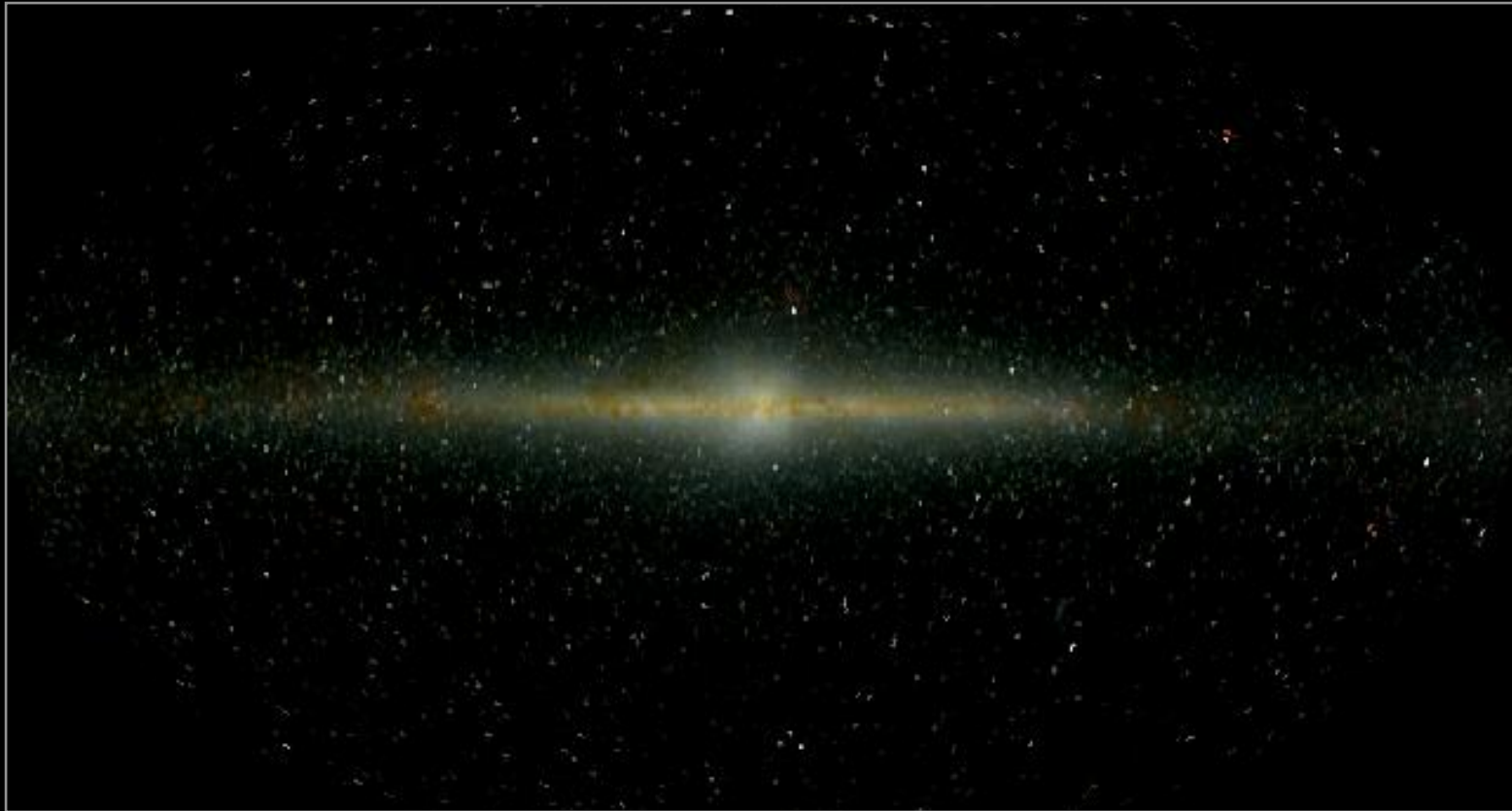# Accretion through cosmic time

J. Bland-Hawthorn (University of Sydney)

"The history of cosmology shows that in every age devout people believe that they have at last discovered the true nature of the Universe."

How does research on galaxies relate to cosmology?

"It is not too much to say that the understanding of why there are these different kinds of galaxy, of how galaxies originate, constitutes the biggest problem in present day astronomy.

The properties of individual stars that make up the galaxies form the classical study of astrophysics, while the phenomena of galaxy formation touches on cosmology.

In fact, the study of galaxies forms a bridge between conventional astronomy and astrophysics on the one hand, and cosmology on the other."

HOYLE 1966

"Half of all cosmology lies in the near field – therefore we can speak of near field cosmology."
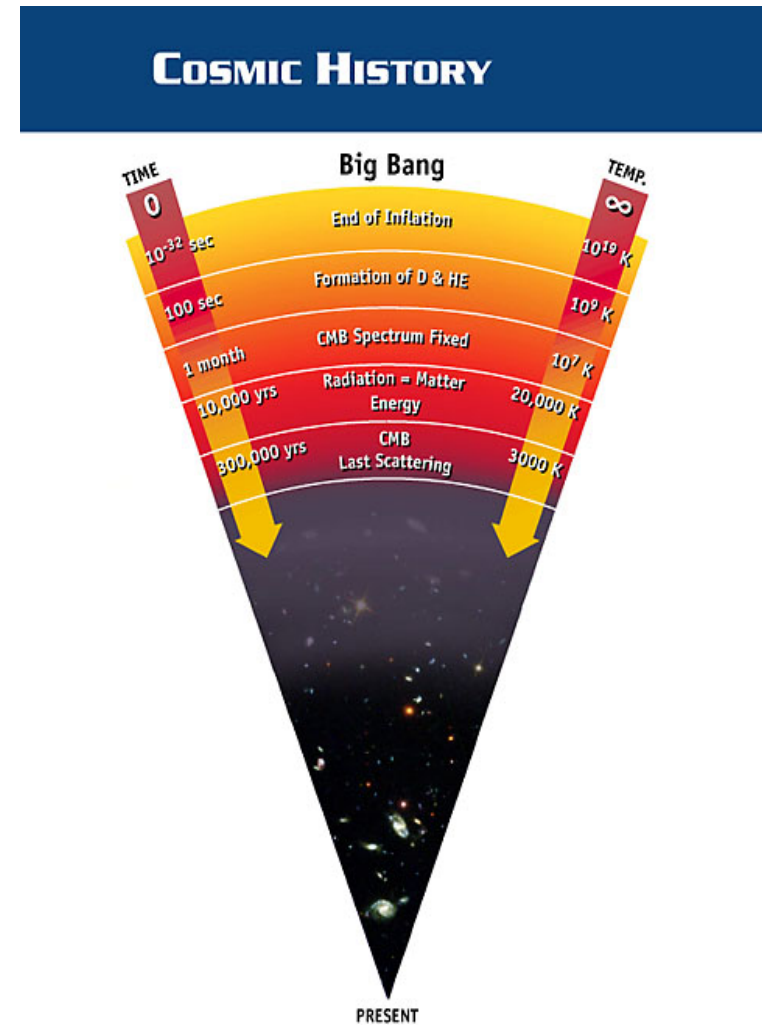
JBH & Freeman 2000-2004; JBH & Peebles 2006

Overview of lecture series

- ❖ A brief history of the universe
- ❖ The story of dark matter
- ❖ First seeds: gaussian random field
- ❖ Gravitational instability on linear scales
- ❖ Silk damping
- ❖ Cosmic microwave background
- ❖ Definition of the standard model
- ❖ Gravitational instability on non-linear scales
- ❖ Extended Press-Schechter theory
- ❖ Zeldovich approximation & Burger's equation
- ❖ Build-up of angular momentum
- ❖ Galaxy formation: spheroids
- ❖ Galaxy formation: disks
- ❖ Gas processes
- ❖ The Local Group

Potted history of the universe

– The universe starts out hot, dense and filled with radiation

– As the universe expands, it cools

  • During the first 3 minutes, particles form
  • After 370,000 years, atoms form
  • After 150,000,000 years, stars form
  • After 400,000,000 years, galaxies and quasars form
  • After 9,000,000,000 years, the Solar System was formed
  • After 13,700,000,000 years, the University of Bologna was formed

COSMIC HISTORY

Big Bang

TIME   TEMP.

0   ∞

End of Inflation

10^{-32} sec 10^{19} K

Formation of D & HE

100 sec 10^{9} K

CMB Spectrum Fixed

1 month 10^{7} K

Radiation = Matter Energy

10,000 yrs   20,000 K

CMB Last Scattering

300,000 yrs   3000 K

PRESENT

Bland-Hawthorn (Bologna 2011)

Reading: early stages of structure formation

Peebles 1993   brings together his earlier books

Padmanabhan 1993   useful topics

Guth 1997   intuitive

Peacock 1999   well organized   (*recommended)

Kaiser 2002   useful topics

Longair 2007   up to date on observations

Binney & Tremaine 2008   useful topics

These are books on more general topics, so you need published papers to establish a narrative.

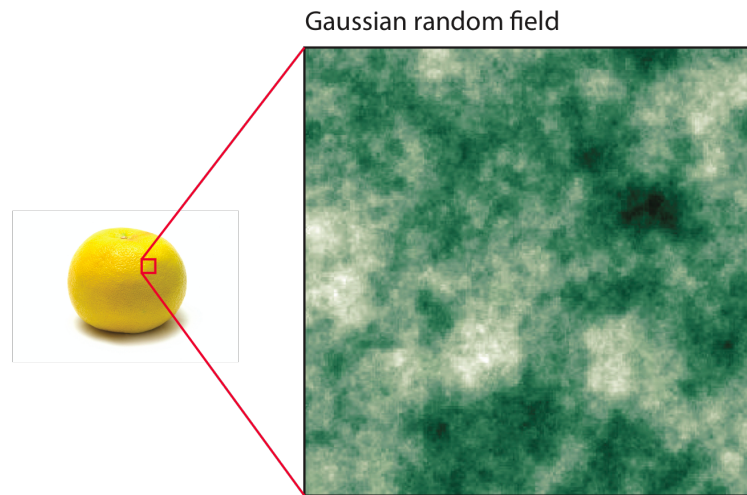In the redshift range z~3100 to z~0.5, accretion is driven by the evolution of **dark matter**...

Bland-Hawthorn (Bologna 2011)

The story of dark matter

The story of dark matter

Gaussian random field

Bland-Hawthorn (Bologna 2011)

The story of dark matter

Gaussian random eld

Filaments & pancakes

The story of dark matter

Gaussian random field

Filaments & pancakes

Hubble flow

The story of dark matter

Gaussian random eld

Filaments & pancakes

Hubble ow

Turnaround

Bland-Hawthorn (Bologna 2011)

The story of dark matter

Gaussian random field

Filaments & pancakes

Hubble flow

Self-similar collapse

Turnaround

Bland-Hawthorn (Bologna 2011)

The story of dark matter

Gaussian random field

Filaments & pancakes

Hubble flow

The Galaxy

Self-similar collapse

Turnaround

Bland-Hawthorn (Bologna 2011)

The emergence of the dark sector

1922	Kapteyn: "dark matter" in Milky Way disk
1933, 37	Zwicky: "dunkle (kalte) materie" in Coma cluster
1937	Smith: "great mass of internebular material" in Virgo cluster
1937	Holmberg: galaxy mass 5×10^{11} $M_{\odot}$ from handful of pairs
1939	Babcock observes rising rotation curve for M31
1940s	large cluster velocity dispersion σ_V confirmed by many observers
1957	van de Hulst: high HI rotation curve for M31
1959	Kahn & Woltjer: MWy-M31 infall $\Rightarrow M_{LocalGroup} = 1.8 \times 10^{12}$ $M_{\odot}$
1970	Rubin & Ford: M31 flat optical rotation curve – see Fig. 1; Freeman 1970
1973	Ostriker & Peebles: halos stabilize galactic disks
1974	Einasto, Kaasik, & Saar; Ostriker, Peebles, & Yahil summarize evidence for cluster DM & galaxy M/L increase with radius
1975; 78	Roberts; Bosma: extended flat HI rotation curves
1978	Mathews: X-rays reveal dark matter of Virgo cluster
1979	Faber & Gallagher: convincing evidence for dark matter
1998	Schmidt, Riess, Perlmutter: SNIa ➡ accelerating universe

Nobel Prize less than a week ago!

Bland-Hawthorn (Bologna 2011)
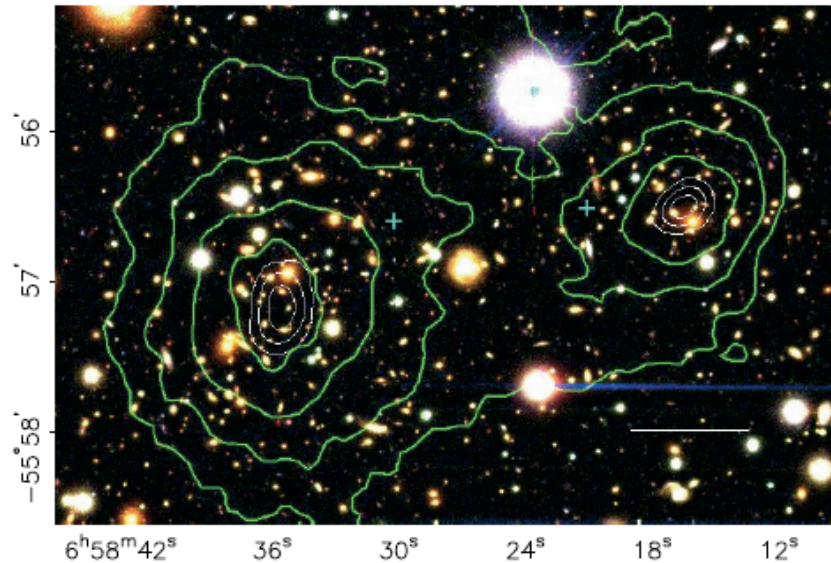
Dark matter on cluster scales...

FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

Quality of weak lensing isodensity contours as good as x-ray contours…

Clowe+ 2007

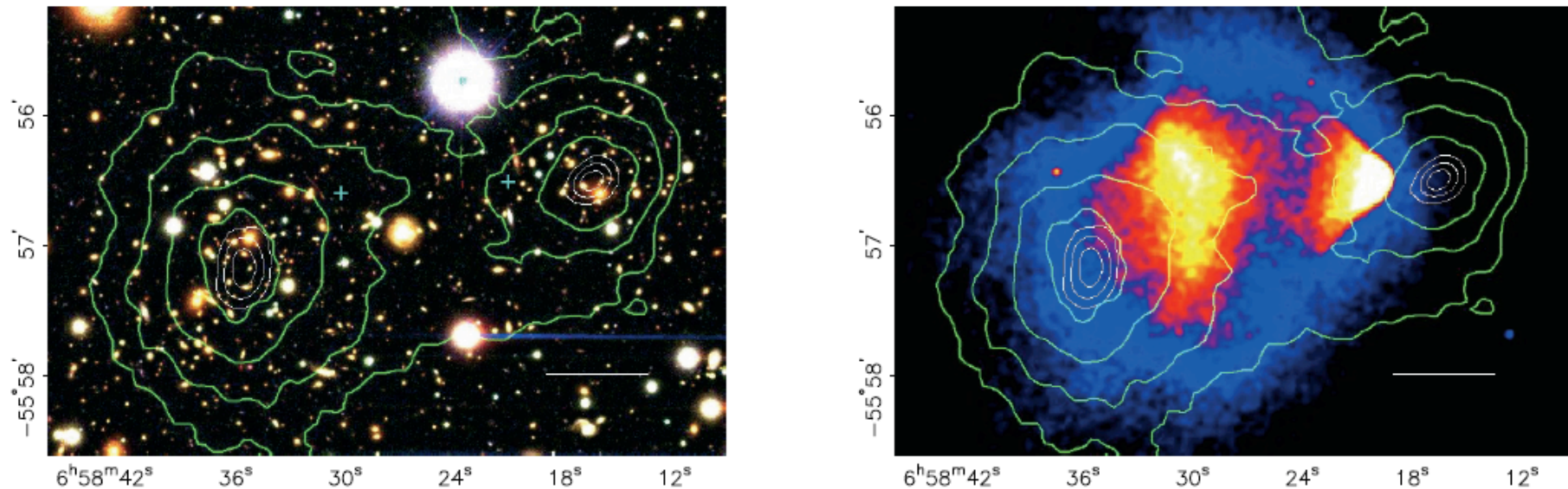Bland-Hawthorn (Bologna 2011)

Dark matter on cluster scales...

FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

Quality of weak lensing isodensity contours as good as x-ray contours…

Clowe+ 2007

Bland-Hawthorn (Bologna 2011)

Dark matter on galaxy scales….

DISTRIBUTION OF DARK MATTER IN NGC 3198
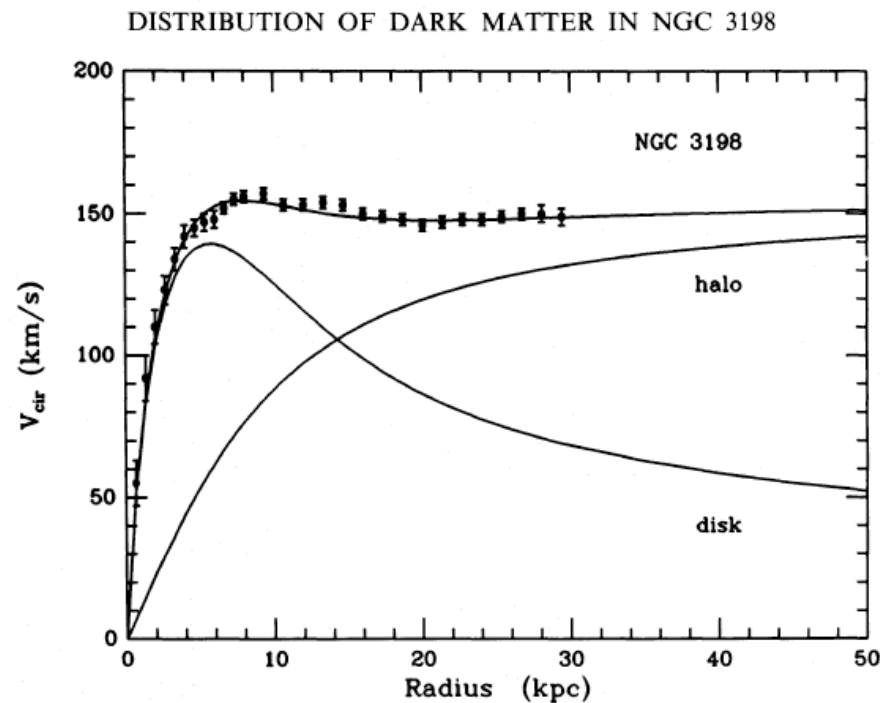
$$\frac{GM}{R} = v^2(R) = const$$

$$\rho R^2 = const$$

If the HI rotation curve is correct, then there must be undetected matter beyond the optical extent of NGC 300…"
Freeman (1970)

Bland-Hawthorn (Bologna 2011)

We now define overdensity

Structure began with density fluctuations

dimensionless

$$\delta(\underline{x}) = \frac{\rho(\underline{x})}{\rho_o} - 1 \longleftarrow \text{density can go negative}$$

comoving coordinate vector

random field

zero mean

averaged over a very large homogeneous volume V
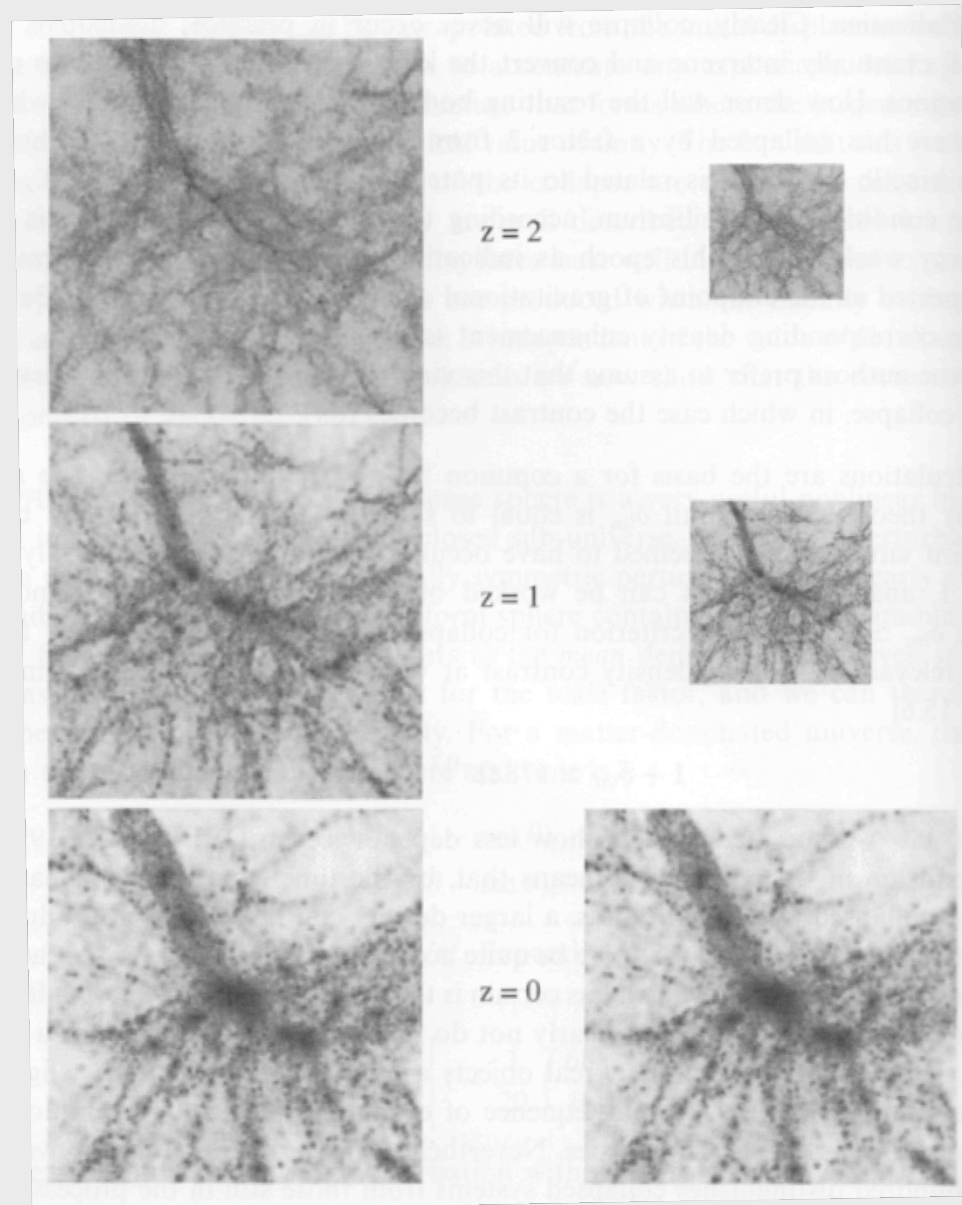
To quantify structure, we define the correlation function

$$\xi(x) = \langle \delta(\underline{x}') \, \delta(\underline{x}'+\underline{x}) \rangle$$

not a vector since isotropic field

comoving
coords, $\underline{x}$

proper coords

note how $\delta(\underline{x})$
evolves with time

$z = 2$

$z = 1$

$z = 0$

Bland-Hawthorn (Bologna 2011)

Many complex topics (EPS, ZA, TTT, etc.) are greatly simplified in Fourier space. This also helps to elucidate how N-body codes work.

Since V is very big, we can use periodic boundary conditions

$$\delta(\underline{x}) = \frac{1}{V} \sum_{\underline{k}} \delta_{\underline{k}} \, e^{i\,\underline{k}\cdot\underline{x}}$$

Fourier mode

$$\underline{k} = 2\pi \, \underline{n} / V^{1/3}$$
$$\underline{n} = (n_1, n_2, n_3)$$

$$\int_V \delta(\underline{x}) \, e^{-i\underline{k}\cdot\underline{x}} \, d^3\underline{x}$$

This is a random variable with zero mean $(\delta_0 = 0)$

$$\xi(x) = \frac{1}{V} \sum_{\underline{k}} P(\underline{k}) \, e^{i\,\underline{k}\cdot\underline{x}}$$

power spectrum F.T. of correlation fn.

$$P(\underline{k}) = \langle |\delta_{\underline{k}}^2| \rangle / V$$

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VARIANCE OF OVERDENSITY

$$\sigma^2 = \xi(0) = \langle \delta^2(\underline{x}) \rangle = \boxed{\frac{1}{V} \sum_{k}} P(k)$$

In the limit of $V \to \infty$

$$\frac{1}{(2\pi)^3} \int d^3\underline{k}$$

FTs allow us to bring in a smoothing scale $k_s \gtrsim K \equiv 2\pi/L$
(to remove fine structure, i.e. high order modes)

$$\sigma_K^2 = \frac{1}{V} \sum_{k<K} P(k) = \frac{1}{V} \sum_{k} W_K^2(\underline{k}) P(k)$$

W = window function
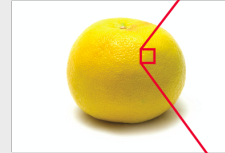
$$= \frac{1}{2\pi^2} \int_0^K k^2 P(k) \, dk$$

For example, simplest power spectra $P(k) \propto k^n$

$$\sigma_K^2 \propto \int_0^K k^{2+n} \, dk \propto K^{3+n}$$

$$\boxed{\sigma_K \propto K^{(3+n)/2}}$$

Bland-Hawthorn (Bologna 2011)

Gaussian random field
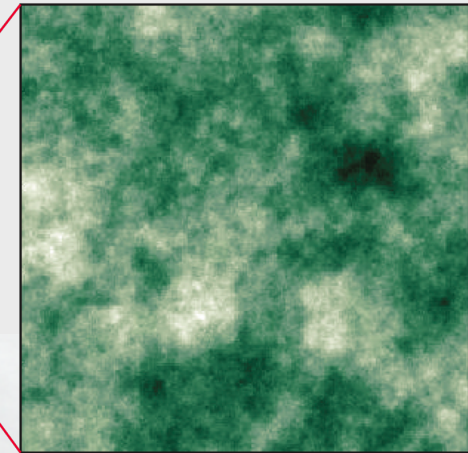
Gaussian Random Field (GRF)

Probability that $\delta(\underline{x})$ lies in $(\delta, \delta + d\delta)$

$$dp = \frac{1}{(2\pi\sigma^2)^{1/2}} \, e^{-\delta^2/2\sigma^2}$$

$\nabla\delta$ is also a GRF so all statistical properties are determined by $P(k)$

$n > 0$ is <u>smoother</u> on large scales compared to *Poisson*

Bland-Hawthorn (Bologna 2011)

Classic paper

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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Physics Department, University of Washington

J. R. BOND[1]

Physics Department, Stanford University

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Received 1985 July 25; accepted 1985 October 9

ABSTRACT

Cosmological density fluctuations are often assumed to be Gaussian random fields. The local maxima of such fields are obvious sites for the formation of nonlinear structures. The statistical properties of the peaks can be used to predict the abundances and clustering properties of objects of various types. In this paper, we derive (1) the number density of peaks of various heights $\nu\sigma_0$ above the rms σ_0; (2) the factor by which the peak density is enhanced in large-scale overdense regions; (3) the n-point peak-peak correlation function in the limit that the peaks are well separated, with special emphasis on the two- and three-point correlations; and (4) the density profiles centered on peaks. To illustrate the predictive power of this semianalytic approach, we apply our formulae to structure formation in the adiabatic and isocurvature $\Omega = 1$ cold dark matter (CDM) models. We assume bright galaxies form only at those peaks in the density field (smoothed on a galactic scale) that are above some global threshold height $\nu_t \approx 3$ fixed by normalizing to the galaxy number density. We find, for example, that the shapes of the peak-peak two- and three-point correlation functions for the adiabatic CDM model agree well with observations before any dynamical evolution, just due to the propensity of the peaks to be clustered in the initial conditions. Only moderate dynamical evolution is required to bring the amplitude of the correlations up to the observed level. The corresponding redshift of galaxy formation z_g in the isocurvature model is too recent ($z_g \approx 0$) for this model to be viable. Even for the adiabatic models $z_g \approx$ 3–4 is predicted. We show that the mass-per-peak ratio in clusters, and thus presumably the cluster mass-to-light ratio, is substantially lower than in the ambient medium, alleviating the Ω problem. We also confirm that the smoothed density profiles of collapsing structures of height $\sim \nu_t$ are inherently triaxial.

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Important notes:

1. $\rho_0 \, \sigma_K \, K^{-3}$ characteristic mass on a scale $L = \frac{2\pi}{K}$

   fluctuation δM

   This single crucial fact leads to Extended Press-Schechter Theory.

2. Mean no. of particles in box K^{-1} on a side is $N \propto K^{-3}$

   $$\sigma^2 \propto N \propto K^{-3}$$

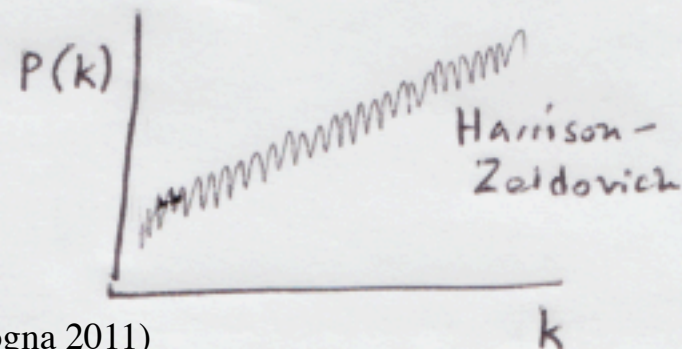 $$\frac{\sigma}{N} \propto N^{-1/2} \propto K^{3/2} \qquad \therefore \, n = 0 \text{ for } Poisson$$

Bland-Hawthorn (Bologna 2011)

3. Zeldovich argued for $n=1$ because if fluctuations in $g_{\mu\nu}$ metric tensor $\sim \delta\Phi/c^2$ were too large on large scales, the universe cannot be homogeneous and isotropic.

If they were too large on small scales, the fluctuations would go relativistic and wash out.

$$\therefore \quad \delta\bar{\Phi} \simeq G \cdot \delta M \cdot K \longrightarrow \propto K^{(3+n)/2}$$

$$\simeq G \cdot \rho_0 \, \sigma_k \, K^{-3} K$$

$$\propto K^{(n-1)/2}$$

Thus $\delta\bar{\Phi}$ can only be independent of scale iff $n=1$

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Gravitational instabilities in an expanding universe

$|\delta(\underline{x})| \ll 1$ at early times

Working in comoving coordinates $\underline{x}$

$$\frac{\partial \rho}{\partial t} + 3H\rho + \nabla \cdot (\rho \underline{v}) = 0 \qquad \text{CONTINUITY EQN.}$$

$$\frac{\partial \underline{v}}{\partial t} + (\underline{v} \cdot \nabla)\underline{v} + 2H\underline{v} + \frac{\ddot{a}}{a}\underline{x} = \frac{1}{a^2}\left(\frac{1}{\rho}\nabla p + \nabla \phi\right)$$

pressure term — EULER'S EQN.

Conservation of momentum

These describe a non-relativistic "cosmic fluid" i.e.

negligible on large scale

disturbed

$$\frac{\partial^2 \delta_{\underline{k}}}{\partial t^2} + 2H\frac{\partial \delta_{\underline{k}}}{dt} + \left(\frac{k^2}{a^2}v_s^2 - 4\pi G\rho_0\right)\delta_{\underline{k}} = 0$$

Sound speed

undisturbed

For any cosmological model, we can solve for overdensity δ_k in terms of H, v_s, ρ_0.

On large scales, $k \to 0$

$$H = \frac{2}{3t} \qquad 4\pi G \rho_0 = \frac{2}{3t^2}$$

Solutions when matter dominates

$$\delta_k \propto t^{2/3} \qquad \delta_k \propto t^{-1}$$

growing   decaying

$3100 \gtrsim z \gtrsim 0.5$

$z \lesssim 0.5$, Λ begins to dominate, $H \to$ constant

$$4\pi G \rho_0 \to 0$$

$$\frac{\partial^2 \delta_k}{\partial t^2} + 2H \frac{\partial \delta_k}{\partial t} = 0$$

$$\delta(t) = c_1 + c_2 \exp(-2Ht)$$

Amazing fact:

Growth is "stalling" today; growth factor is down 10%

Bland-Hawthorn (Bologna 2011)

Amazing fact:

the universe appears to have
 entered a 2nd epoch of inflation
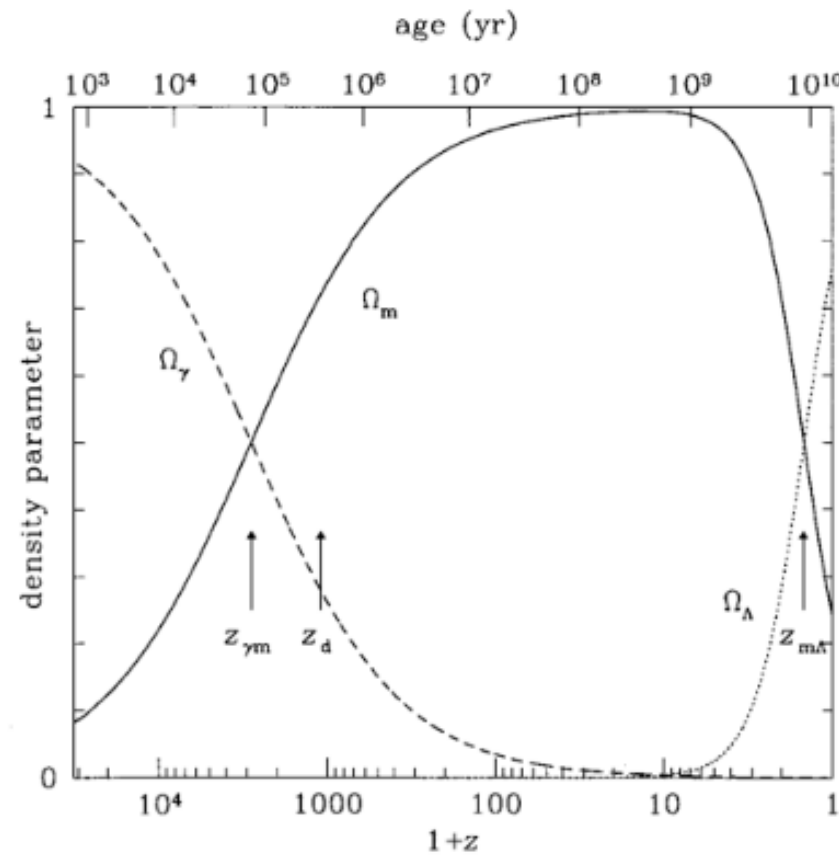
Bland-Hawthorn (Bologna 2011)

But we also need the equivalent formula for the radiation-dominated era ($z \gtrsim 3100$) to understand

These describe a non-relativistic "cosmic fluid" i.e.

$$\text{negligible on large scale}$$

$$\frac{\partial^2 \delta_k}{\partial t^2} + 2H\frac{\partial \delta_k}{dt} + \left(\frac{k^2}{a^2}v_s^2 - 4\pi G \rho_o \right)\delta_k = 0$$

disturbed

undisturbed

Sound speed

during expansion.

$$\frac{\partial^2 \delta_k}{\partial t^2} + 2H\frac{\partial \delta_k}{\partial t} + \left(\frac{k^2 c^2}{3a^2} - \frac{32\pi}{3}G\rho_o \right)\delta_k = 0$$

$\frac{1}{t}$

$$H = \frac{1}{2t} \qquad \frac{32\pi G \rho_o}{3} = \frac{1}{t^2}$$

$$\frac{k^2 c^2}{3a^2} - \frac{1}{t^2} \qquad\qquad ct \sim \text{horizon scale}$$

$$\frac{k}{a} \gtrsim \frac{1}{ct} \quad , \qquad \text{first term dominates}$$

radiation pressure stabilizes perturbations smaller than $\sim ct$, δ_k oscillates.

Probing the Universe with the Lyα forest – I. Hydrodynamics of the low-density intergalactic medium

Nickolay Y. Gnedin[1] and Lam Hui[2]

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[2]NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

non-rel. fluid equation solved explicitly in these papers; filter mass scale for CDM and gas also used.

ABSTRACT

We introduce an efficient and accurate alternative to full hydrodynamic simulations, hydro-PM (HPM), for the study of the low column density Lyα forest ($N_{H_I} \lesssim 10^{14}$ cm^{-2}). It consists of a particle mesh (PM) solver, modified to compute, in addition to the gravitational potential, an effective potential due to the gas pressure. Such an effective potential can be computed from the density field because of a tight correlation between density and pressure in the low-density limit ($\delta \lesssim 10$), which can be calculated for any photo-re-ionization history by a method
...elation exists, in part, because of minimal shock heating
...e carefully the density and velocity fields as well as
...PM versus hydrodynamic simulations, and find good
...able of reproducing measurable quantities, such as the
...d from full hydrodynamic simulations, to a precision
...e discuss how, by virtue of its speed and accuracy, HPM
...a cosmological probe.
...ing of the gas (or baryon) fluctuation relative to that of
...nite gas pressure. First, it is shown that the conventional
...is smoothed on the Jeans scale is incorrect for general
...e correct linear filtering scale is in general smaller than
...ger prior to it. Secondly, it is demonstrated that in the
...er, combined with suitable pre-filtering of the initial
...e low-density IGM. However, such an approximation
...HPM, unless a non-uniform pre-filtering scheme is

EFFECT OF REIONIZATION ON STRUCTURE FORMATION IN THE UNIVERSE

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ABSTRACT

I use simulations of cosmological reionization to quantify the effect of photoionization on the gas fraction in low-mass objects, in particular the characteristic mass scale below which the gas fraction is reduced compared to the universal value. I show that this characteristic scale can be up to an order of magnitude lower than the linear-theory Jeans mass, and that even if one defines the Jeans mass at a higher overdensity, it does not track the evolution of this characteristic suppression mass. Instead, the filtering mass, which corresponds directly to the scale over which baryonic perturbations are smoothed in linear perturbation theory, provides a remarkably good fit to the characteristic mass scale. Thus, it appears that the effect of reionization on structure formation in both the linear and nonlinear regimes is described by a single characteristic scale, the filtering scale of baryonic perturbations. In contrast to the Jeans mass, the filtering mass depends on the full thermal history of the gas instead of the instantaneous value of the sound speed, so it accounts for the finite time required for pressure to influence the gas distribution in the expanding universe. In addition to the characteristic suppression mass, I study the full shape of the probability distribution to find an object with a given gas mass among all the objects with the same total mass, and I show that the numerical results can be described by a simple fitting formula that again depends only on the filtering mass. This simple description of the probability distribution may be useful for semianalytical modeling of structure formation in the early universe.

Subject headings: cosmology: theory — galaxies: formation — intergalactic medium — large-scale structure of universe

Bland-Hawthorn (Bologna 2011)

$$\frac{k}{a} \gtrsim \frac{1}{ct} \quad,$$

first term dominates
radiation pressure stabilizes perturbations
smaller than ~ ct, δ_k oscillates.

On large scales, $k \to 0$
(larger than ct)

$$\delta_k \propto t \qquad \delta_k \propto t^{-1}$$

these affect both matter and radiation

$3100 \gtrsim z \gtrsim 1100$, dark matter fluctuations start to grow
$\delta_k \propto t^{2/3}$ but baryons still locked to radiation
until decoupling at $z \simeq 1100$, i.e.
photon-baryon viscosity is very large.
(also thermal conductivity)

Silk damping (1968):
sound waves wipe out
fine structure

Amazing fact:

dark matter is the **only** reason
structure below 10 Mpc survived
the epoch $3100 < z < 1100$

Growth of fluctuations

• Linear theory

• Basic elements have been understood for 30 years (Peebles, Sunyaev & Zeldovich)

• Numerical codes agree to better than 0.1% (Seljak+ 2003)
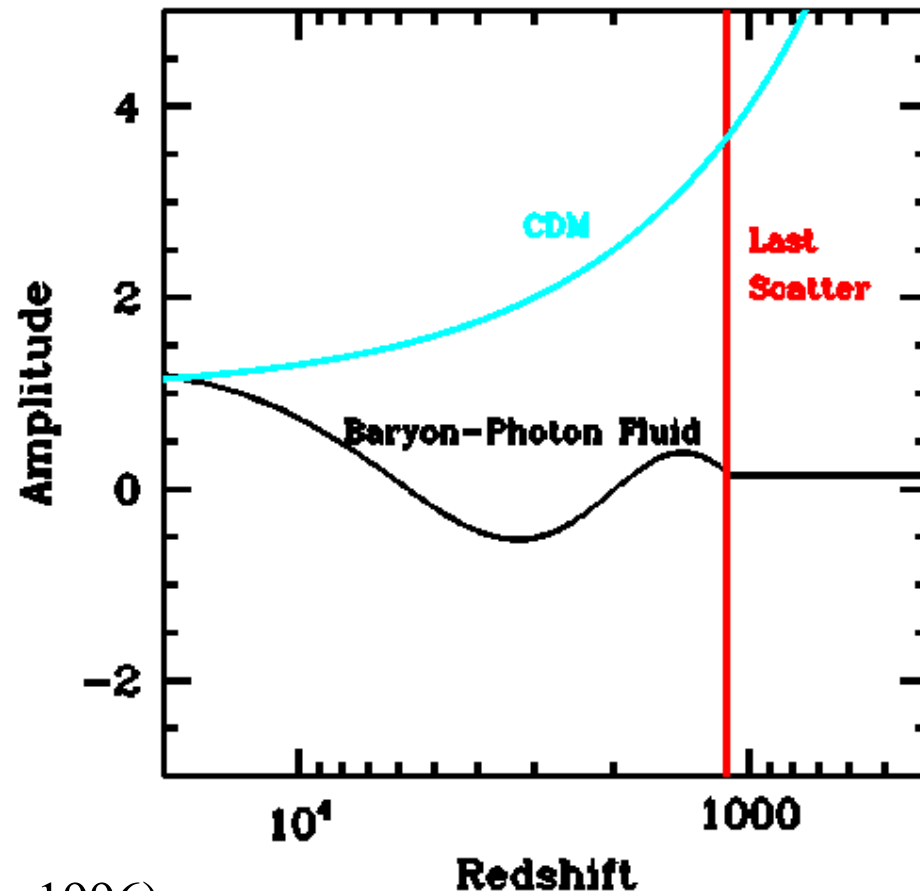
CMBFAST (Seljak & Zaldarriaga 1996)
relativistic fluid eqn solved explicitly

Bland-Hawthorn (Bologna 2011)
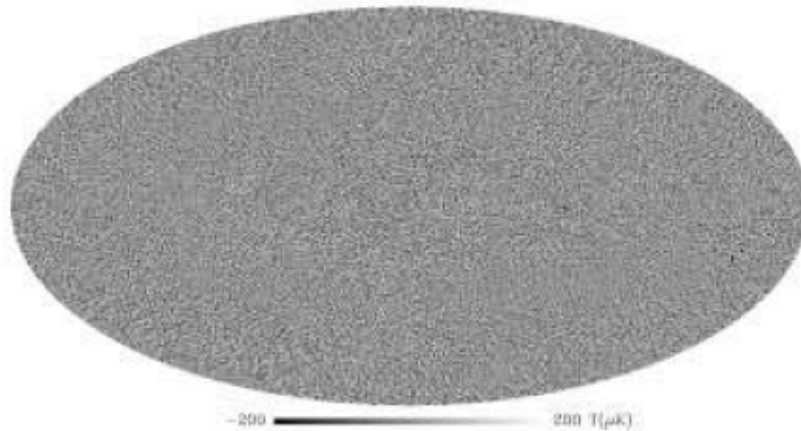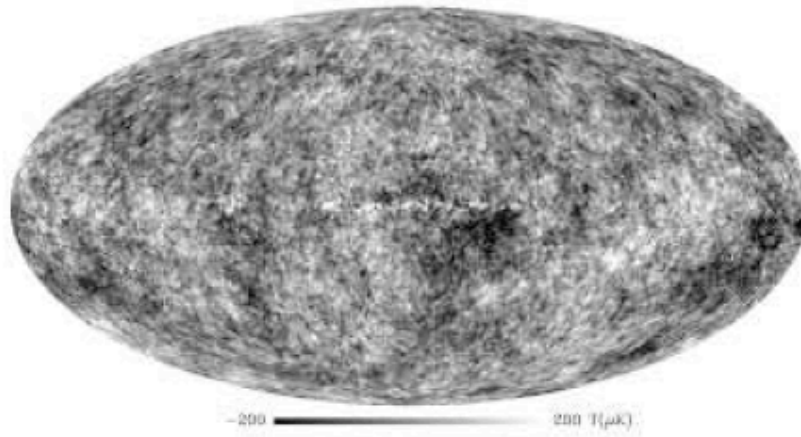
The CMB fluctuations are a byproduct of the **first epoch of accretion.**

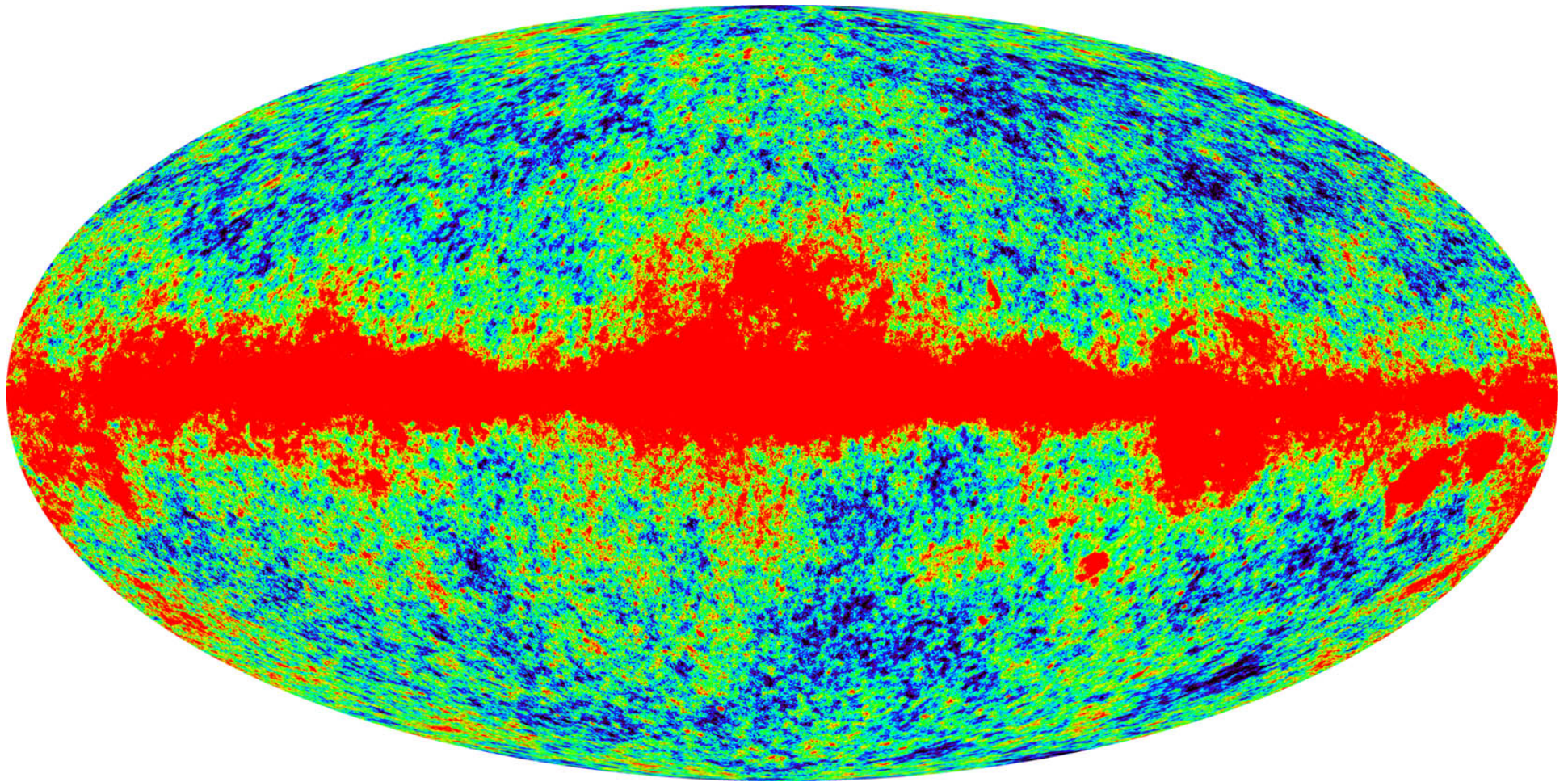The photon-baryon fluid reacted to the collapse of DM, which took place even before neutrals existed!

Foreground contamination 370,000 years after the Big Bang — photons and baryons took 120,000 years to decouple…
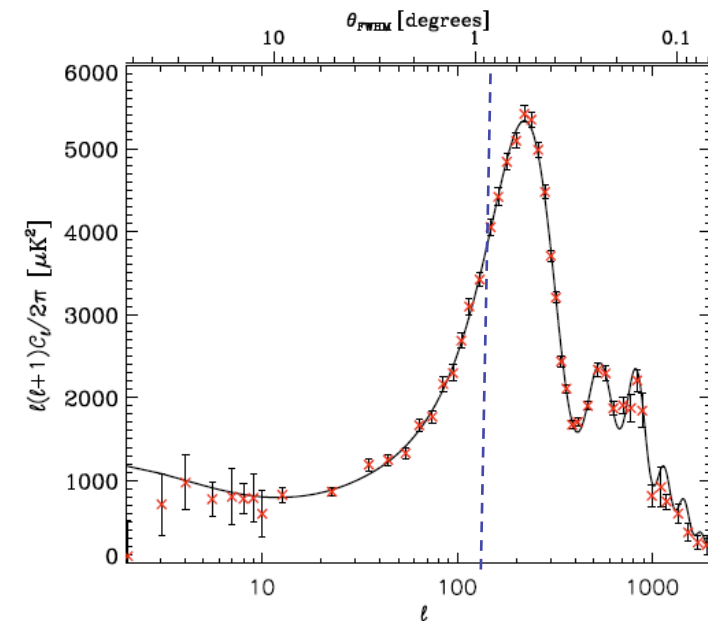
Bland-Hawthorn (Bologna 2011)

Ka - 33GHz

Bland-Hawthorn (Bologna 2011)
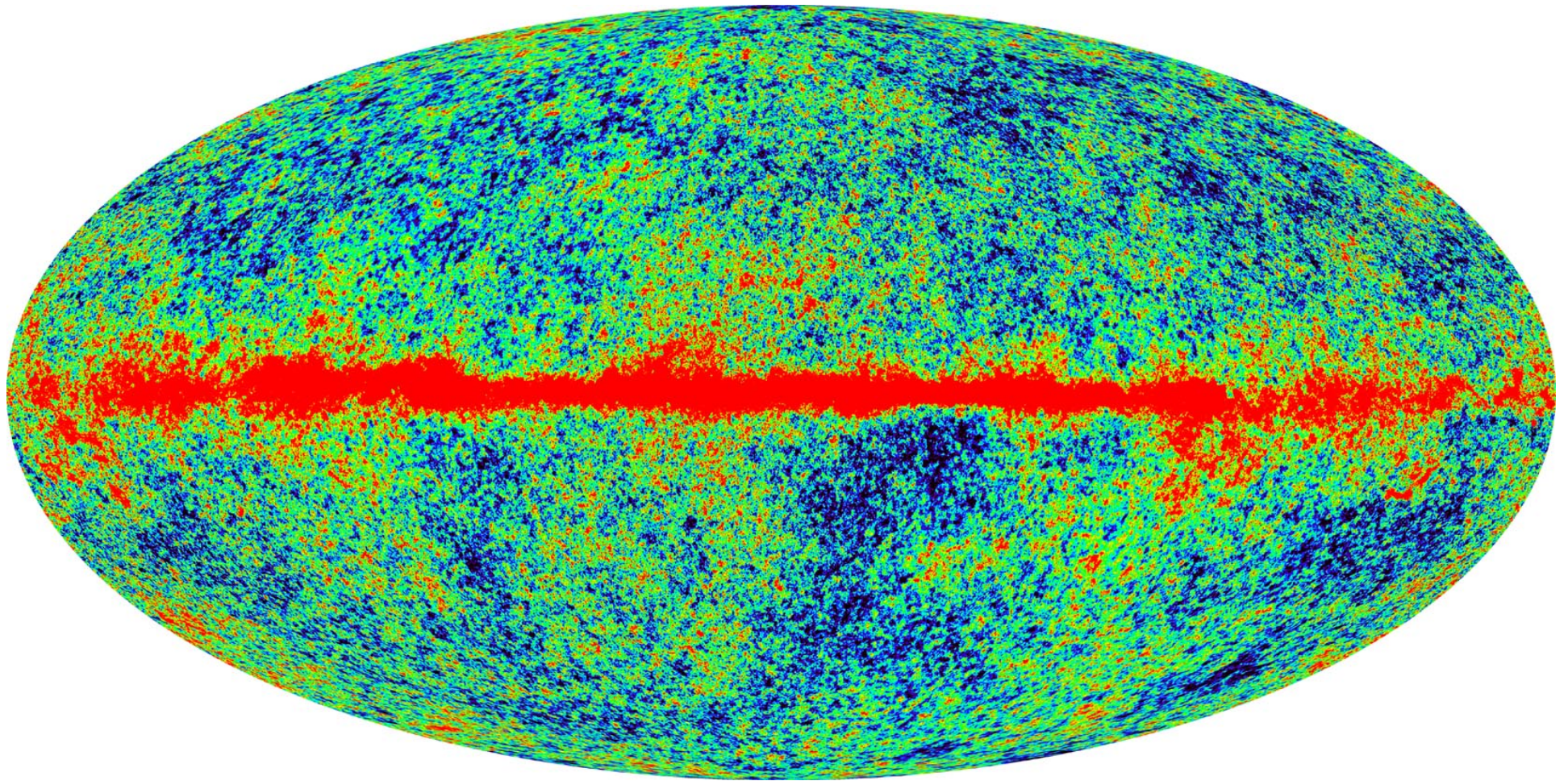
Q - 41GHz
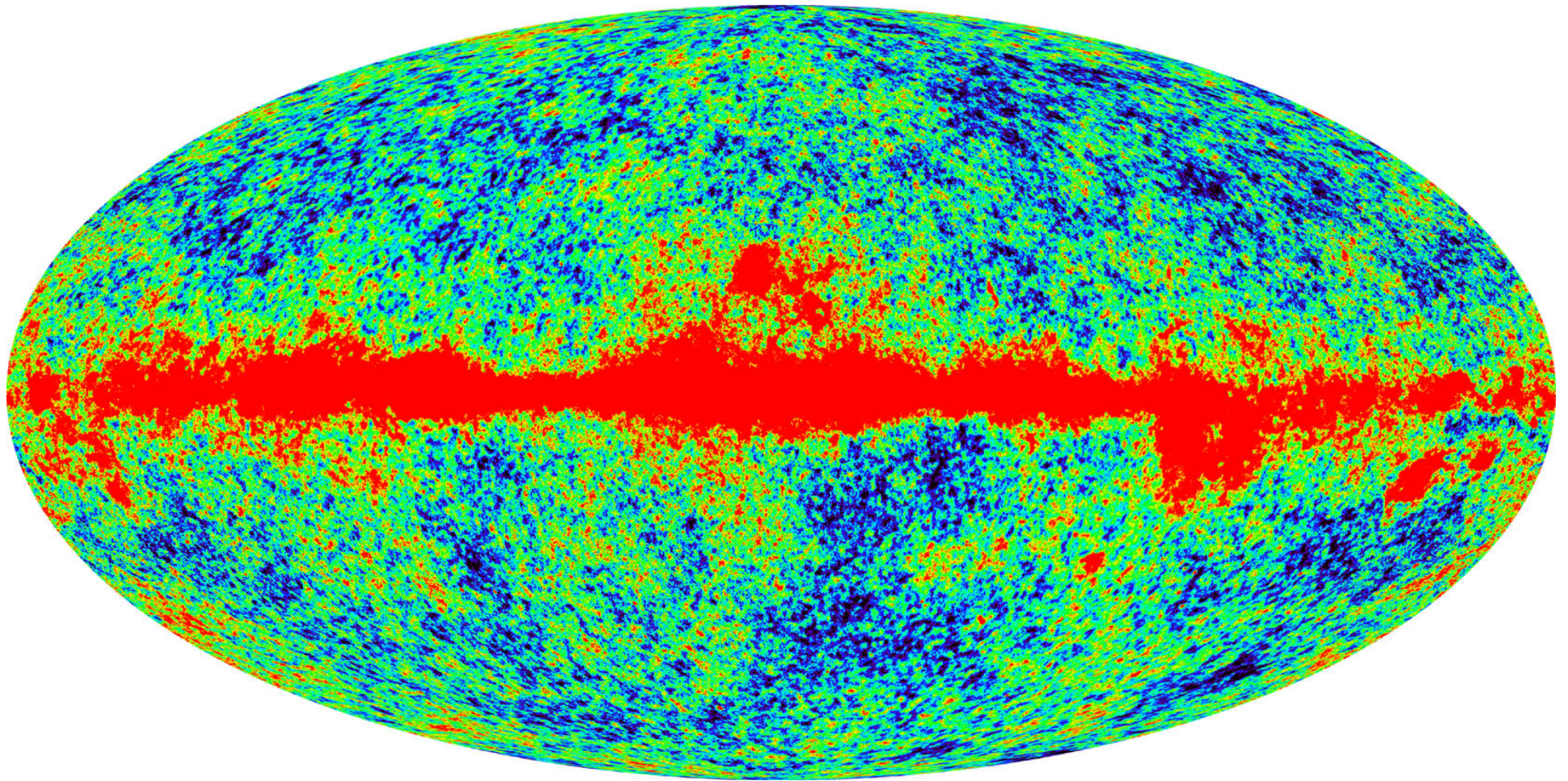
Bland-Hawthorn (Bologna 2011)

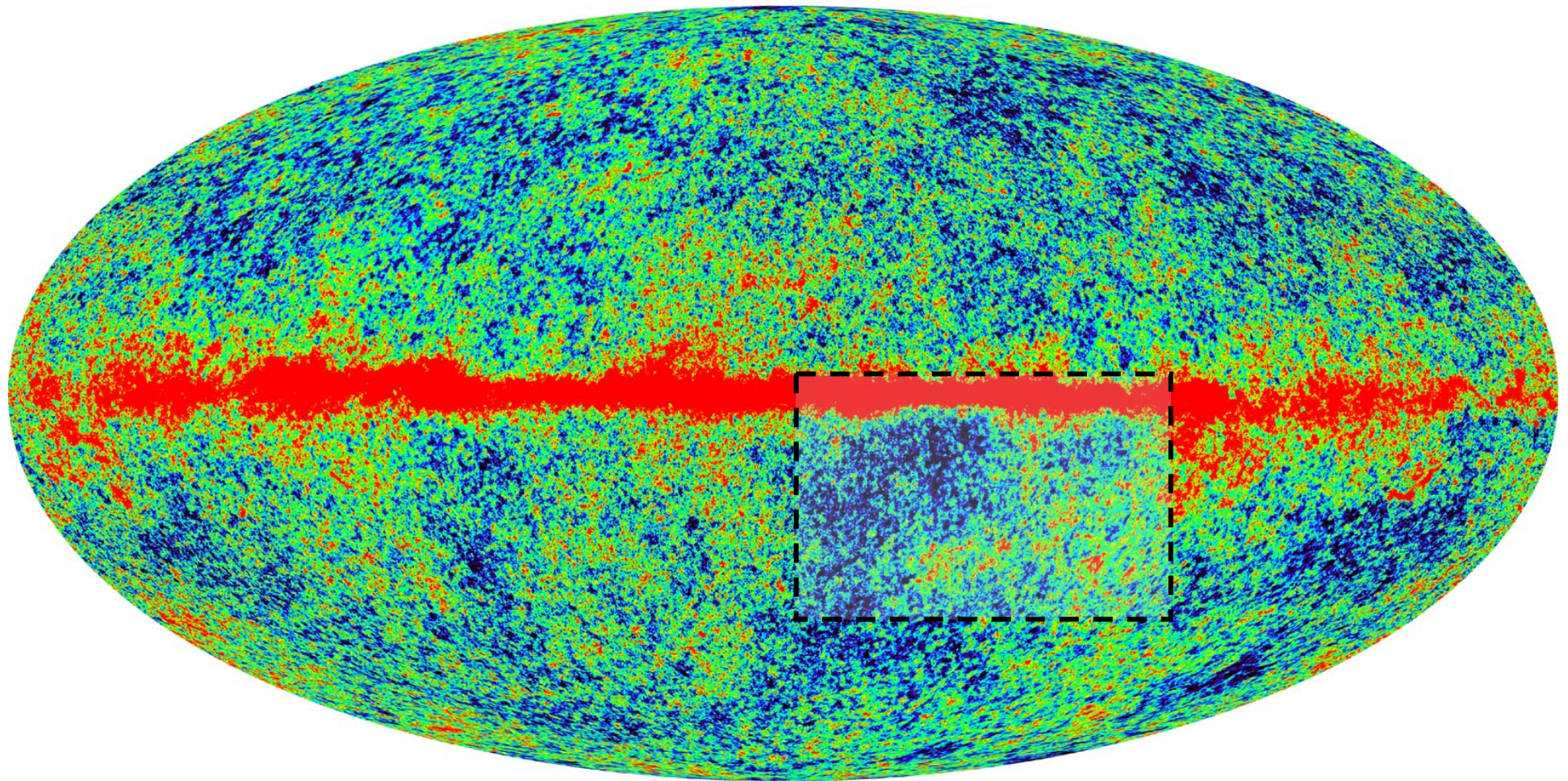# V - 61GHz
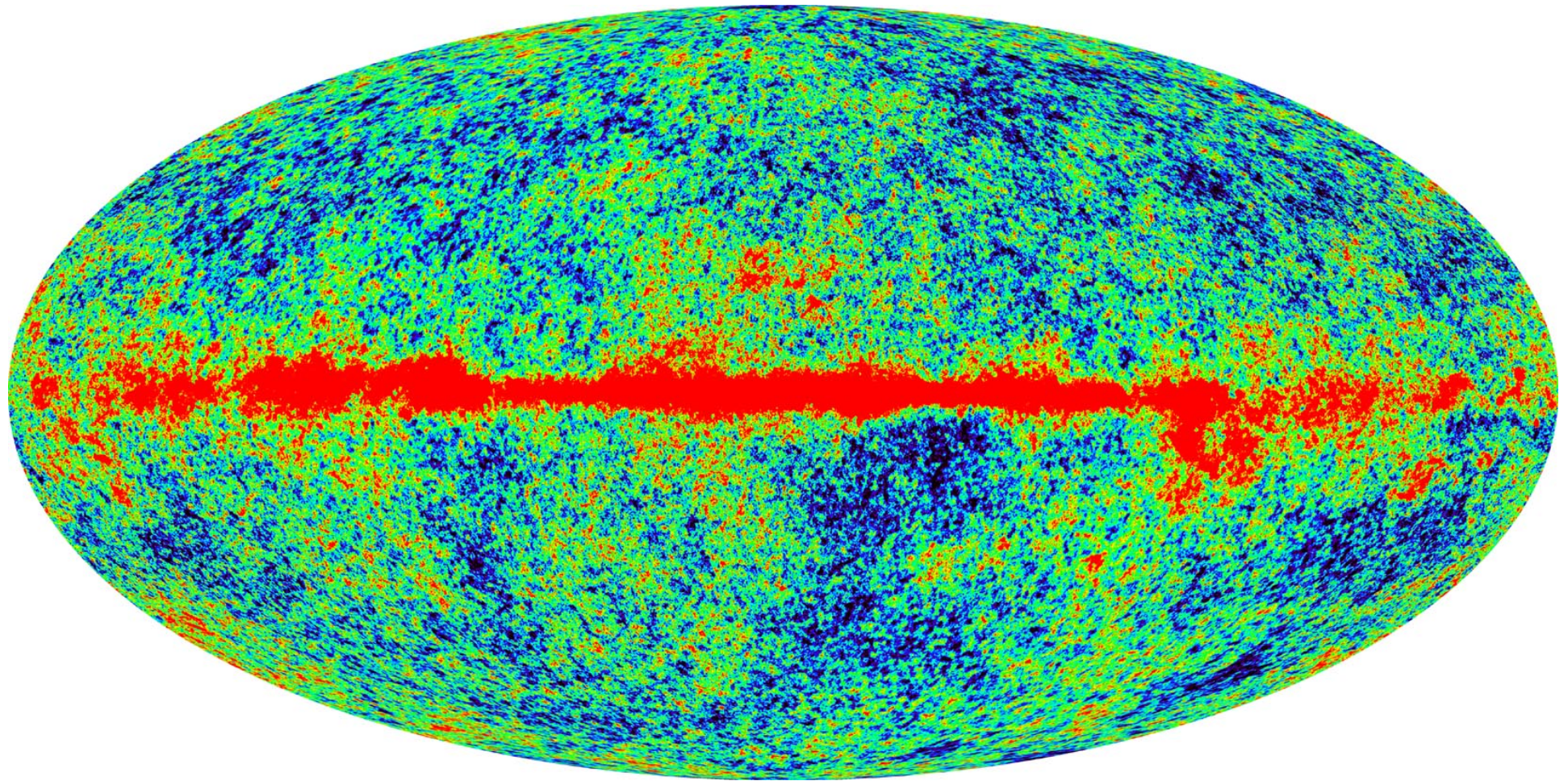
Bland-Hawthorn (Bologna 2011)

W - 94GHz

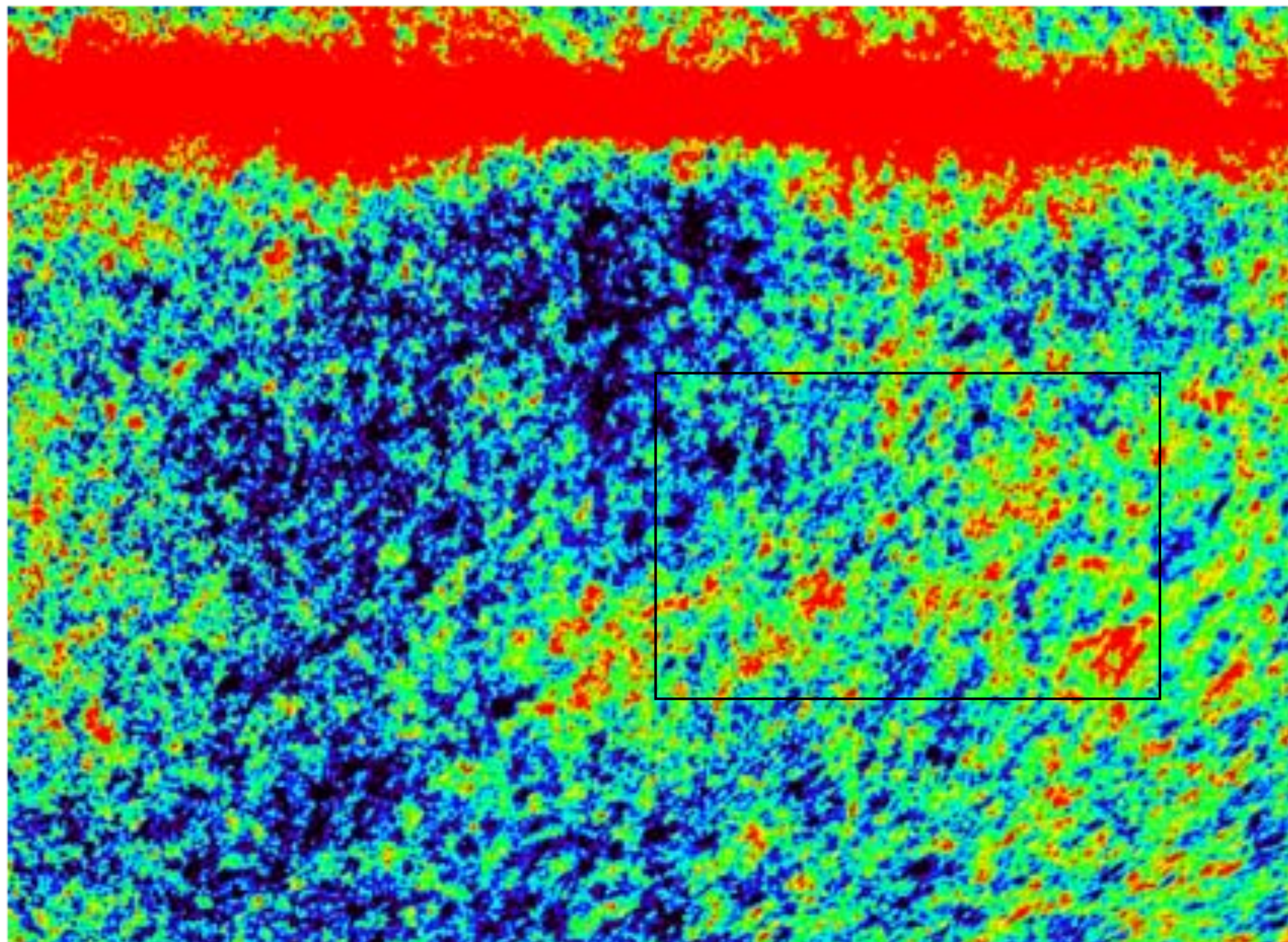Bland-Hawthorn (Bologna 2011)

W - 94GHz
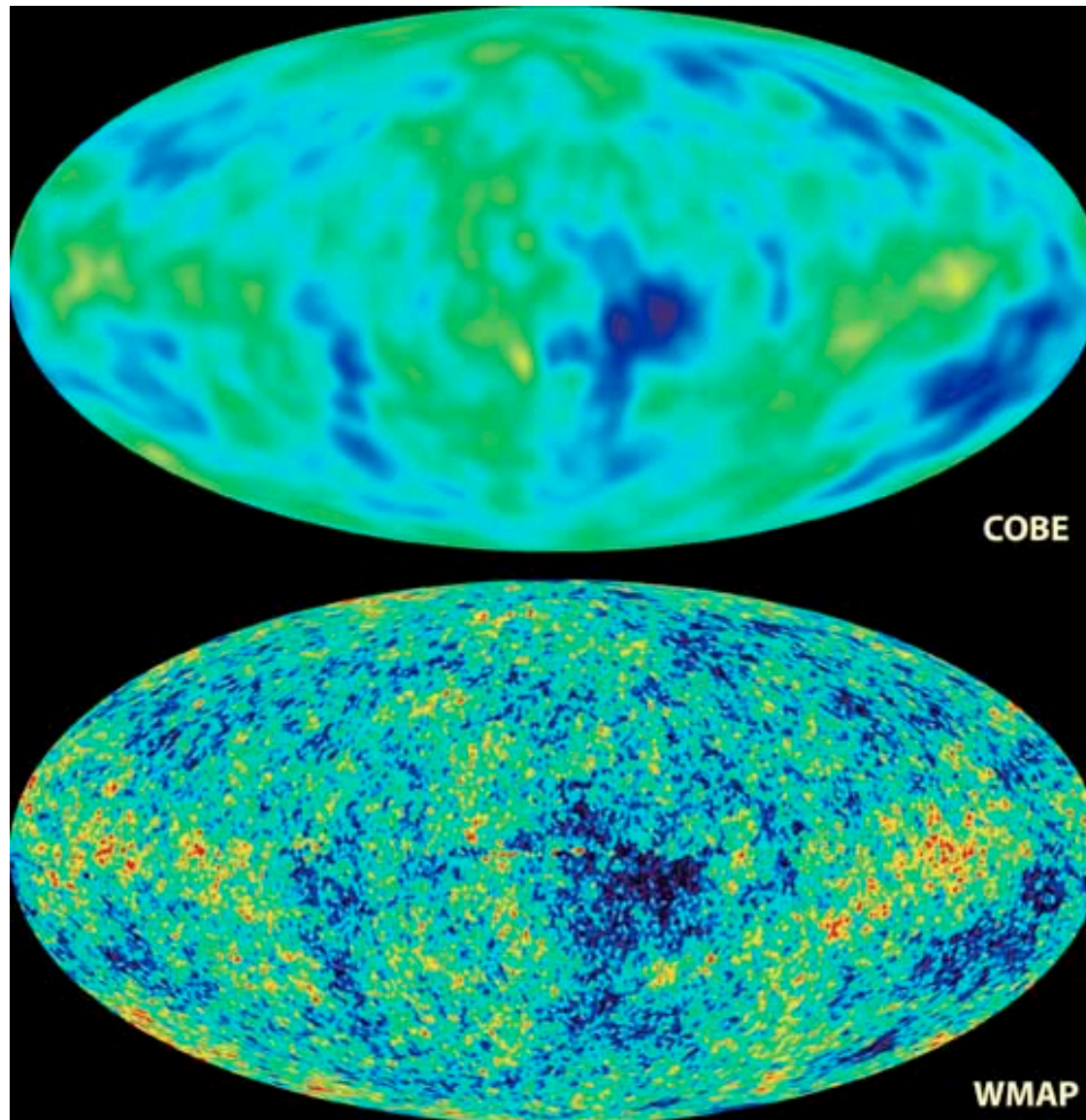
Bland-Hawthorn (Bologna 2011)

Cold spots are evidence for
mass concentrations since
photons lose energy here

2° is causally connected at z~1100

5°

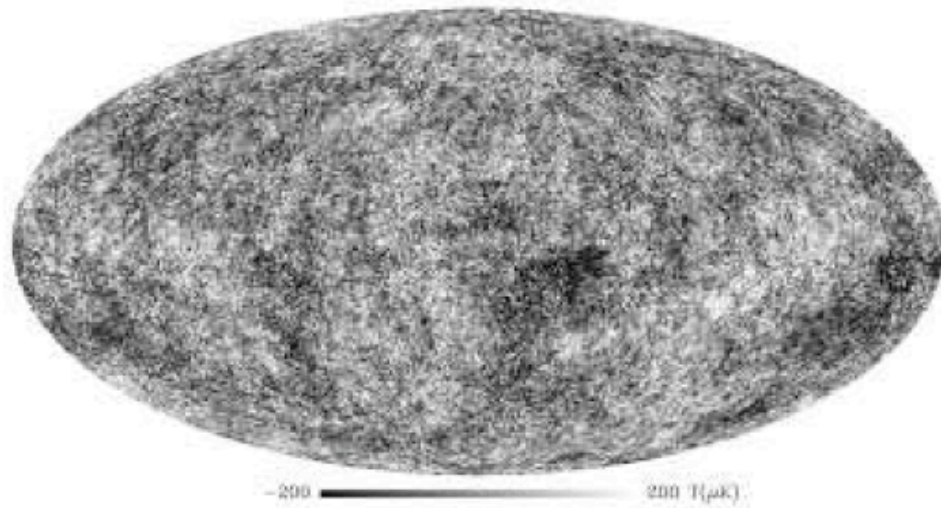The sky contains 10,000 of these
independent cells
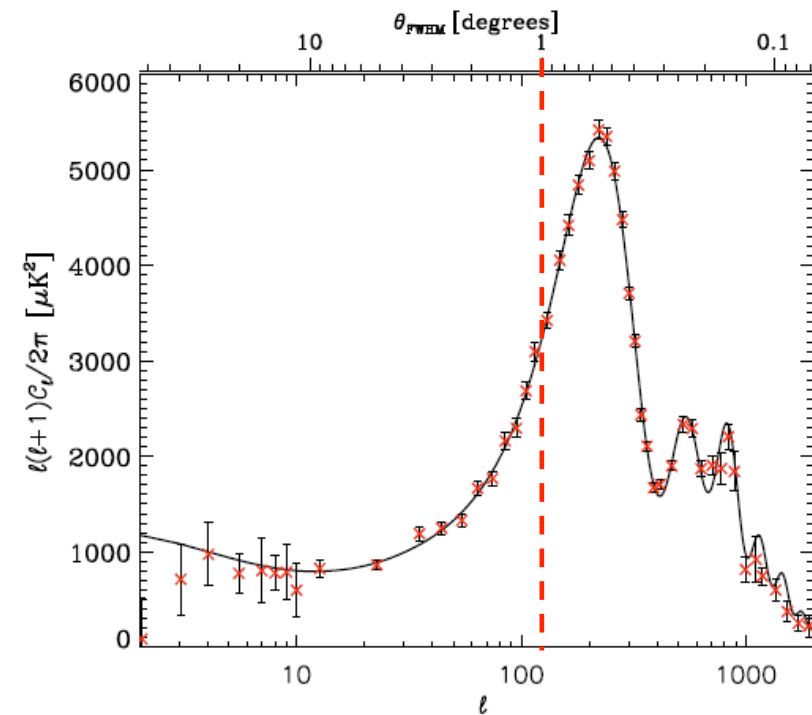
FOREGROUND CORRECTED MAP

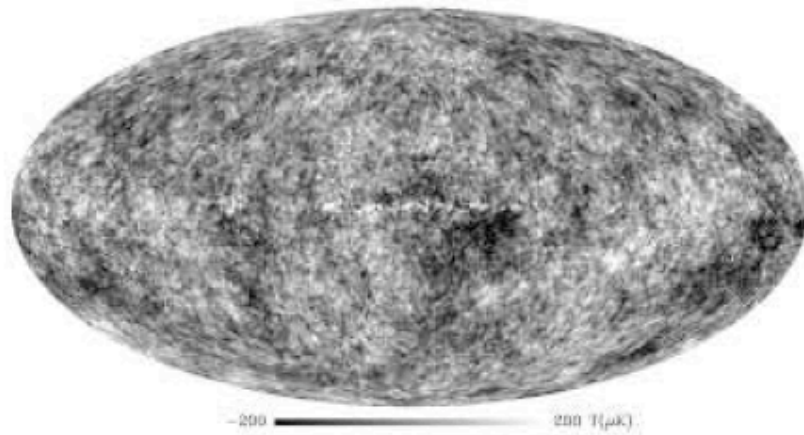
Bland-Hawthorn
(Bologna 2011)

Where is the information?

Take the CMB map...

Separate signal above/below 1º...

Bland-Hawthorn (Bologna 2011)
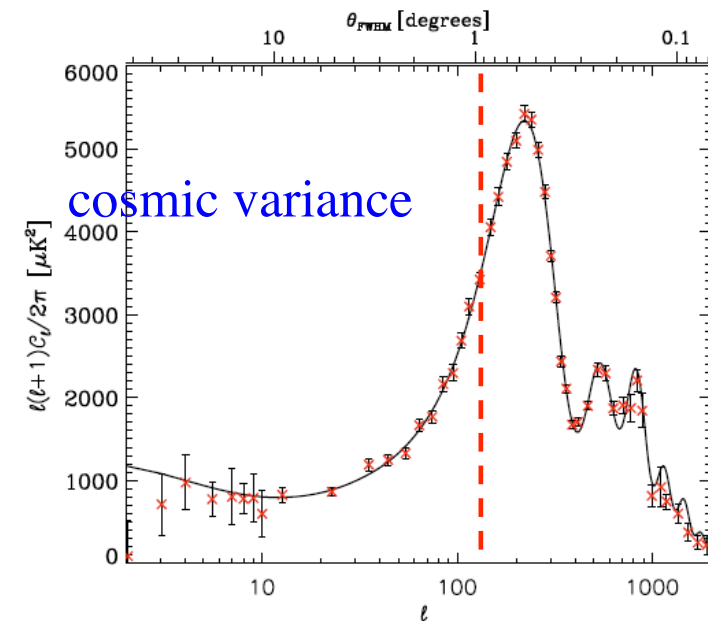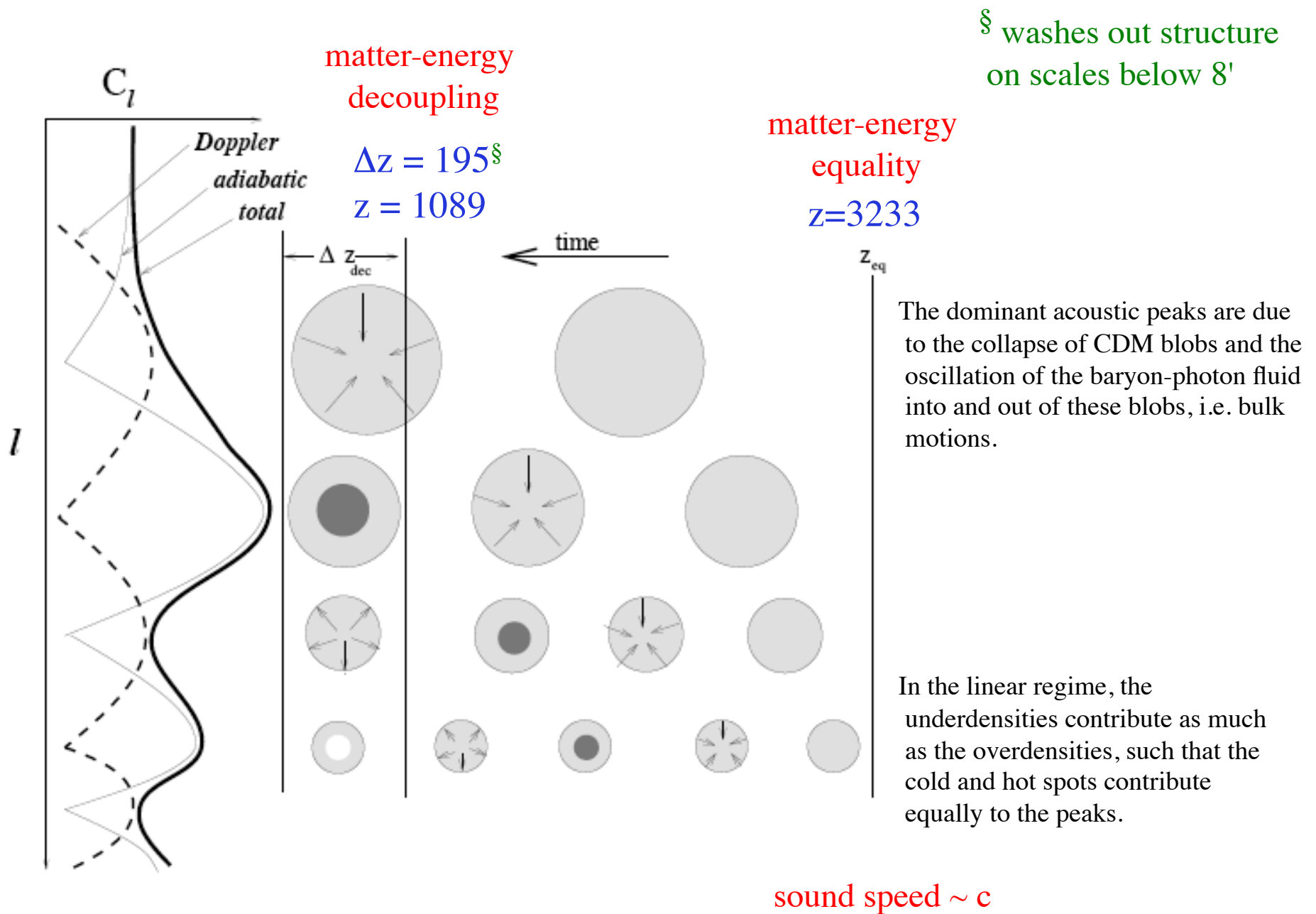
Foreground contamination 370,000 years after the Big Bang — photons and baryons took 120,000 years to decouple…

cosmic variance

matter-energy
decoupling

$\Delta z = 195^{\S}$
$z = 1089$

matter-energy
equality
$z=3233$

§ washes out structure
on scales below 8'

C_l

Doppler
adiabatic
total

l

time

Δz_{dec}

z_{eq}

The dominant acoustic peaks are due
to the collapse of CDM blobs and the
oscillation of the baryon-photon fluid
into and out of these blobs, i.e. bulk
motions.

In the linear regime, the
underdensities contribute as much
as the overdensities, such that the
cold and hot spots contribute
equally to the peaks.

sound speed ~ c

sound horizon ~ event horizon ~ 2°

Bland-Hawthorn (Bologna 2011)

Figure 11. The dominant acoustic peaks in the CMB power spectra are caused by the collapse of dark matter over-densities and the oscillation of the photon-baryon fluid into and out of these over-densities. After matter becomes the dominant component of the Universe, at $z_{eq} \approx 3233$ (see Table 1), cold dark matter potential wells (gray spots) initiate in-fall and then oscillation of the photon-baryon fluid. The phase of this in-fall and oscillation at z_{dec} (when photon pressure disappears) determines the amplitude of the power as a function of angular scale. The bulk motion of the photon-baryon fluid produces 'Doppler' power out of phase with the adiabatic power. The power spectrum (or C_ℓs) is shown here rotated by $90°$ compared to Fig. 10. Oscillations in fluids are also known as sound. Adiabatic compressions and rarefactions become visible in the radiation when the baryons decouple from the photons during the interval marked Δz_{dec} ($\approx 195 \pm 2$, Table 1). The resulting bumps in the power spectrum are analogous to the standing waves of a plucked string. This very old music, when converted into the audible range, produces an interesting roar (Whittle 2003). Although the effect of over-densities is shown, we are in the linear regime so under-densities contribute an equal amount. That is, each acoustic peak in the power spectrum is made of equal contributions from hot and cold spots in the CMB maps (Fig. 12). Anisotropies on scales smaller than about $8'$ are suppressed because they are superimposed on each other over the finite path length of the photon through the surface Δz_{dec}.
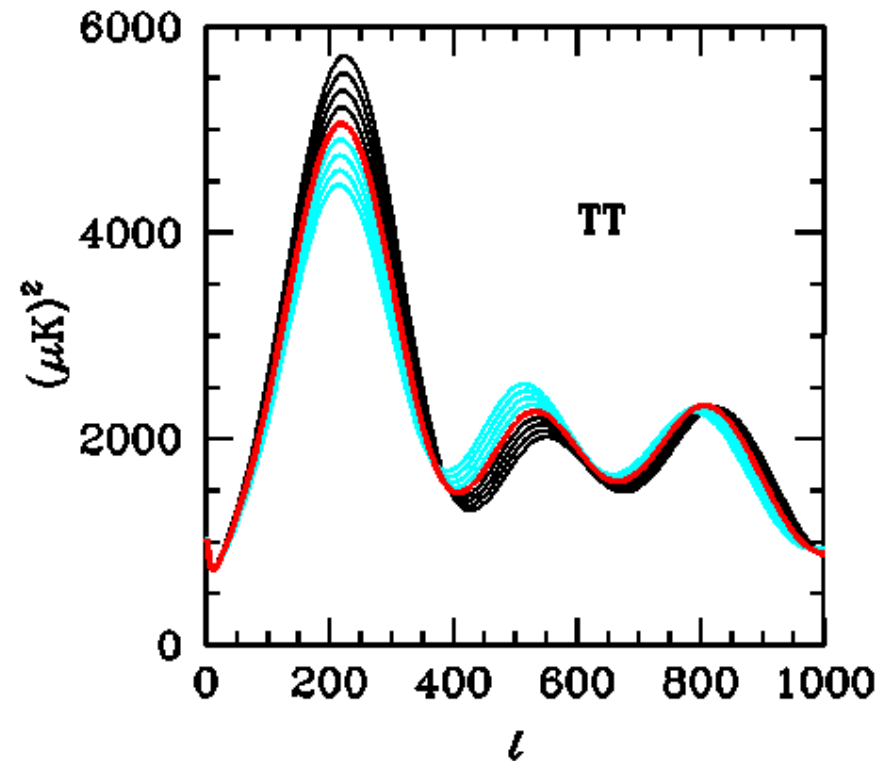
Bland-Hawthorn
(Bologna 2011)

Determining basic parameters

Baryon Density

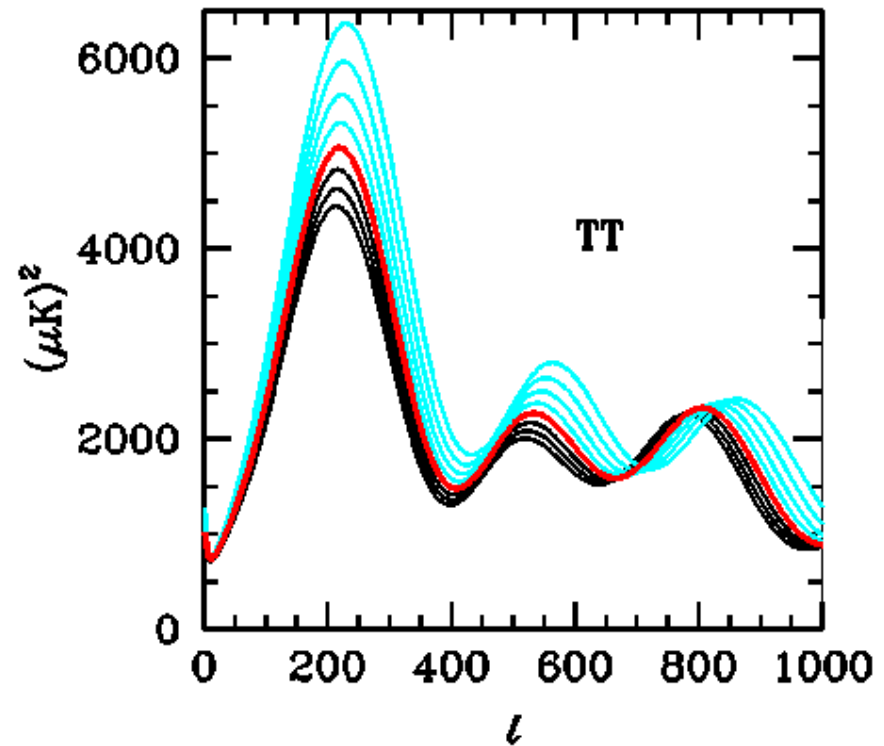$\Omega_b h^2 = 0.015, 0.017 \ldots 0.031$

also measured through D/H

Determining basic parameters
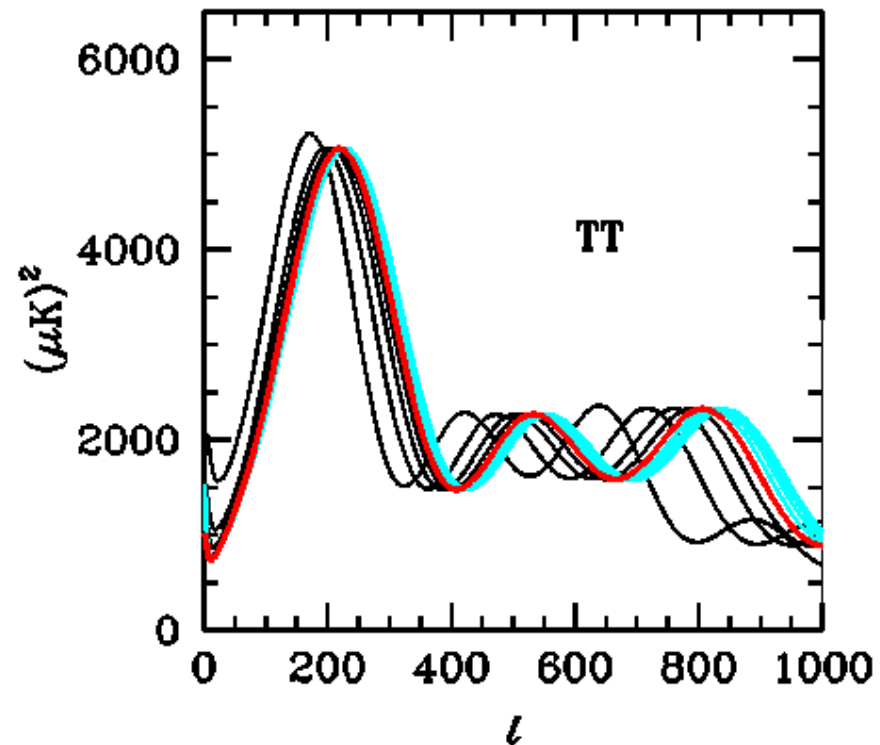
Matter Density

$\Omega_m h^2 = 0.16, \ldots 0.33$

Determining Basic Parameters

Angular Diameter Distance

$w = -1.8,..,-0.2$

When combined with measurement of matter density constrains data to a line in Ω_m-w space
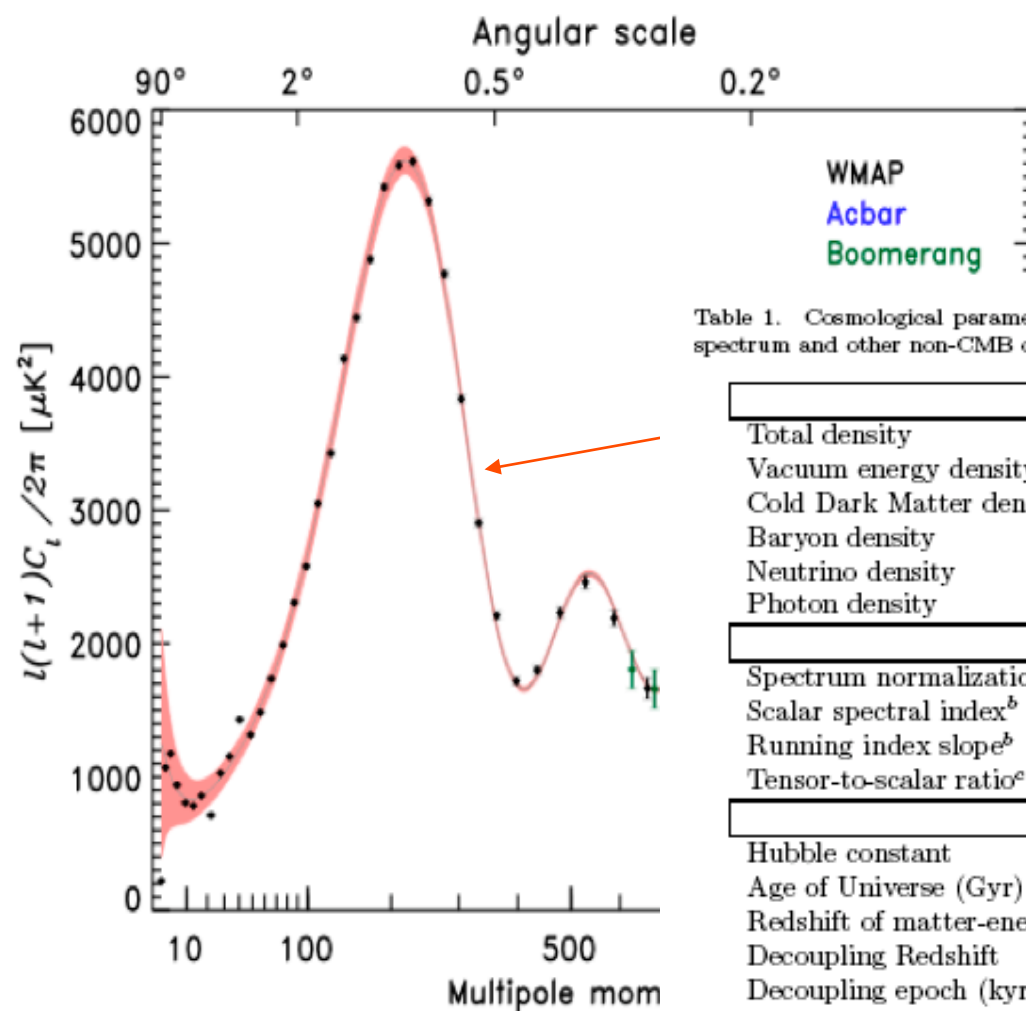
Temperature

85% of sky

Table 1. Cosmological parameters describing the best-fitting FRW model to the CMB power spectrum and other non-CMB observables (cf. Bennett et al. 2003).

Composition of Universe[a]		
Total density	Ω_o	1.02 ± 0.02
Vacuum energy density	Ω_Λ	0.73 ± 0.04
Cold Dark Matter density	Ω_{CDM}	0.23 ± 0.04
Baryon density	Ω_b	0.044 ± 0.004
Neutrino density	Ω_ν	< 0.0147 95% CL
Photon density	Ω_γ	$4.8 \pm 0.014 \times 10^{-5}$
Fluctuations		
Spectrum normalization[b]	A	$0.833^{+0.086}_{-0.083}$
Scalar spectral index[b]	n_s	0.93 ± 0.03
Running index slope[b]	$dn_s/d\ln k$	$-0.031^{+0.016}_{-0.018}$
Tensor-to-scalar ratio[c]	$r = T/S$	< 0.71 95% CL
Evolution		
Hubble constant	h	$0.71^{+0.04}_{-0.03}$
Age of Universe (Gyr)	t_0	13.7 ± 0.2
Redshift of matter-energy equality	z_{eq}	3233^{+194}_{-210}
Decoupling Redshift	z_{dec}	1089 ± 1
Decoupling epoch (kyr)	t_{dec}	379^{+8}_{-7}
Decoupling Surface Thickness (FWHM)	Δz_{dec}	195 ± 2
Decoupling duration (kyr)	Δt_{dec}	118^{+3}_{-2}
Reionization epoch (Myr, 95% CL))	t_r	180^{+220}_{-80}
Reionization Redshift (95% CL)	z_r	20^{+10}_{-9}
Reionization optical depth	τ	0.17 ± 0.04

[a] $\Omega_i = \rho_i/\rho_c$ where $\rho_c = 3H^2/8\pi G$
[b] at a scale corresponding to wavenumber $k_0 = 0.05$ Mpc^{-1}
[c] at a scale corresponding to wavenumber $k_0 = 0.002$ Mpc^{-1}

Bland-Hawthorn (Bologna 2011)
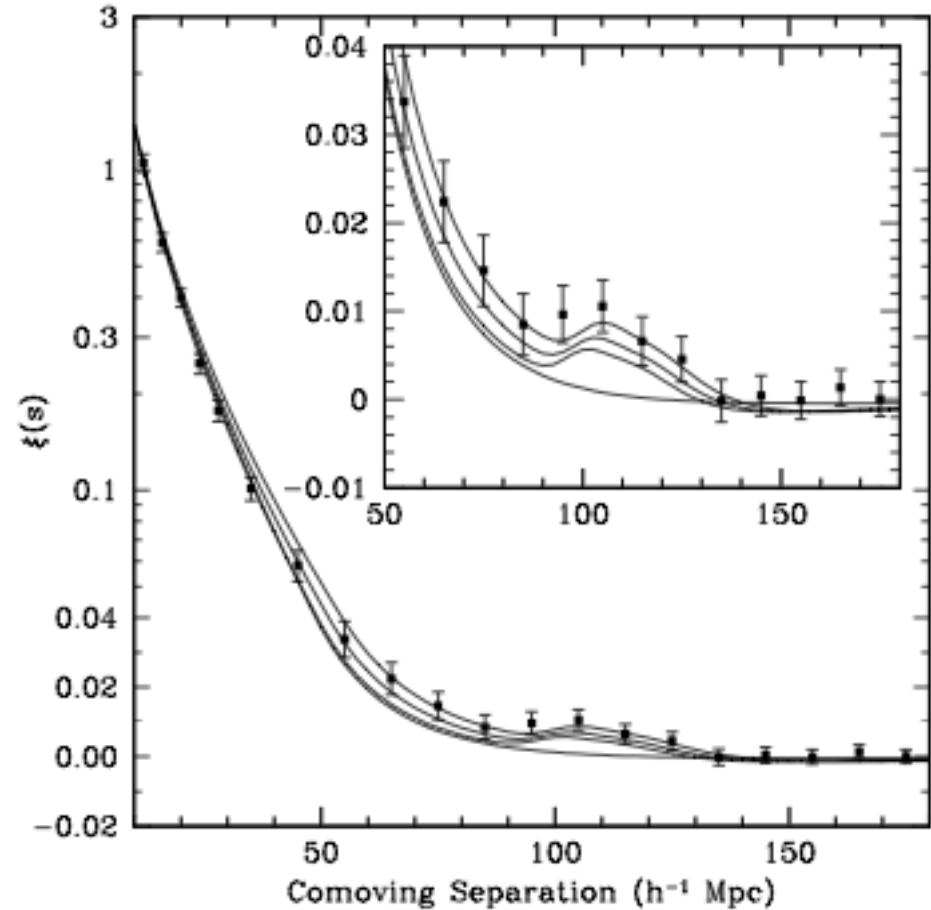
BAO first detected by
Peacock et al 2001 (2dFGRS)

DETECTION OF THE BARYON ACOUSTIC PEAK IN
FUNCTION OF SDSS LUMINOUS

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MASATAKA FUKUGITA,[16] JOSHUA A. FRIEMAN,[10,17] KARL GLAZEBRO
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MARK SUBBARAO,[17,28] ALEXANDER S. SZALA
DOUGLAS L. TUCKER,[10] BRIAN YANNY,[10] AN
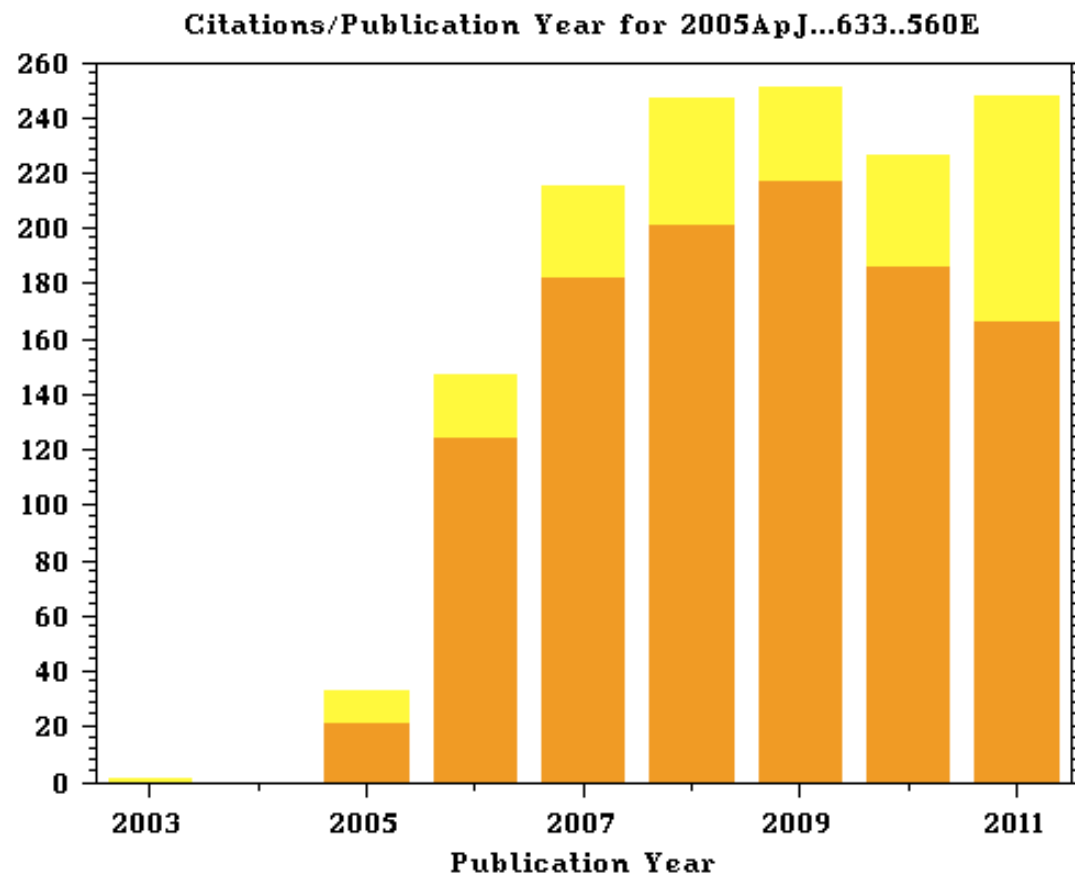
ABSTRACT

We present the large-scale correlation function measured from
red galaxies from the Sloan Digital Sky Survey. The survey regi
$0.16 < z < 0.47$, making it the best sample yet for the study of larg
in the correlation function at $100 \, h^{-1}$ Mpc separation that is an exce
of the imprint of the recombination-epoch acoustic oscillations on the low-redshift clustering of matter. This detec-
tion demonstrates the linear growth of structure by gravitational instability between $z \approx 1000$ and the present and
confirms a firm prediction of the standard cosmological theory. The acoustic peak provides a standard ruler by
which we can measure the ratio of the distances to $z = 0.35$ and $z = 1089$ to 4% fractional accuracy and the absolute
distance to $z = 0.35$ to 5% accuracy. From the overall shape of the correlation function, we measure the matter
density $\Omega_m h^2$ to 8% and find agreement with the value from cosmic microwave background (CMB) anisotropies.
Independent of the constraints provided by the CMB acoustic scale, we find $\Omega_m = 0.273 \pm 0.025 + 0.123(1 + w_0) +
0.137\Omega_K$. Including the CMB acoustic scale, we find that the spatial curvature is $\Omega_K = -0.010 \pm 0.009$ if the dark
energy is a cosmological constant. More generally, our results provide a measurement of cosmological distance,
and hence an argument for dark energy, based on a geometric method with the same simple physics as the micro-
wave background anisotropies. The standard cosmological model convincingly passes these new and robust tests of
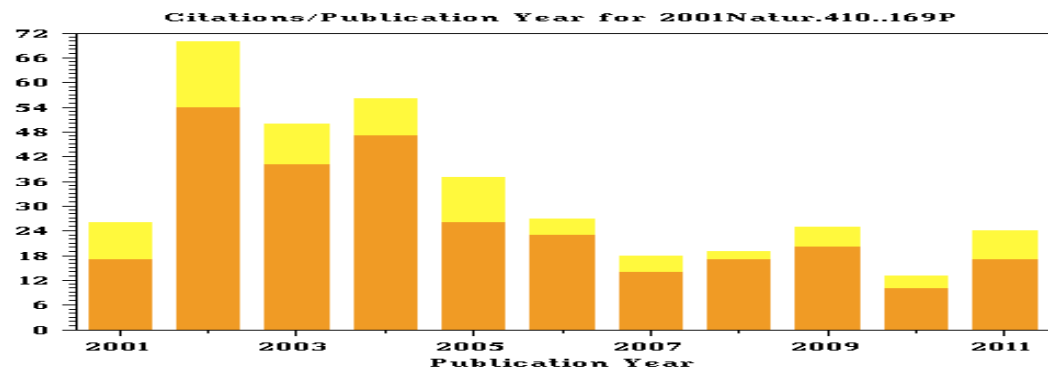its fundamental properties.

Sloan impact

Citations/Publication Year for 2005ApJ...633..560E

Eisenstein

Citations/Publication Year for 2001Natur.410..169P

Peacock

Consistent Parameters

	WMAP+CBI +ACBAR	All CMB(Bond)	CMB+ 2dFGRS	CMB+SDSS (Tegmark)
$\Omega_b h^2$	$.023 \pm .001$	$.0230 \pm .0011$	$.023 \pm .001$	$.0232 \pm .0010$
h	$.73 \pm .05$	$.72 \pm .05$	$.73 \pm .03$	$.70 \pm .03$
n_s	$.97 \pm .03$	$.967 \pm .029$	$.97 \pm .03$	$.977 \pm .03$
σ_8	$.83 \pm .08$	$.85 \pm .06$	$.84 \pm .06$	$.92 \pm .08$

$$\Omega = \rho / \rho_{crit} \qquad \rho_{crit} = 3H_o^2 / 8\pi G \qquad h = H_o / 100$$

Bland-Hawthorn (Bologna 2011)

The standard ΛCDM model

- on large scales, the universe is homogeneous and isotropic
- the geometry of the universe is flat
- the dark matter is cold
- the relative densities of DM, DE, baryons are established by WMAP
- the initial density fluctuations were small, described by a GRF, with $P(k) \approx k$

Are there surprises in store?

"The history of cosmology shows that in every age devout people believe that they have at last discovered the true nature of the Universe."

- Surely there are!

- After all...
  - why the inflaton field?
  - why the dark sector?
  - why do we live in a special time?

- Our baryonic 4% universe is defined by a myriad of parameters. Do we really believe that the dominance of the dark sector is sustained by two constants?
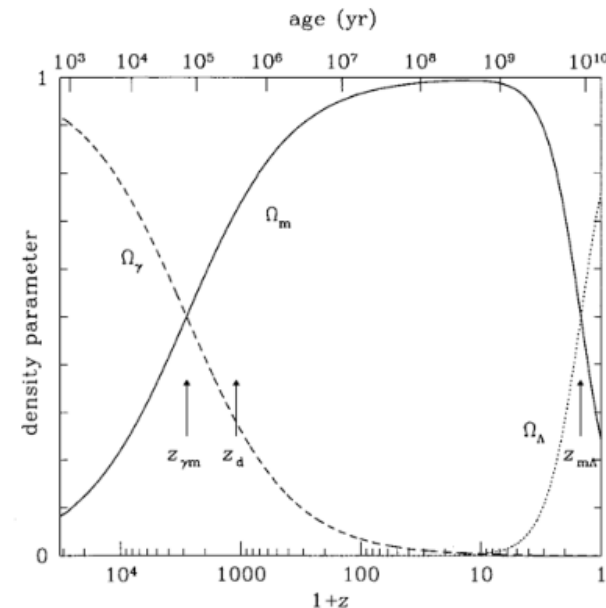
Bland-Hawthorn (Bologna 2011)

Are there surprises in store?

"The history of cosmology shows that in every age devout people believe that they have at last discovered the true nature of the Universe."

- Dark sector comprises more than one component (i.e. new states of matter and energy)

- Dark sector self-annihilates or interacts with baryons (but we cannot be sure until we tackle the panoply of known mechanisms e.g. Galactic Centre; Su et al 2010)

- Missing dimensions are revealed (e.g. LHC in 2012?)

Bland-Hawthorn (Bologna 2011)

Conclusions

- There are known knowns
- There are known unknowns
- There are unknown knowns
- There are unknown unknowns

Bland-Hawthorn (Bologna 2011)