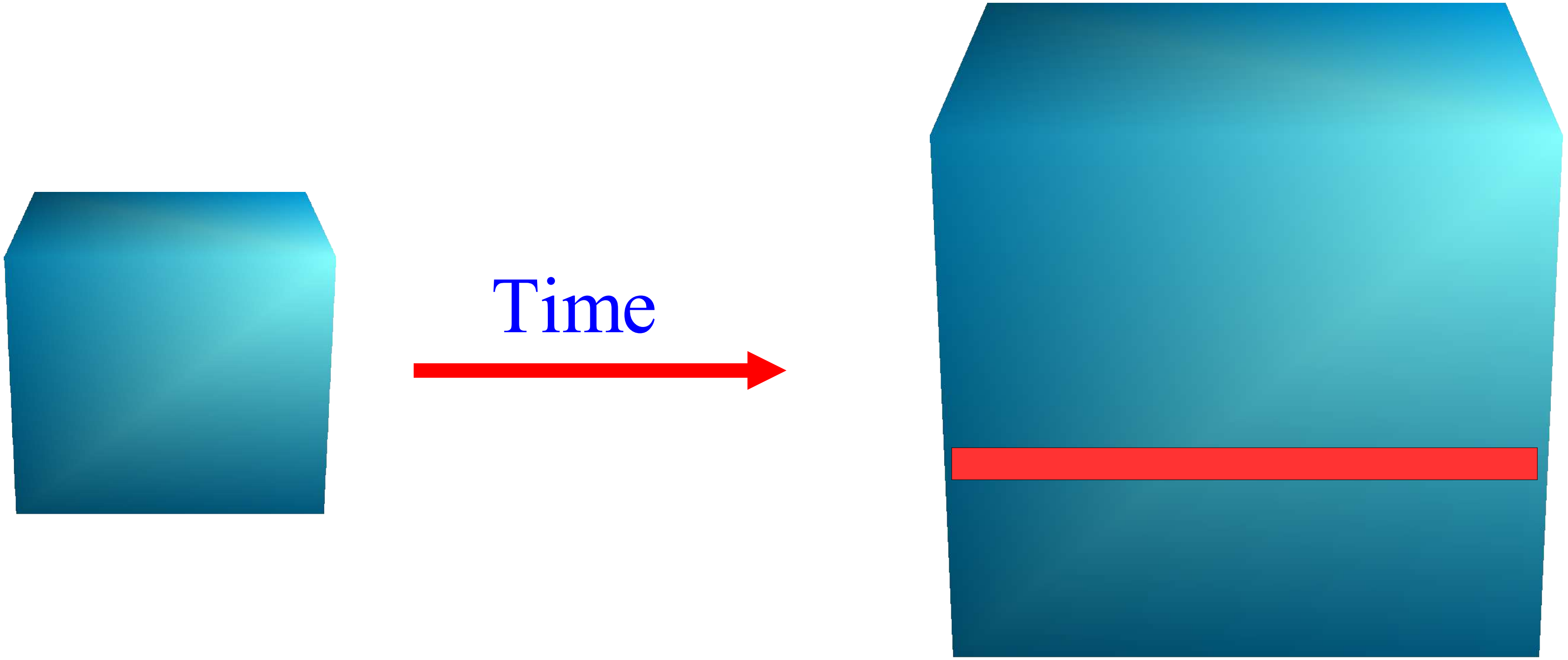
Steidel et al 1999



The Emergence of the Cosmic Initial Conditions

- Temperature-temperature and temperature-E-polariz'n power spectra for *WMAP* and interferometers
- Best flat ΛCDM model has:
  (Bennett et al 2003)
  $t_o = 13.7 \pm 0.2$ Gyr
  $h = 0.71 \pm 0.03$ $\sigma_8 = 0.84 \pm 0.04$
  $\Omega_t = 1.02 \pm 0.02$ $\Omega_m = 0.27 \pm 0.04$
  $\Omega_b = 0.044 \pm 0.004$
  $\tau_e = 0.17 \pm 0.07$
- Parameters in excellent agreement with earlier data

Evolving the Universe in a computer



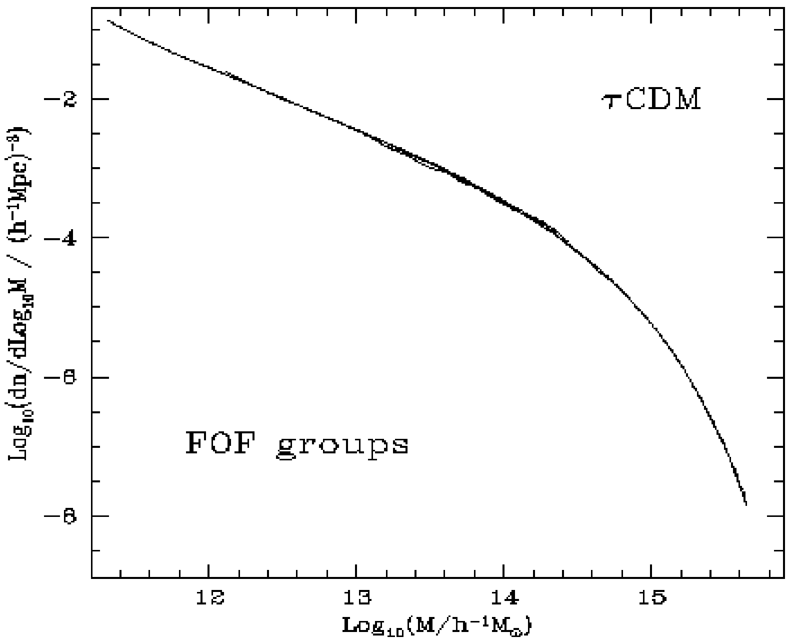
- Follow the matter in an expanding cubic region
- Start 450,000 years after the Big Bang
- Match initial conditions to the observed Microwave Background
- Calculate evolution forward to the present day

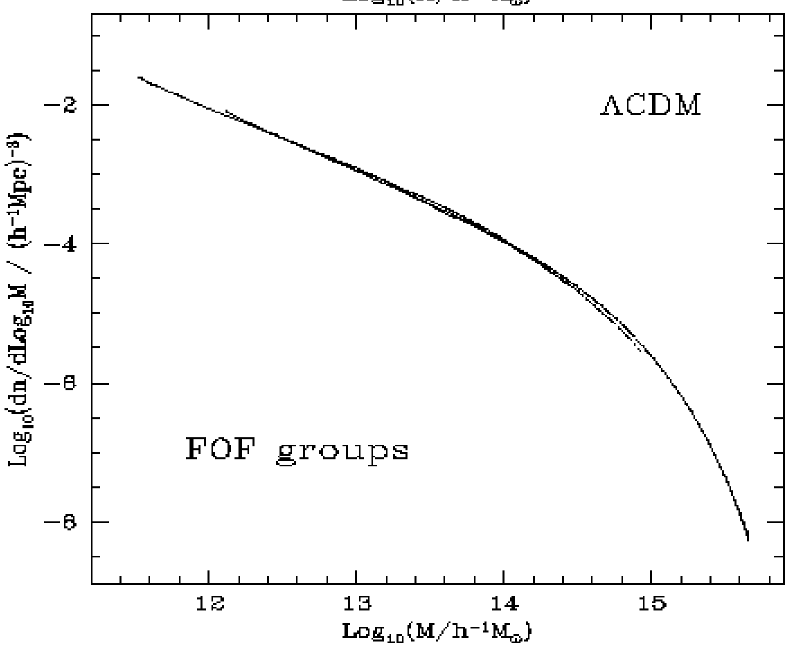
What are simulations good for?

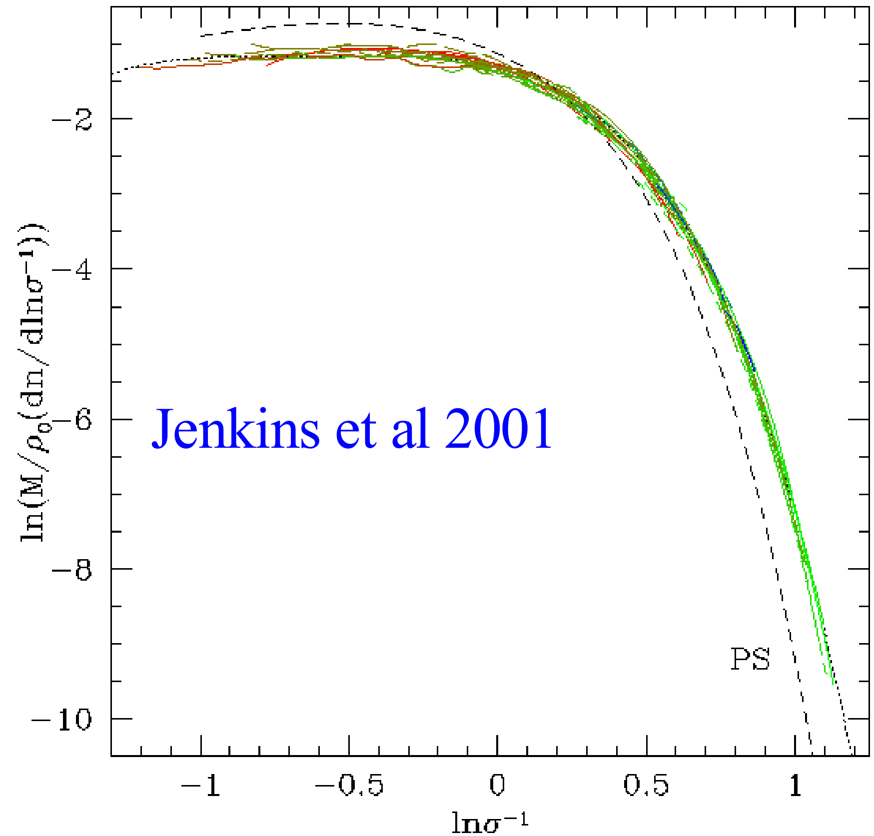
- To gain intuition and to make precise predictions for behaviour in the nonlinear regime
- To model observational effects
  -- selection bias
  -- visual appearance
  -- effects of observational errors
  -- "cosmic variance"
- To extrapolate into (as yet) unobserved regimes
  -- smaller scales
  -- higher redshifts
- To understand links between high and low z objects

Utility of results is usually limited by accuracy with which observables are modelled (M_B, B-V, τ_{HI}, L_X, T_X, ΔT_{SZ}, κ, γ,..) .

Are simulations accurate enough? Halo abundance as a function of mass







Results from simulations of different scale and resolution *can* agree at the few percent level (also for power spectra, correlation functions...)

Abundance of halos can be predicted to within about 20% from the linear power spectrum.

Requirements for 'precision' results

- Accurate initial conditions
  --- artifact-free uniform particle load
  --- accurate and accurately imposed initial PS
  --- correct velocities (thermal and bulk)

- Large enough simulated volume
  --- minimal effects from sparse Fourier sampling
  --- small cosmic variance in relevant statistics

- Accurate time integration
  --- good linear growth rates
  --- proper treatment of highly nonlinear regions

- Proper testing of effects of resolution limitations
  --- softening of gravitional interaction
  --- discreteness effects (relaxation, sampling noise)

Gravitational effects of structure on the CMB

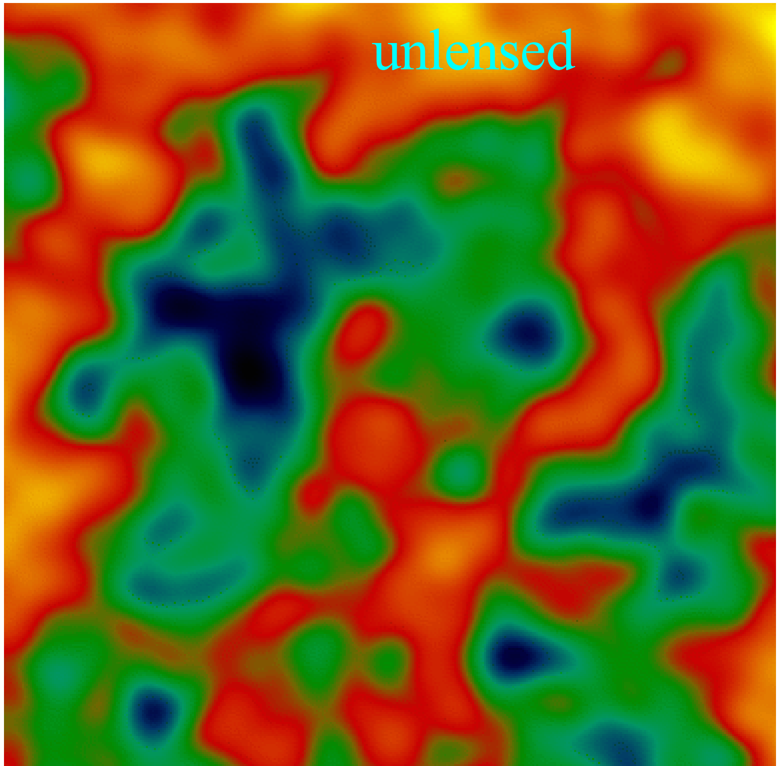
- The integrated Sachs-Wolfe effect
  --- vanishes in an Einstein de Sitter universe
  --- affects only the lowest multipole modes
  --- can be isolated by cross-correlation with observed large-sky-coverage samples of galaxies/clusters

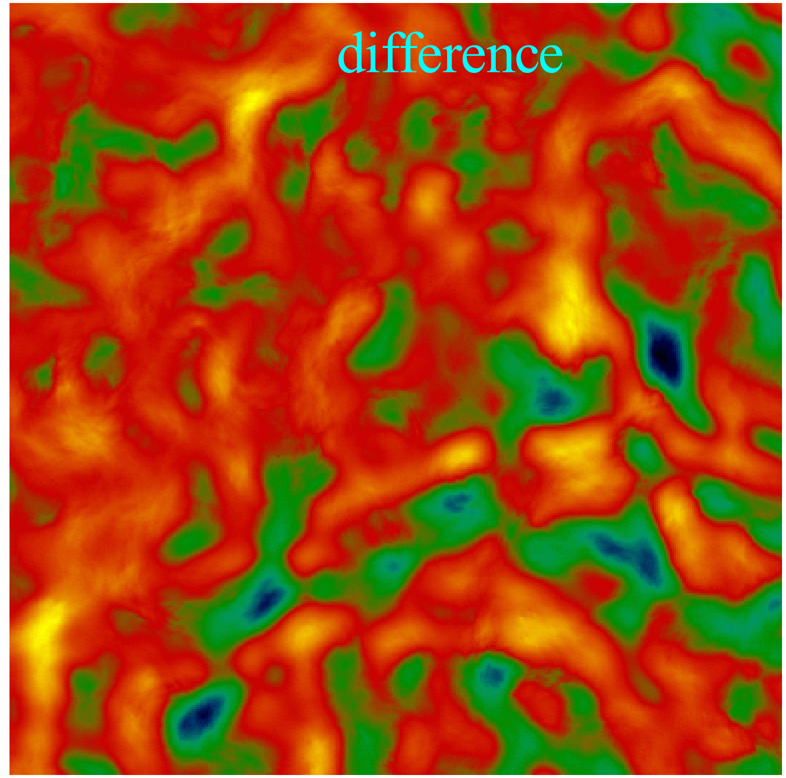
- The Rees-Sciama effect
  --- differential gravitational redshift due to passage through a time-dependent potential (e.g. a collapsing or moving cluster)

- Gravitational lensing
  --- conserves ΔT but distorts pattern
  --- smooths the power spectrum
  --- introduces non-gaussian features
  --- convergence map recoverable from the ΔT map

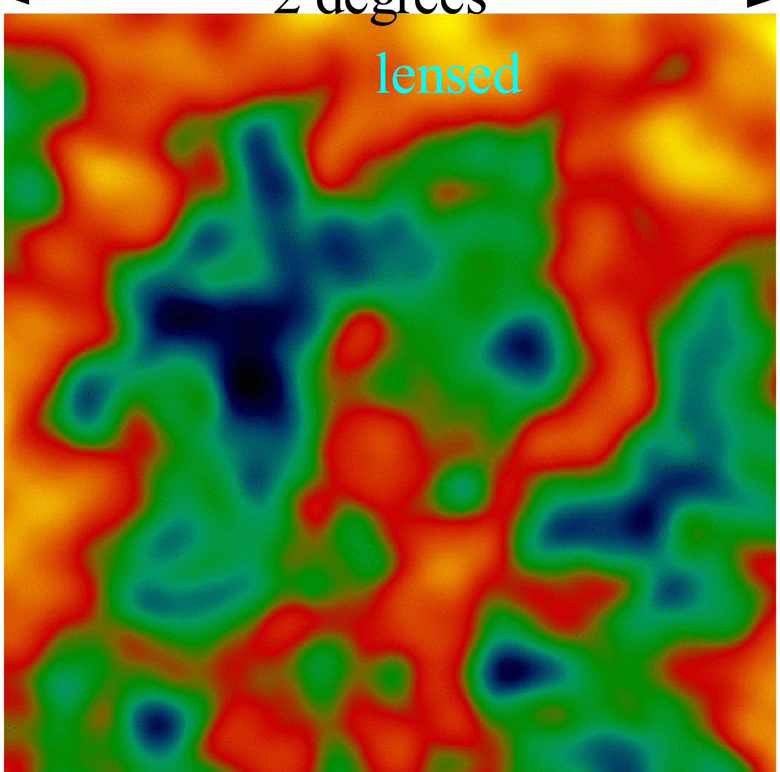
Lensing of the CMB

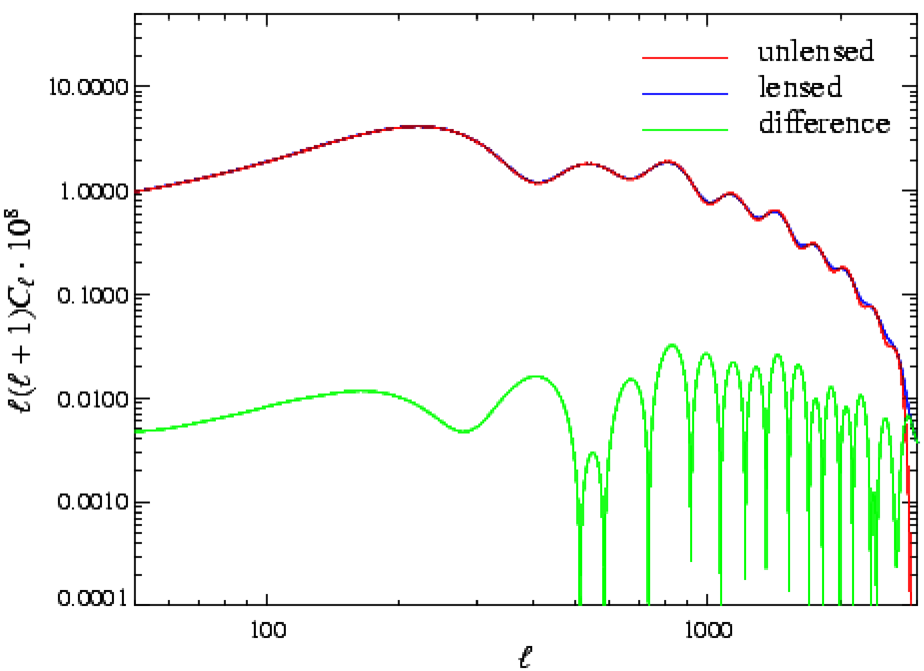
Pfrommer 2002
(Masters thesis)





2 degrees



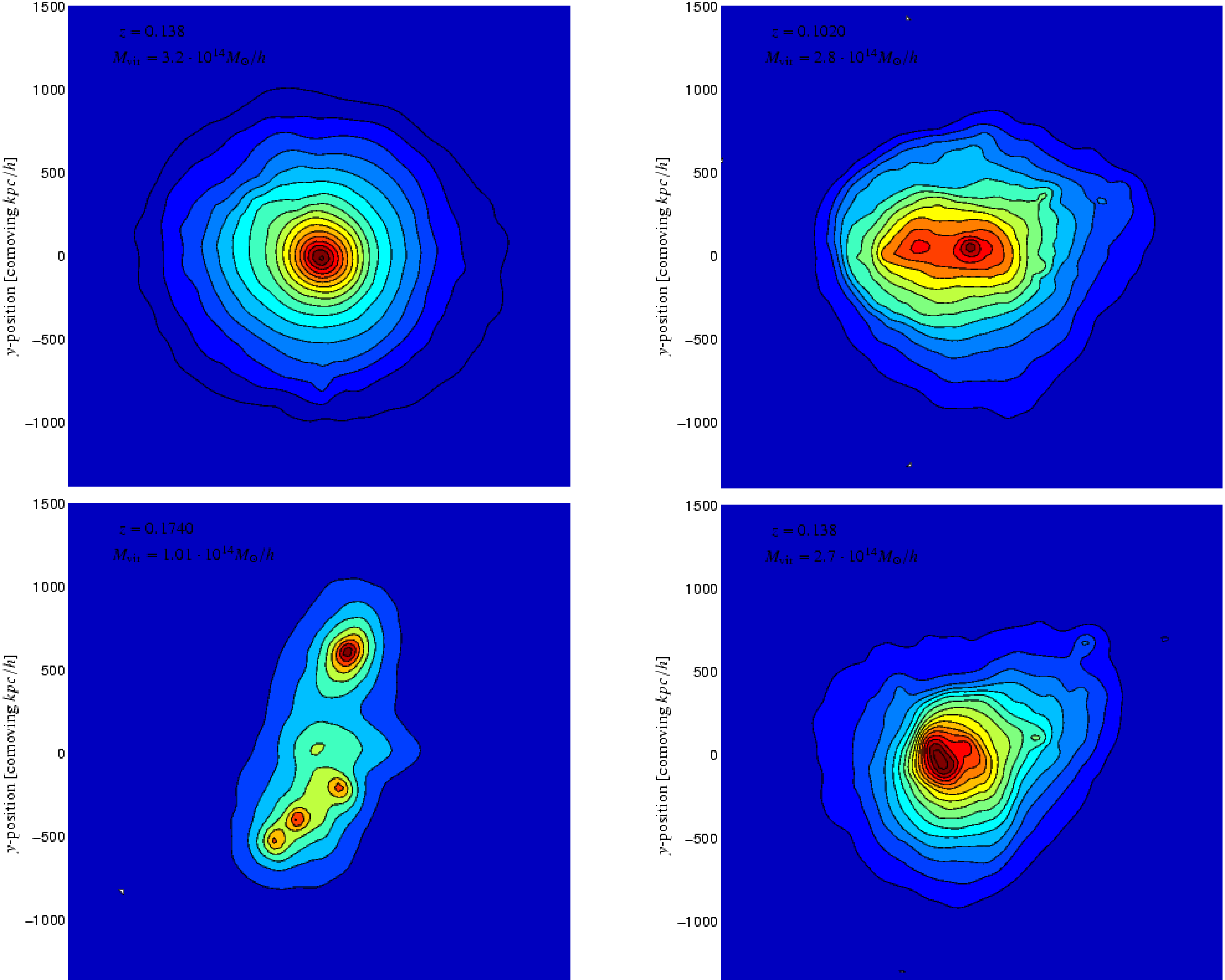


Baryonic structure imprints on the CMB

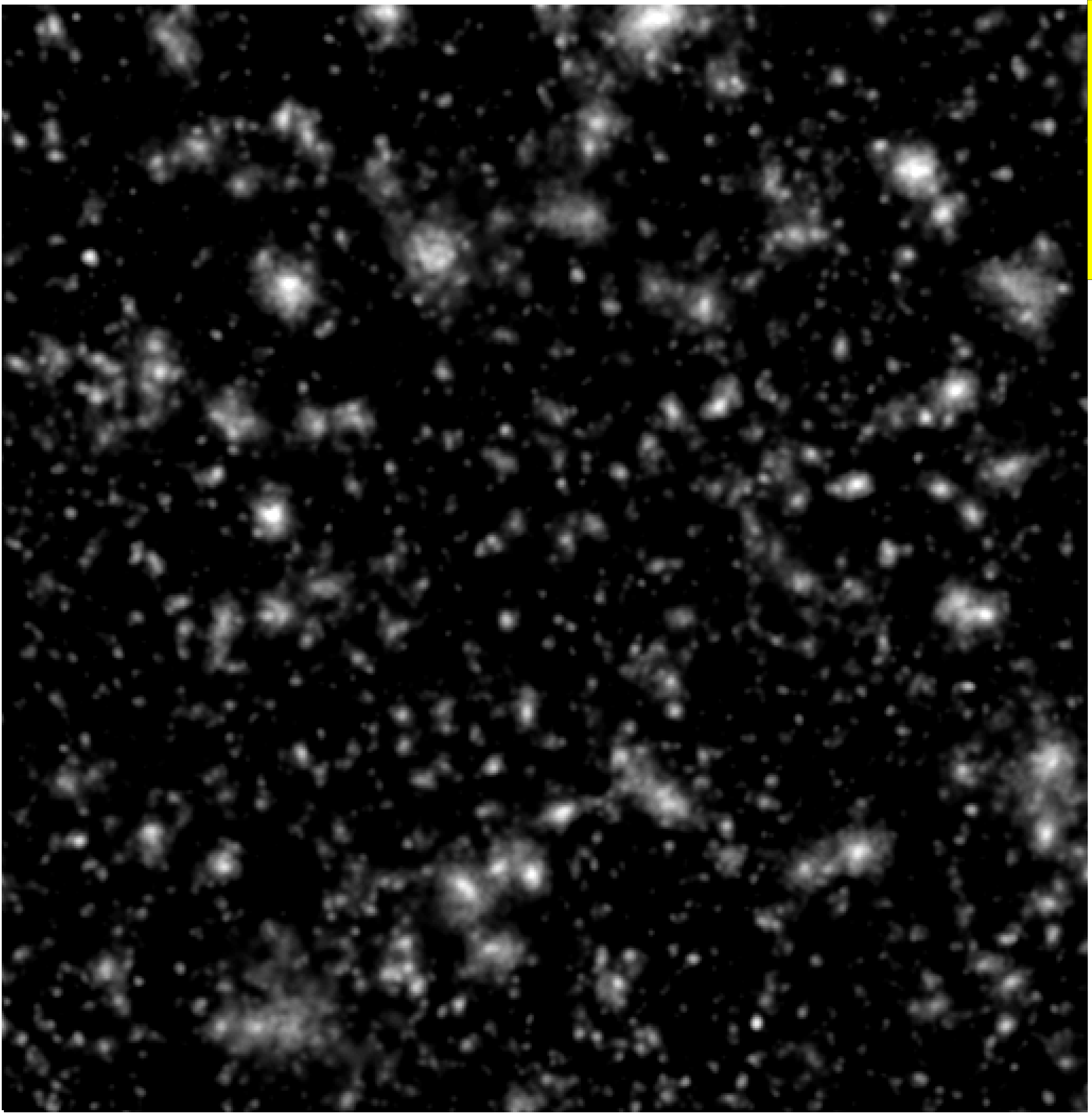
- Thermal SZ effect from galaxy clusters/LSS
  - --- surface brightness $\propto$ line integral of electron pressure
  - --- frequency variation *almost* independent of gas temp.
  - --- no effect at 217 Ghz

- Kinematic SZ effect
  - --- surface brightness $\propto$ line integral of electron momentum
  - --- frequency variation corresponds to variation in T
  - --- typical values smaller than thermal SZ/primary fluct'ns
  - --- significant effects at reionisation

- Compton scattering effects from reionisation
  - --- principal effect is washing out of high l structure
  - --- strength $\propto$ line integral of Thompson optical depth
  - --- WMAP τ requires early reionisation



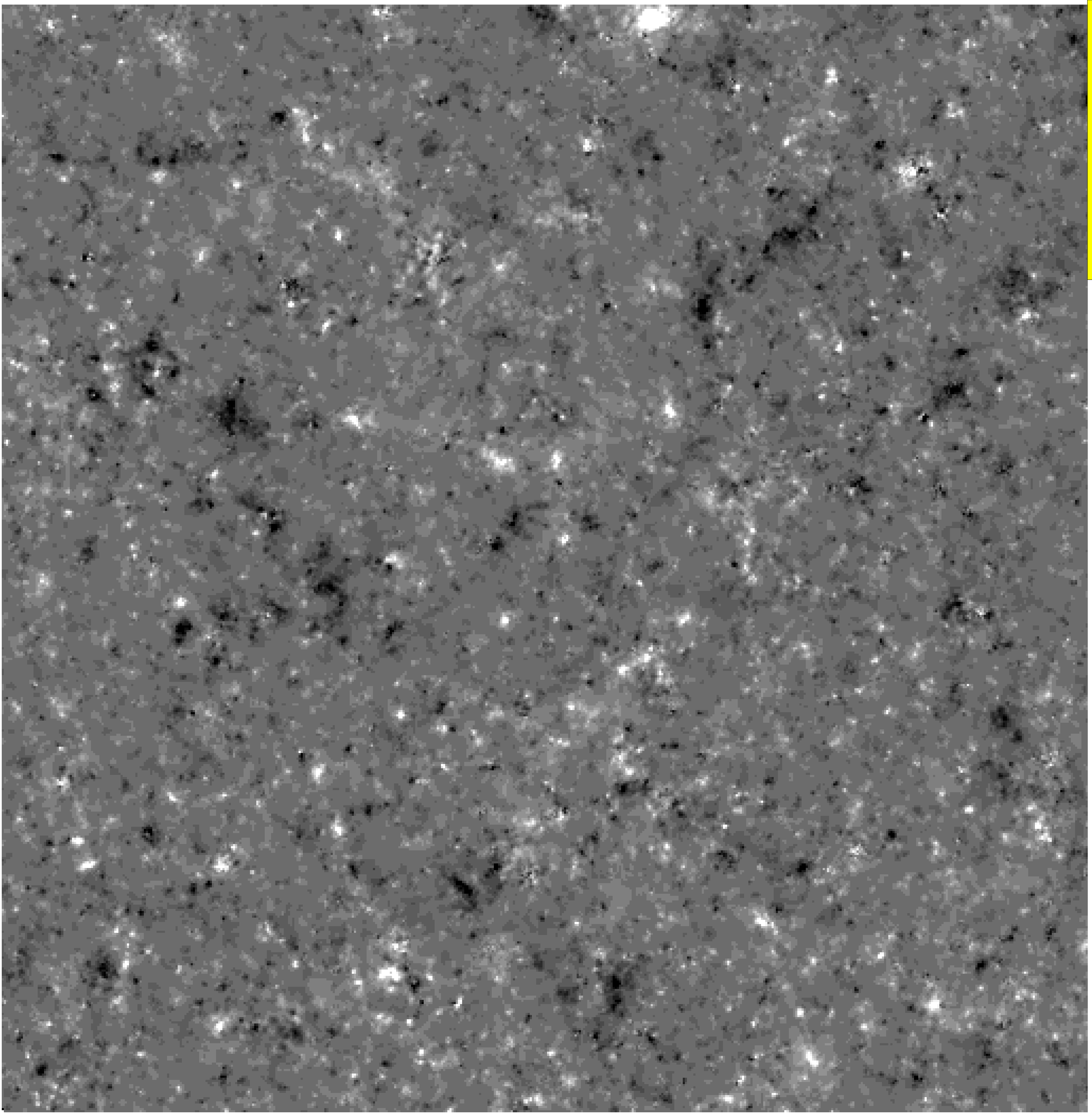
z = 0.138
$M_{\rm vir} = 3.2 \cdot 10^{14} M_\odot/h$
z = 0.1020
$M_{\rm vir} = 2.8 \cdot 10^{14} M_\odot/h$
z = 0.1740
$M_{\rm vir} = 1.01 \cdot 10^{14} M_\odot/h$
z = 0.138
$M_{\rm vir} = 2.7 \cdot 10^{14} M_\odot/h$
y-position [comoving kpc/h]
1500
1000
500
0
−500
−1000



Thermal SZ effect for a 1 degree patch

Yoshida, priv comm

Constructed from past light-cone back to z ~ 5

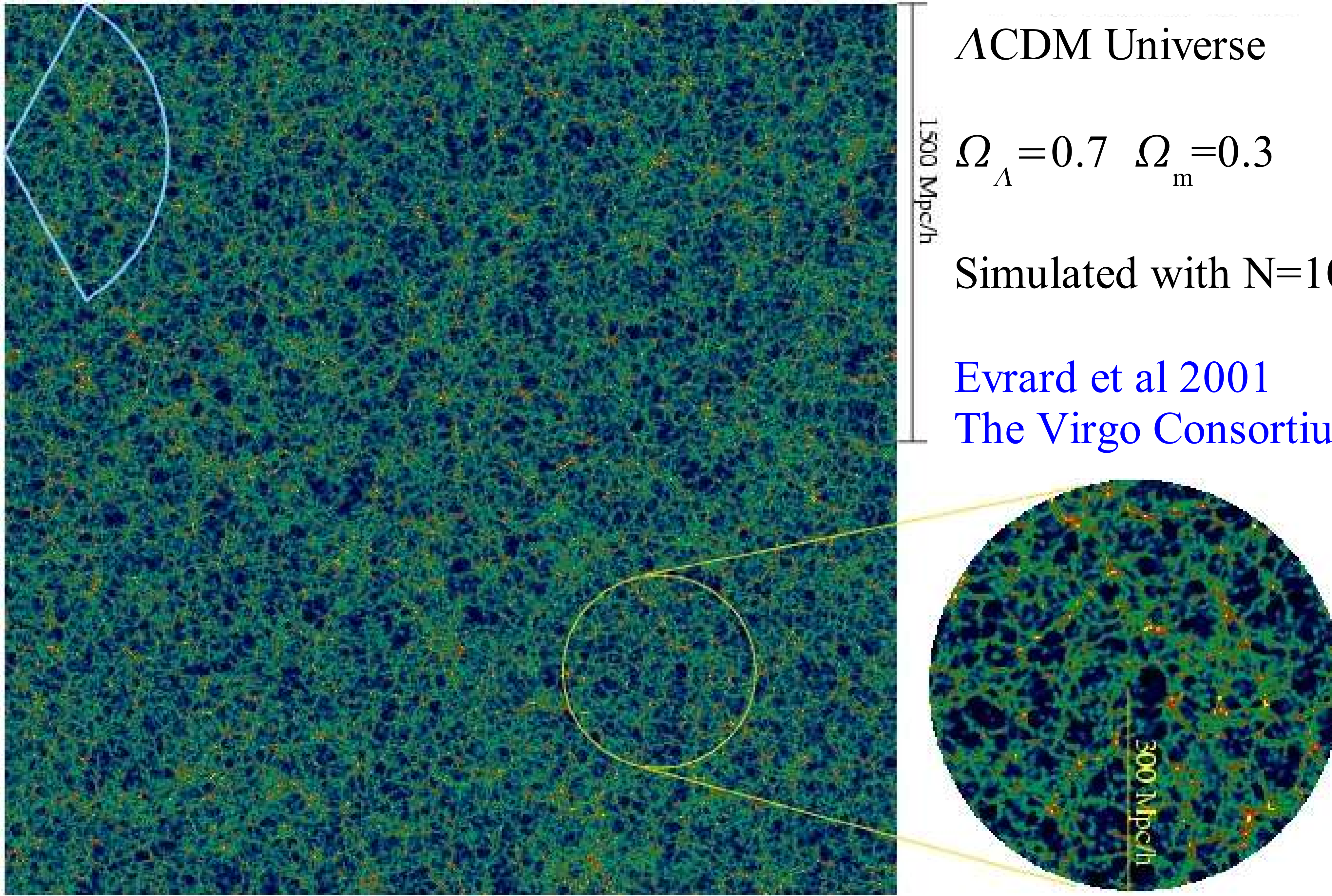


Kinetic SZ effect for a 1 degree patch

Yoshida, priv comm

Constructed from past light-cone back to z ~ 5

Simulating the whole visible Universe



ΛCDM Universe

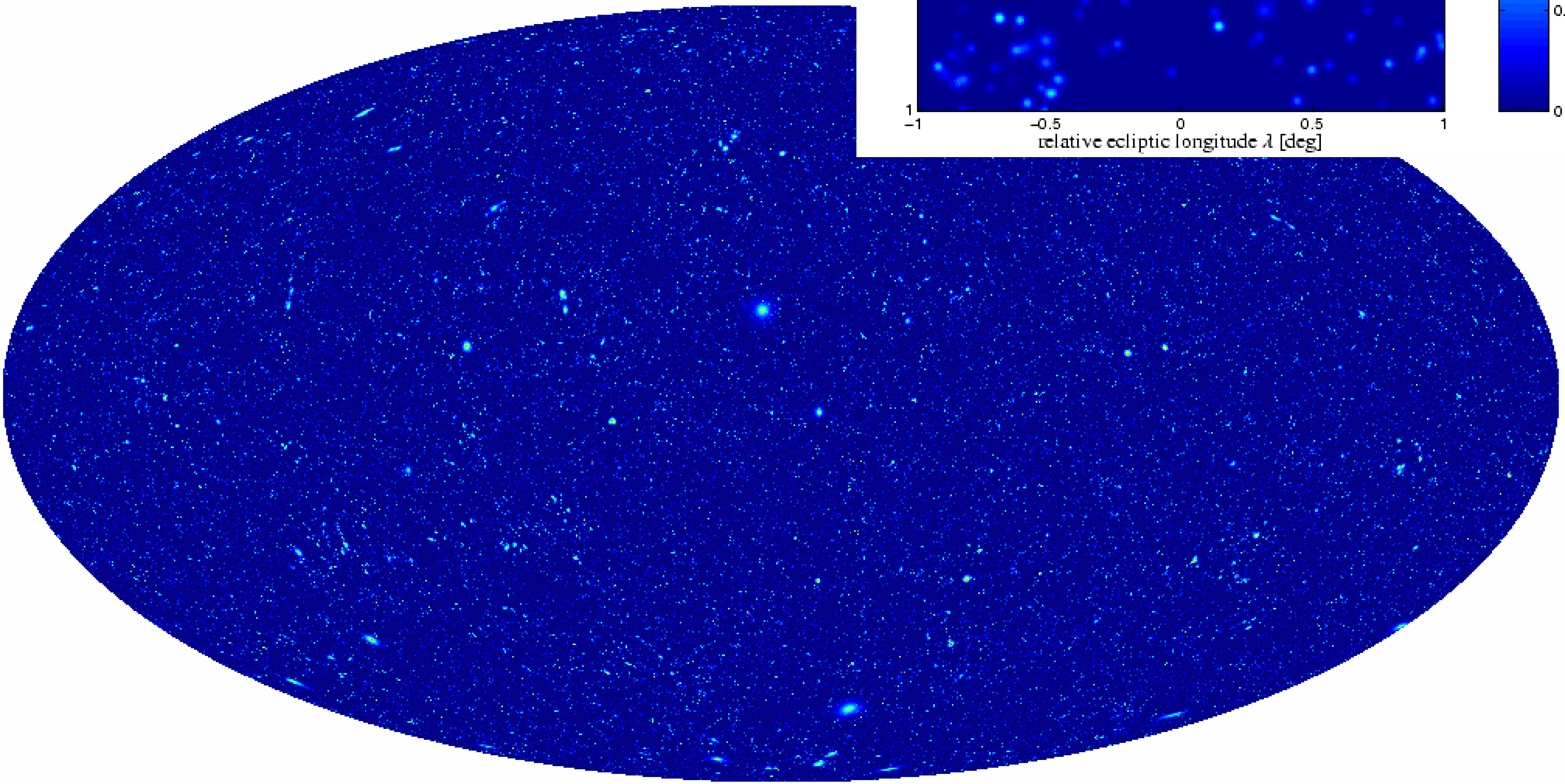
$\Omega_\Lambda=0.7 \quad \Omega_m=0.3$

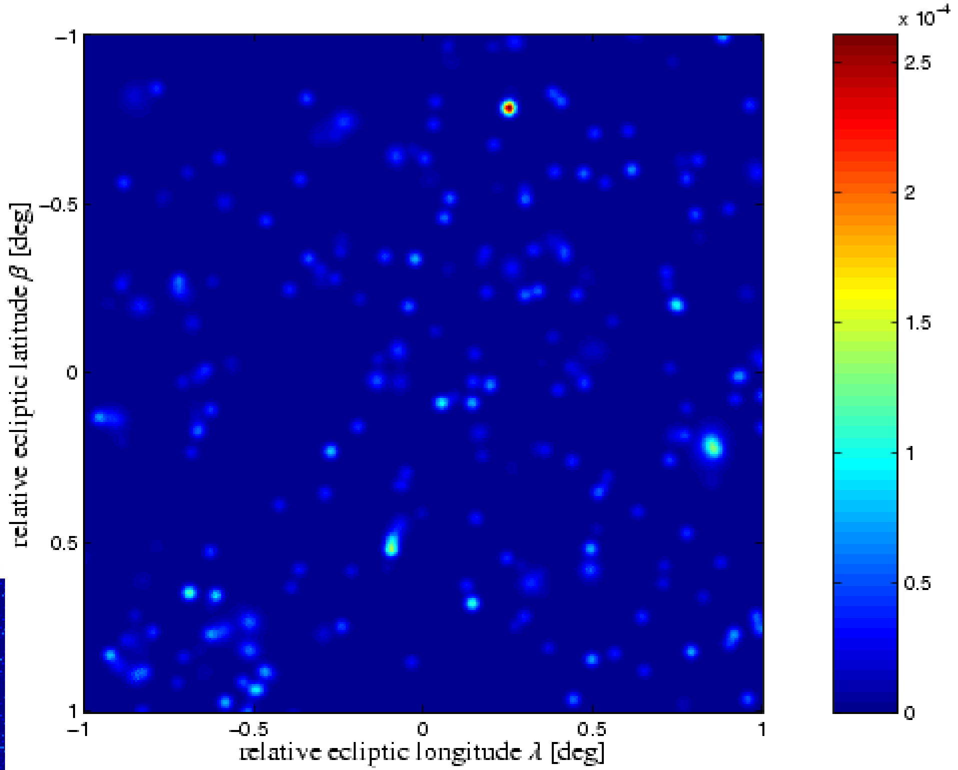
Simulated with $N=10^9$

Evrard et al 2001
The Virgo Consortium

Thermal SZ map from the Hubble volume simulation + high resolution simulations

Pfrommer, Schaefer
Planck Simulation Pipeline





Kinetic SZ map from the Hubble volume simulation + high resolution simulations

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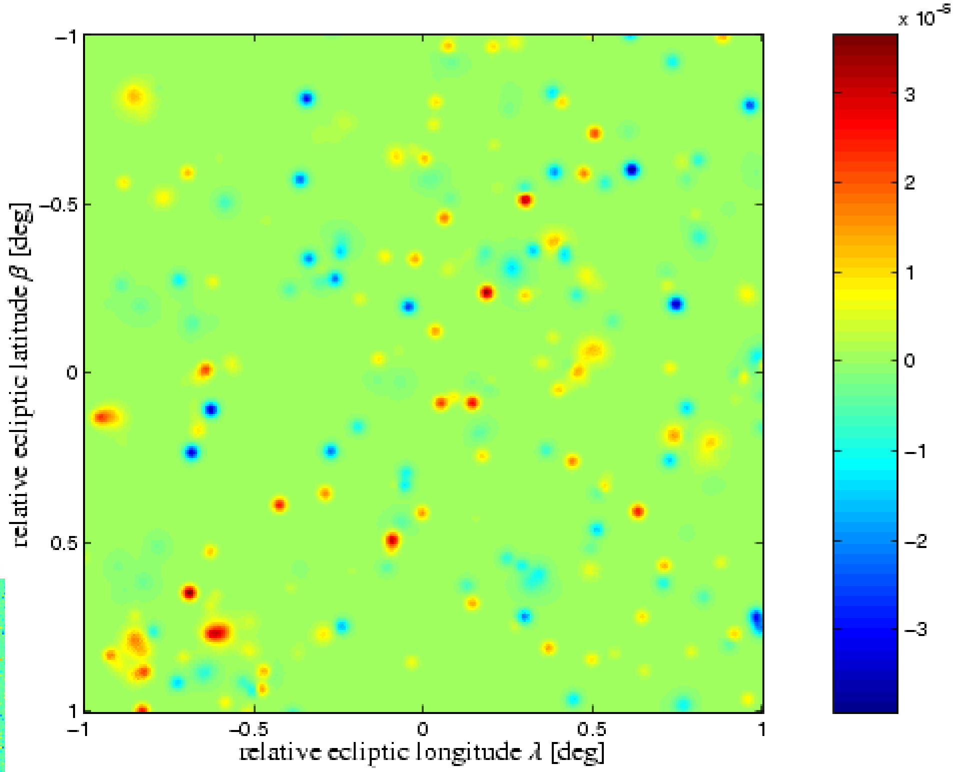
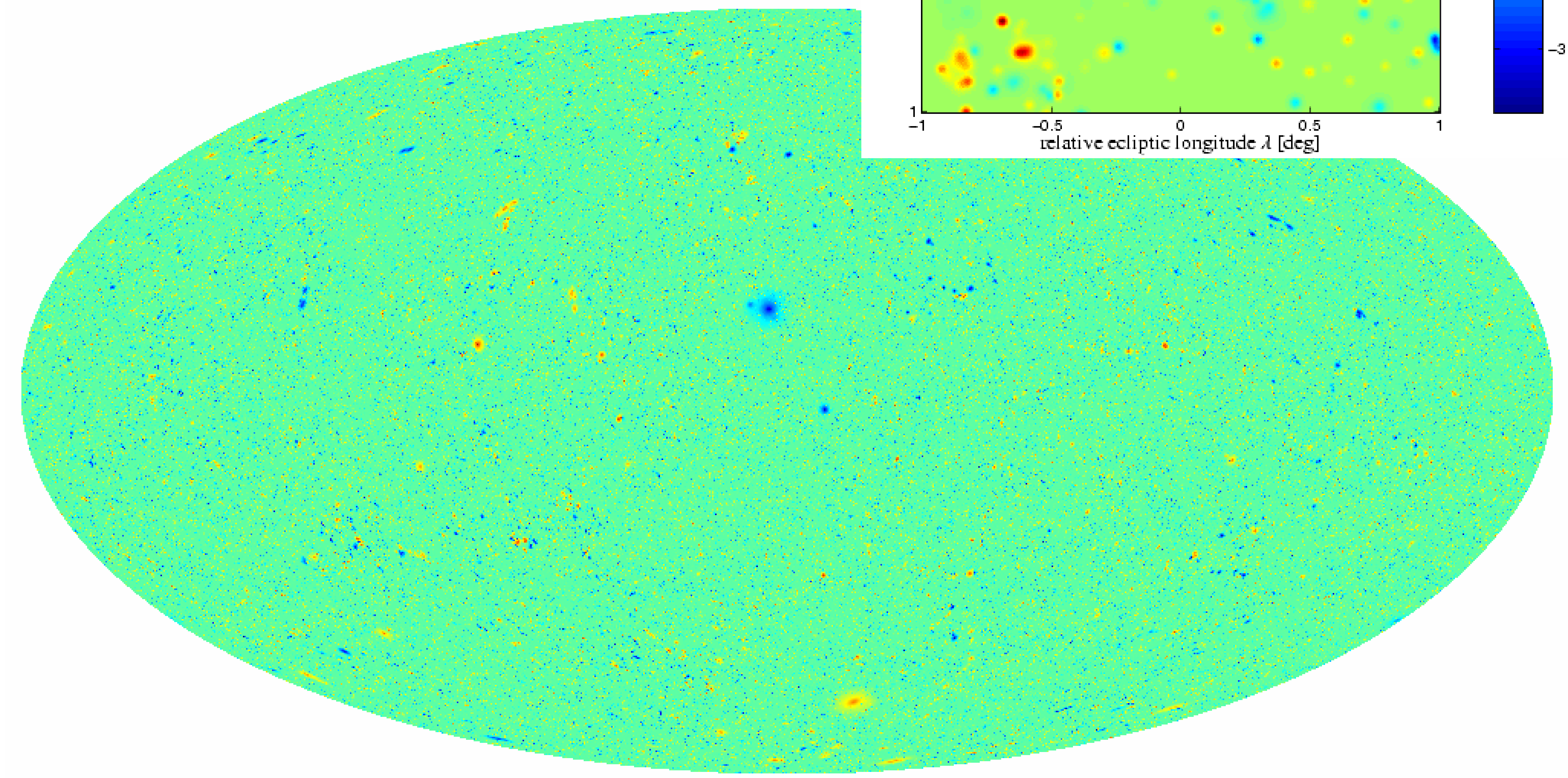
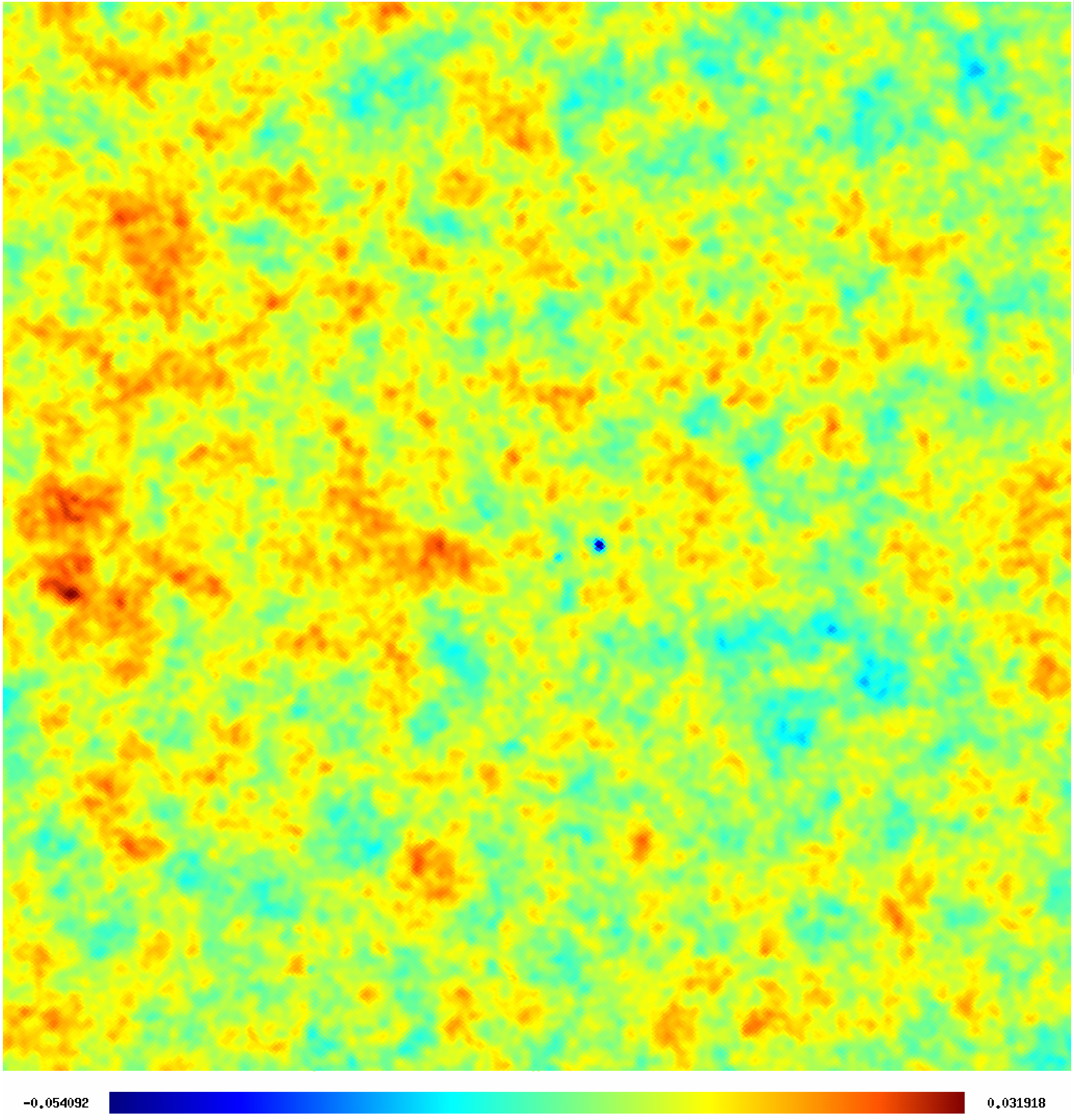






20 degree patch from the Planck simulation pipe-line with central massive cluster

Schaefer & Pfrommer

143 GHz

Foregrounds included

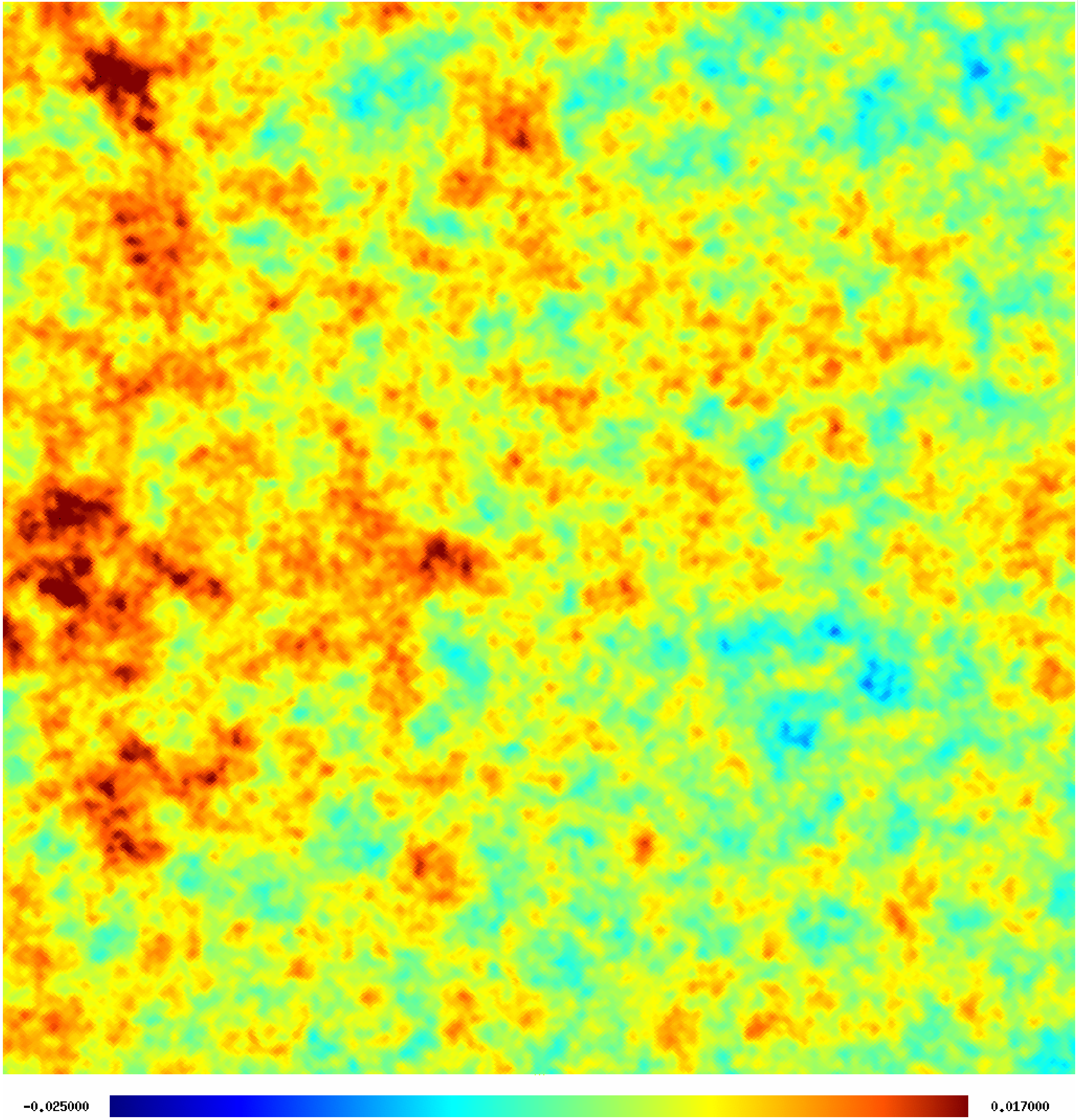
-- synchrotron

-- free-free

-- dust

-- CO

No noise or planets



20 degree patch from the Planck simulation pipeline with central massive cluster

Schaefer & Pfrommer

217 GHz

Foregrounds included

-- synchrotron

-- free-free

-- dust

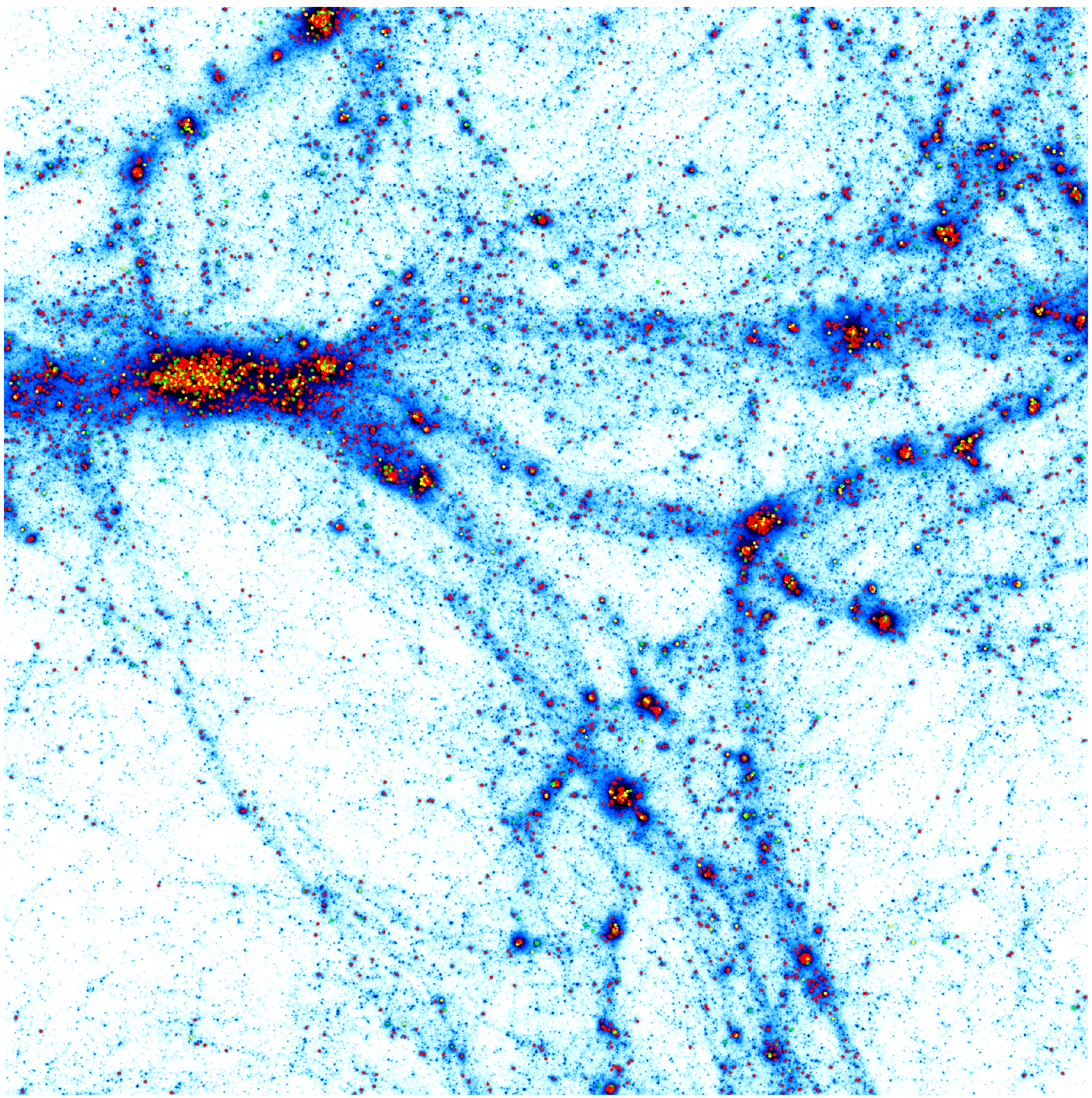
-- CO

No noise or planets

Field vs cluster evolution of the galaxy population

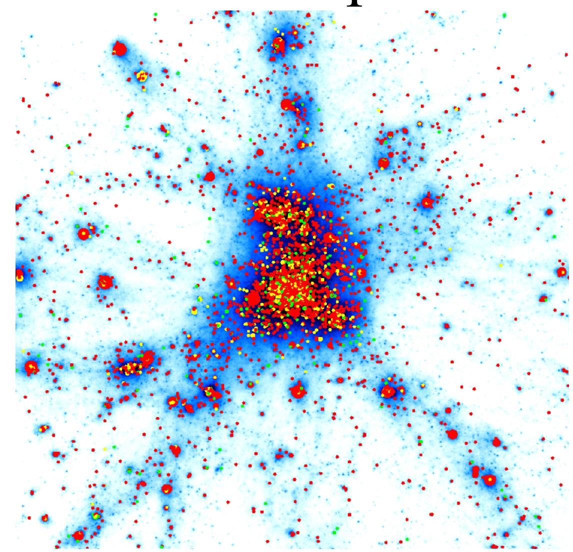
Stoehr 2003 (PhD thesis)

40 h^{-1}Mpc



$\rho_* = 0.9 \langle \rho_0 \rangle$

20 h^{-1}Mpc



$\rho_* = 3.5 \langle \rho_0 \rangle$

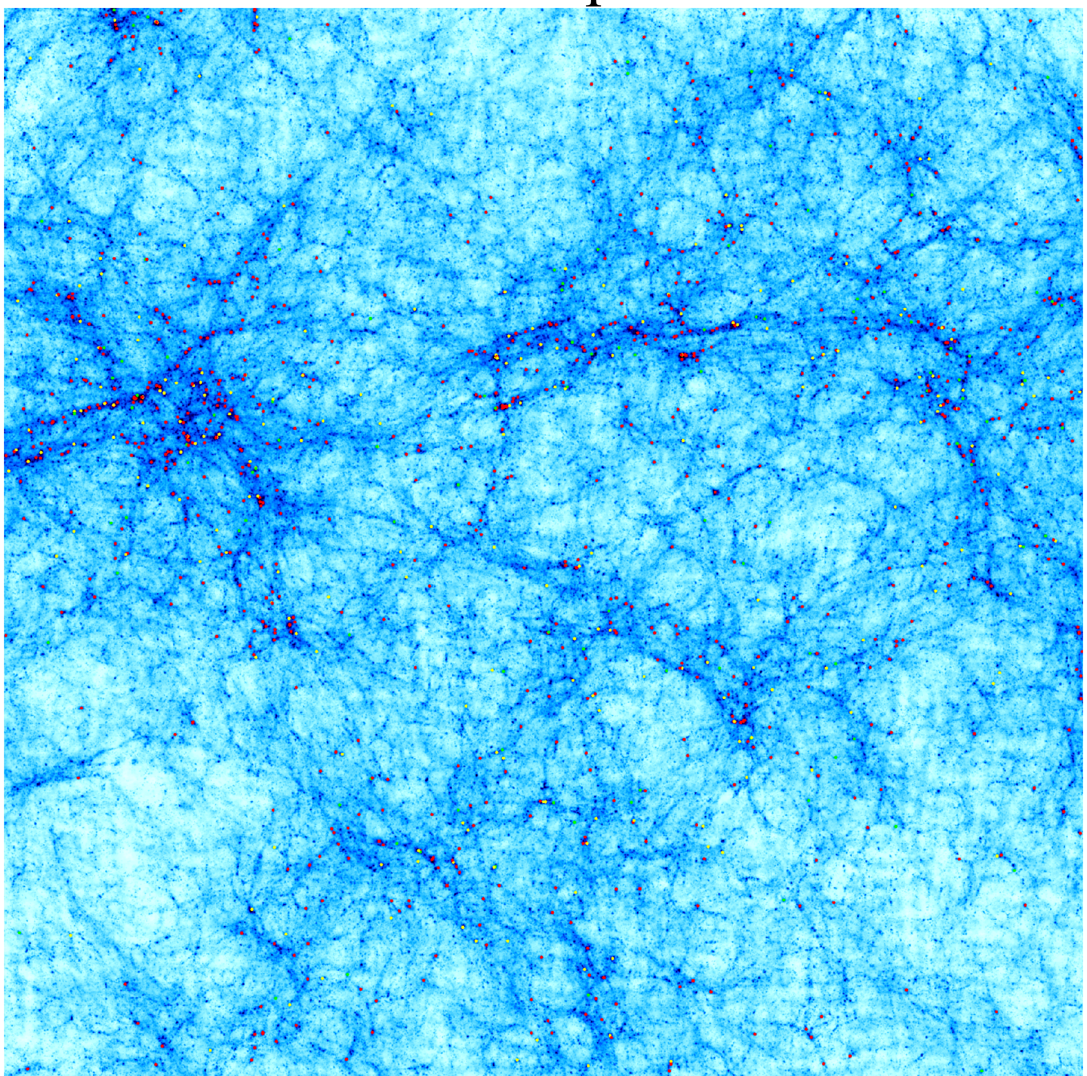
$M_{gal} > 10^9 M_{sun}$

$z = 0$

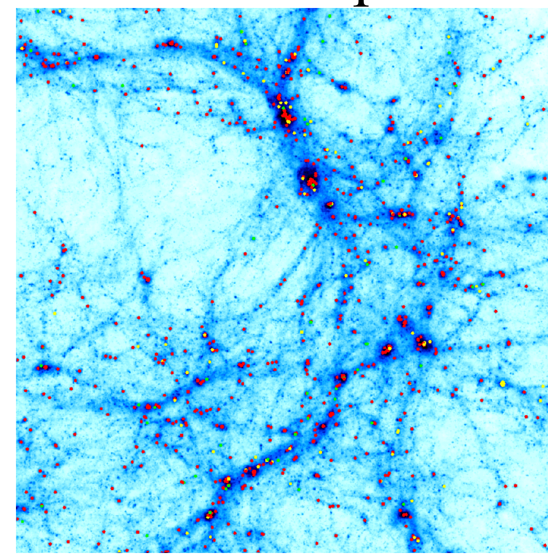
Galaxy formation included in DM simulations by semi-analytic models

Field vs cluster evolution of the galaxy population

$40\ h^{-1}\mathrm{Mpc}$



$20\ h^{-1}\mathrm{Mpc}$



$\rho_* = 0.5\ \langle \rho_0 \rangle$

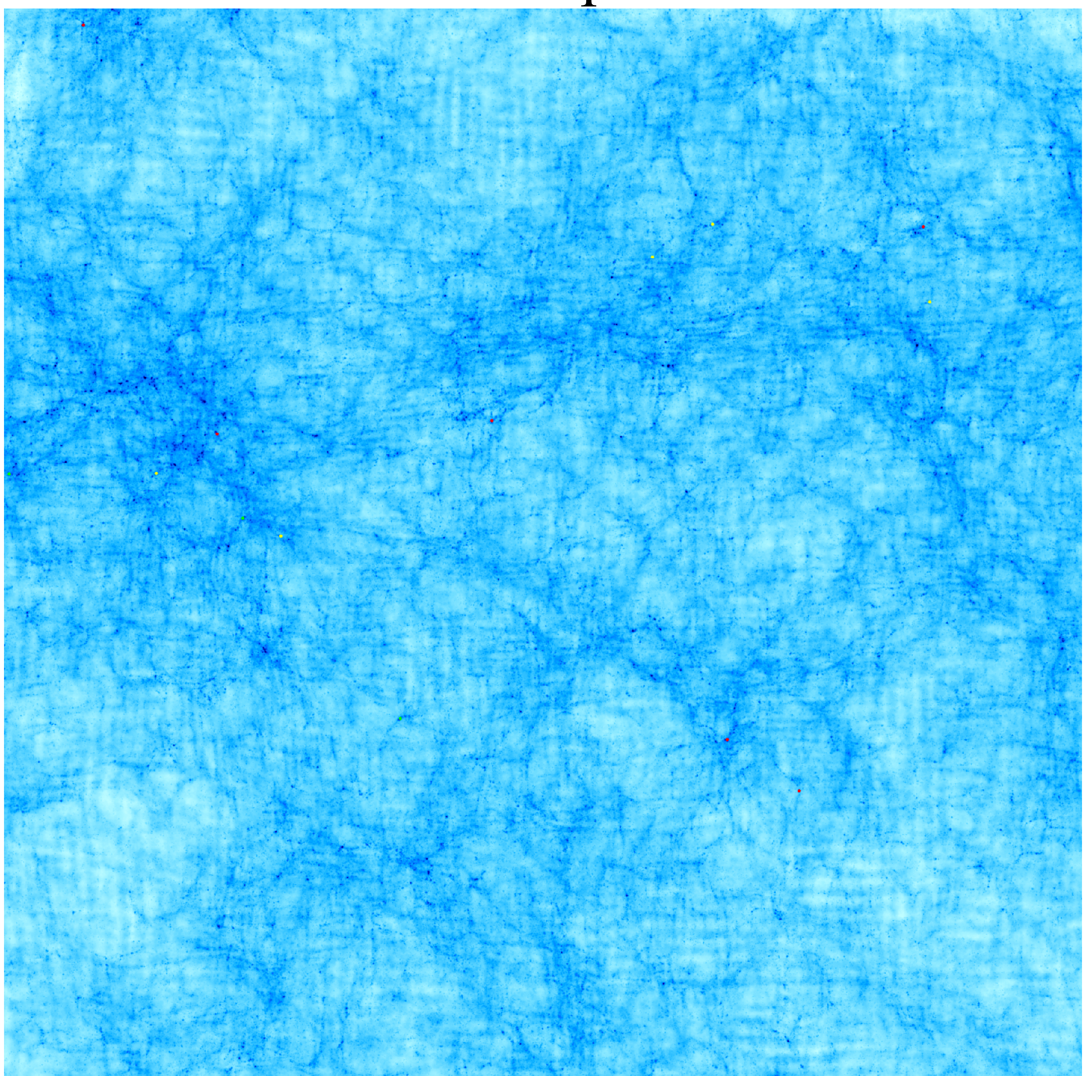
$\rho_* = 0.17\ \langle \rho_0 \rangle$

$M_{gal} > 10^9\ M_{sun}$

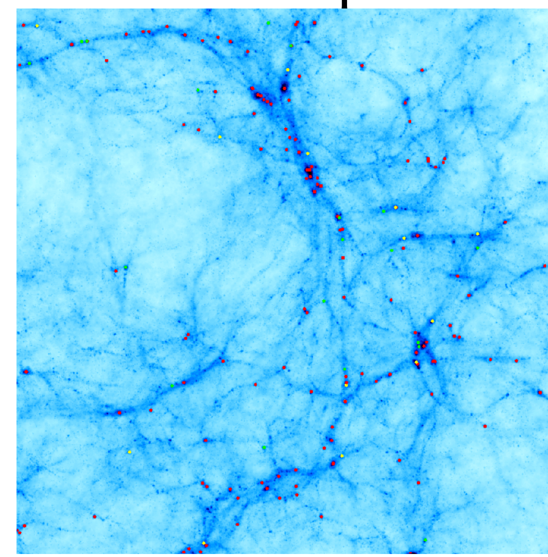
$z = 5$

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



20 h^{-1}Mpc



$\rho_* = 0.093 \langle \rho_0 \rangle$

$\rho_* = 0.018 \langle \rho_0 \rangle$

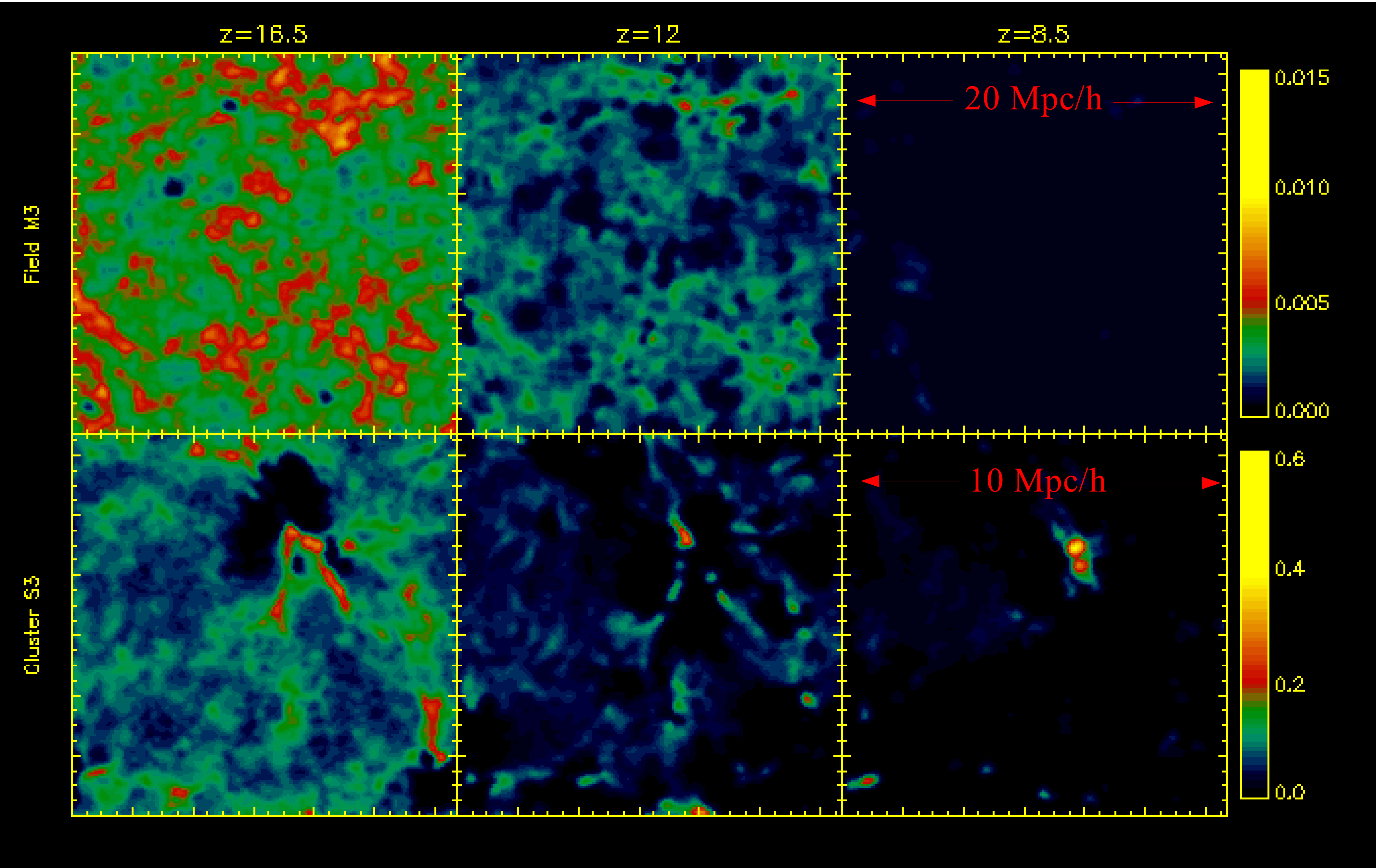
$M_{gal} > 10^9 M_{sun}$

z = 10

Reionization of cluster and field regions

Ciardi, Stoehr & White 2003

Are motions visible on the CMB sky?



Optical depth to electron scattering in comparison to *WMAP*

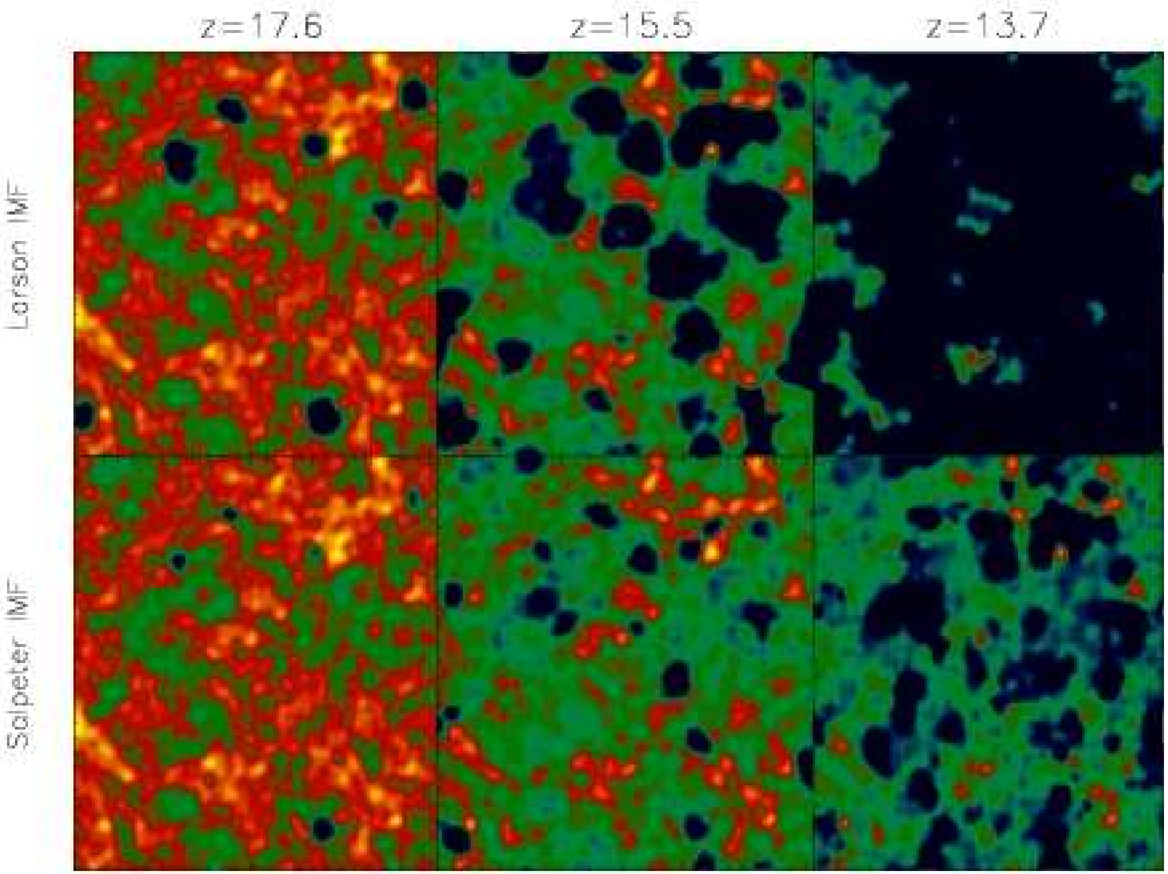
- Reionisation efficiency depends on:

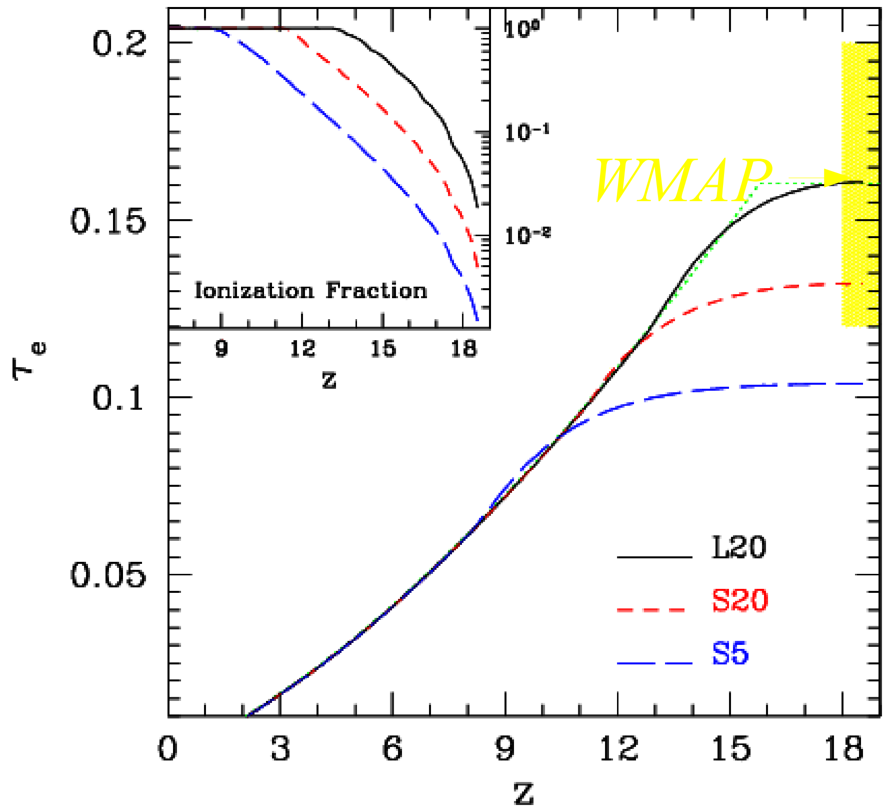
  $\epsilon_{\text{massive * form.}} \times \epsilon_{\gamma\ \text{prod.}} \times \epsilon_{\text{escape}}$

- Optimistic but physically plausible efficiencies reproduce the *WMAP* τ_e

without -- miniquasars
-- H_2 cooling/Pop III stars
-- galaxies with $M_{tot} < 10^9\, M_\odot$

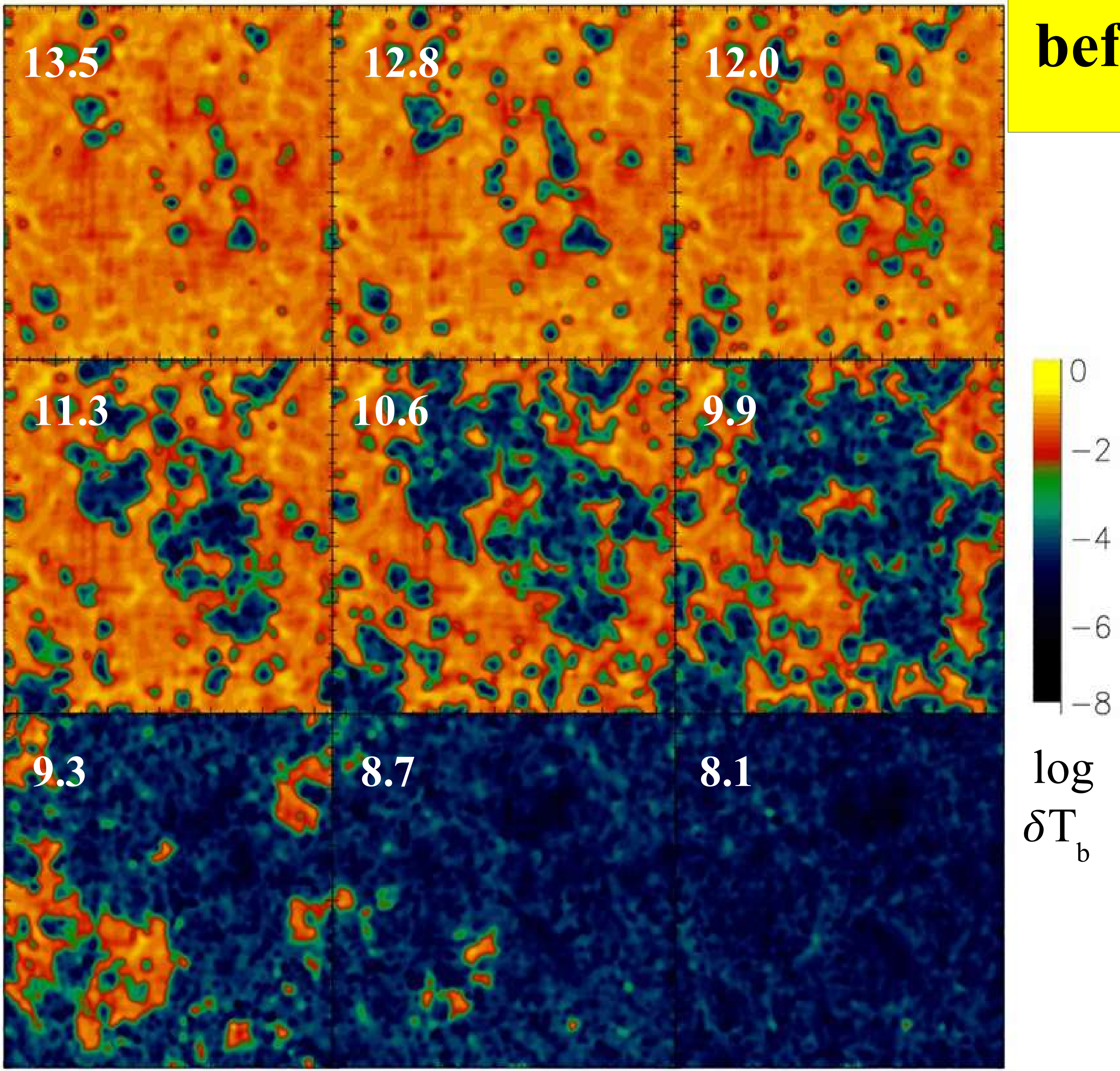
Ciardi, Ferrara & White 2003





Seeing structure before reionisation

Ciardi & Madau 2003



Pre-reionisation sources of UV

↓

resonant scattering of Ly α photons

↓

Decoupling of CMB and 21cm spin-flip temperatures

↓

Detectable 21cm emission (LOFAR)

Open issues on the CMB/structure formation interface

- How accurate must DM simulations be for precision cosmology?
  --- Are fitting formulae (e.g. Peacock/Dodds) good enough?
  --- Are baryonic effects on the mass distribution significant?
- Are correlations between DM and baryonic effects significant?
  --- correlation of lensing and SZ effects?
  --- correlation of point sources with structure in the DM?
- Do we need to include additional DM or DE physics?
  --- DM self-interaction, annihilation, interaction with baryons?
  --- fluctuations in the DE field? DE effects on gravity?
- Is the small scale baryonic physics important for CMB?
  --- cooling and feedback within clusters?
  --- early enrichment of the IGM -- resonant line scattering?
- Do nonlinear secondary effects influence primary measurements?
  --- can SZ contribution to PS be accurately estimated/measured?
  --- what about effects from reionisation?