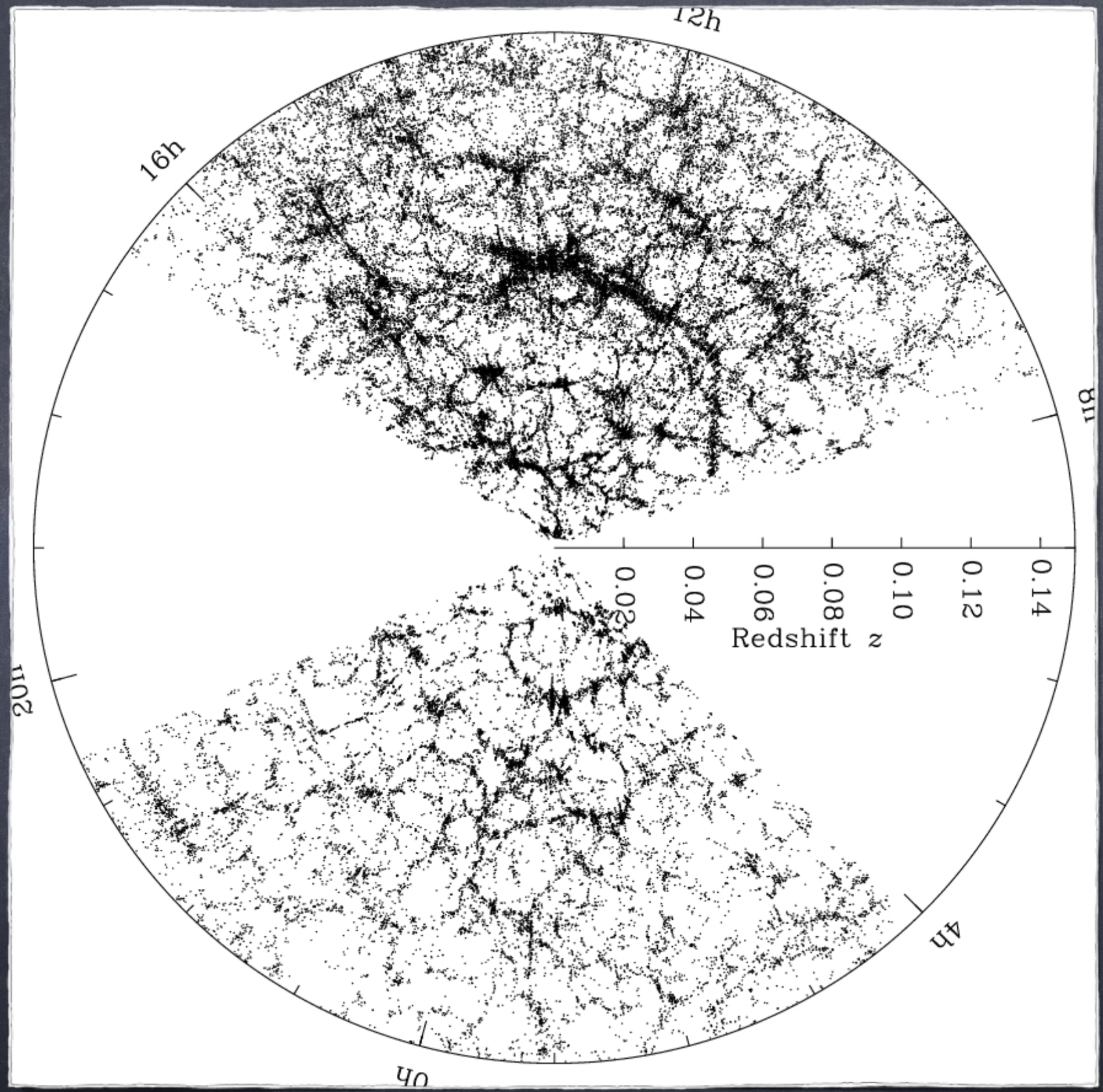
Cosmology and the Sunyaev-Zel'dovich Sky

- Observations and Simulations -

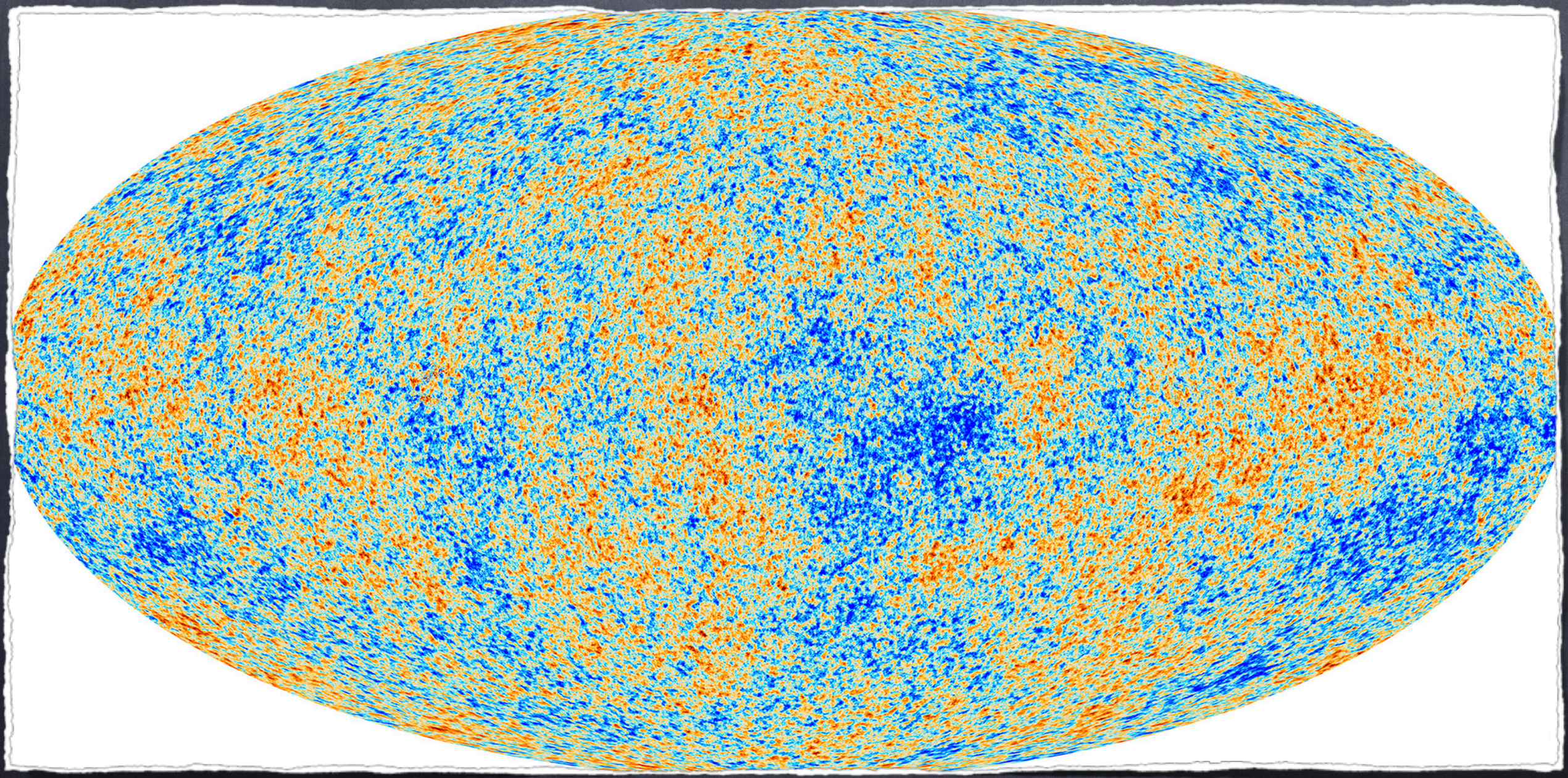
Samuel Flender
Argonne National Laboratory



The “cosmic web”

The Sloan Digital Sky Survey

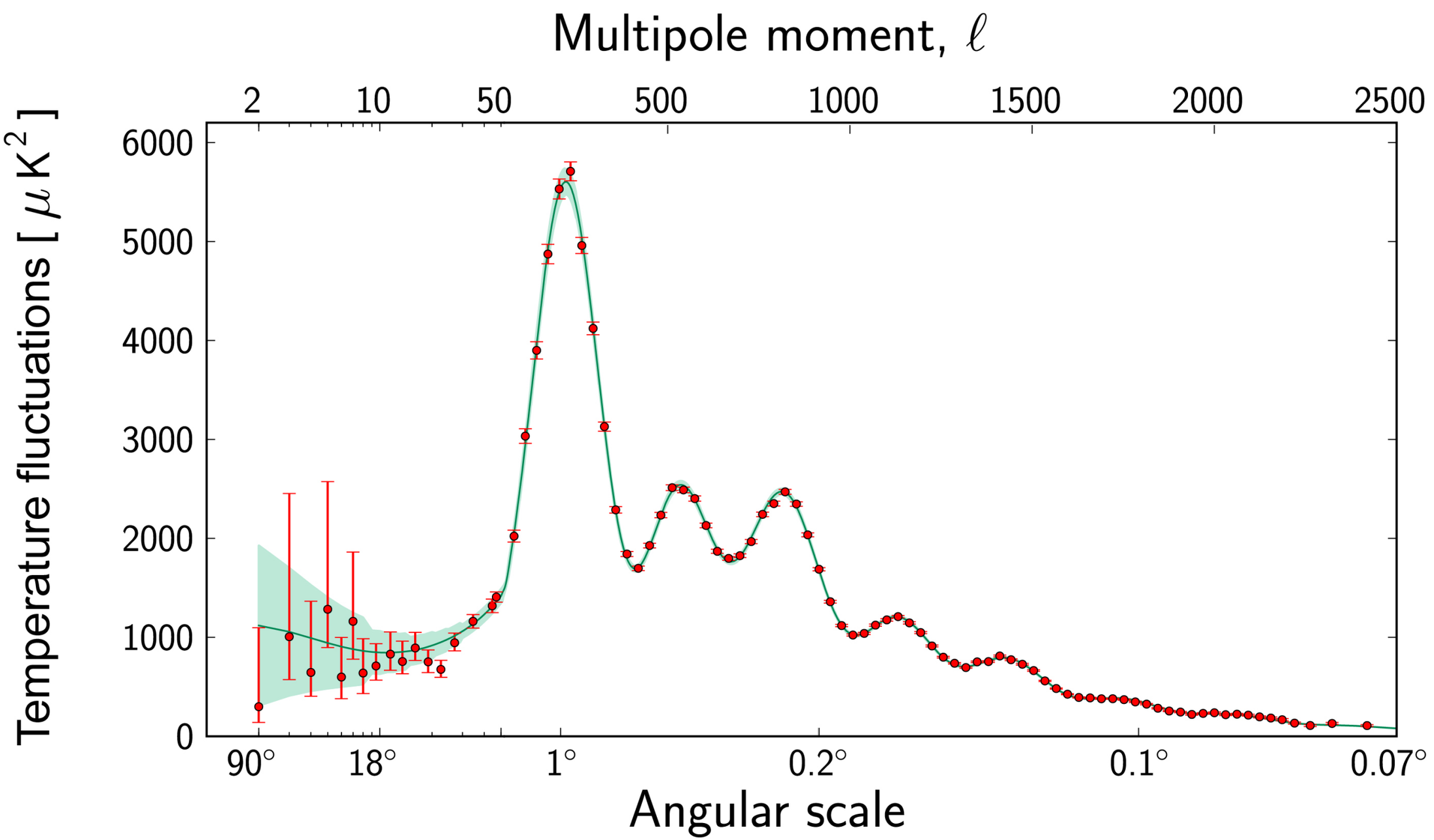
The cosmic microwave background (CMB)



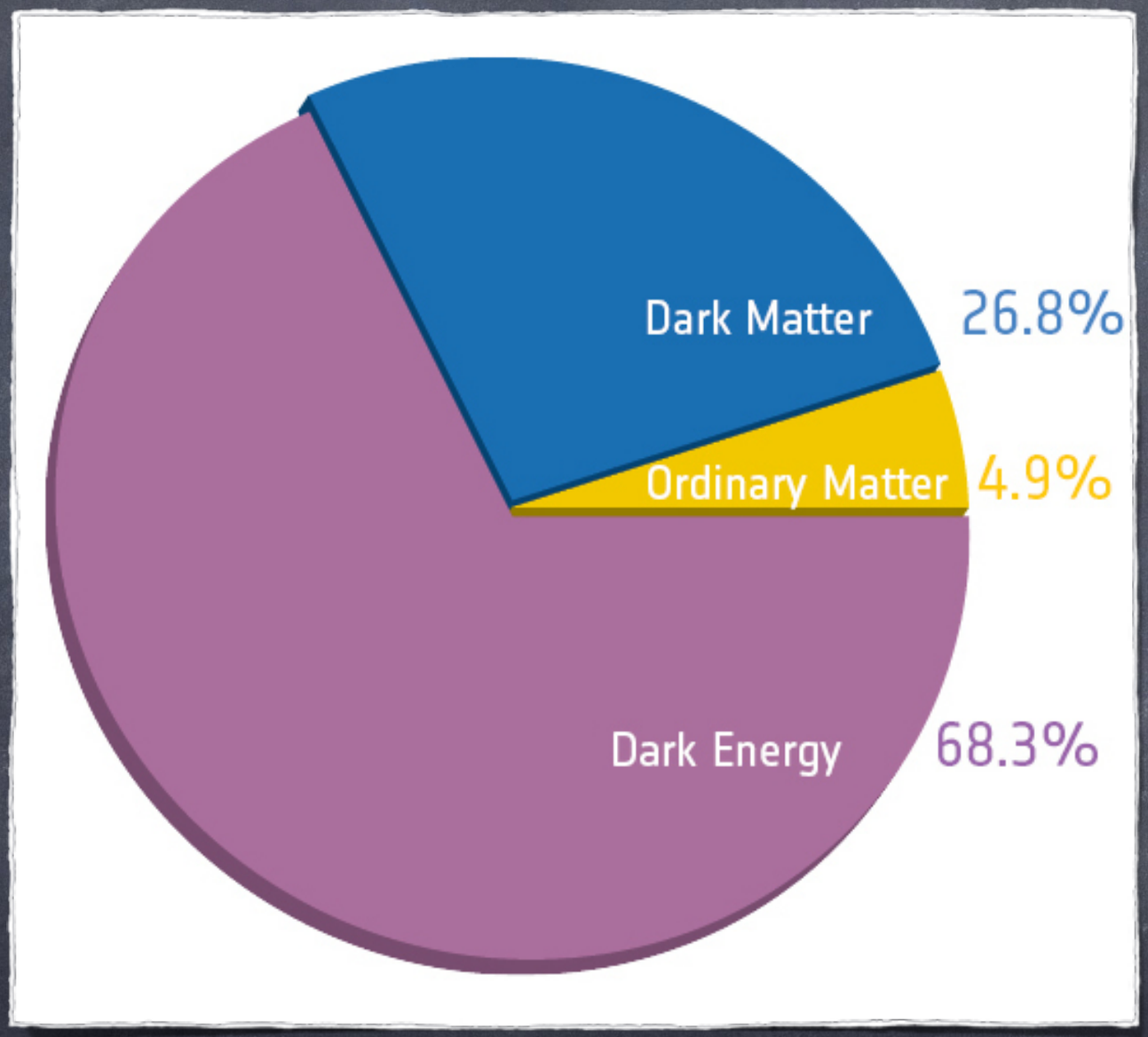
The Universe ~400k years after the Big Bang

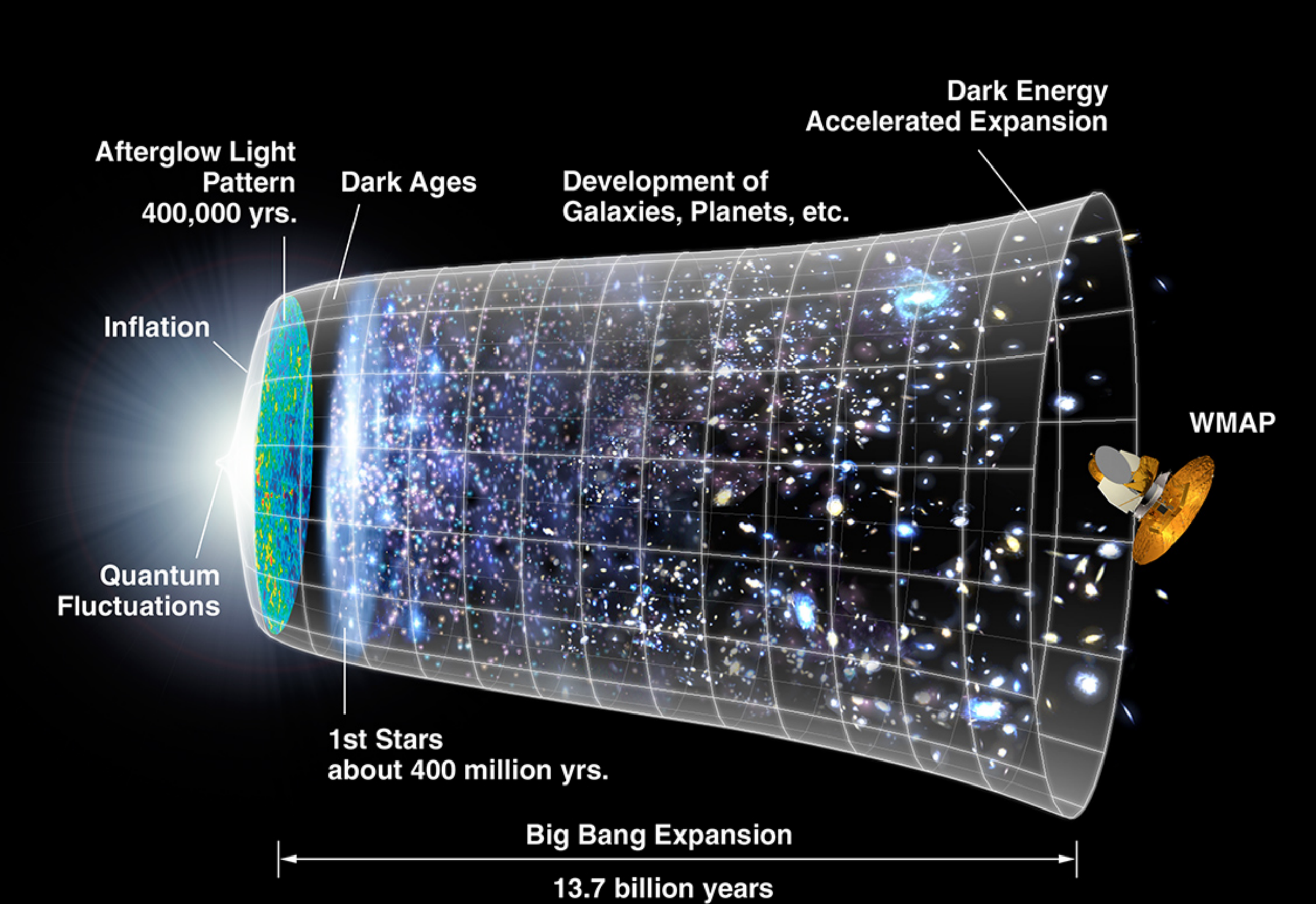
temperature fluctuations $O(10^{-5})$

Planck collaboration 2015


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μ K^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

The content of the Universe today



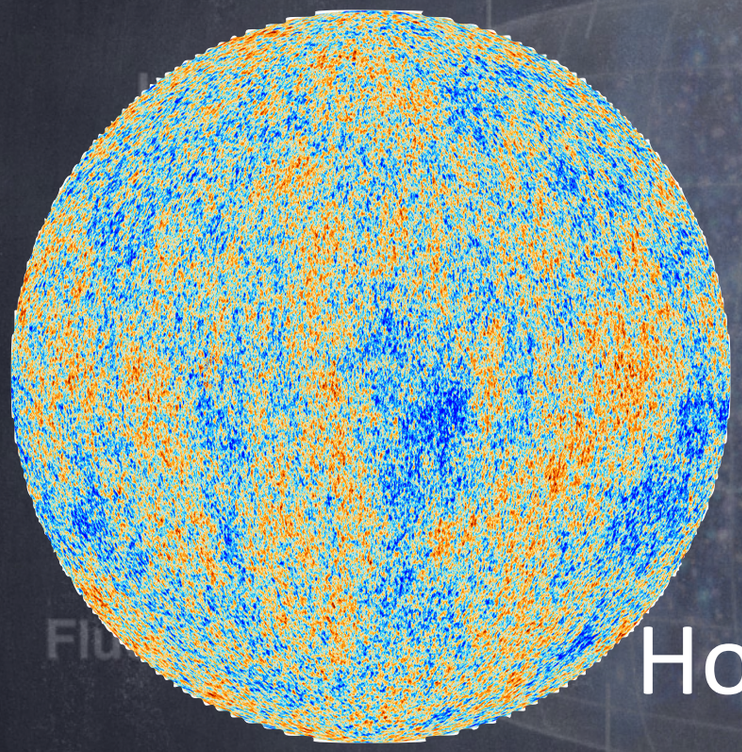

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

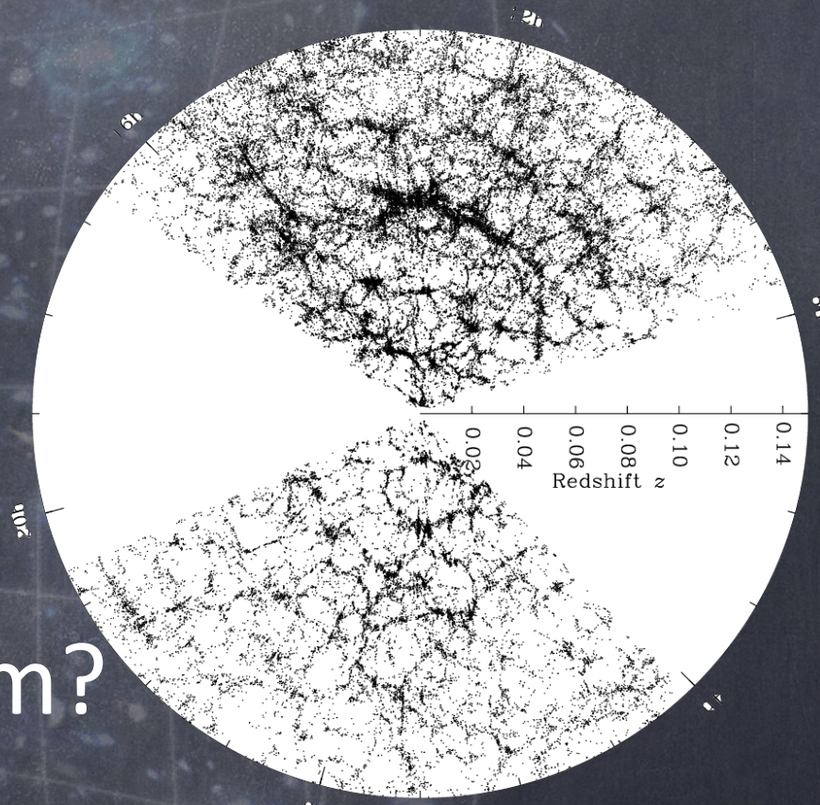
Afterglow Light Pattern 400,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion





How does structure form?

1st Stars about 400 million yrs.

Big Bang Expansion

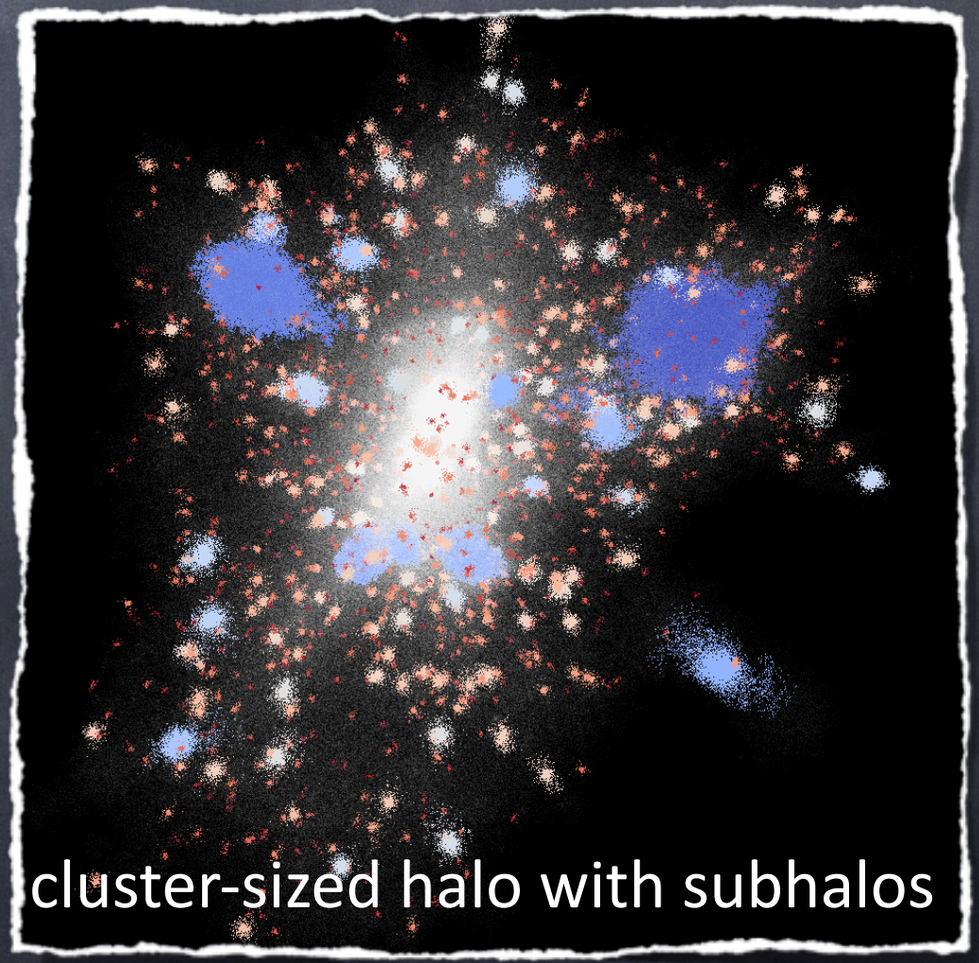
13.7 billion years

Perturbations grow

- Density perturbations in the primordial Universe $O(10^{-5})$ grow due to gravity
- Once dark matter density reaches some threshold, it collapses into a dark matter *halo*
- dark matter halos host *galaxies* and *clusters of galaxies*

Milky Way - sized DM halo

Source: cerncourier.com/cws/article/cern/50213



cluster-sized halo with subhalos

Heitmann et al 2015, Q Continuum simulation

Linear theory

$$
\begin{aligned}
\text{continuity equation}: \quad & \delta' + \nabla \cdot \mathbf{v} &&= 0, \\
\text{Poisson equation}: \quad & \Delta\phi &&= 4\pi G a^2 \bar{\rho}\delta, \\
\text{Euler equation}: \quad & \mathbf{v}' + \mathcal{H}\mathbf{v} &&= -\nabla\phi.
\end{aligned}
$$

Linear theory

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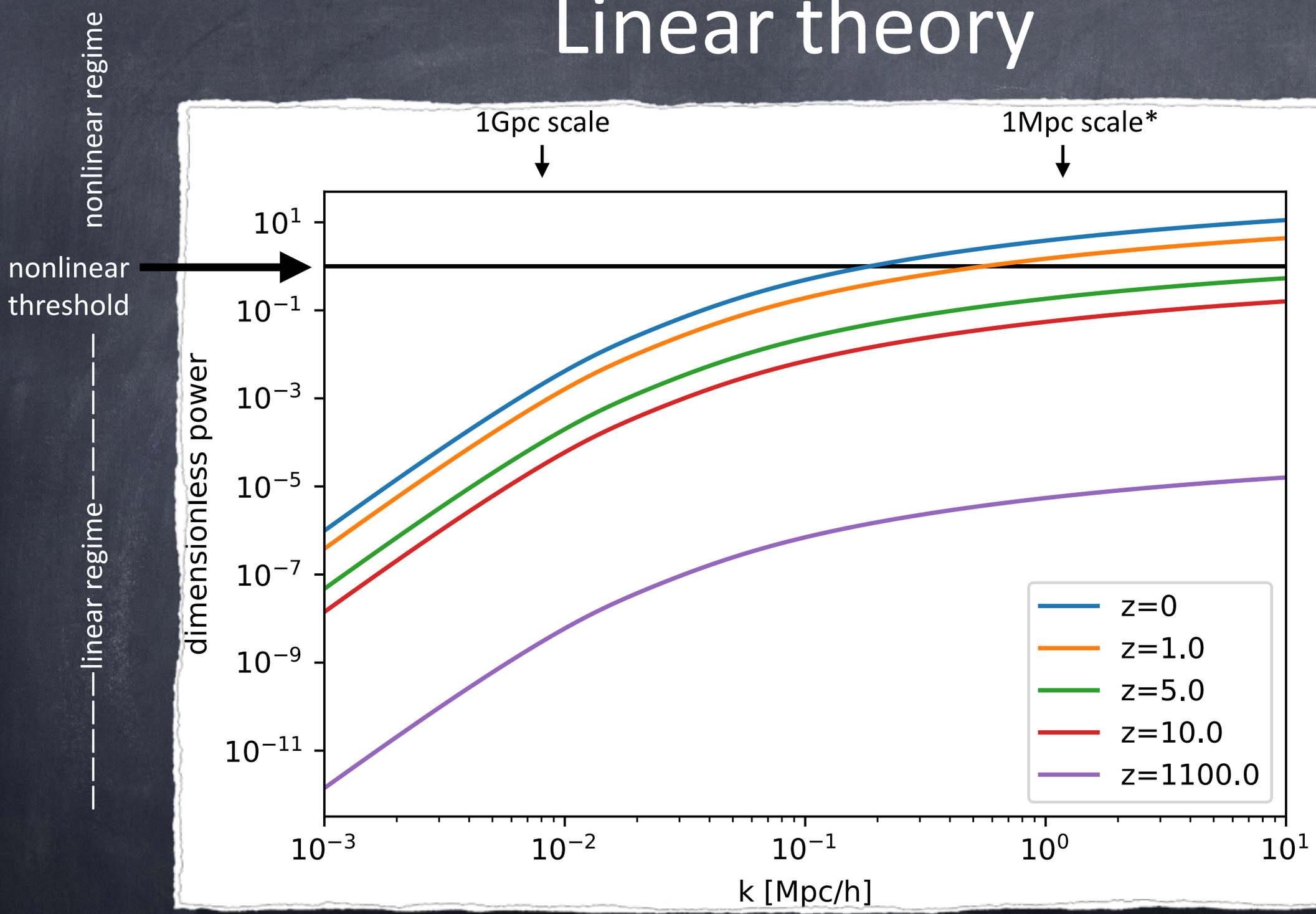
\end{aligned}
$$

$$\delta(k) \propto k^2 \phi(k) (1+z)^{-1}$$

Density perturbations grow at the same rate at all scales

Linear theory

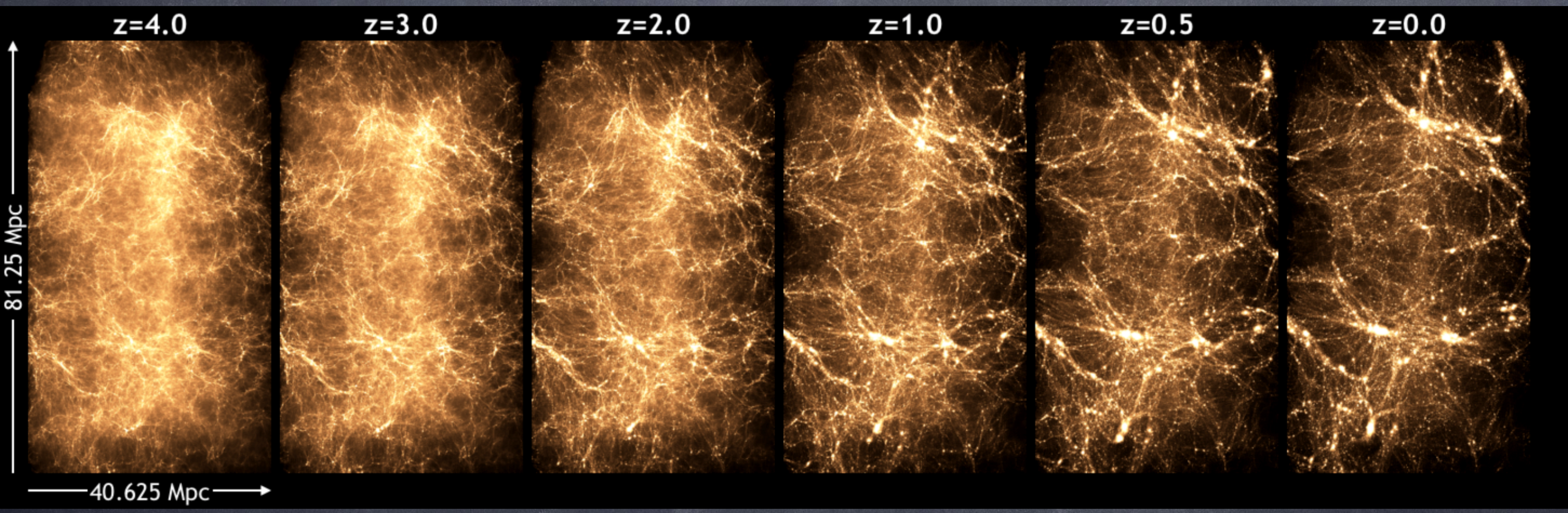


Structures on larger scales collapse later

— “bottom-up” formation —

*1pc = 3.26 lightyears

Simulating structure formation



The Q Continuum *N*-body Simulation

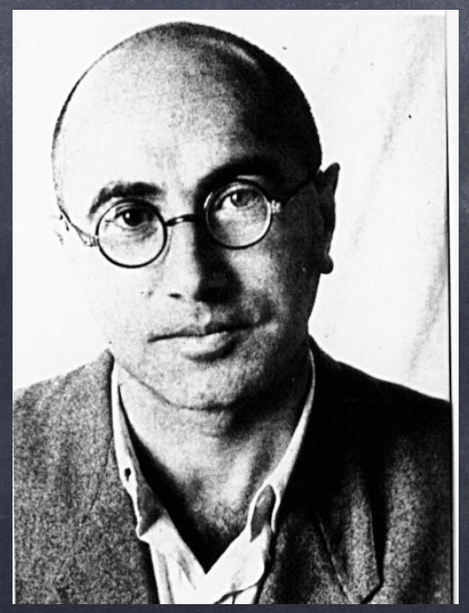
L_{box} = 1300 Mpc, N_{part} = 0.55 Trillion, $m_p = 1.48 \times 10^8 M_{sol}$

(Heitmann et al 2015)

The Sunyaev-Zel’dovich effect

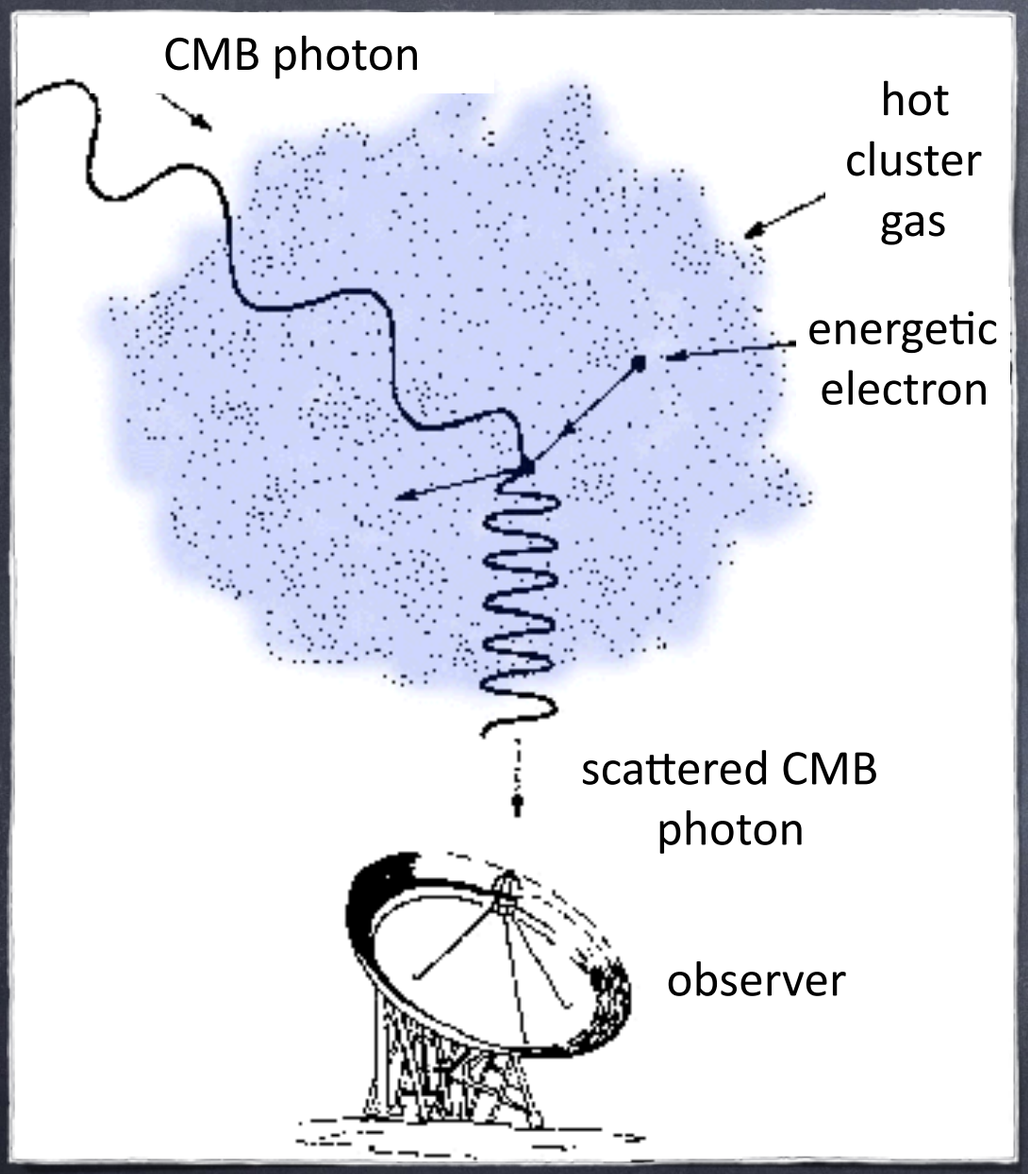
— the microwave imprint of galaxy clusters —

Rashid Sunyaev



Yakov Zel’dovich

The Sunyaev-Zel'dovich effect



Carlstrom+2002

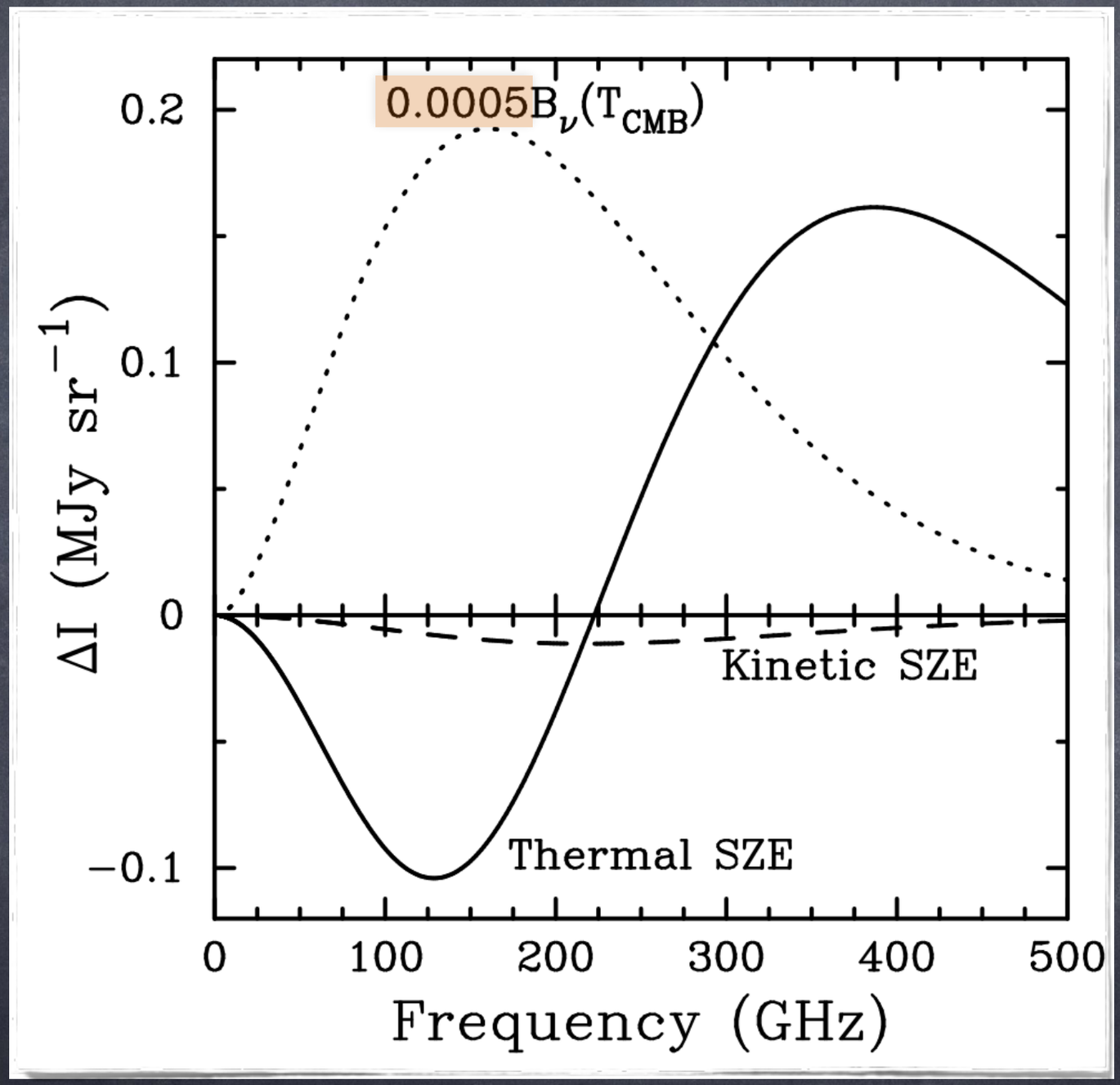
- Galaxy clusters contain hot gas - the intra-cluster medium (ICM)
- Inverse Compton scattering of CMB photons with free electrons inside the ICM
- *thermal* SZ: sourced by the thermal motion of electrons

$$\left(\frac{\Delta T}{T}\right)_{\rm tSZ} = \frac{\sigma_T}{m_e c^2}\int {\rm d}l\, P_e(l)$$

- *kinematic* SZ: sourced by the bulk motion of cluster with respect to CMB

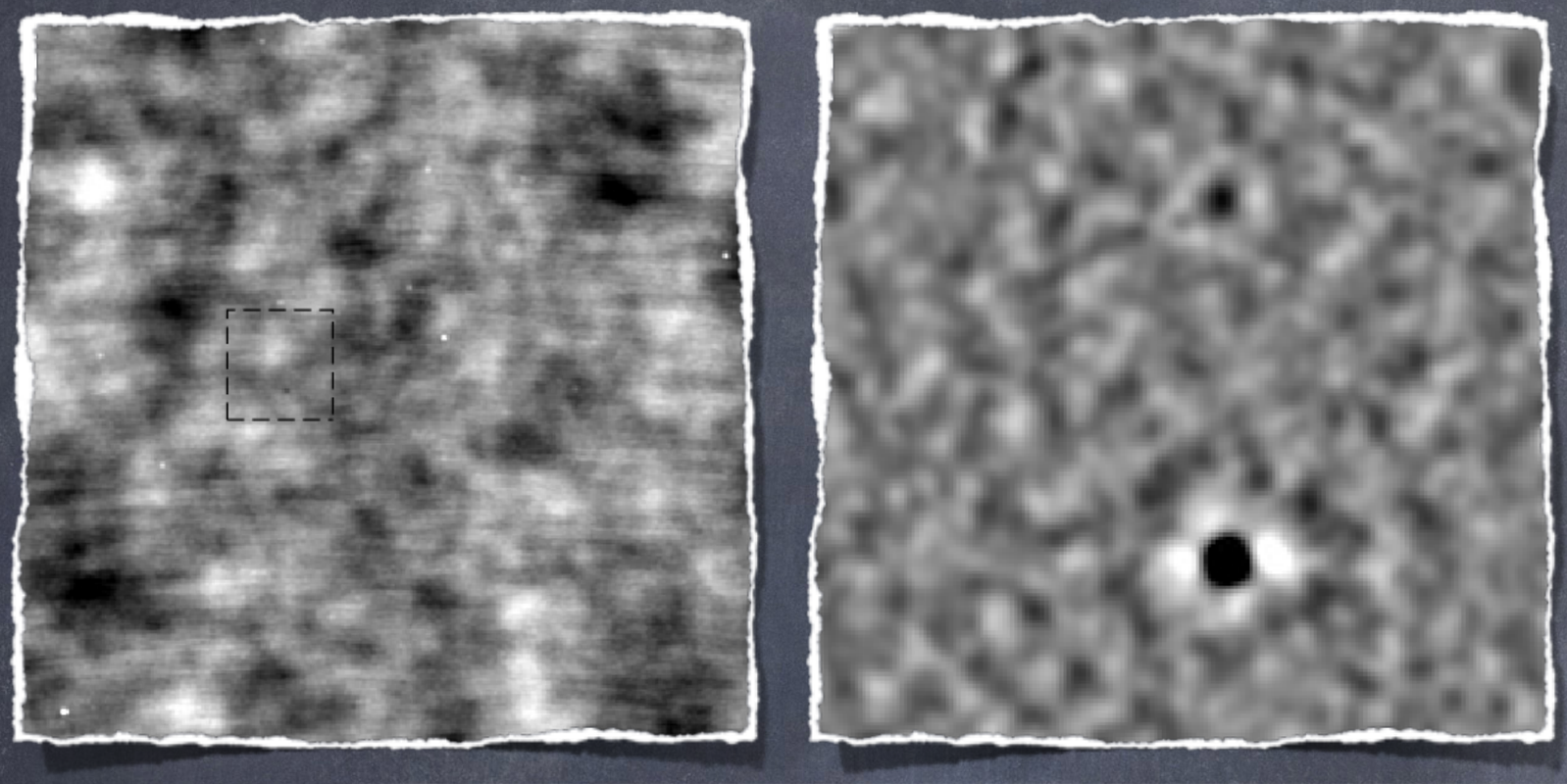
$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} = \sigma_T \int {\rm d}l\, n_e \frac{v_{\rm los}}{c} = \tau \frac{v_{\rm los}}{c}$$

It is a *small* effect

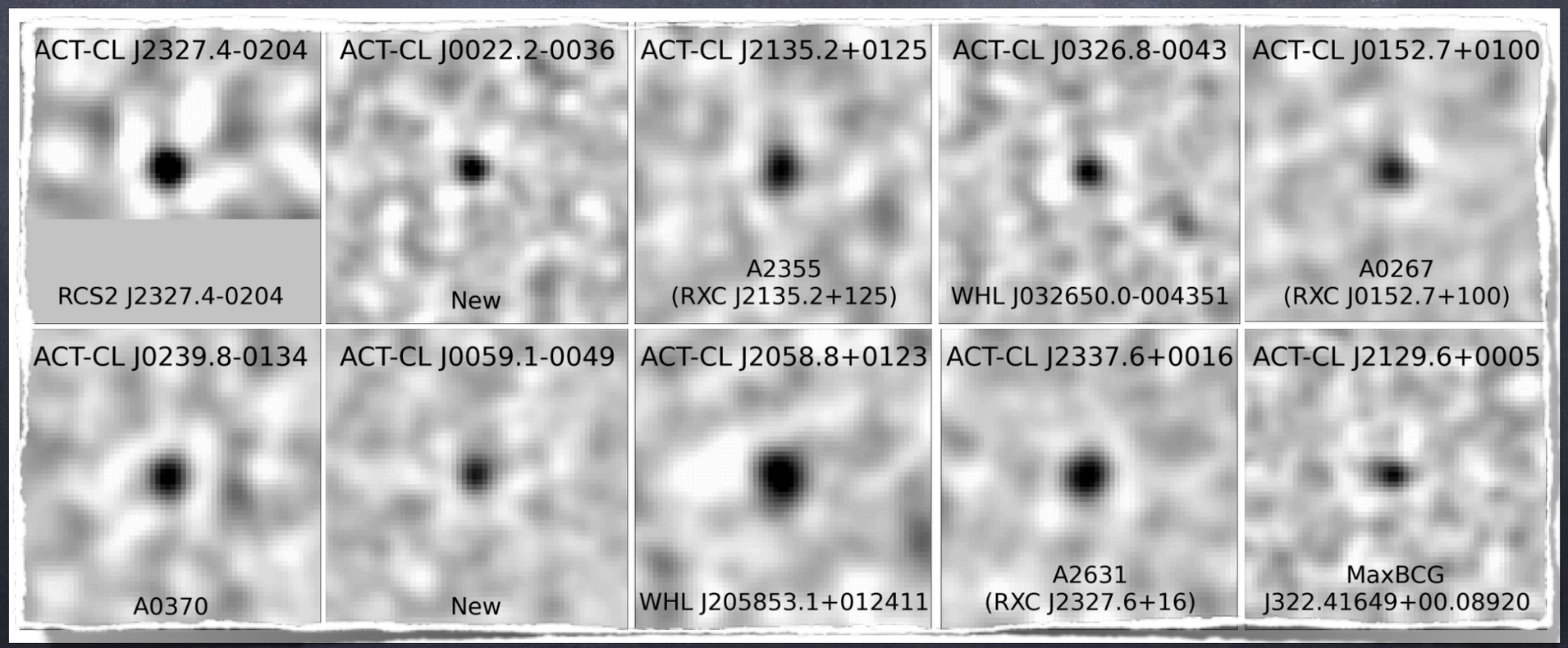


Carlstrom+2002

Finding new clusters using tSZ

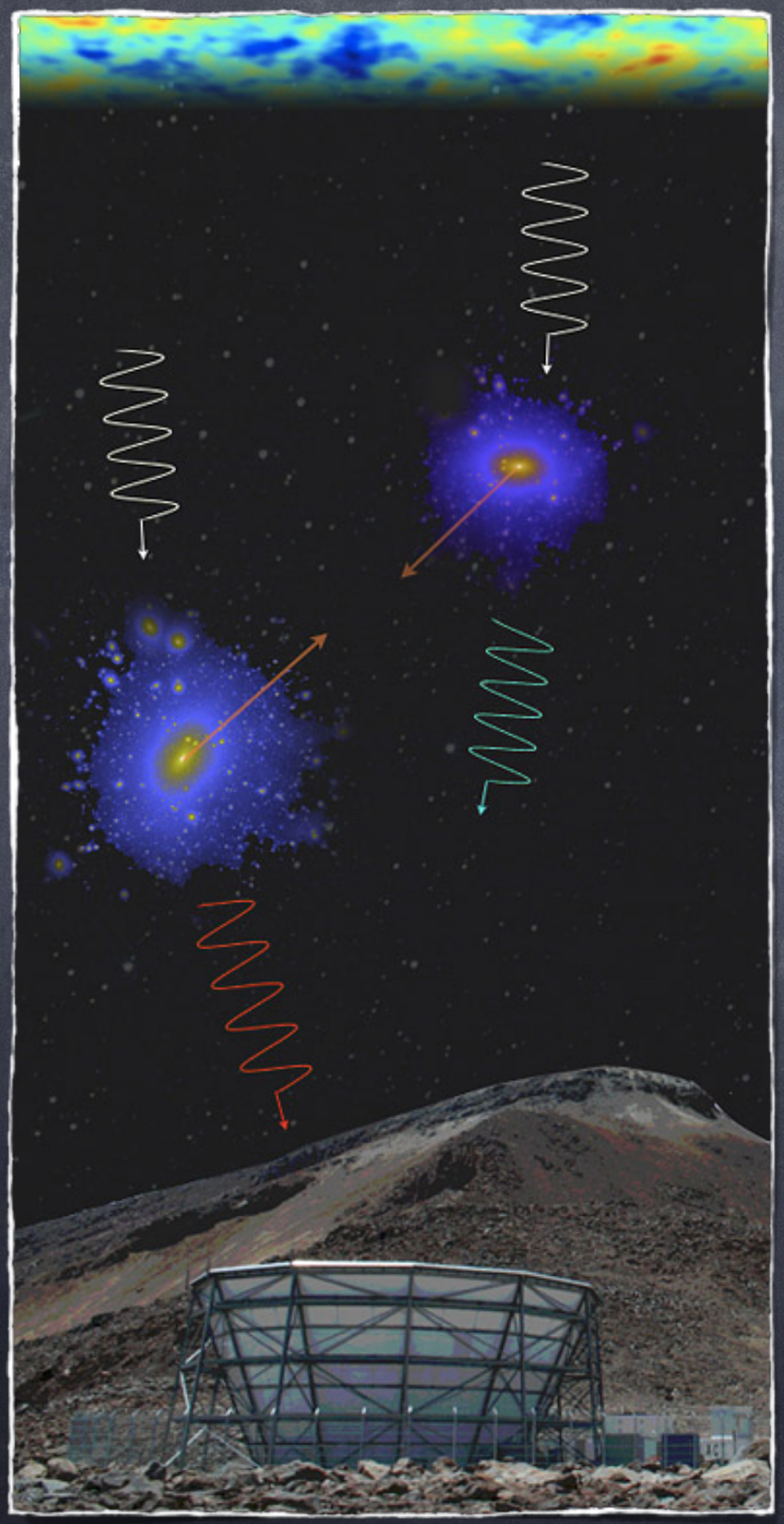


Bleem+15



Hasselfield+13

The pairwise kSZ signal
- a probe of cosmology and astrophysics -



$$\frac{\Delta T_{\mathrm{pkSZ}}}{T_{\mathrm{CMB}}}(r,z) = \bar{\tau}_{\mathrm{eff}} \frac{v_{12}(r,z)}{c}$$

optical depth (astrophysics)

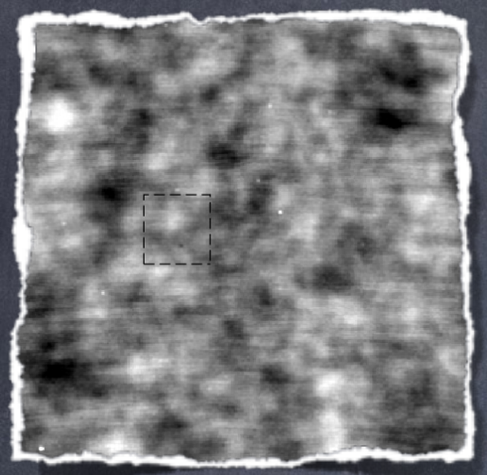
pairwise velocity (cosmology)

$$v_{12} \sim \xi_{v\delta} \sim f\sigma_8^2$$

growth function

amplitude of density perturbations

Pairwise kSZ measurement in practice



(matched-filtered) CMB map

cluster positions

$$\hat{T}_{\rm kSZ} = \frac{\sum_{ij} c_{ij} T_{ij}}{\sum_{ij} c_{ij}^2}$$

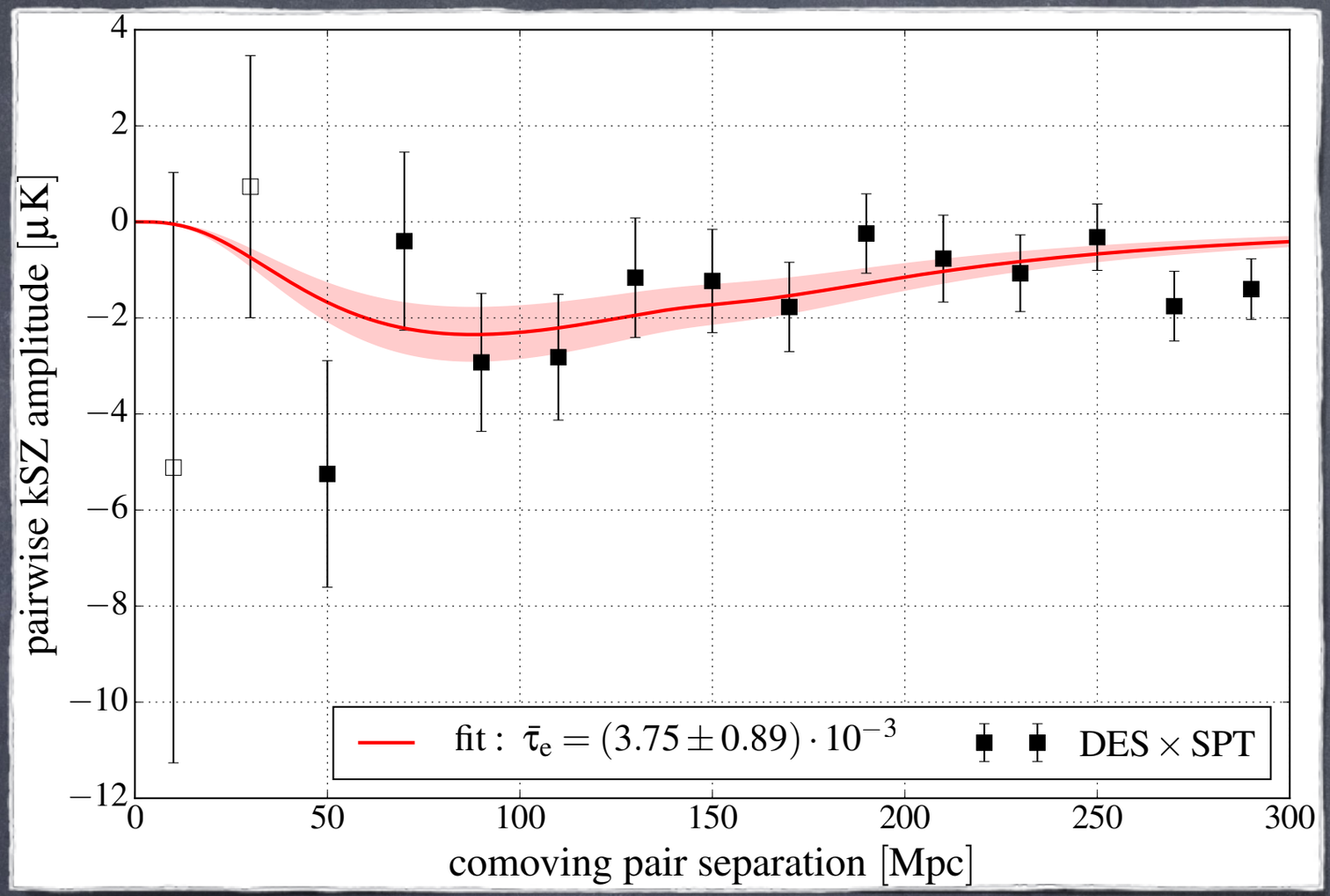
$$c_{ij} = \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2}$$

geometric weights

The pairwise estimator

Ferreira+99, Hand+12

Pairwise kSZ signal with SPT and DES-Y1 Redmapper clusters

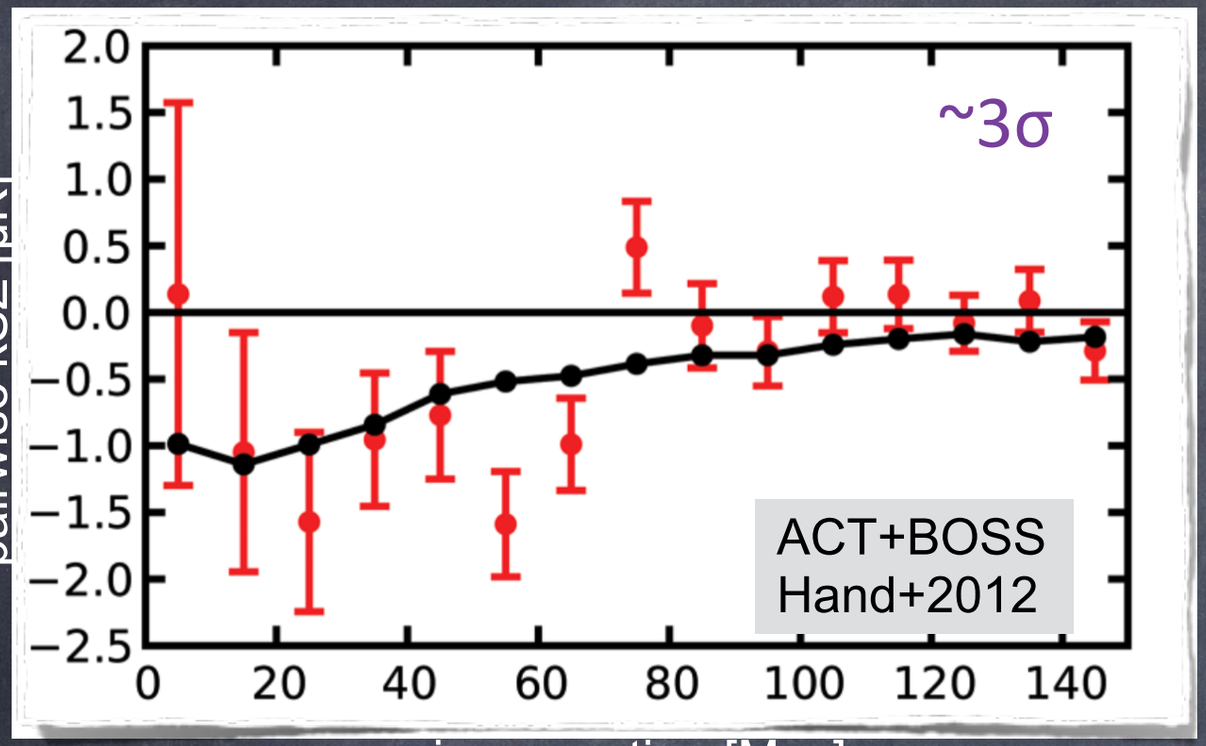


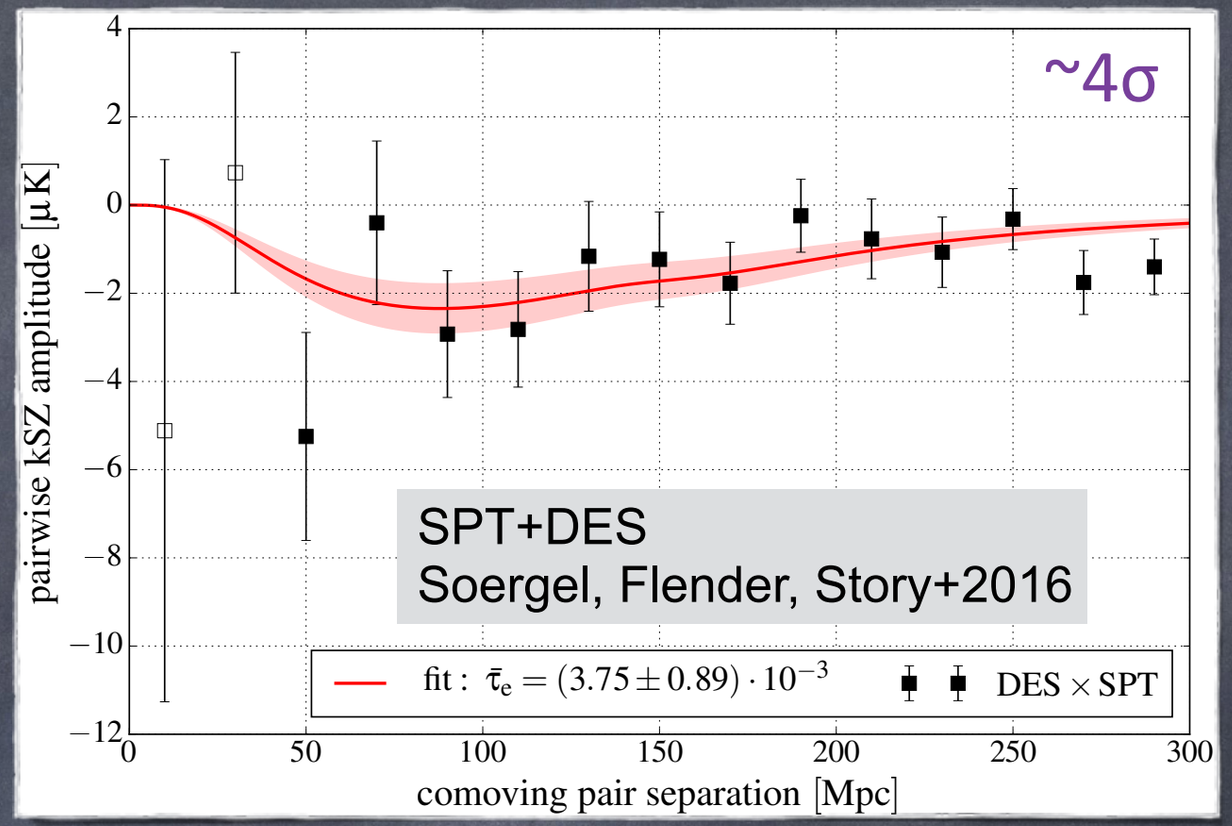
~6000 RM clusters
20<λ<60
0.1<z<0.8

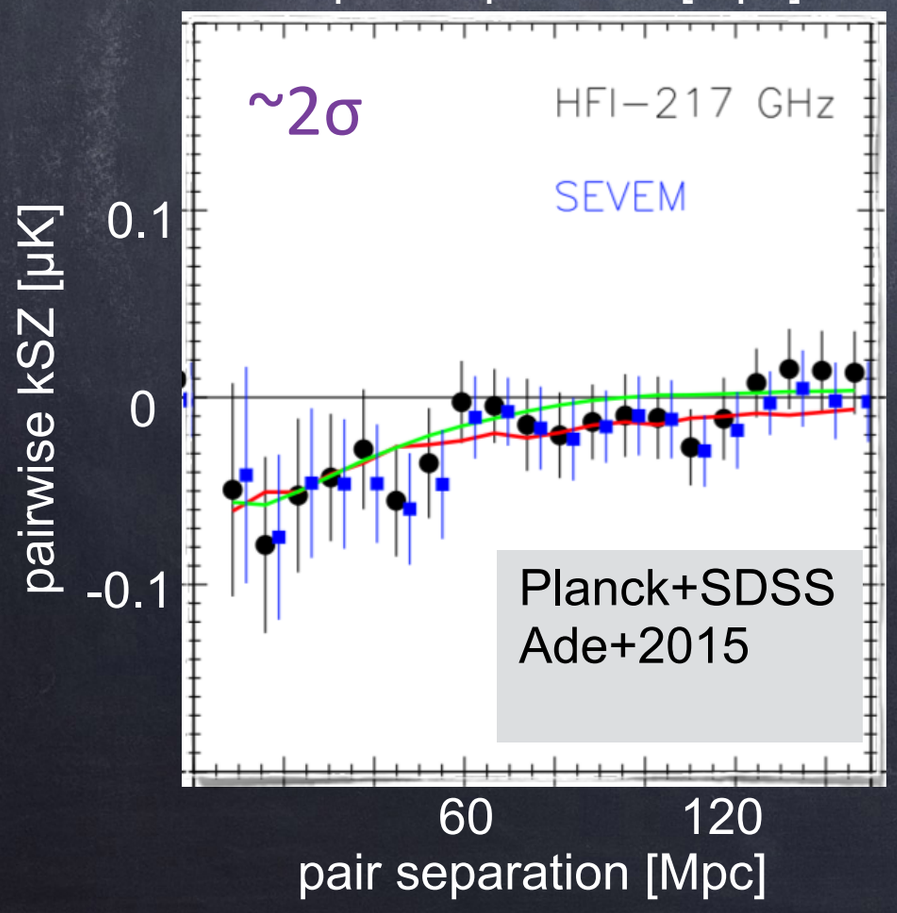
$$T_{\rm pkSZ}(r,a) = \bar{\tau}_e \, \frac{T_{\rm CMB}}{c} \, \frac{2\,b\,\xi^{\delta v}(r,a)}{1+b^2\,\xi(r,a)} \times \left[1 - \exp\left(-\frac{r^2}{2\,\sigma_r^2}\right)\right]$$

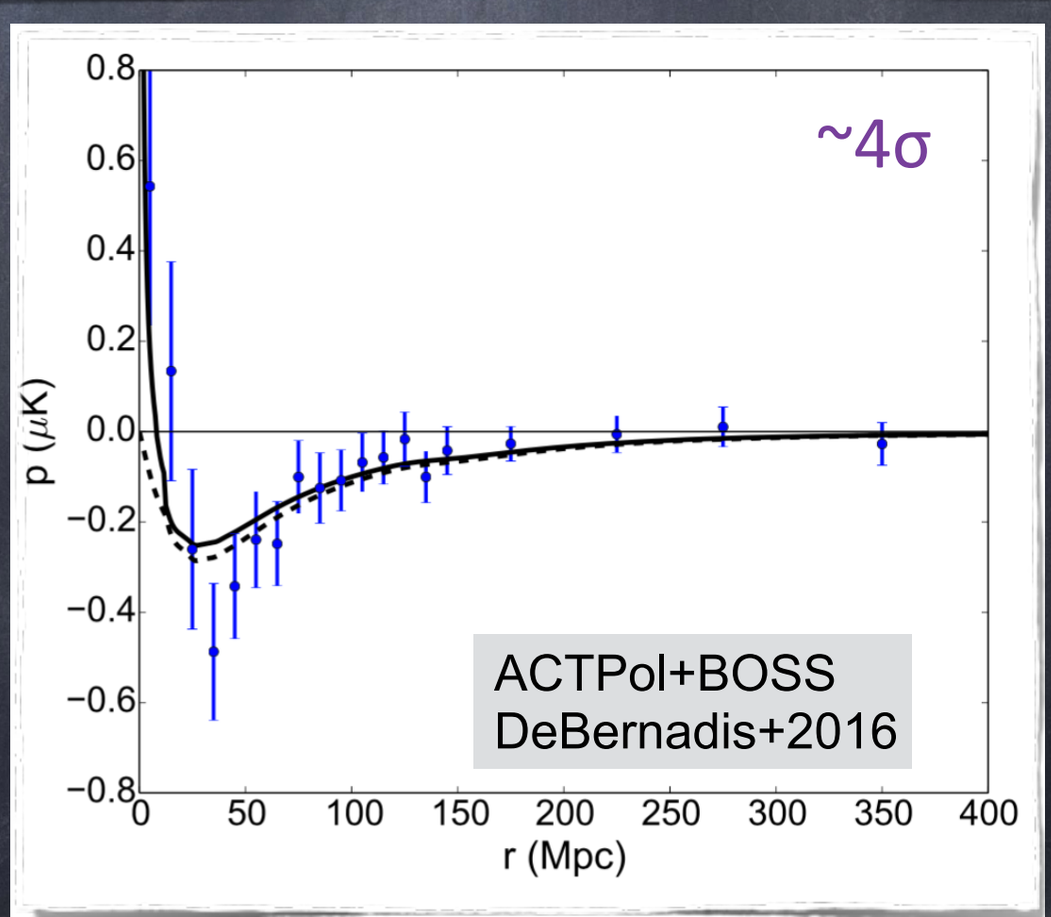
$$\bar{\tau}_e = (3.75 \pm 0.89) \cdot 10^{-3} \qquad (4.2\sigma)$$

Pairwise kSZ landscape

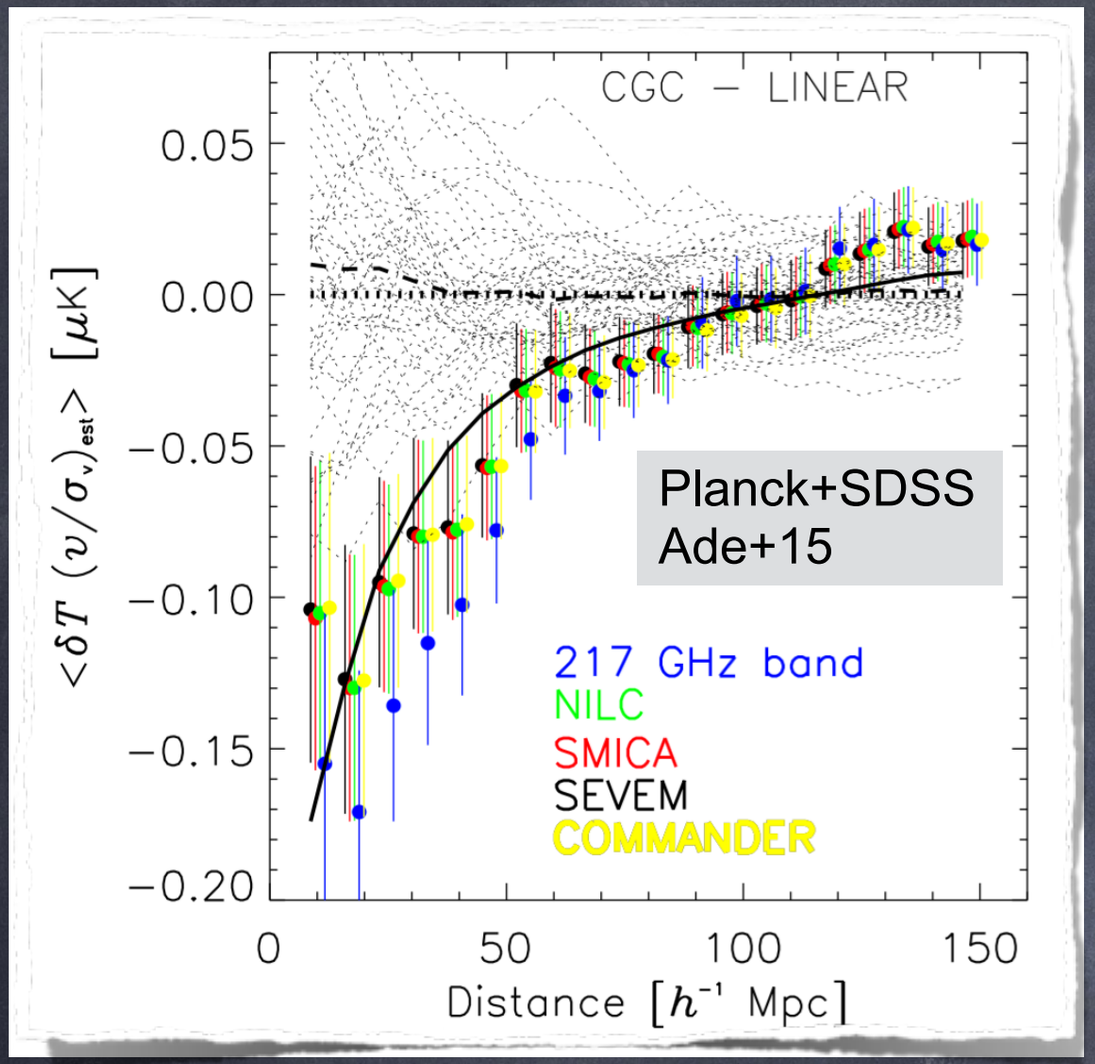








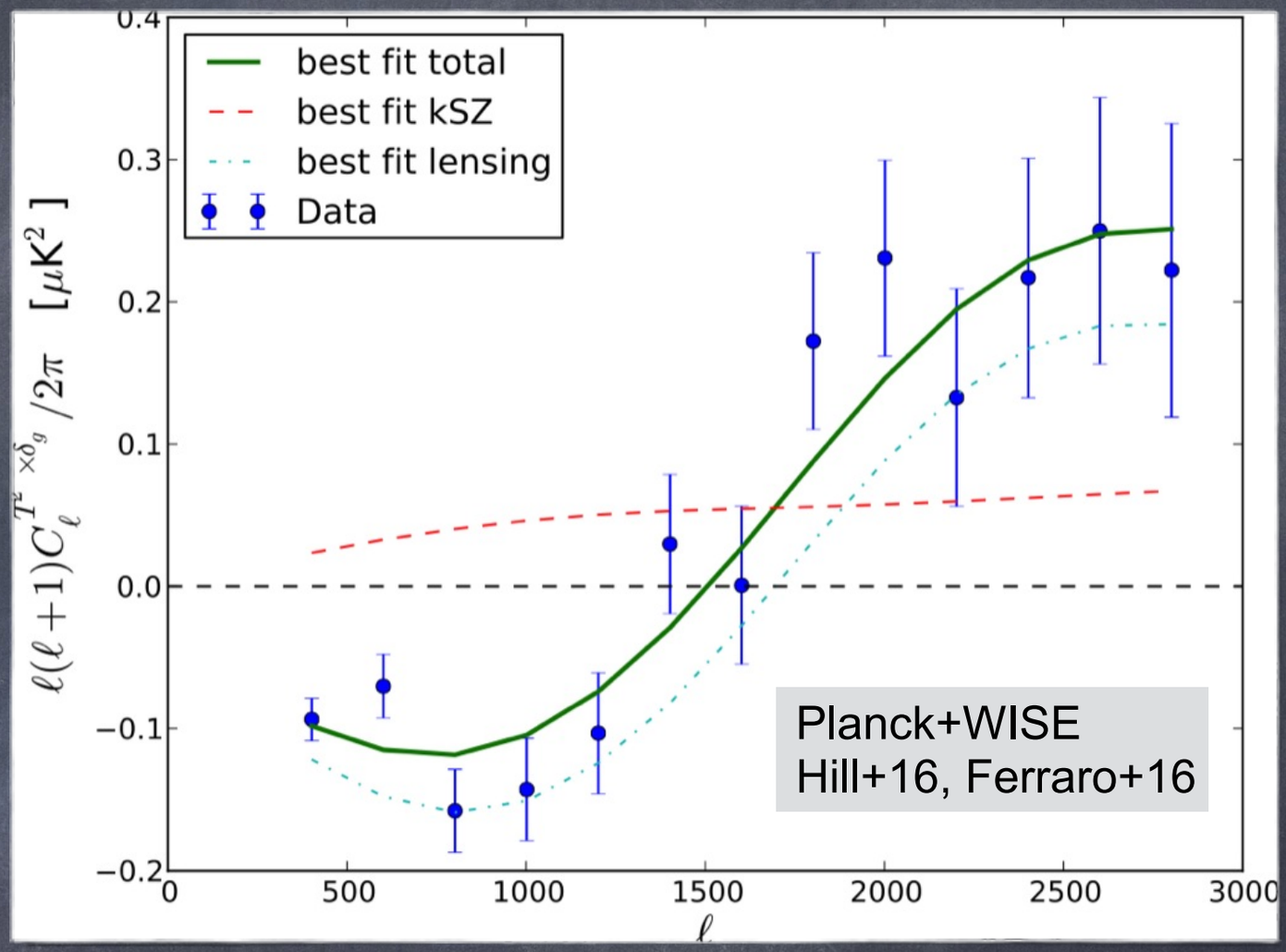
Other kSZ estimators



velocity reconstruction

$$\langle \frac{\Delta T}{T}\ v_{\rm rec} \rangle$$

Ade+2015, Schaan+2015



projected field estimator

$$\langle \left(\frac{\Delta T}{T}\right)^2\ \delta_g \rangle$$

Hill+2016, Ferraro+2016

Future measurements

data scenario	method	predicted S/N	Reference
SPT-3G × DES	pairwise kSZ	$\sim 18-30$	Keisler & Schmidt (2013)
Adv.ACTPol × DESI	pairwise kSZ	$\sim 20-57$	Flender et al. (2016)
Adv.ACTPol × SPHEREx	pairwise kSZ	~ 55	Doré et al. (2016)
Adv.ACTPol × WISE	projected kSZ	~ 120	Ferraro et al. (2016)
Adv.ACTPol × DESI	pairwise kSZ power spectrum	~ 30	Sugiyama et al. (2016)
CMB StageIV × DESI	pairwise kSZ power spectrum	$\sim 50-100$	Sugiyama et al. (2016)

high S/N measurements are expected!

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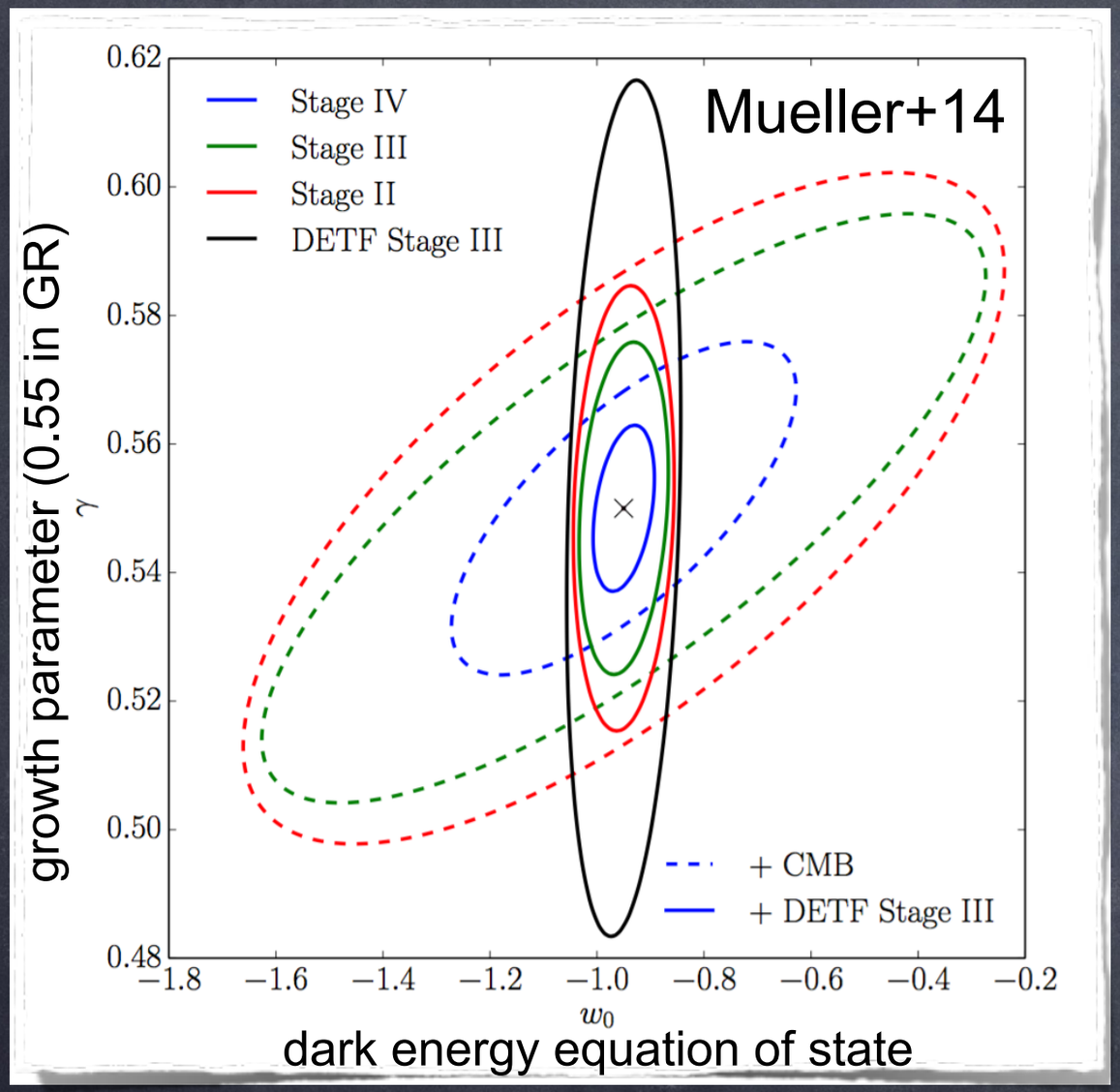
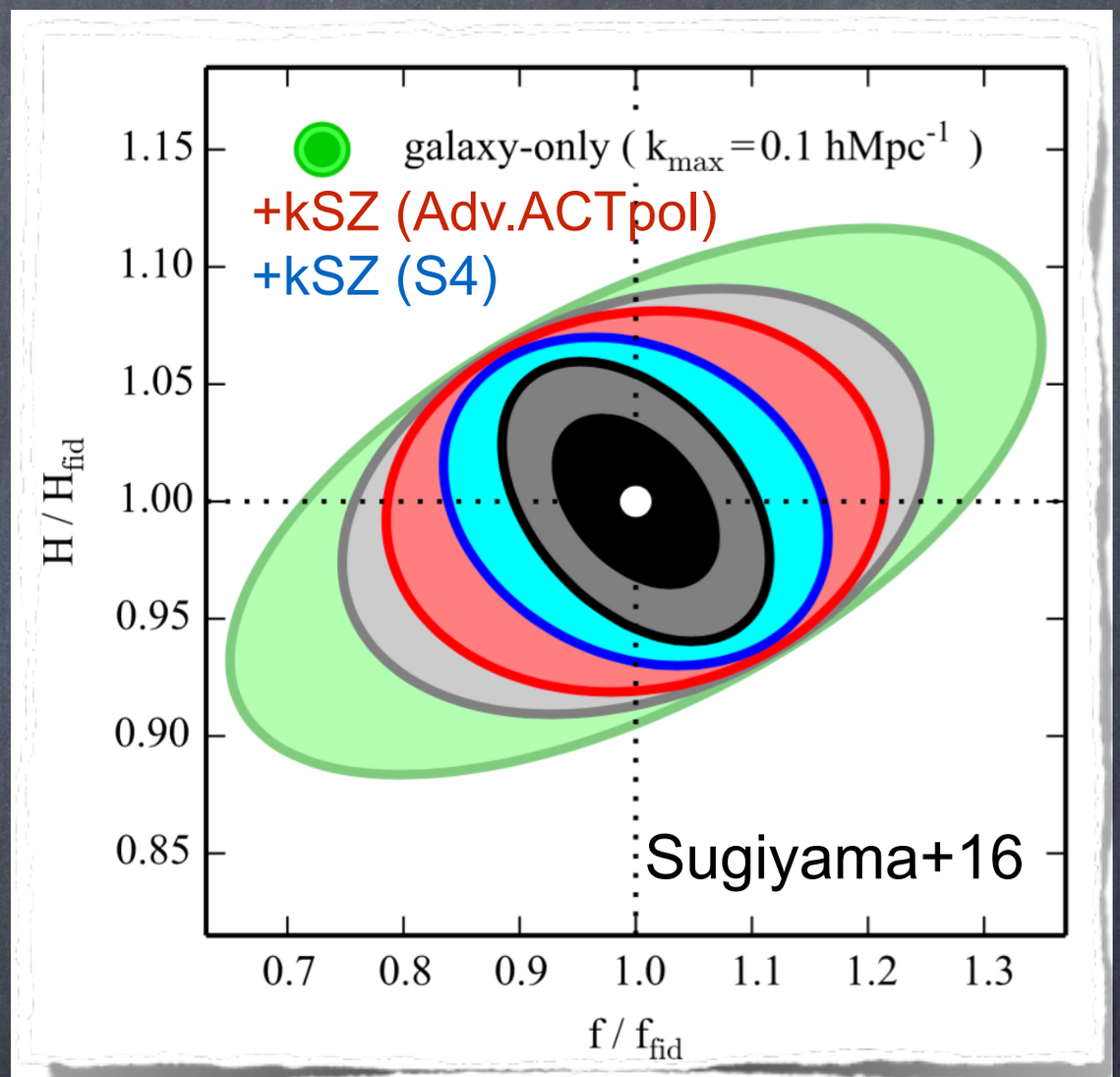
what can we learn?

kSZ Cosmology

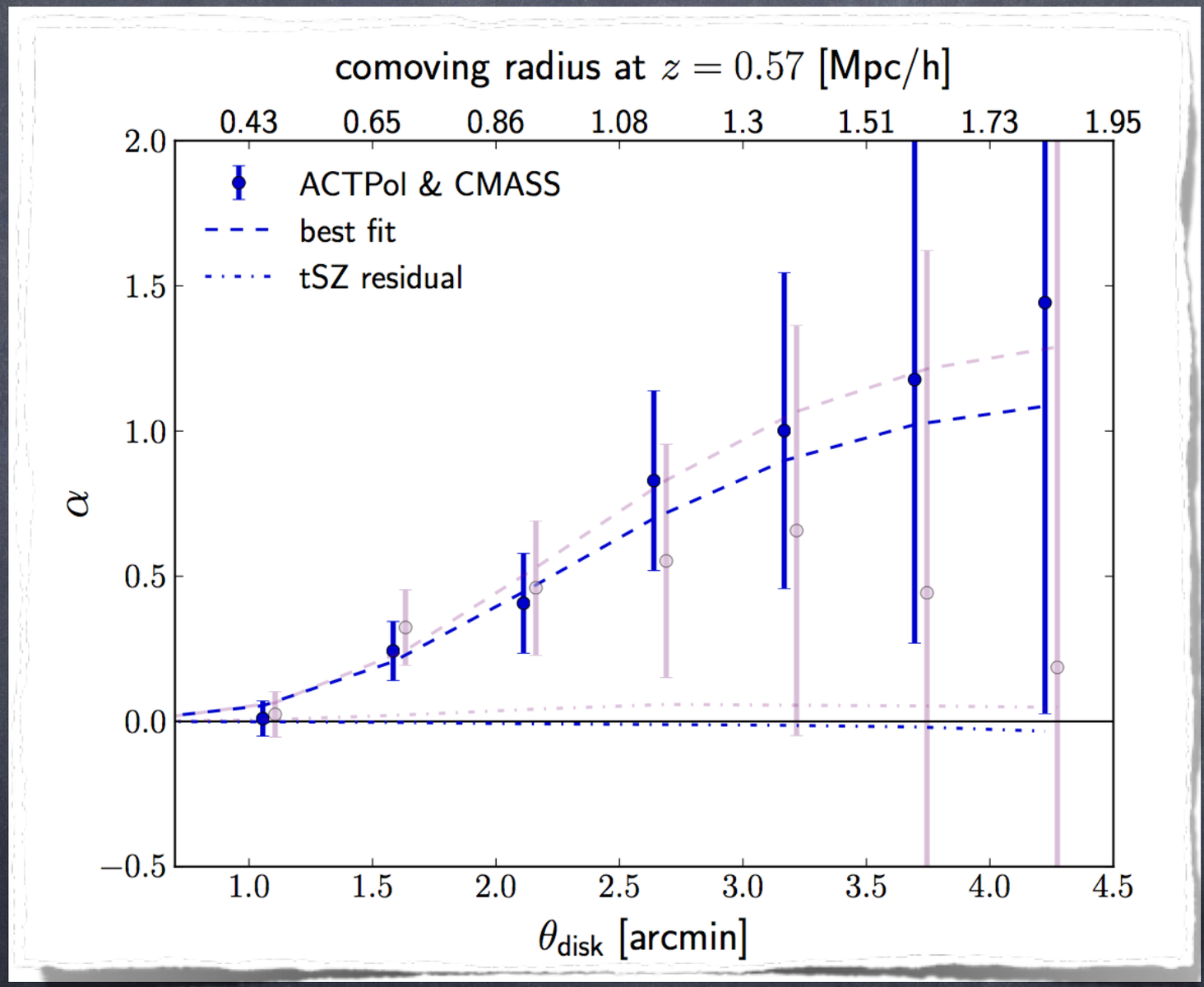


kSZ can help constrain w_0, γ



marginalized 1σ errors on H and f
improve by ~50-70%

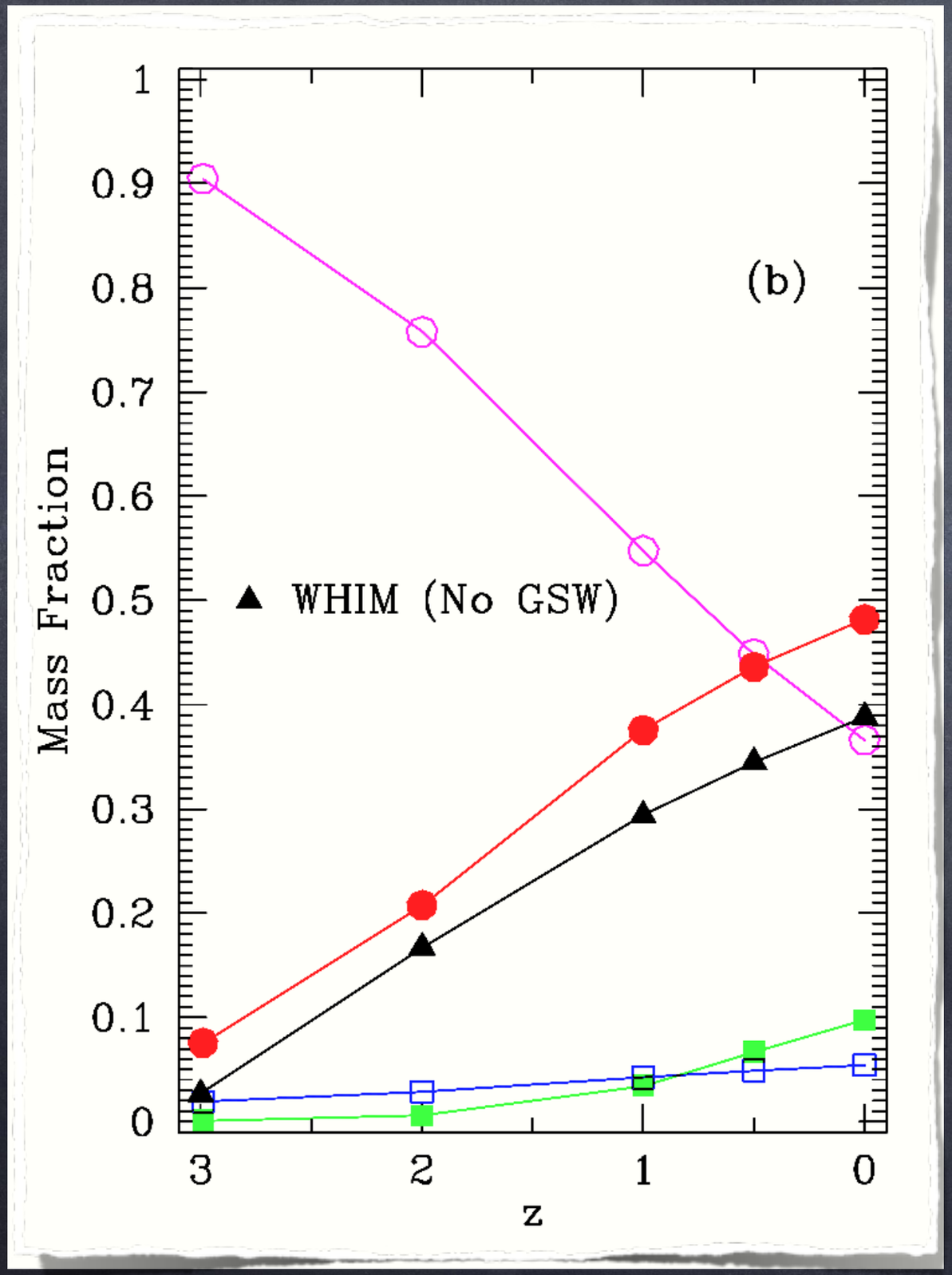
kSZ as probe of gas around halos



The kSZ signal as a probe of gas around halos out to large radii

Schaan+15

Where is the gas?



○ $T<10^5$K (Warm)

● $T=10^5-10^7$K (WHIM)

■ $T>10^7$K (Hot)

□ Galaxies (Cold)

At z=0, ~50% of baryons are in the warm-hot intergalactic medium

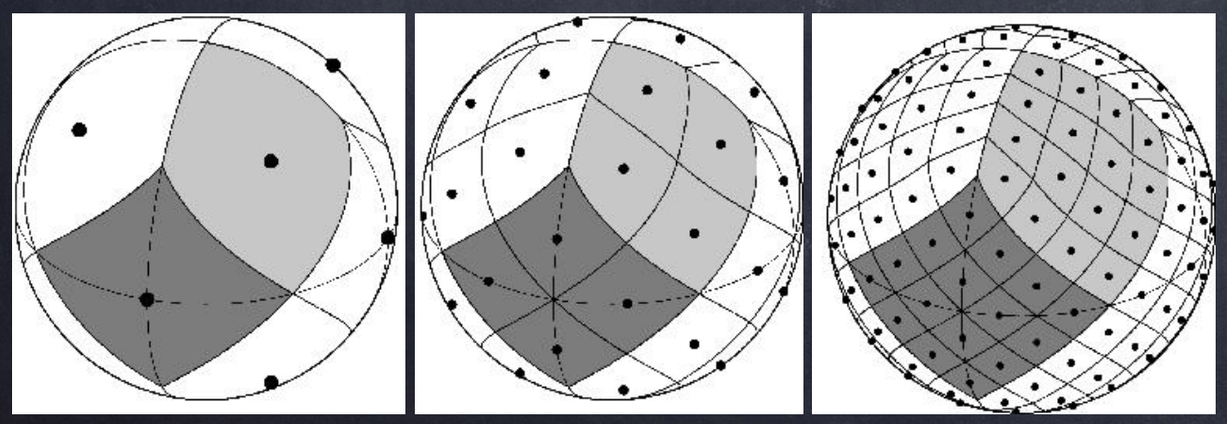
(Cen&Ostriker05)

Modeling the SZ sky

Do we understand what we measure?

Modeling the SZ signal with *N*-body simulations

- **The "Mira Universe" simulation**
  Heitmann+15
  - Mira supercomputer
  - ~200 hours on 2048 compute nodes
  - HACC (Hardware/Hybrid Accelerated Cosmology Code) (Habib et al 2014)
  - box size L=2100 Mpc
  - 30 Billion particles
  - mass resolution 10^{10} M_{sun}
  - 100 snapshots 0<z<10



nside=1 nside=2 nside=4

Particle output
1 TB per snapshot

friends-of-friends halo finder
spherical overdensity algorithm

halos

lightcone equation solver

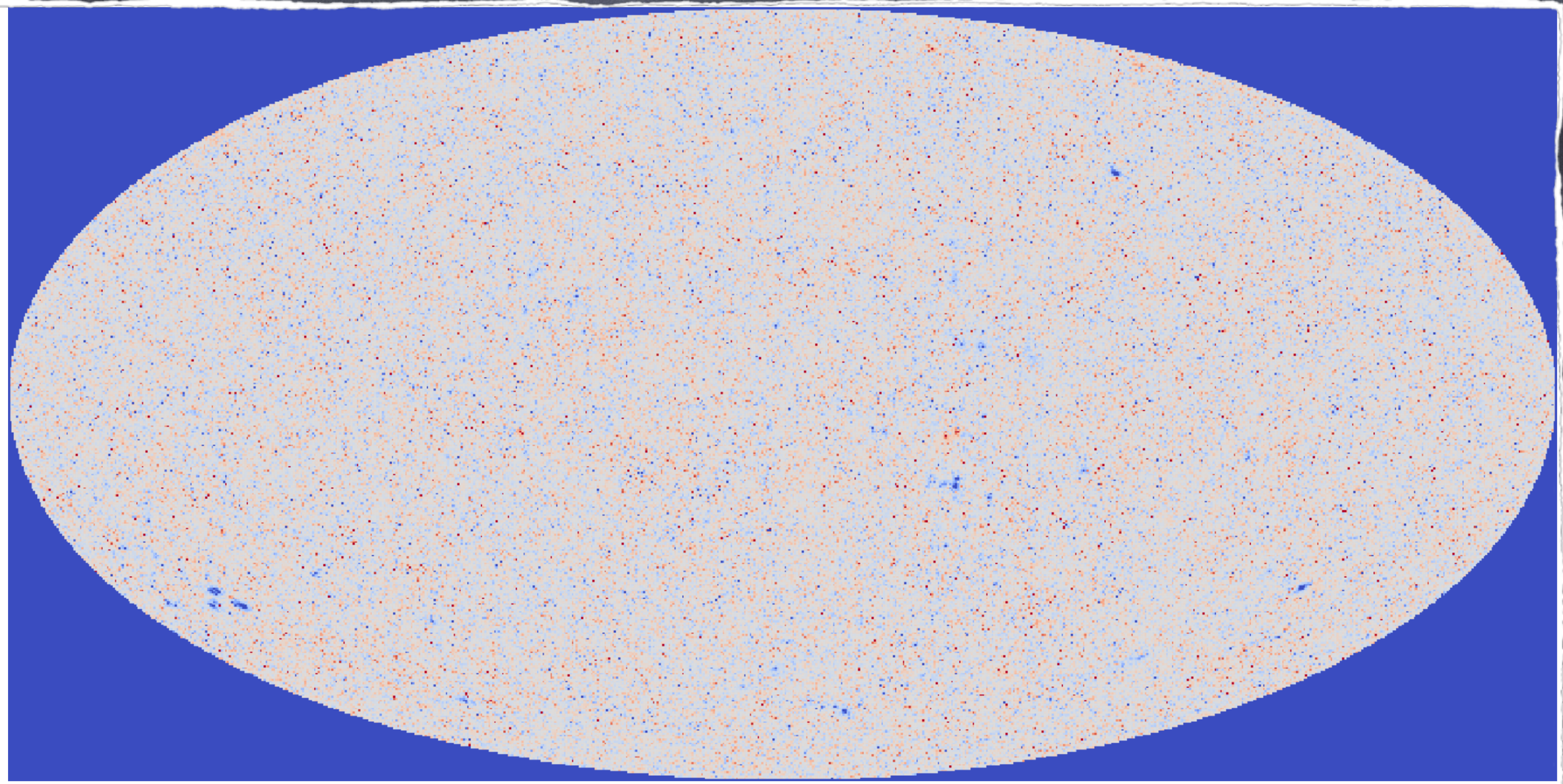
halo lightcone
17 Mio halos $M_{200}>10^{13}$ Msol/h, z<1

semi-analytic model (Shaw+10) *Healpix (Gorski+99)*

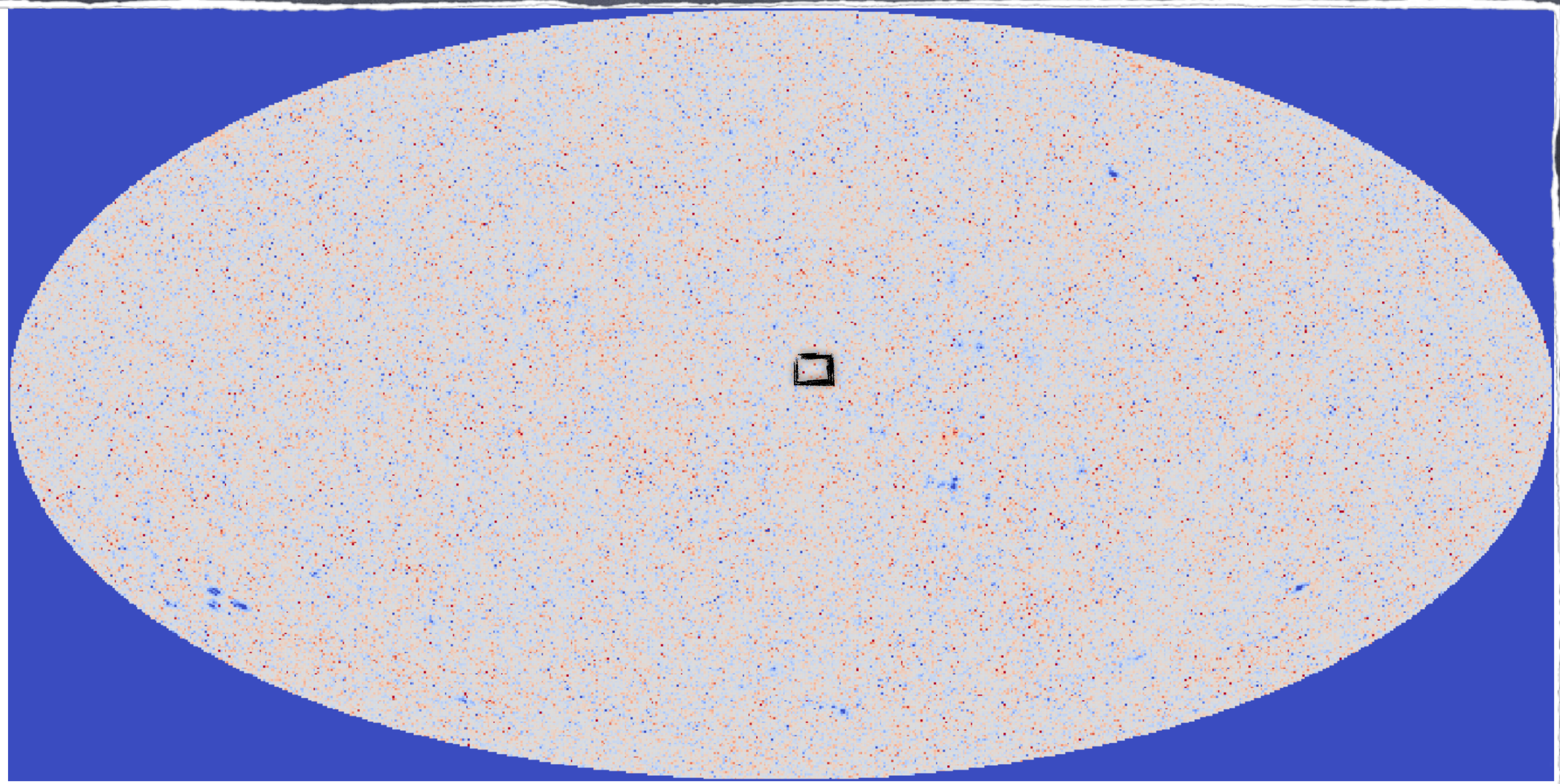
full-sky SZ map
3GB, nside=8192, npix~800Mio, pixel size 0.5'

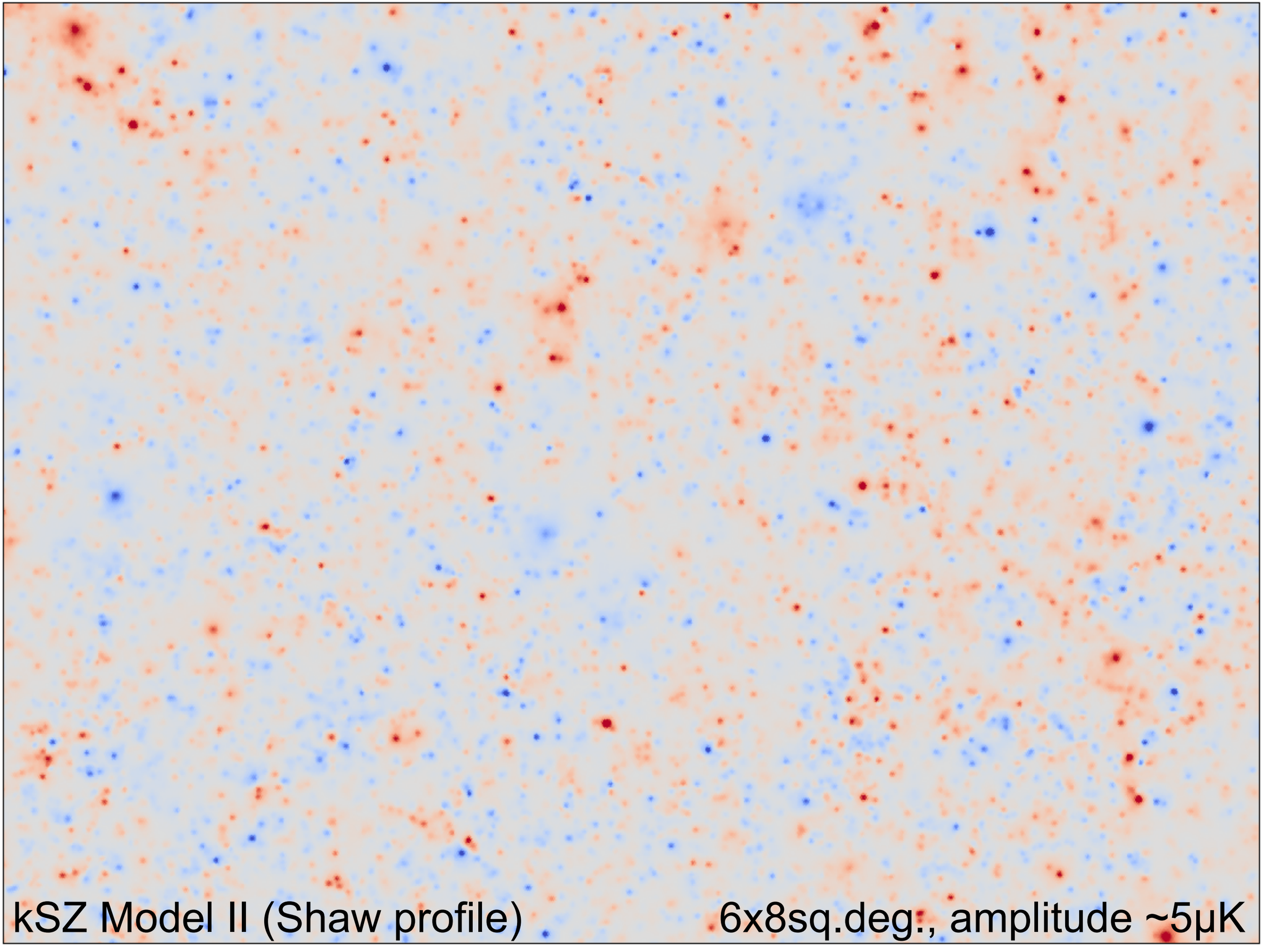
*C++, MPI; 32x12 processes: ~1hour

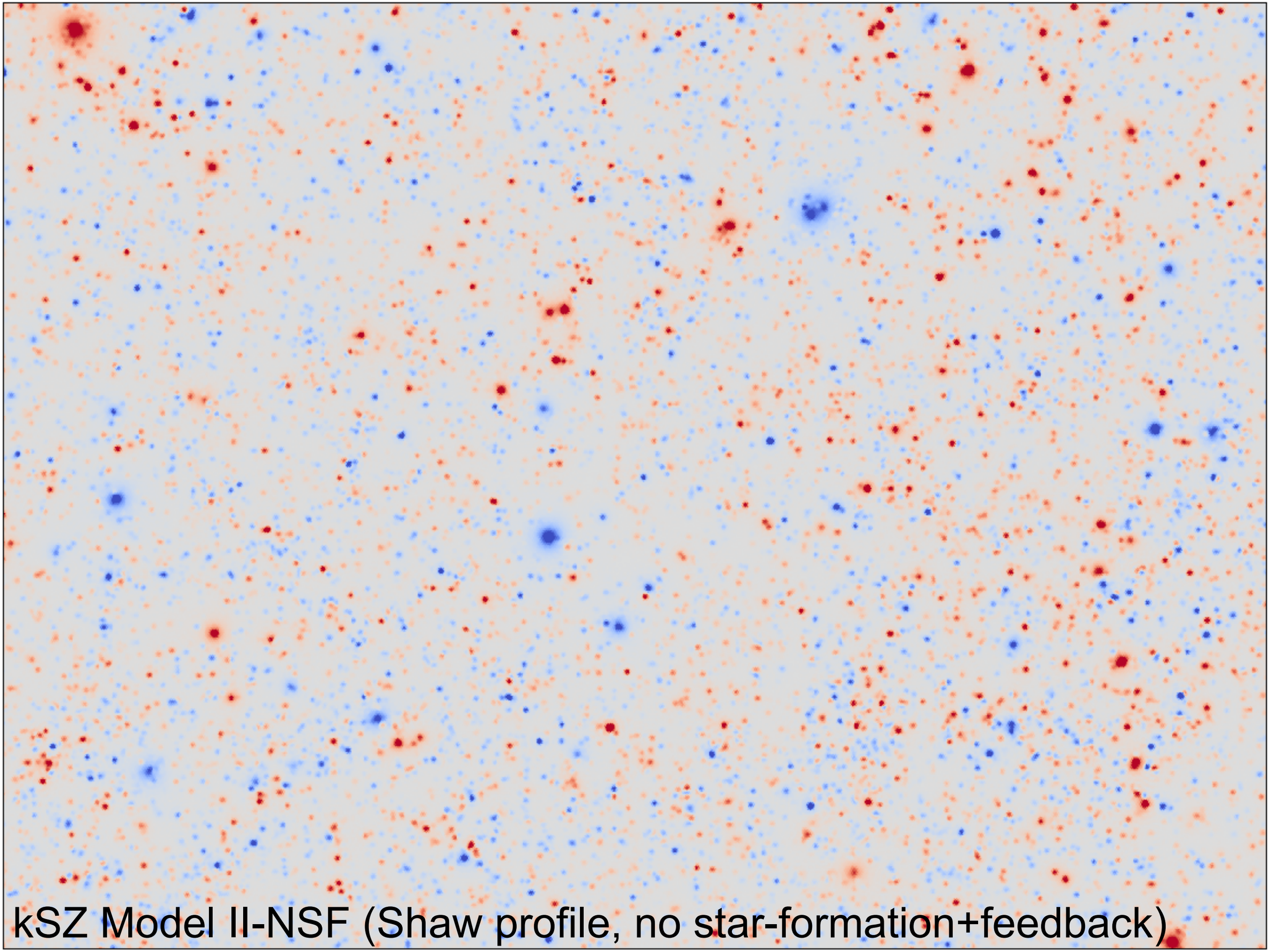
A full-sky map of the kinematic SZ signal



A full-sky map of the kinematic SZ signal

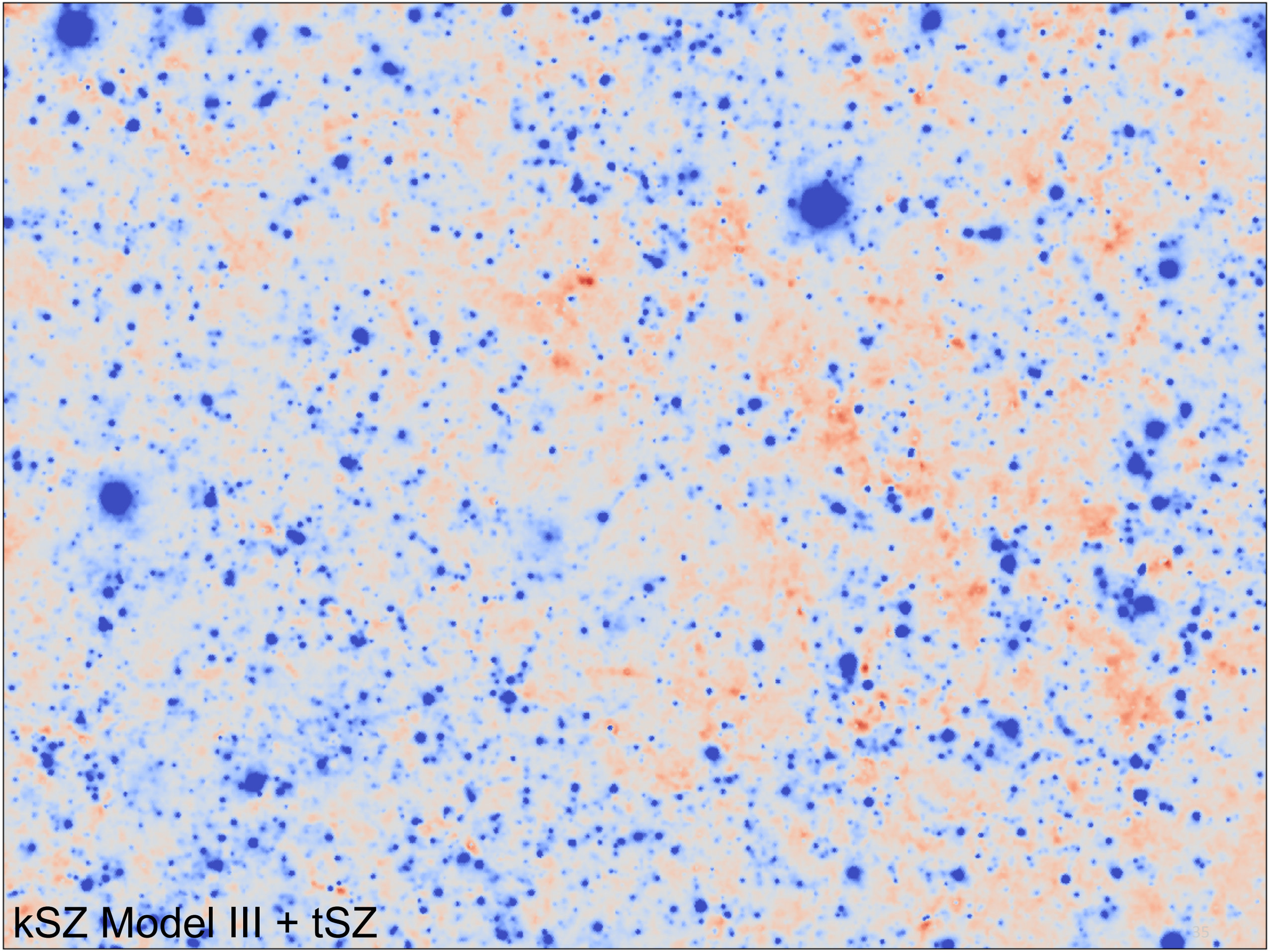


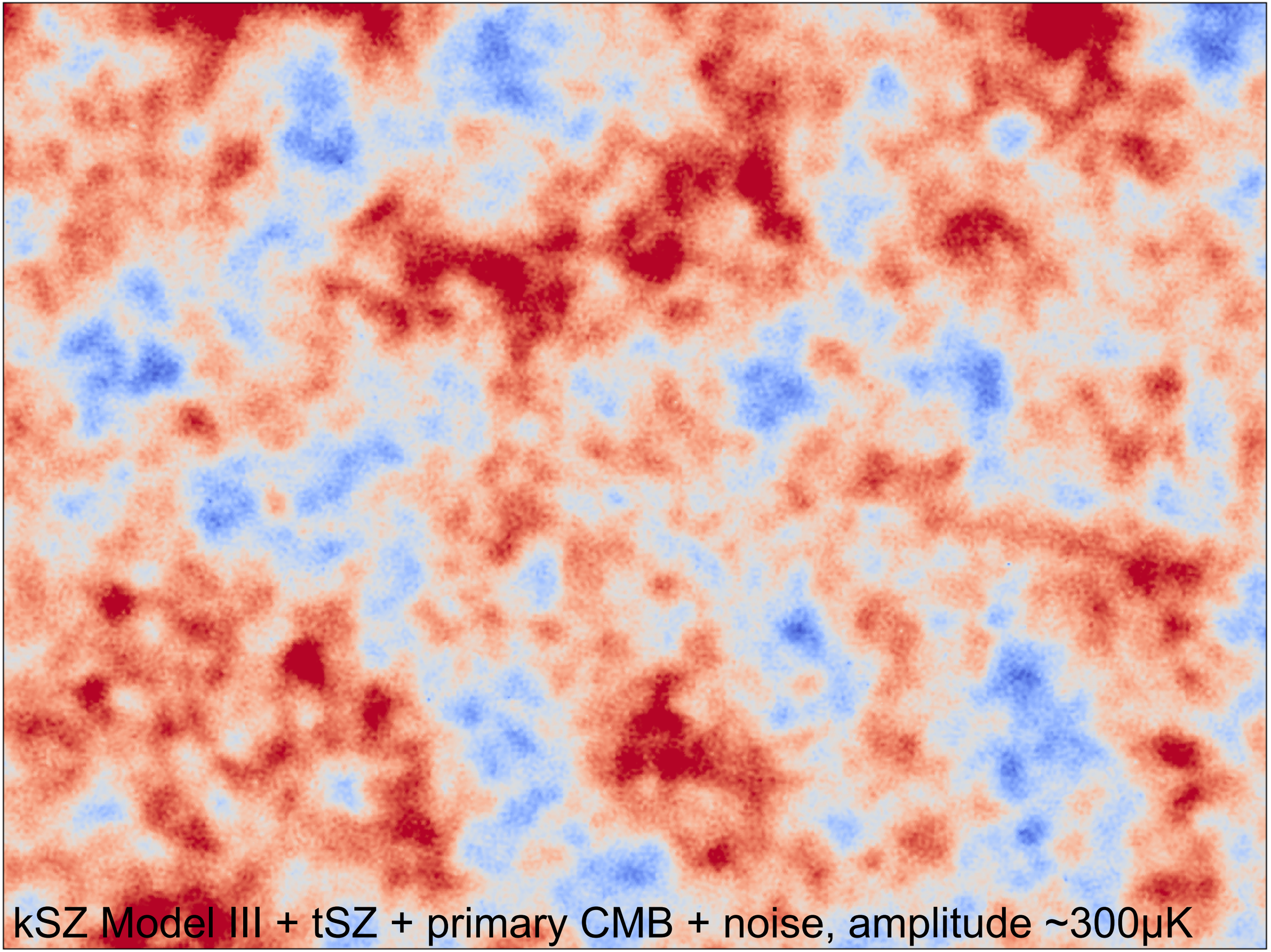

kSZ Model II (Shaw profile)
6x8sq.deg., amplitude ~5μK

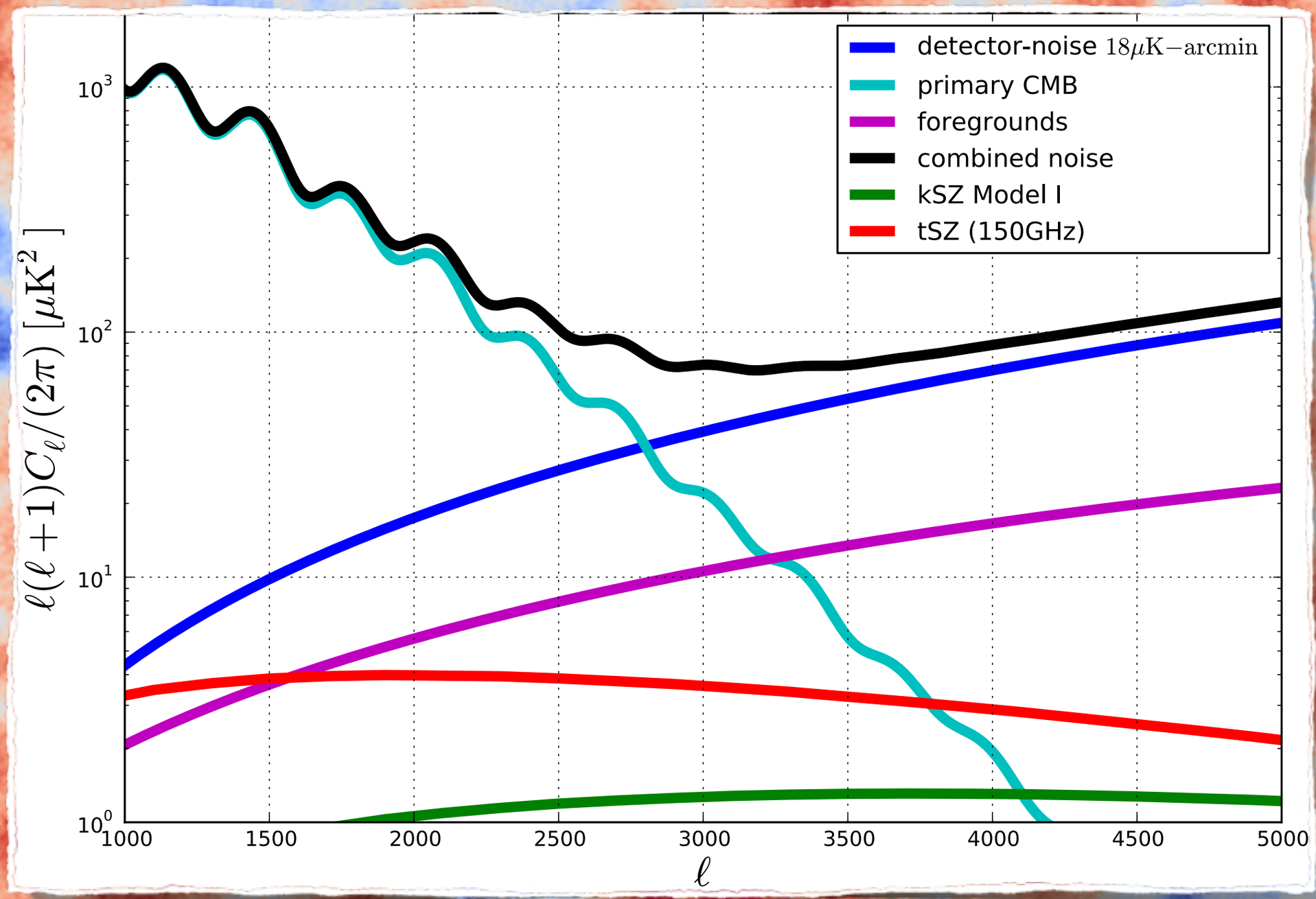

kSZ Model II-NSF (Shaw profile, no star-formation+feedback)

kSZ Model II (Shaw profile)

kSZ Model III (Shaw profile + filaments)


kSZ Model III + tSZ


kSZ Model III + tSZ + primary CMB + noise, amplitude ~300μK



kSZ Model III + tSZ + primary CMB + noise

The matched filter:

signal profile noise spectrum

$$\Psi_{\ell m} = \frac{\tau^{\star}_{\ell m} / N_{\ell}}{\sum_{\ell m} |\tau^{2}_{\ell m}| / N_{\ell}}$$

kSZ Model III + tSZ + primary CMB + noise

kSZ Model III + tSZ + primary CMB + noise, matched-filtered

The pairwise estimator:

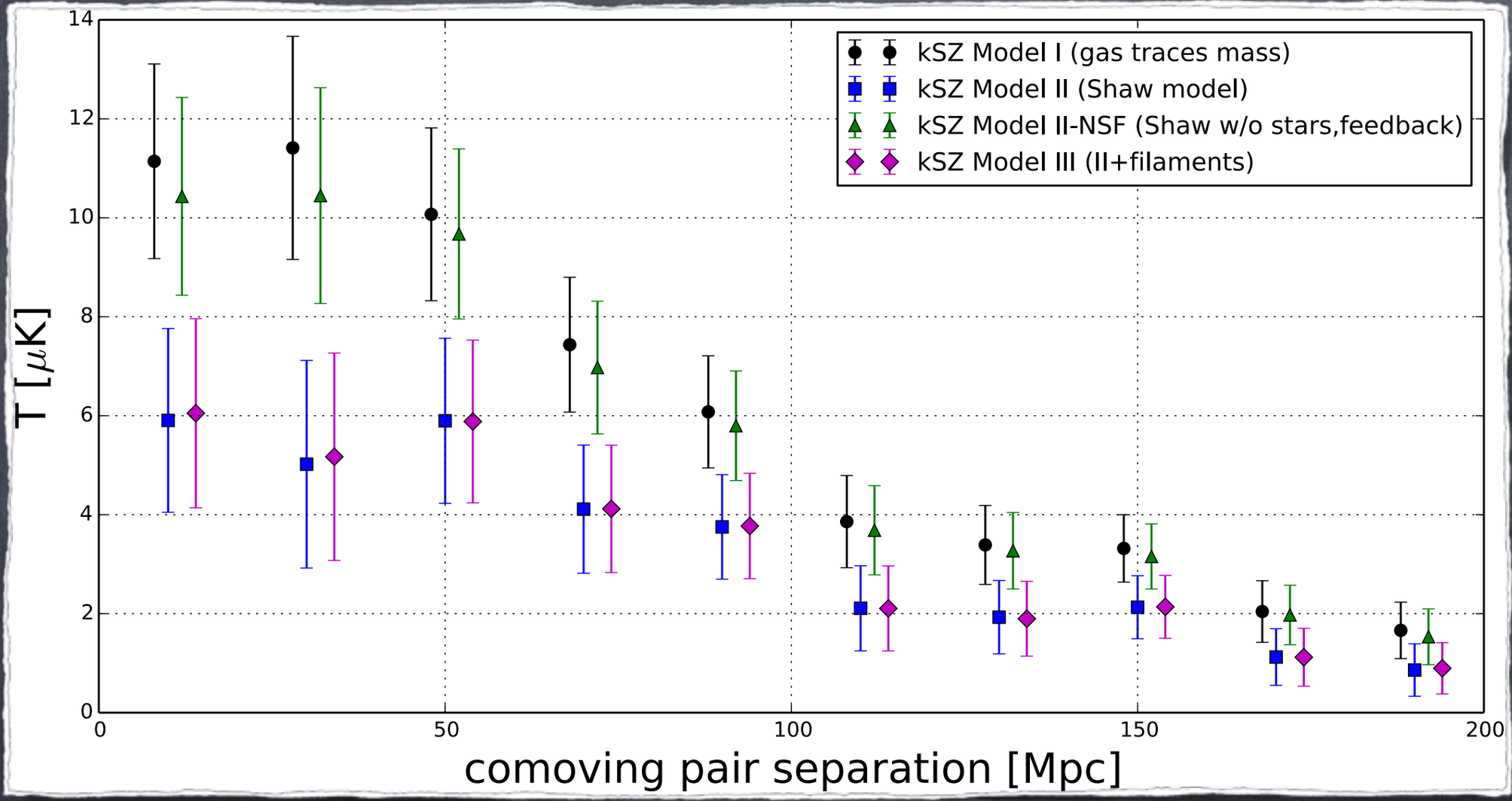
$$\hat{T}_{\rm kSZ} = \frac{\sum_{ij} c_{ij} T_{ij}}{\sum_{ij} c_{ij}^2}$$

$$c_{ij} = \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2}$$

Ferreira+98, Hand+12

kSZ Model III + tSZ + primary CMB + noise, matched-filtered

Simulated pairwise kSZ signal



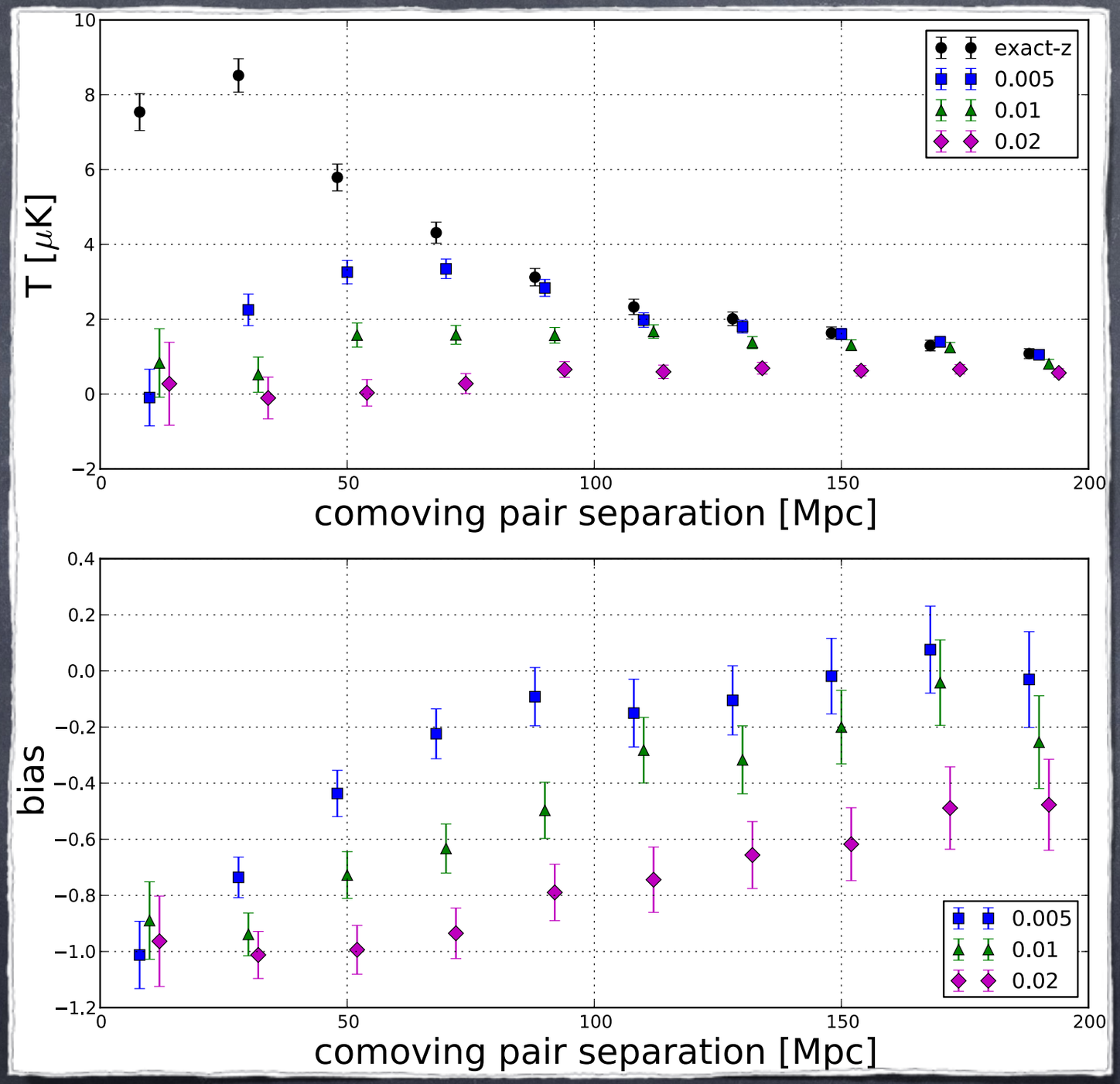
$$\hat{T}_{\rm kSZ} = \frac{\sum_{ij} c_{ij} T_{ij}}{\sum_{ij} c_{ij}^2}$$

$$c_{ij} = \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2}$$

* astrophysical effects suppress the pairwise kSZ signal by a factor ~2

Flender et al, ApJ 823 (2016)

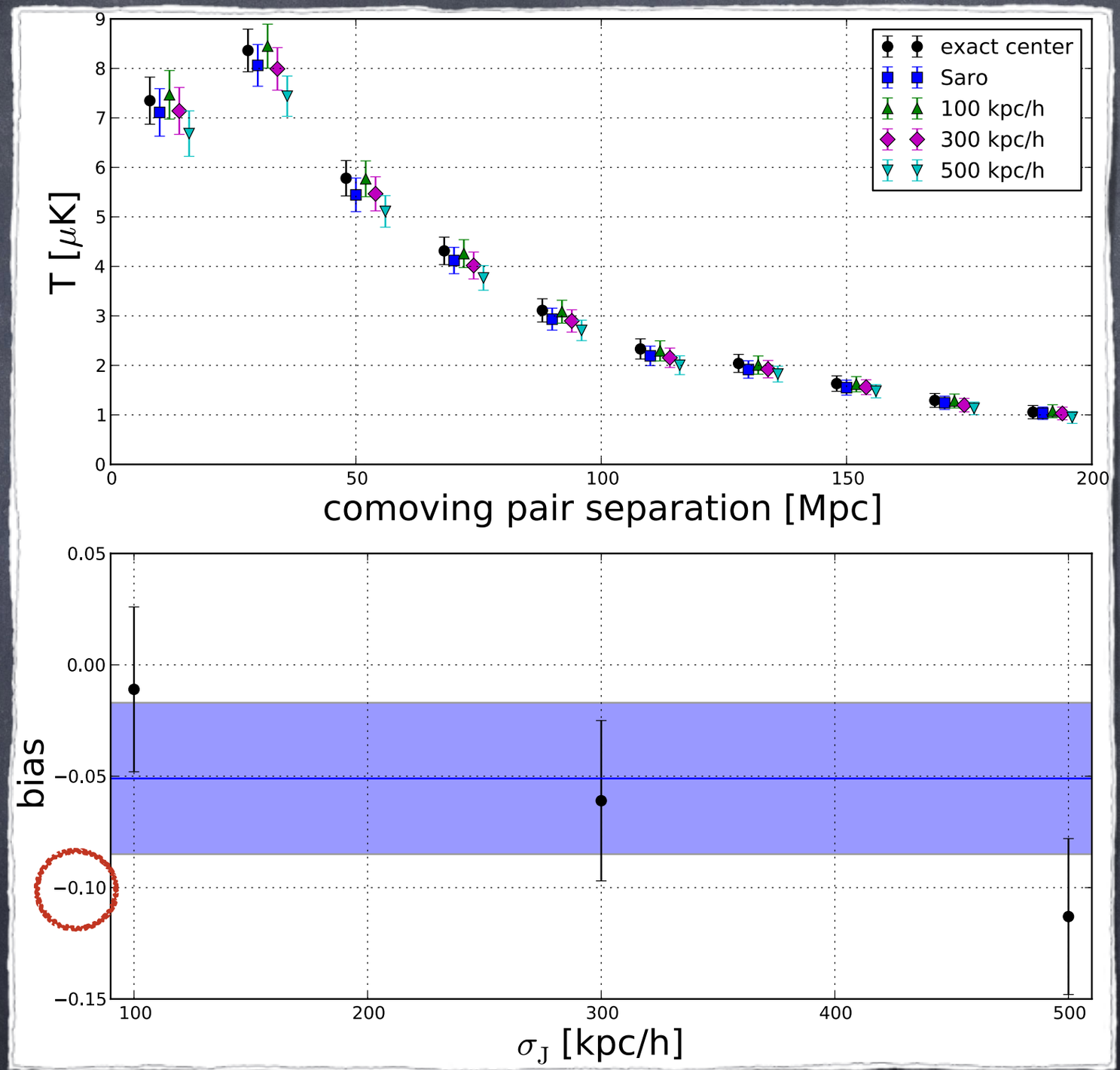
Impact of photometric redshift errors



complete suppression

redshift errors can completely suppress the signal at small separations!

Impact of mis-centering



10% bias

Saro+15
mis-centering model

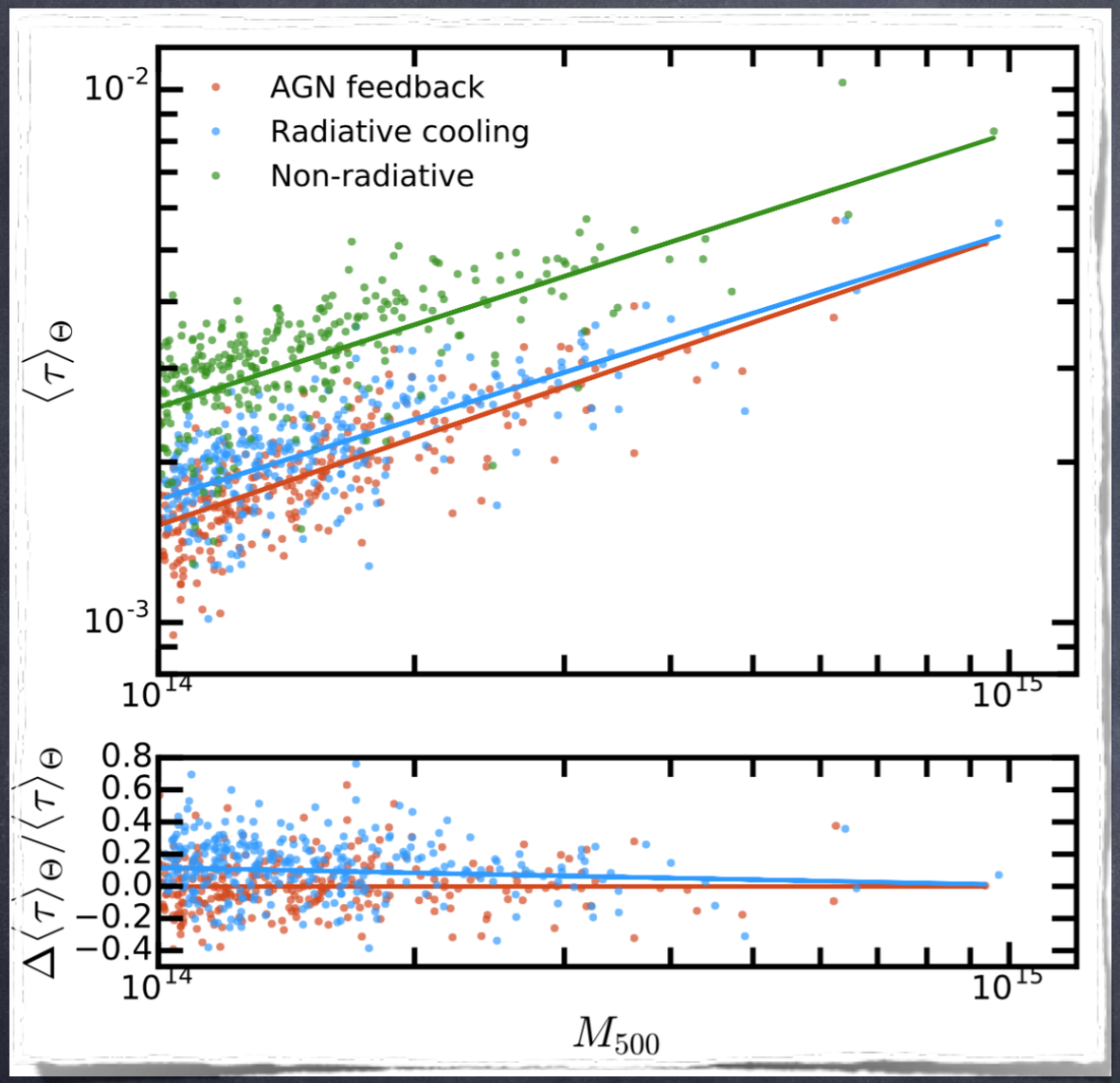
Mis-centering can bias the signal low by up to 10%

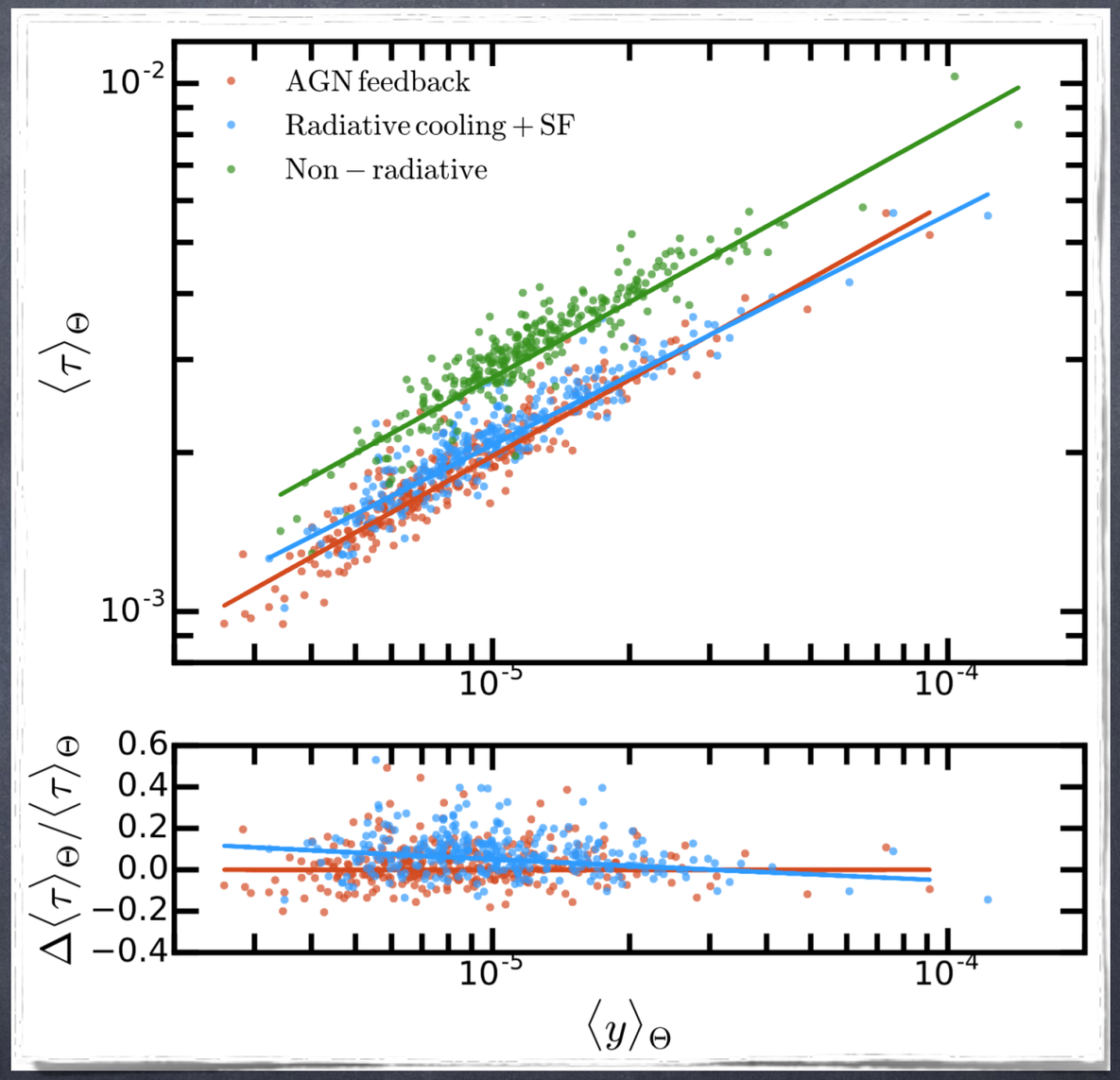
Modeling the gas in galaxy clusters

goal: percent-level constraints on τ

Hydrodynamical simulations

(Battaglia 2016)





- simple scaling relations τ-M, τ-y
- however: ~50% modeling uncertainty (different subgrid models)
- can we do better?

Simulation vs semi-analytic modeling

- **Hydrodynamical simulations**
  - pro: follows detailed hydrodynamical evolution of ICM
  - con: results depend on sub-grid modules
  - con: need large simulation boxes + high resolution computationally very expensive —> cannot explore many different models

- **Semi-analytic modeling**
  - *con*: need to simplify the physics
  - *pro*: computationally efficient
  - *pro*: can be observationally calibrated using MCMC
  - idea: constrain τ using an observationally calibrated, semi-analytic model

The ICM model

$$\frac{dP_{\rm tot}(r)}{dr} = -\rho_g(r)\frac{d\Phi(r)}{dr}$$

$$P_{tot} \propto \rho_g^{\Gamma}$$

hydrostatic equilibrium ✓

$$F_*(M_{500}) = f_* \times \left(\frac{M_{500}}{3\times10^{14}\,M_\odot}\right)^{-S_*}$$

stars form, depending on mass ✓

$$E_{g,f} = E_{g,i} + \epsilon_{\rm DM}|E_{DM}| + \epsilon_{\rm f} M_* c^2 + \Delta E_p$$

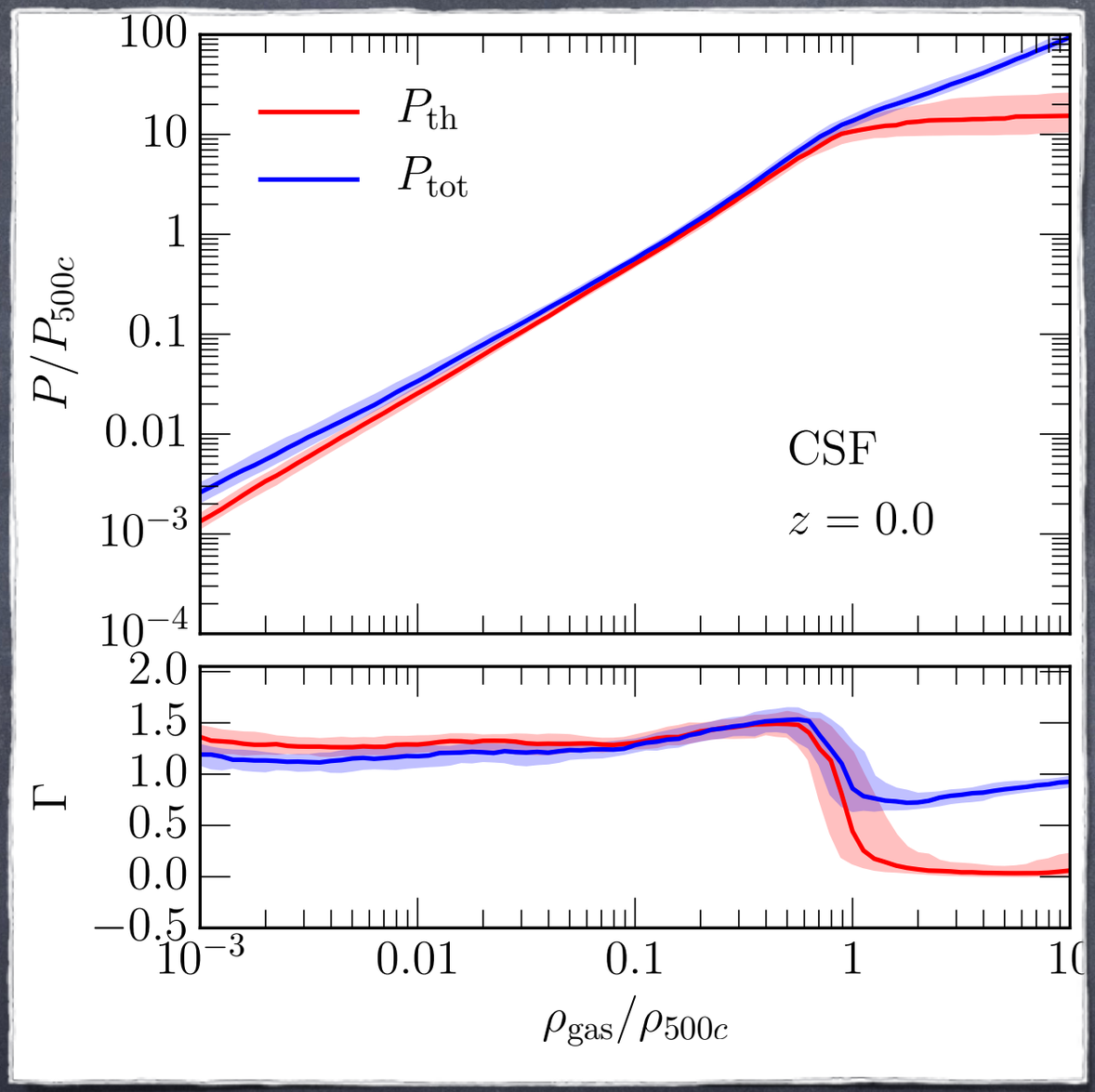
energy feedback ✓

$$\frac{P_{nt}}{P_{tot}}(z) = \alpha(z)\left(\frac{r}{R_{500}}\right)^{n_{nt}}$$

non-thermal pressure ✓

Ostriker et al (2005), Bode & Ostriker (2006), Shaw et al (2010)

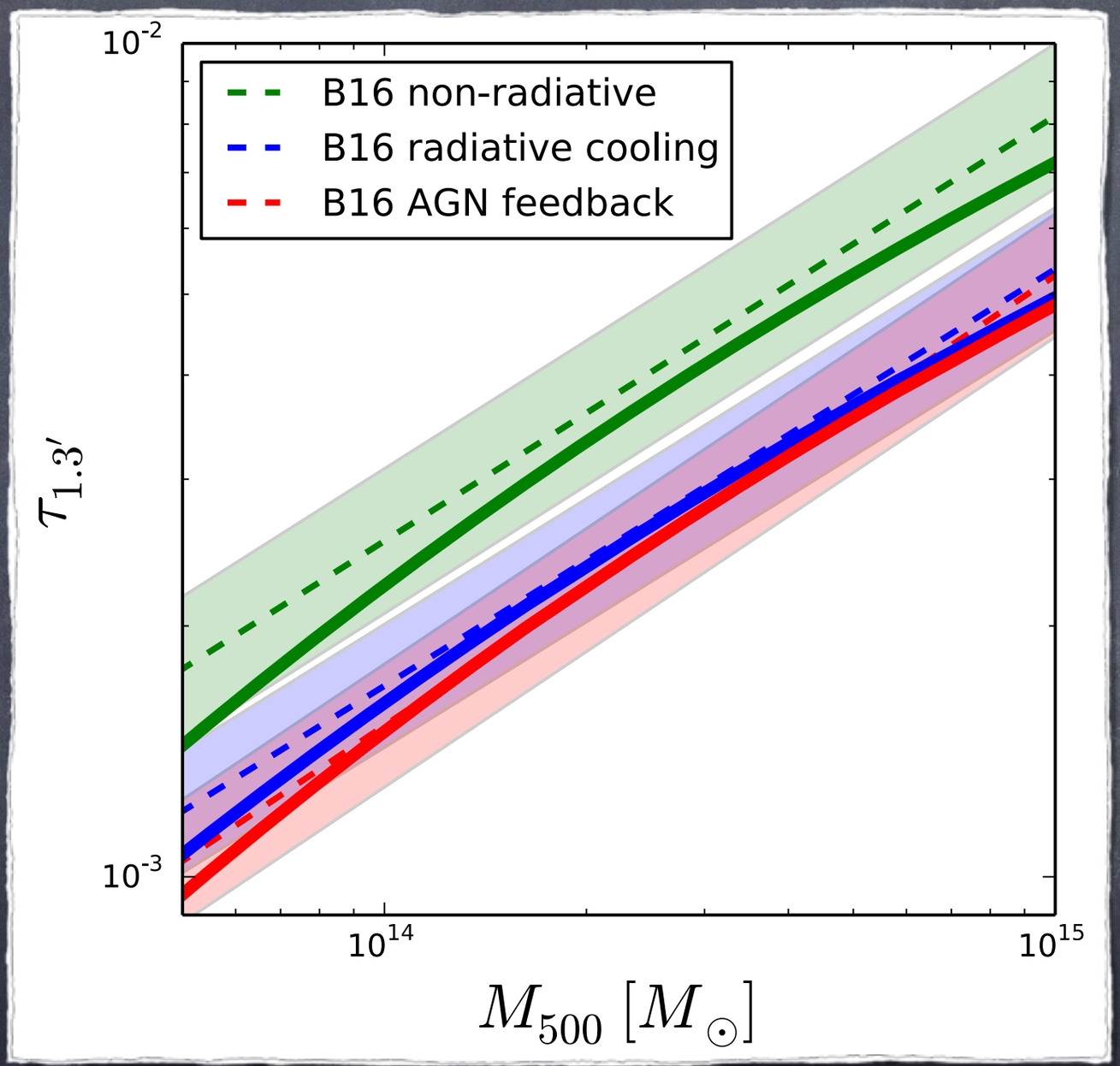
5. Cooling



plot by Erwin Lau

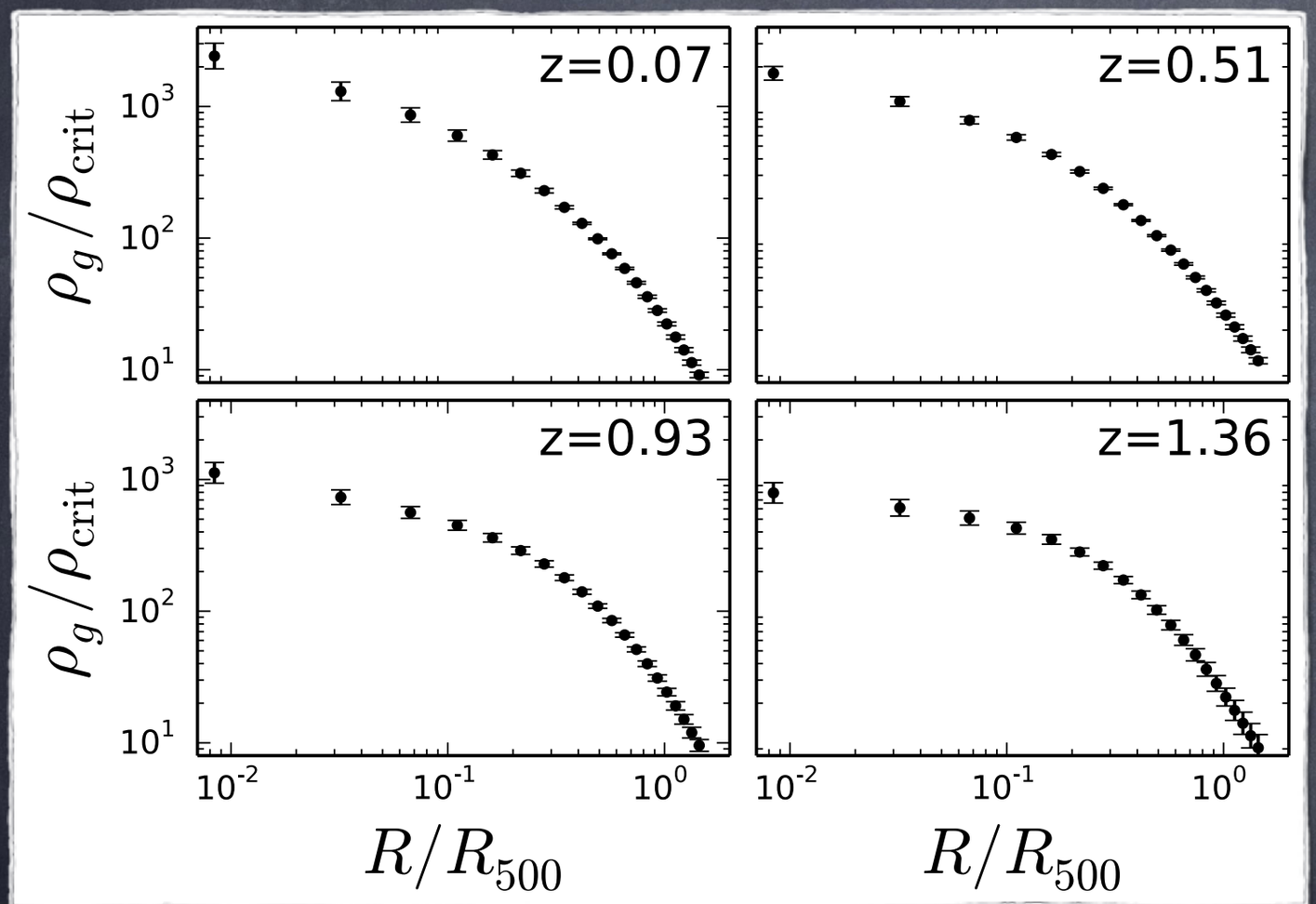
$$\Gamma = \begin{cases} 1.2 & r/R_{500} > x_{\rm break} \\ \tilde{\Gamma}(1+z)^{\gamma} & r/R_{500} \leq x_{\rm break} \end{cases}$$

Comparison to hydrodynamical simulations

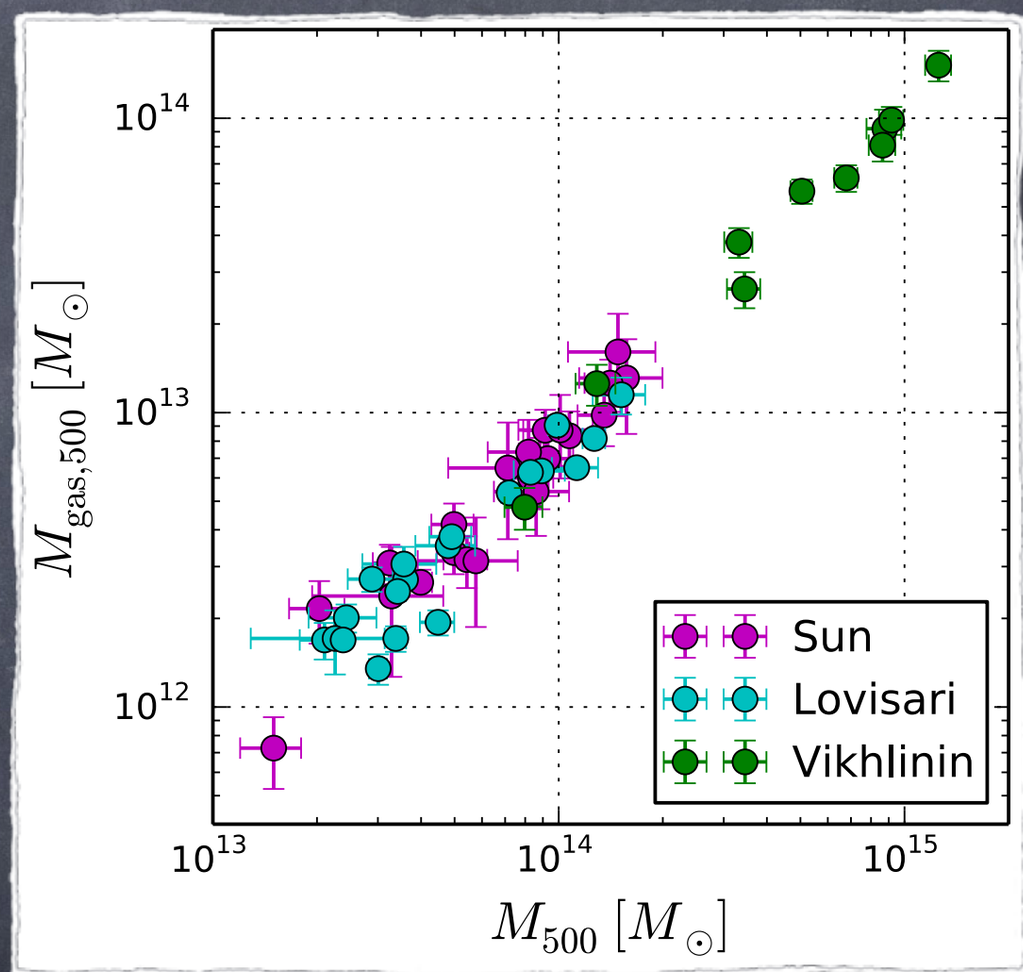


Our model is computationally efficient and can reproduce results from hydrodynamical simulations

The data

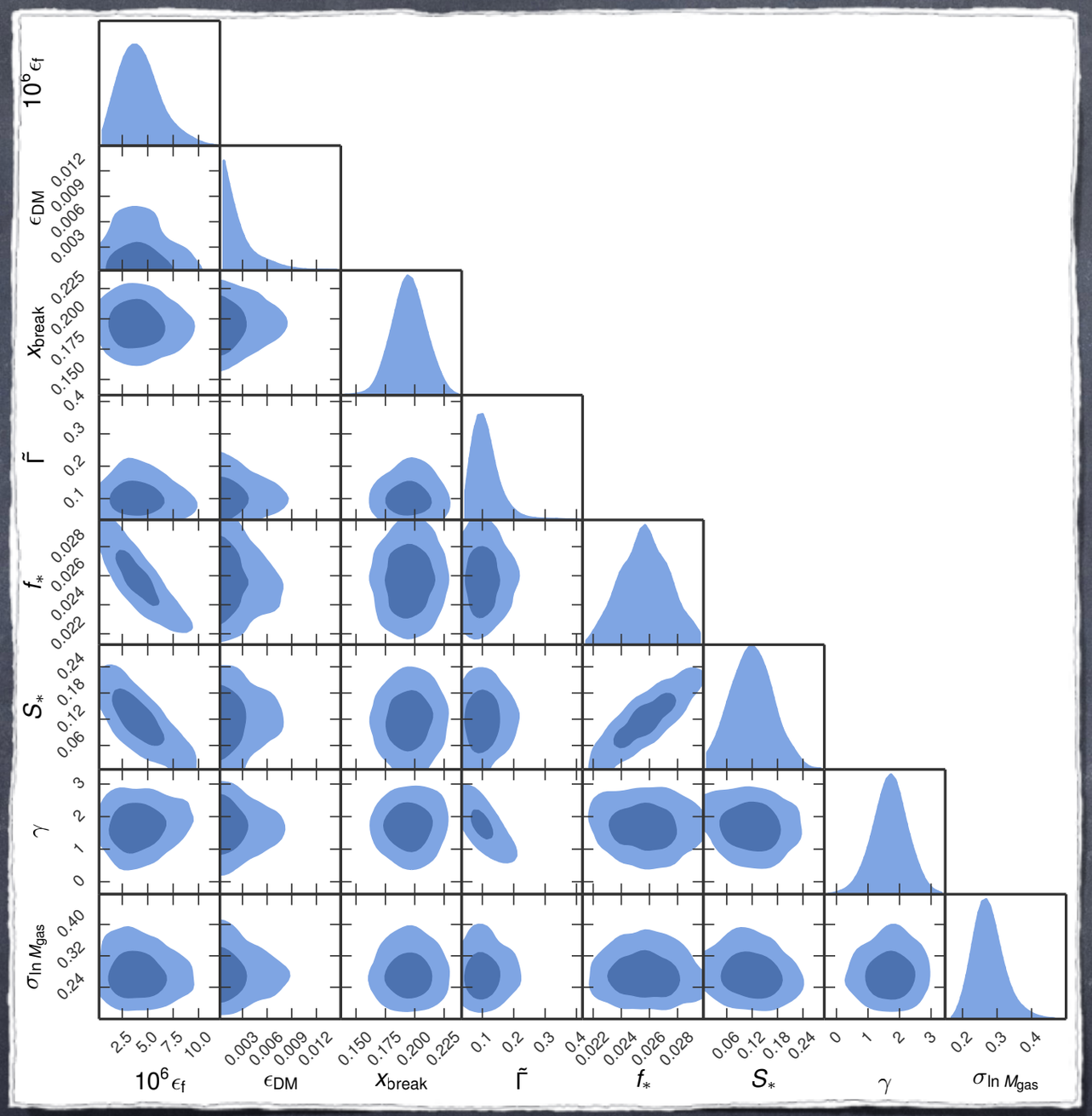


Chandra measurements of gas density profiles of SPT-selected clusters (McDonald+2013)



gas mass measurements (Vikhlinin+06, Sun+09, Lovisari+15)

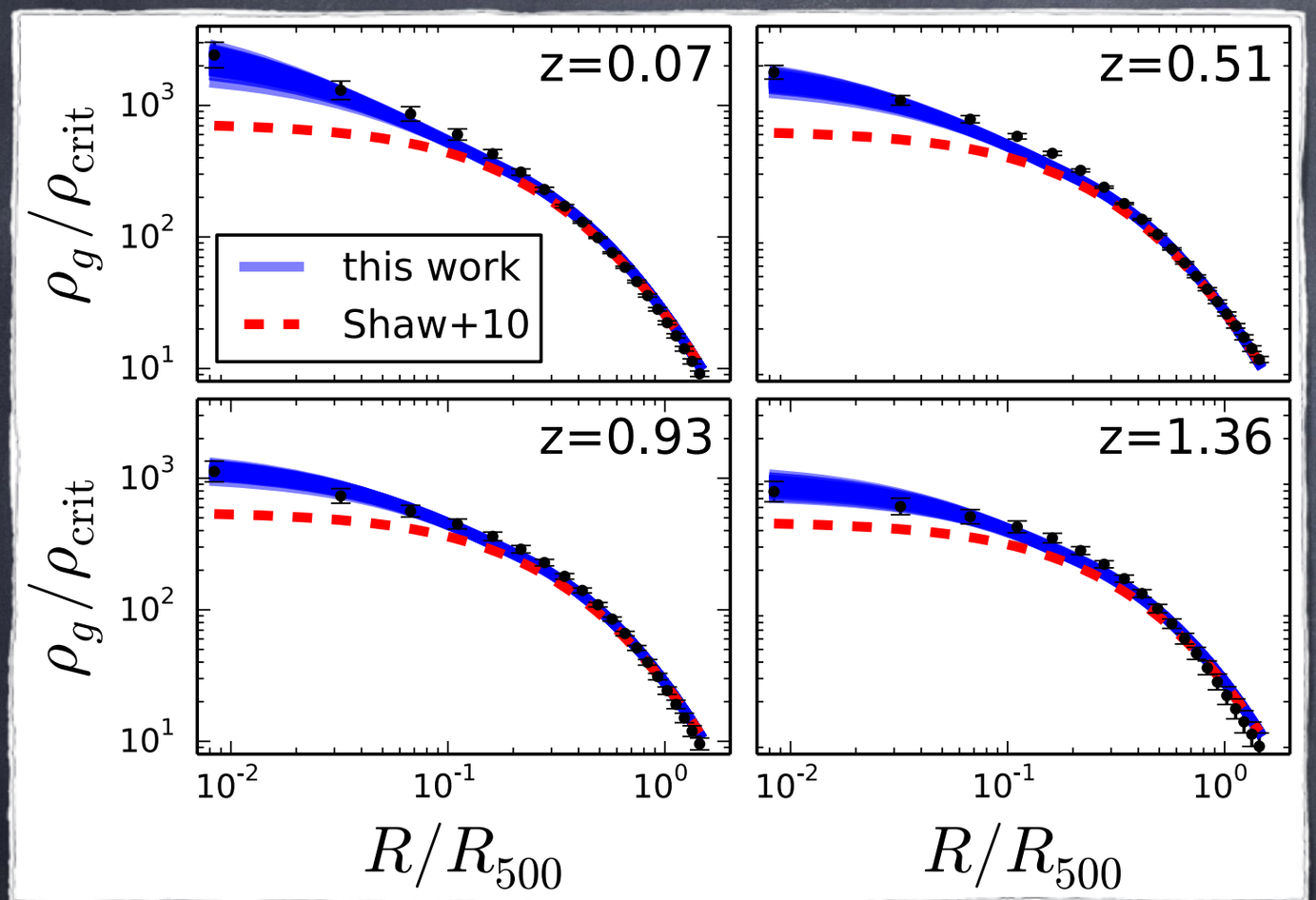
Parameter contours

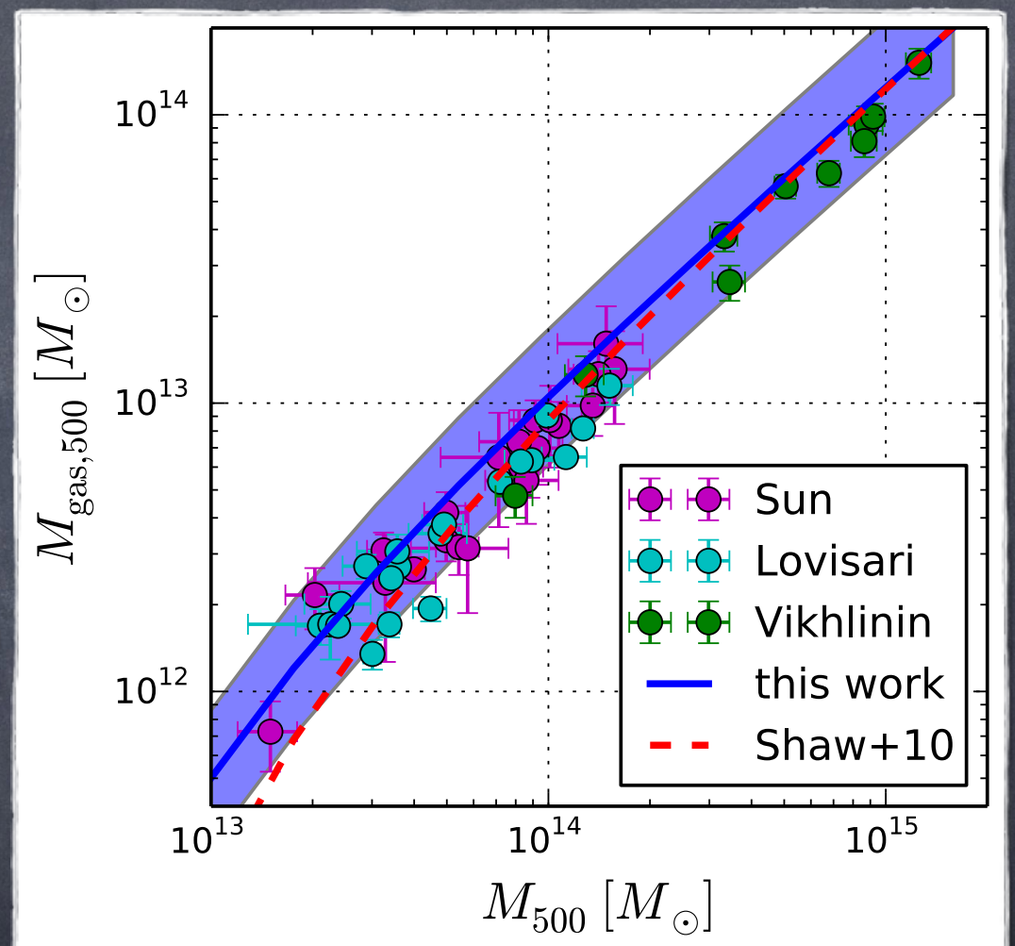


estimated probability contours, using Markov-chain Monte-Carlo algorithm

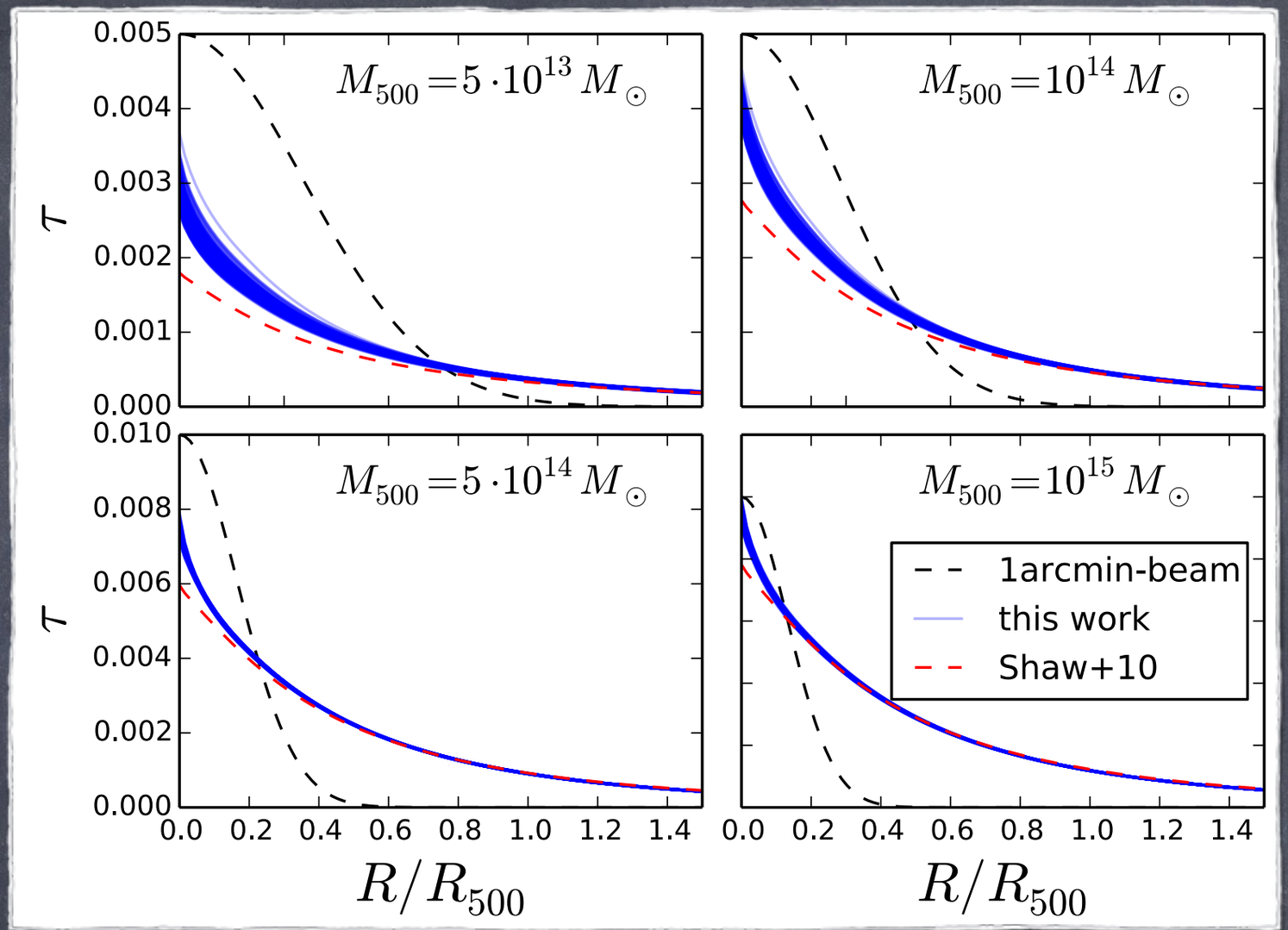
- `emcee*, mpi4py` (Python)
  *http://dan.iel.fm/emcee/current/
- 240 MPI processes (24 per compute node): ~30 minutes

Result: a calibrated model





Prediction for τ



$M_{500}/M_\odot$	$10^3\tau(r=0)$	$10^3\tau(r=R_{500})$	$10^3\tau_{500}$
5×10^{13}	2.84 ± 0.34 (12%)	0.37 ± 0.02 (4.7%)	0.71 ± 0.04 (6.3%)
10^{14}	3.97 ± 0.29 (7.2%)	0.28 ± 0.02 (3.5%)	0.96 ± 0.02 (3.9%)
5×10^{14}	7.27 ± 0.27 (3.6%)	0.90 ± 0.01 (1.2%)	1.82 ± 0.01 (0.8%)
10^{15}	9.32 ± 0.37 (4%)	1.18 ± 0.01 (0.8%)	2.36 ± 0.02 (1%)

Flender, Nagai, McDonald, ApJ 837 (2017)

Summary

- We can (and did) measure the **relative motion of galaxy clusters** using their kinematic SZ signature.

- **Gas matters**: the amplitude of the kSZ signal depends strongly on astrophysical effects (factor of ~2 effect)

- **Semi-analytic modeling** is a valuable tool for understanding the gas and SZ signal (~6% calibration of average τ)

- Our prior on τ can be implemented into future pairwise kSZ analyses