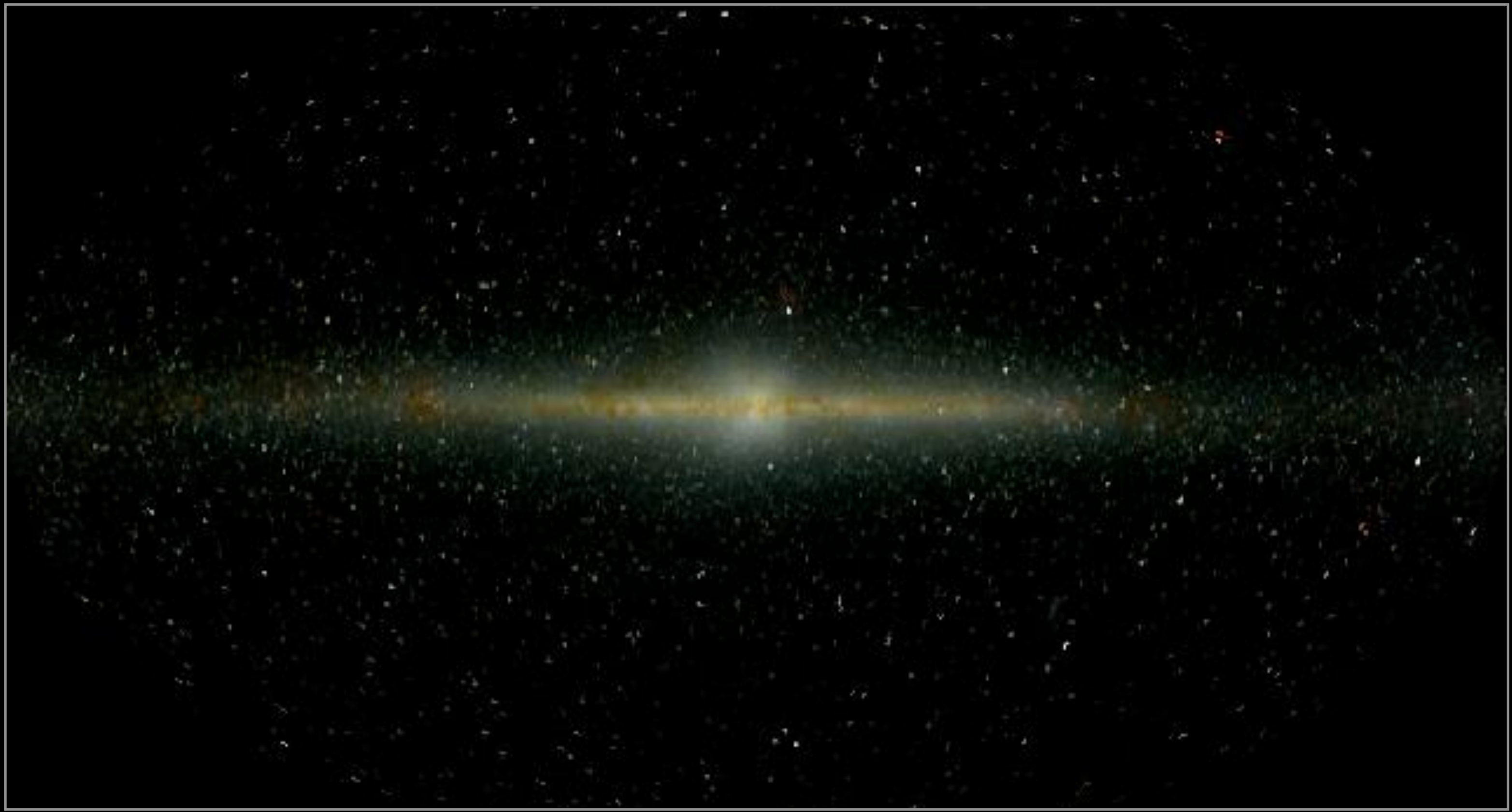
The Local Group in cosmological context

J. Bland-Hawthorn & S. Sharma (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

"Roughly half of all cosmological information lies in the near field – a complete understanding of galaxies requires both near field and far field cosmology."

JBH 1999; JBH & Freeman 2000-2004; JBH & Peebles 2006

Overview of lecture series

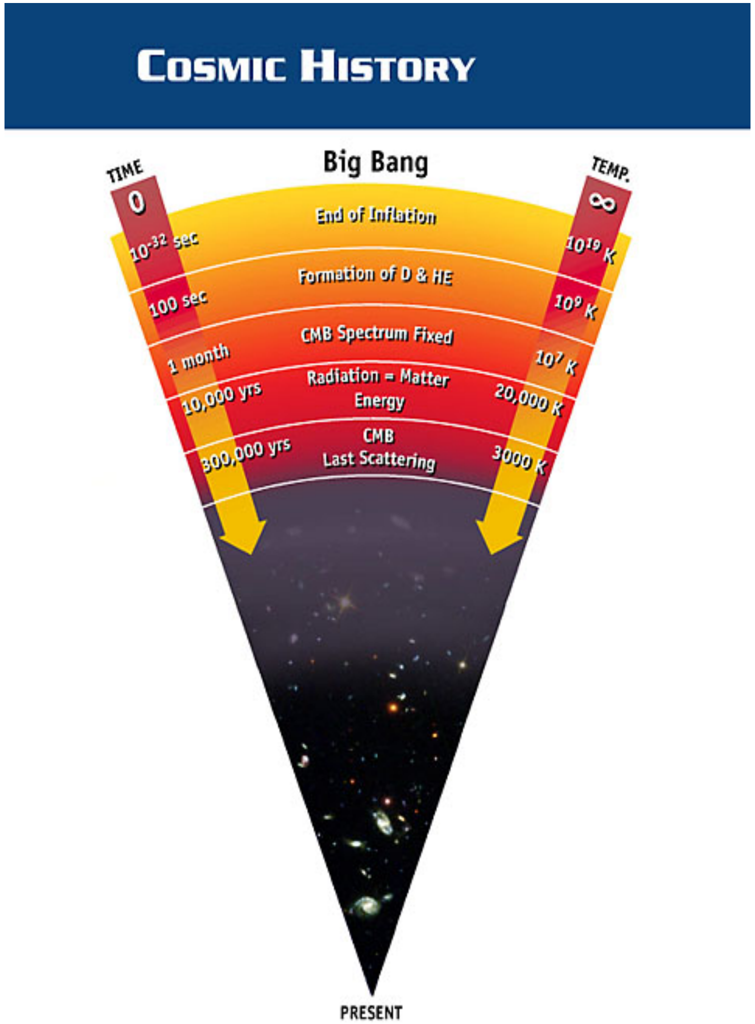
- A brief history of the universe
- The story of dark matter
- First seeds: gaussian random field
- Gravitational instability on linear scales
- Silk damping
- Cosmic microwave background
- Definition of the standard model
- Gravitational instability on non-linear scales
- First stars and metals
- Extended 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 Sydney was founded



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
Mo, vdBosch & White 2010	comprehensive review (*recommended)

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

Amazing fact:

the existence of the dark sector

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 $5 \times 10^{11}\ M_{\odot}$ 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 a few weeks ago!

Bland-Hawthorn (Sydney 2012)

Dark matter on cluster scales...

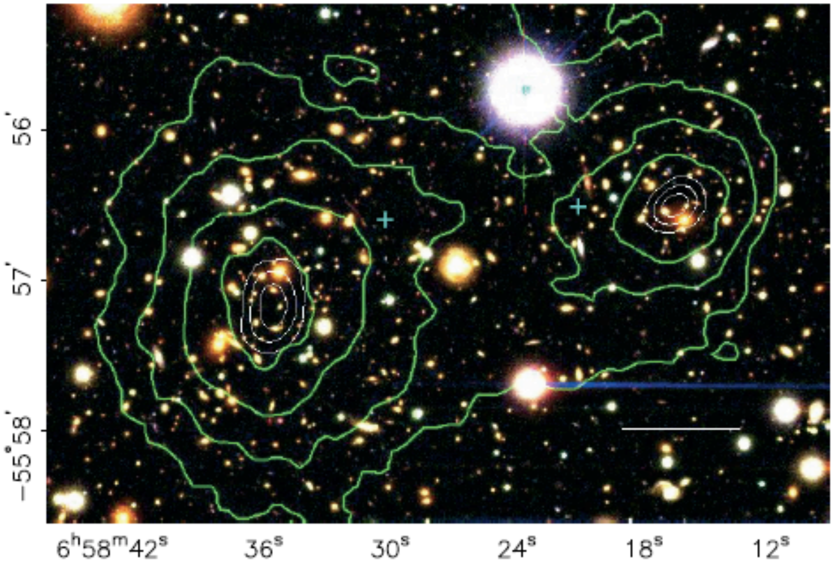
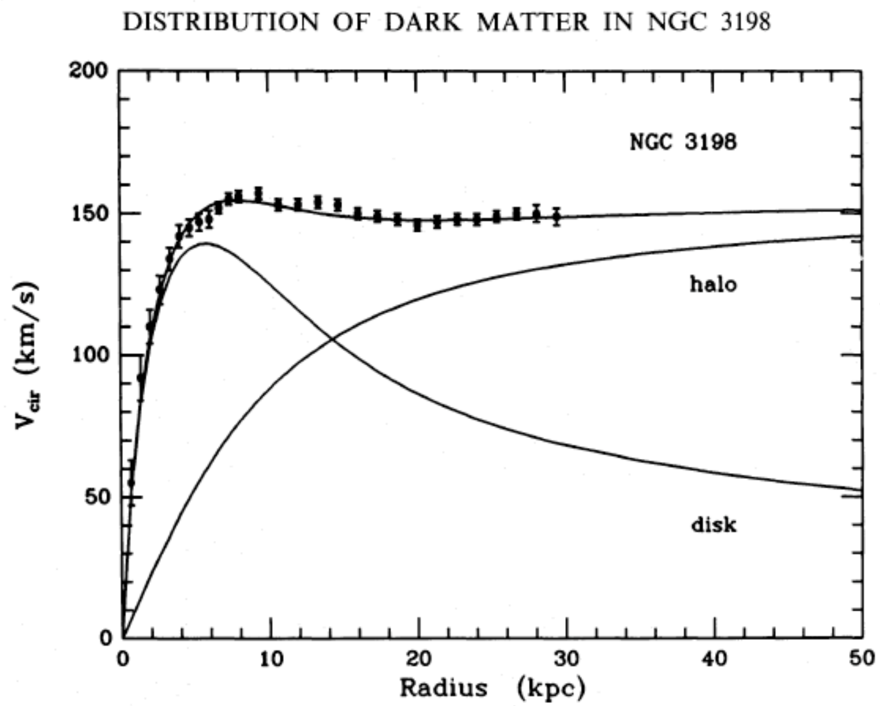


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with 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

Dark matter on galaxy scales….



$$\frac{GM}{R} = v^2(R) = const$$

$$\rho R^2 = const$$

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

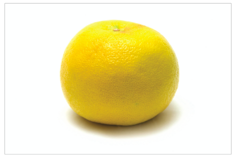
Bland-Hawthorn (Sydney 2012)

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

Amazing fact:

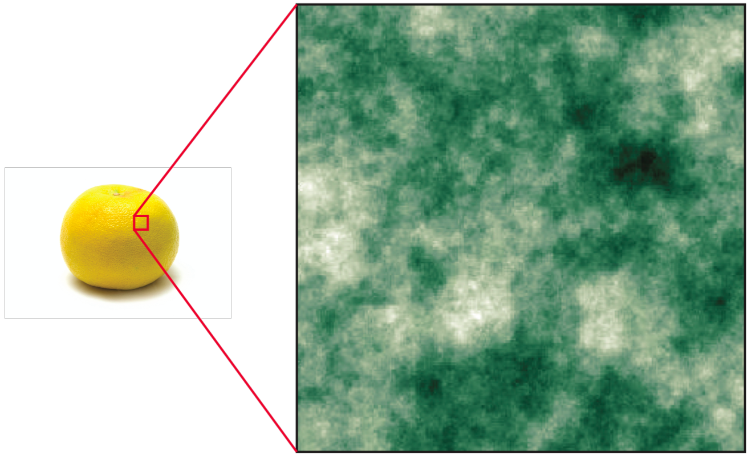
The universe was once the size of a grapefruit

The story of dark matter

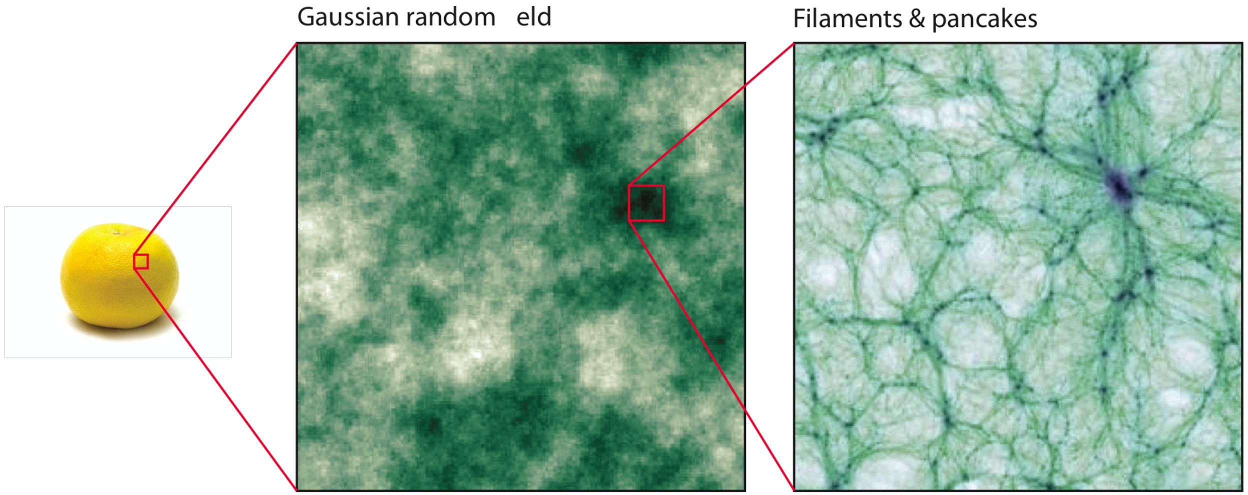


The story of dark matter

Gaussian random field

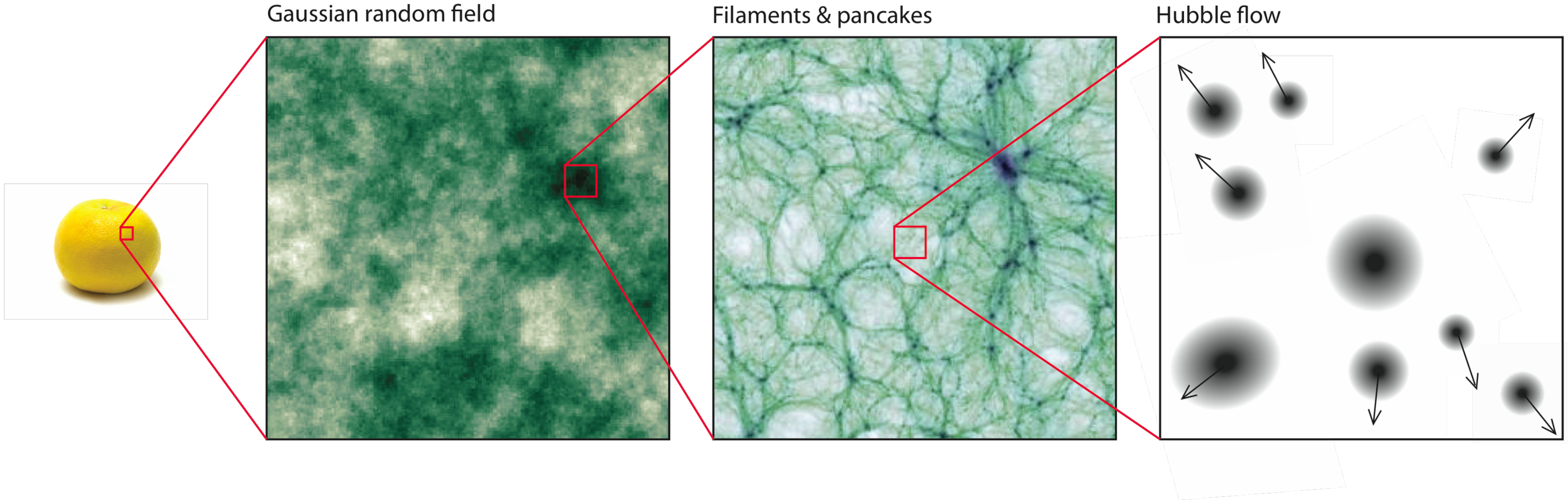


The story of dark matter



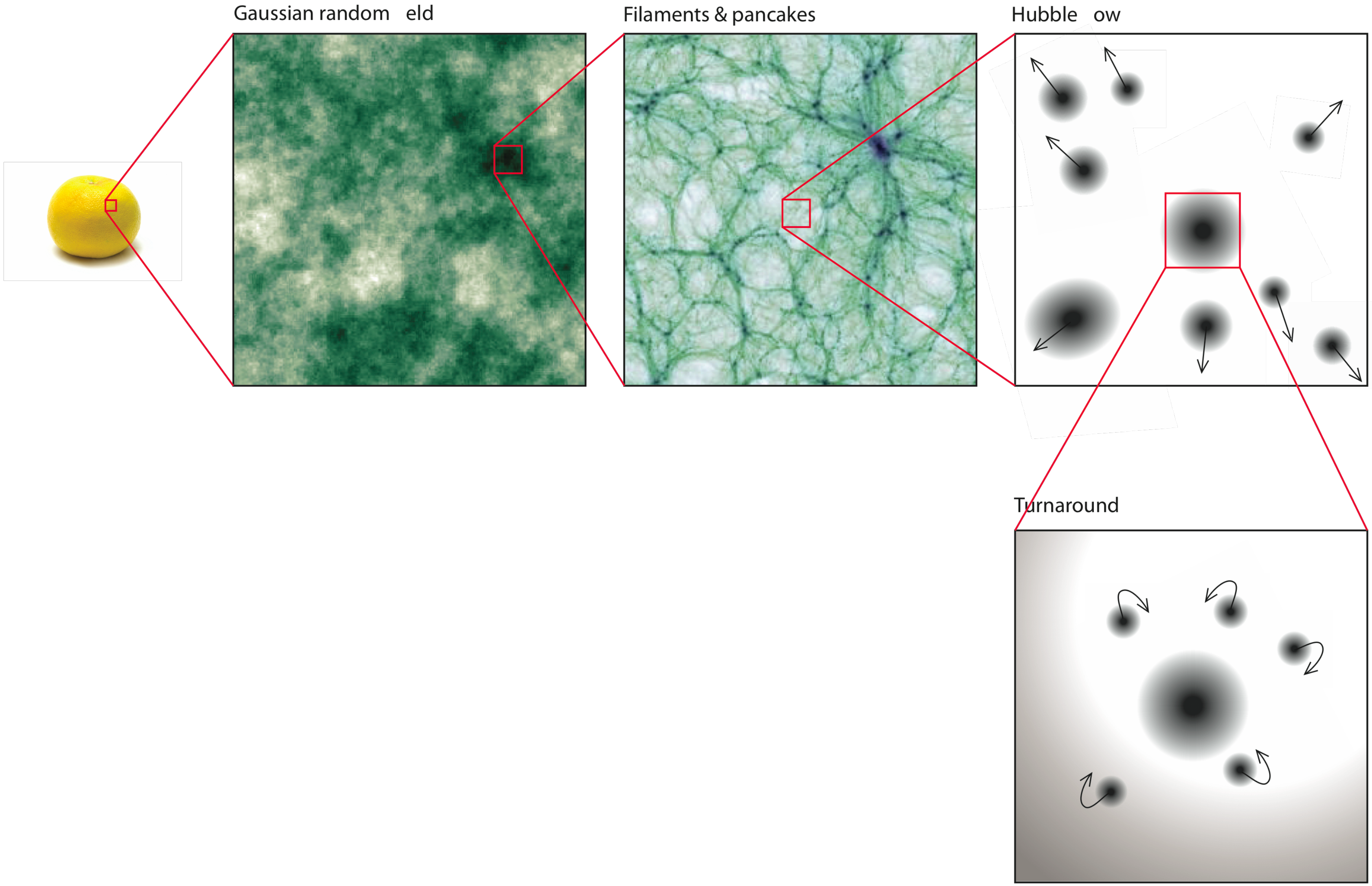
Bland-Hawthorn (Sydney 2012)

The story of dark matter



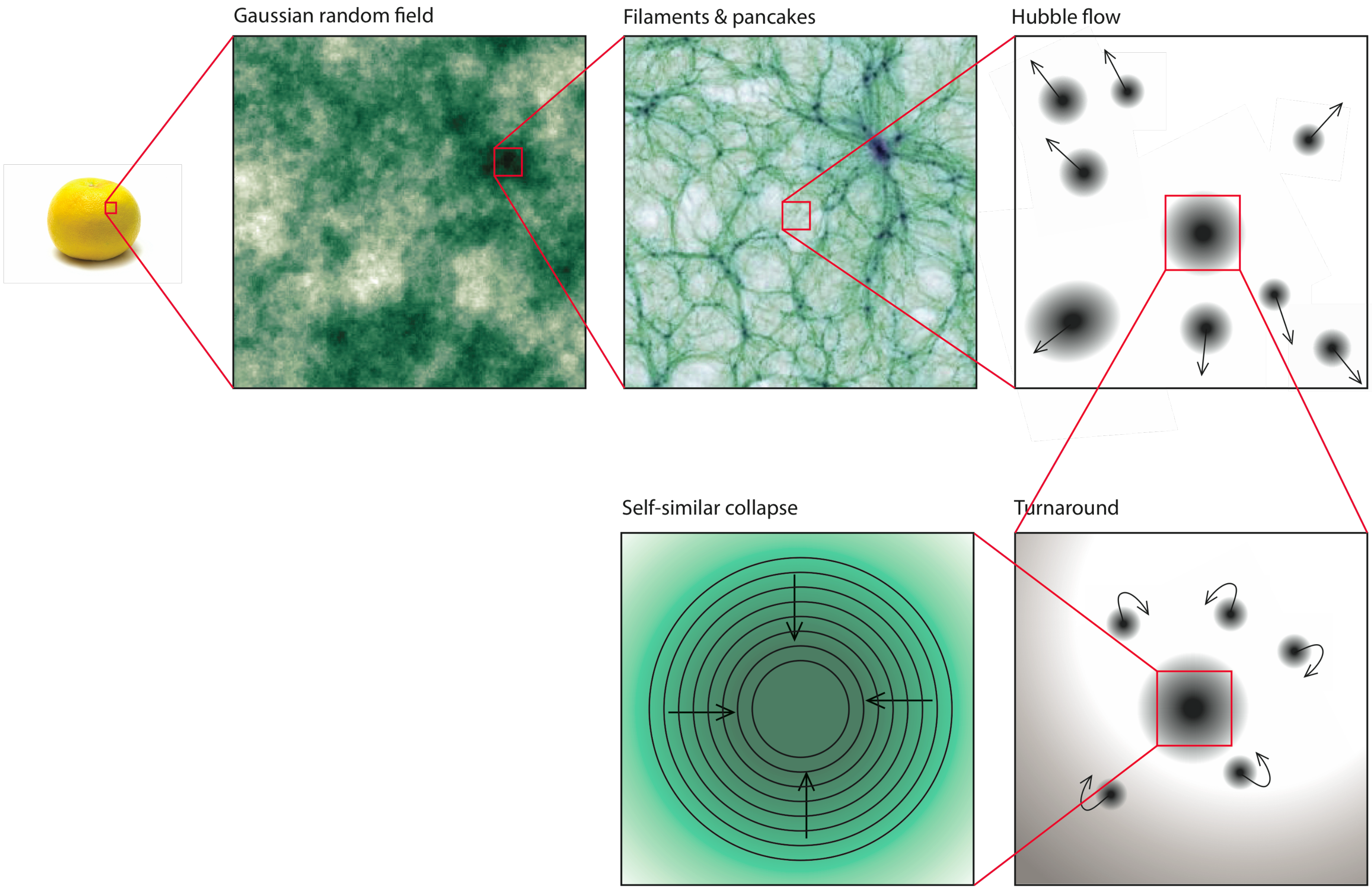
Bland-Hawthorn (Sydney 2012)

The story of dark matter



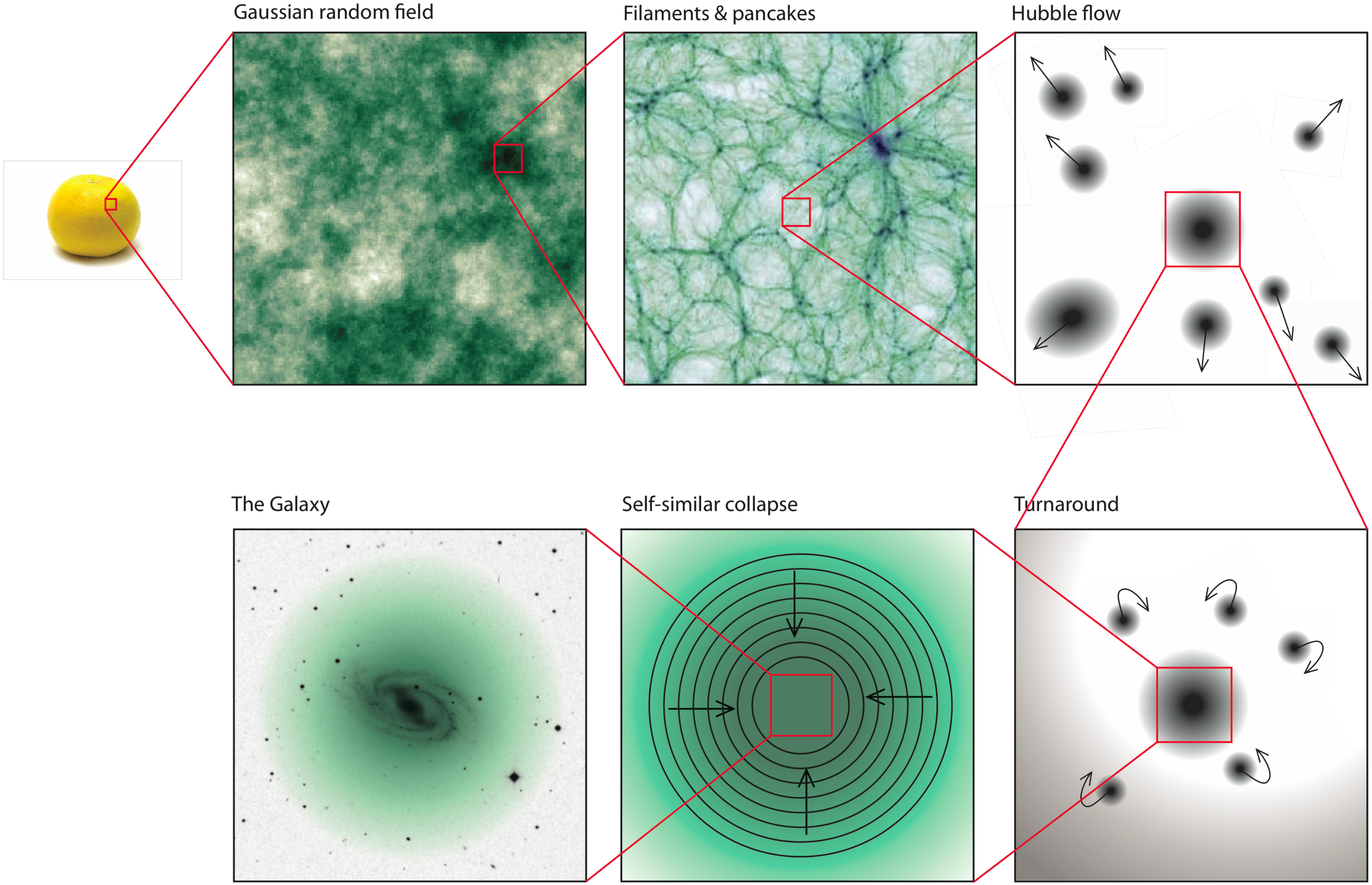
Bland-Hawthorn (Sydney 2012)

The story of dark matter



Bland-Hawthorn (Sydney 2012)

The story of dark matter



Bland-Hawthorn (Sydney 2012)

We now define overdensity

Structure began with density fluctuations

dimensionless

comoving coordinate vector

$$\delta(\underline{x}) = \frac{\rho(\underline{x})}{\rho_0} - 1$$

density can go negative

random field

zero mean

averaged over a very large homogeneous volume V

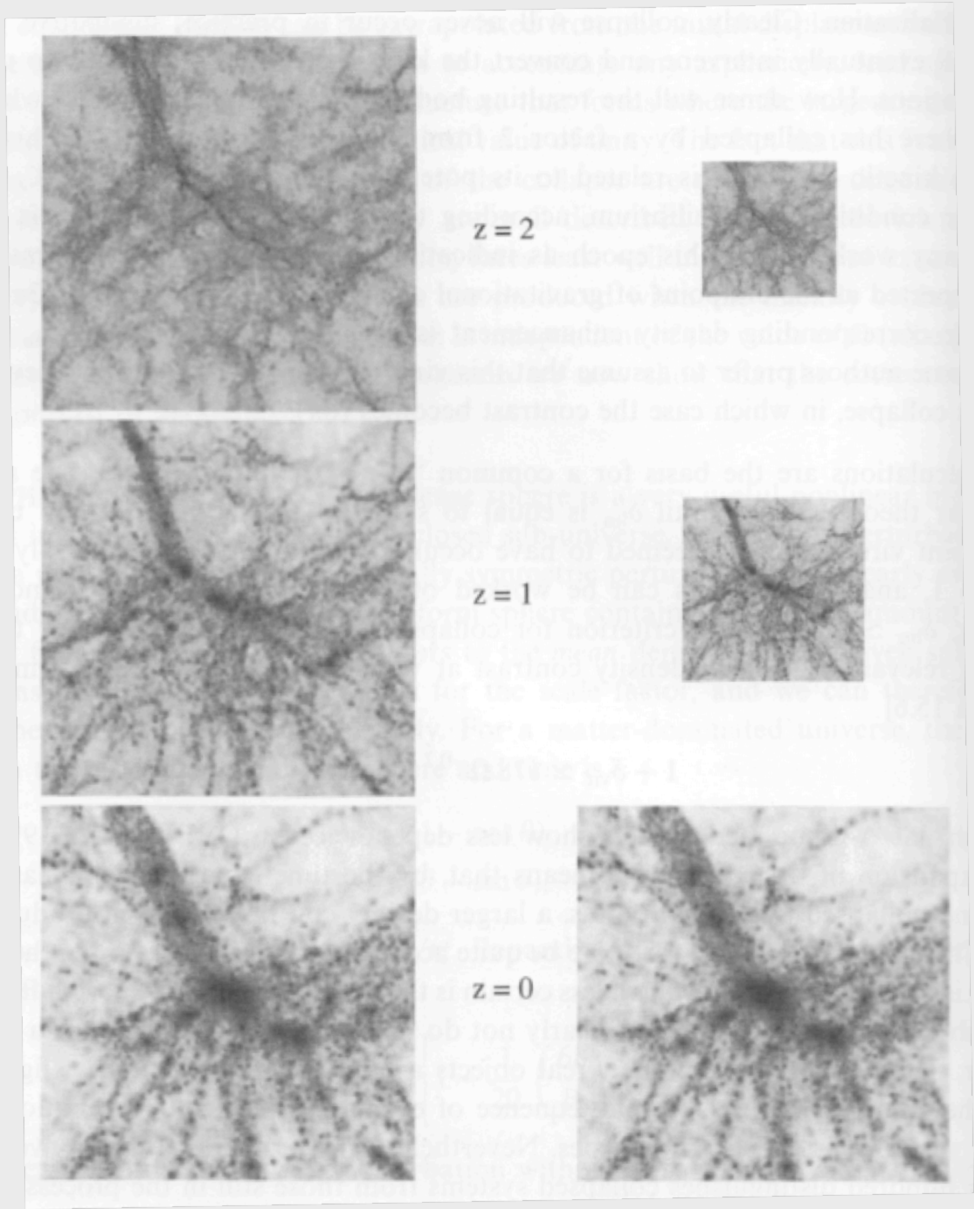
To quantify structure, we define the correlation function

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

not a vector since isotropic field

comoving coords, $\underline{x}$

proper coords



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

Bland-Hawthorn (Sydney 2012)

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 <u>zero</u> 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.

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

VARIANCE OF OVERDENSITY

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

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)

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

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

W = window function

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 (Sydney 2012)

THE ASTROPHYSICAL JOURNAL, 304:15–61, 1986 May 1

a. initially equal power about mean but in time highly asymmetric as voids grow

b. structures are never spherical nor even ellipsoidal

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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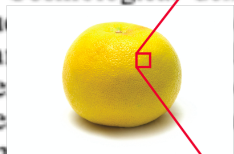
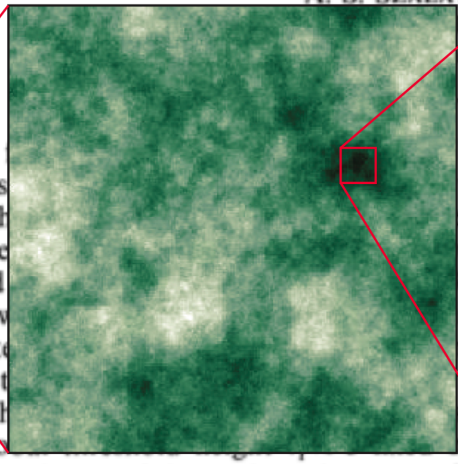
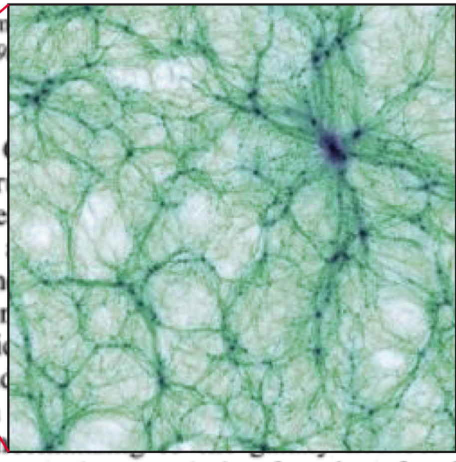






Cosmological density ... maxima of ... the peaks ... paper, we ... which the ... ction in the ... ons; and (4) the density profiles ... pproach, we apply our formulae to ... tter (CDM) models. We assume brigh ... lactic scale) that are above some gl ... density. We find, for example, that the shapes 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.

Bland-Hawthorn (Sydney 2012)

Important notes:

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

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

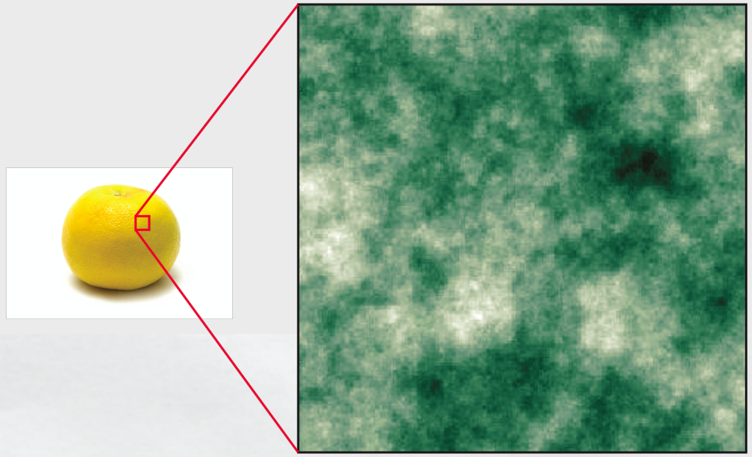
2. Mean no. of particles in box K^{-1} on a side is $N \propto K^{-3}$

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

$$\frac{\sigma}{N} \propto N^{-1/2} \propto K^{3/2}$$

$\therefore\ n = 0$ for *Poisson*

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* $(n=0)$

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.

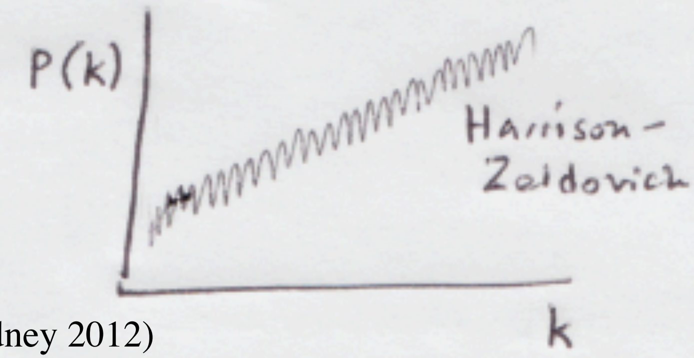
$$\therefore\ \delta\Phi \simeq G.\,\delta M.\,K$$

$$\simeq G.\,\rho_o\,\underbrace{\sigma_K}_{\propto K^{(3+n)/2}}\,K^{-3}\,K$$

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

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

Later, power law index n=1 was discovered to be a key prediction of Guth's inflation (1980).



Non-relativistic gravitational instabilities in an expanding universe

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

Working in comoving coordinates $\underline{x}$

$$\frac{\partial \rho}{\partial t} + 3H\rho + \nabla \cdot (\rho \underline{v}) = 0$$

CONTINUITY EQN.

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

EULER'S EQN.

Conservation of momentum

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

$$\frac{\partial^2 \delta_{\underline{k}}}{\partial t^2} + 2H\frac{\partial \delta_{\underline{k}}}{dt} + \Big(\overbrace{\frac{k^2}{a^2} v_s^2}^{\text{negligible on large scale}} - 4\pi G \rho_0\Big)\delta_{\underline{k}} = 0$$

disturbed

undisturbed

Sound speed

Bland-Hawthorn (Sydney 2012)

For any cosmological model, we can solve for overdensity $\delta_{\underline{k}}$ in terms of H, v_s, ρ_0.

On large scales, $k \to 0$ $\quad H = \frac{2}{3t} \quad 4\pi G \rho_0 = \frac{2}{3t^2}$

Solutions when matter dominates : $\quad \delta_{\underline{k}} \propto t^{2/3} \quad \delta_{\underline{k}} \propto t^{-1}$

growing $\quad$ decaying

$3100 \gtrsim z \gtrsim 0.5$

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

$4\pi G \rho_0 \to 0$

$$\frac{\partial^2 \delta_{\underline{k}}}{\partial t^2} + 2H \frac{\partial \delta_{\underline{k}}}{\partial t} = 0$$

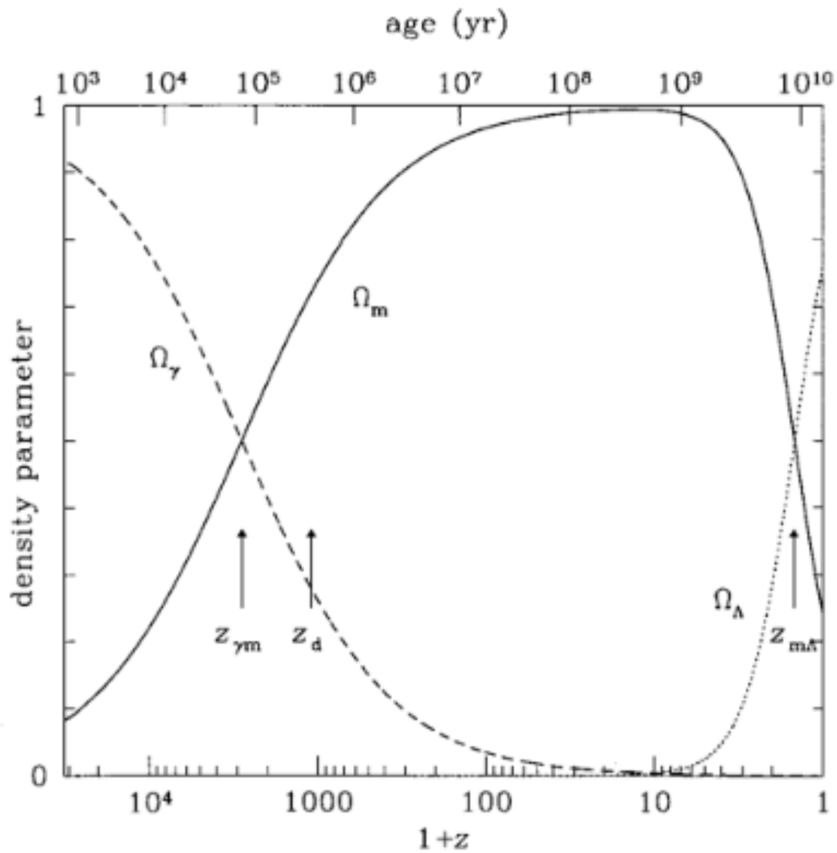
$$\delta(t) = c_1 + c_2 \exp(-2Ht)$$

Amazing fact:

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

Amazing fact:

the universe appears to have entered a 2nd epoch of inflation



Bland-Hawthorn (Sydney 2012)

Many "analytic" studies solve

$$\frac{\partial^2 \delta}{\partial t^2} + 2H \frac{\partial \delta}{\partial t} = 4\pi G \rho_0 \delta$$

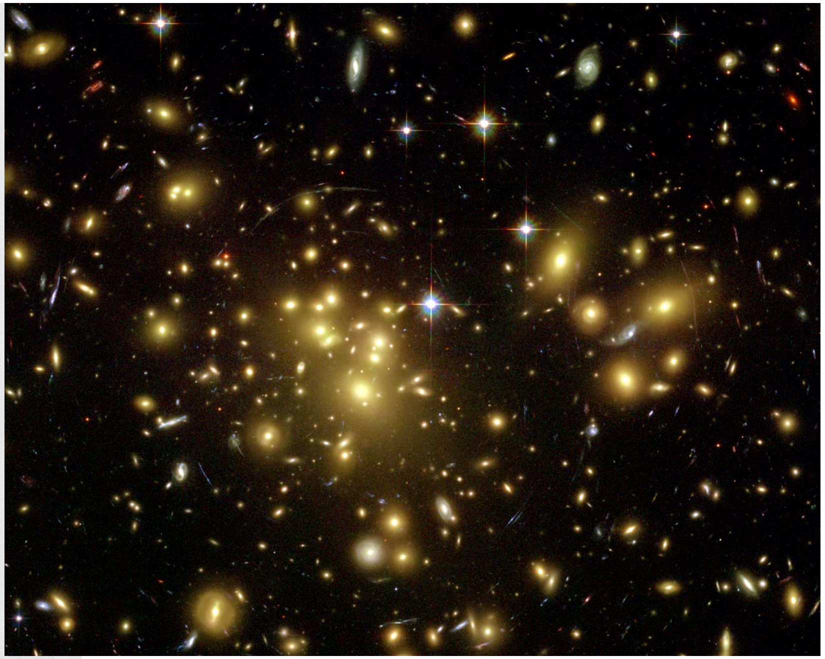
The growing density perturbation maintains its shape in comoving coordinates, growth factor $D(t)$

$$D(t) \propto \frac{(\Omega_\Lambda a^3 + \Omega_m)^{\frac{1}{2}}}{a^{3/2}} \int_0^a \frac{a'^{3/2}\, da'}{(\Omega_\Lambda a'^3 + \Omega_m)^{3/2}}$$

$1 < z < 10^3$,

$$D(t) \propto a(t)$$

The gravitational potential $\delta\Phi \propto \frac{\delta}{a}$ does <u>not</u> grow in comoving coordinates!

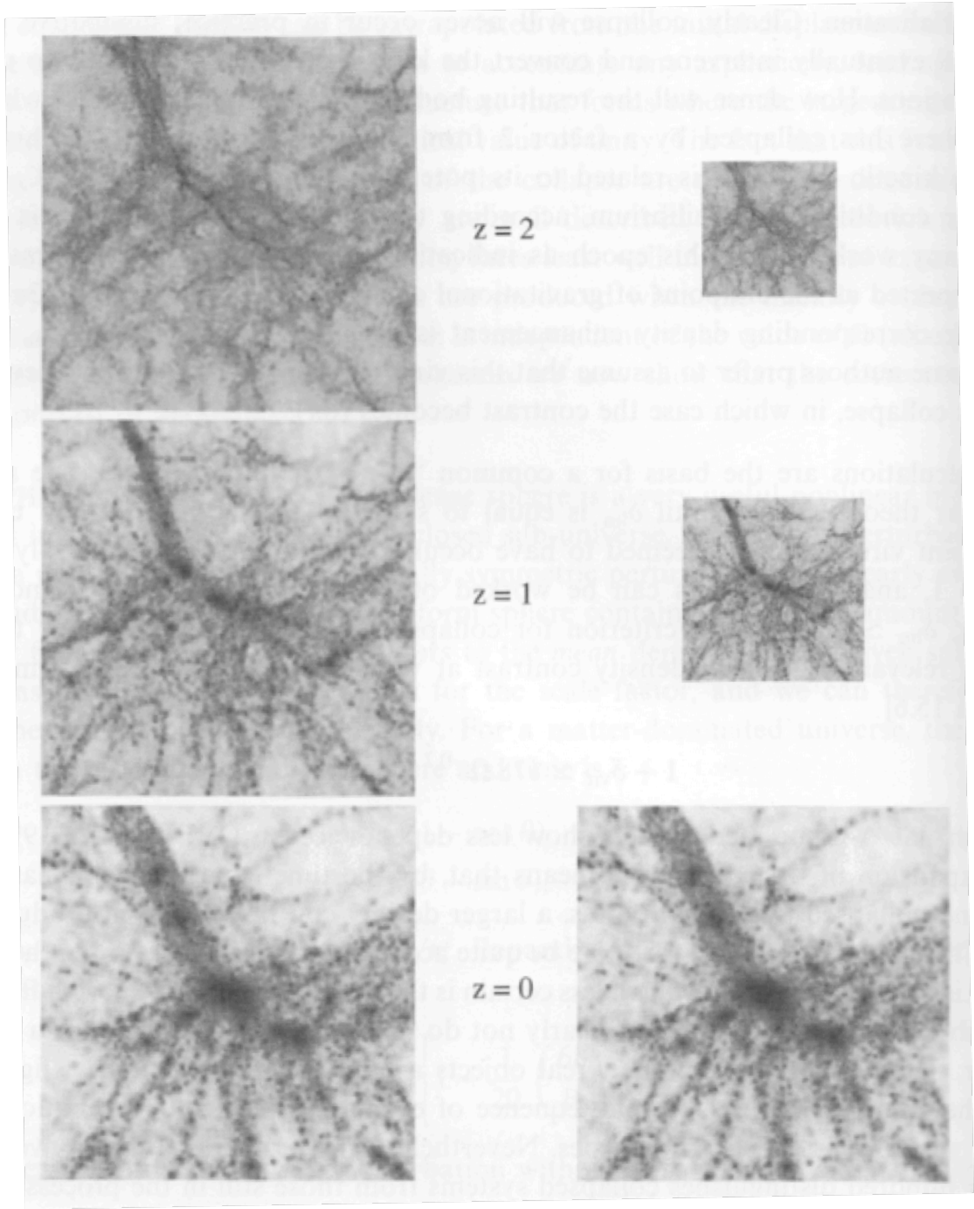


Abell 1689

Amazing fact:

Cluster potentials are "frozen in" relics of the inflationary epoch

hence we use abundance of clusters to constrain amplitude of P(k)...



Bland-Hawthorn (Sydney 2012)

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

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

$$\frac{\partial^2 \delta_{\underline{k}}}{\partial t^2} + 2H\frac{\partial \delta_{\underline{k}}}{dt} + \Big(\overbrace{\frac{k^2}{a^2}v_s^2}^{\text{negligible on large scale}} - 4\pi G\rho_0\Big)\delta_{\underline{k}} = 0$$

disturbed

Sound speed

undisturbed

N

S ... during

... ansion.

W

th

$$\frac{\partial^2 \delta_{\underline{k}}}{\partial t^2} + 2H\frac{\partial \delta_{\underline{k}}}{\partial t} + \left(\frac{k^2c^2}{3a^2} - \frac{32\pi}{3}G\rho_0\right)\delta_{\underline{k}} = 0$$

$1/t$

$$H = \frac{1}{2t} \qquad \frac{32}{3}\pi G\rho_0 = \frac{1}{t^2}$$

$$\frac{k^2c^2}{3a^2} - \frac{1}{t^2}$$

$ct \sim$ horizon scale

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

radiation pressure stabilizes perturbations smaller than $\sim ct$, $\delta_{\underline{k}}$ oscillates.

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

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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 ($N_{\rm H\,I} \lesssim 10^{14}$ 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
…lation exists, in part, because of minimal shock heating
… carefully the density and velocity fields as well as
…IPM versus hydrodynamic simulations, and find good
…able of reproducing measurable quantities, such as the
…d from full hydrodynamic simulations, to a precision
… 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
… 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
… low-density IGM. However, such an approximation
…HPM, unless a non-uniform pre-filtering scheme is

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EFFECT OF REIONIZATION ON STRUCTURE FORMATION IN THE UNIVERSE

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Received 2000 February 7; accepted 2000 June 7

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 (Sydney 2012)

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

radiation pressure stabilizes perturbations smaller than $\sim ct$, $\delta_{\underline{k}}$ oscillates.

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

$$\underbrace{\delta_{\underline{k}} \propto t \qquad \delta_{\underline{k}} \propto t^{-1}}_{\text{these affect both matter and radiation}}$$

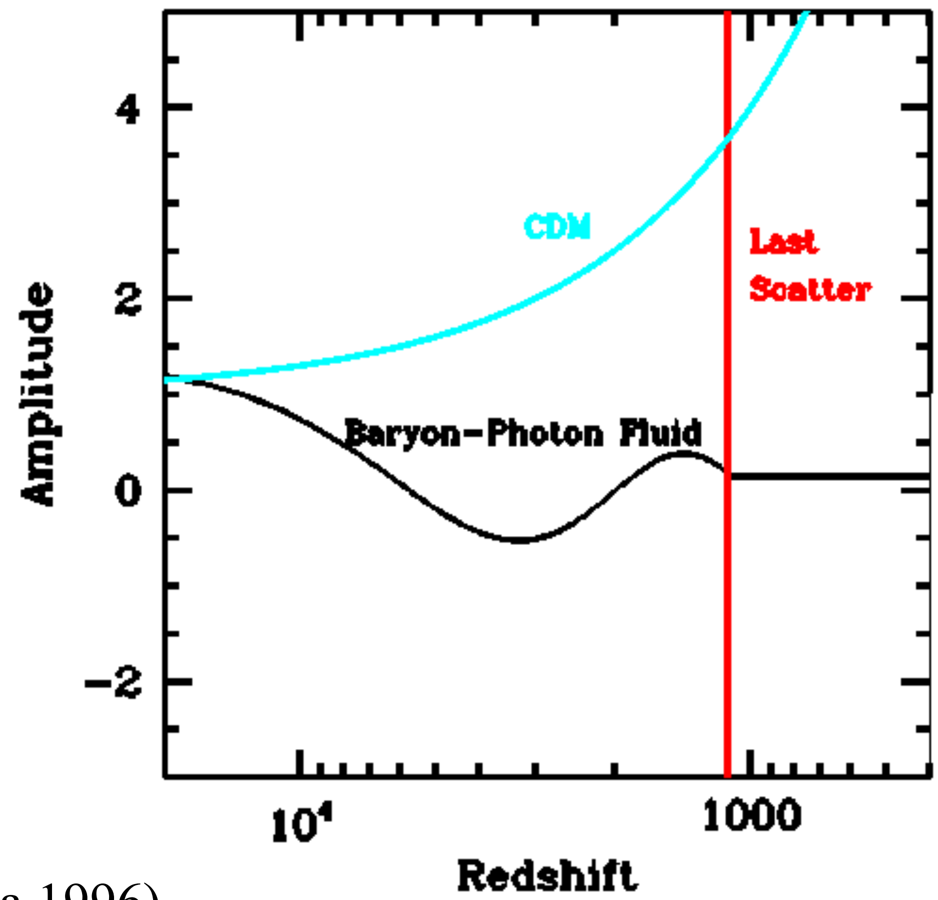
$3100 \gtrsim z \gtrsim 1100$, dark matter fluctuations start to grow $\delta_{\underline{k}} \propto t^{2/3}$ but baryons still locked to radiation until decoupling at $z \simeq 1100$, i.e. photon-baryon viscosity is very large. (also thermal conductivity)

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

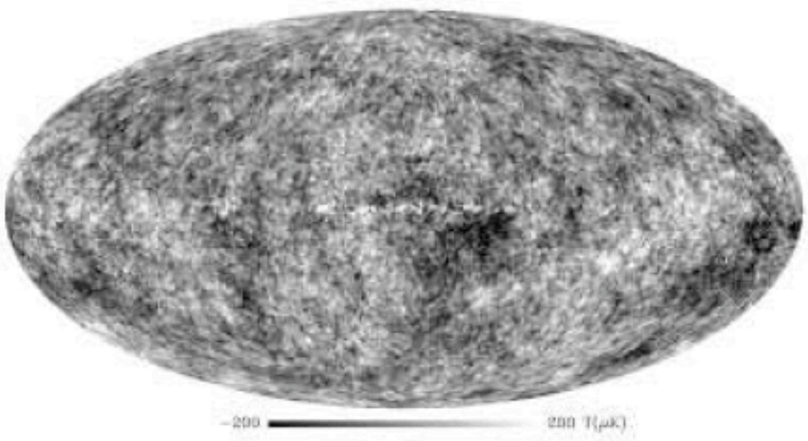
Amazing fact:
dark matter is the ***only*** reason structure below 10 Mpc survived the epoch 3100 < z < 1100

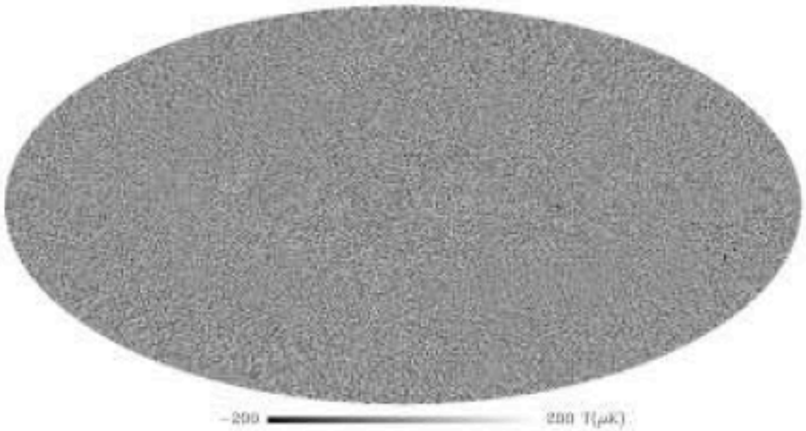
Growth of fluctuations

- 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

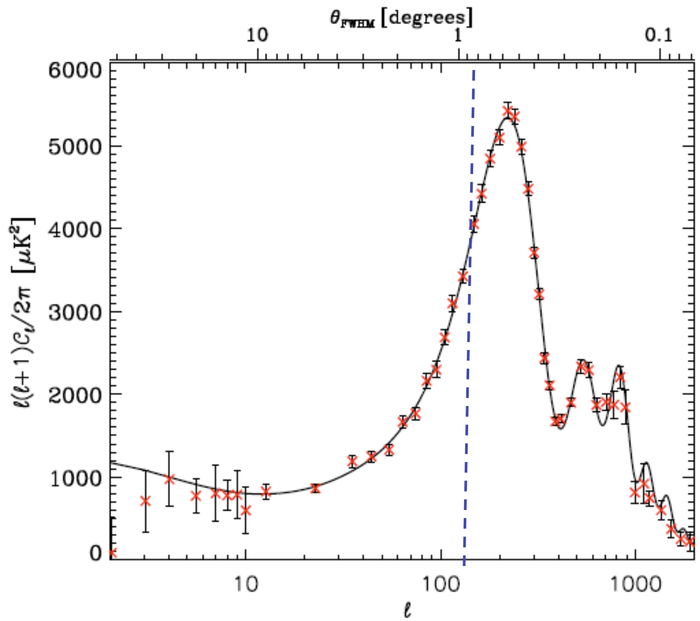




The CMB fluctuations are a byproduct of the **first epoch of accretion.**

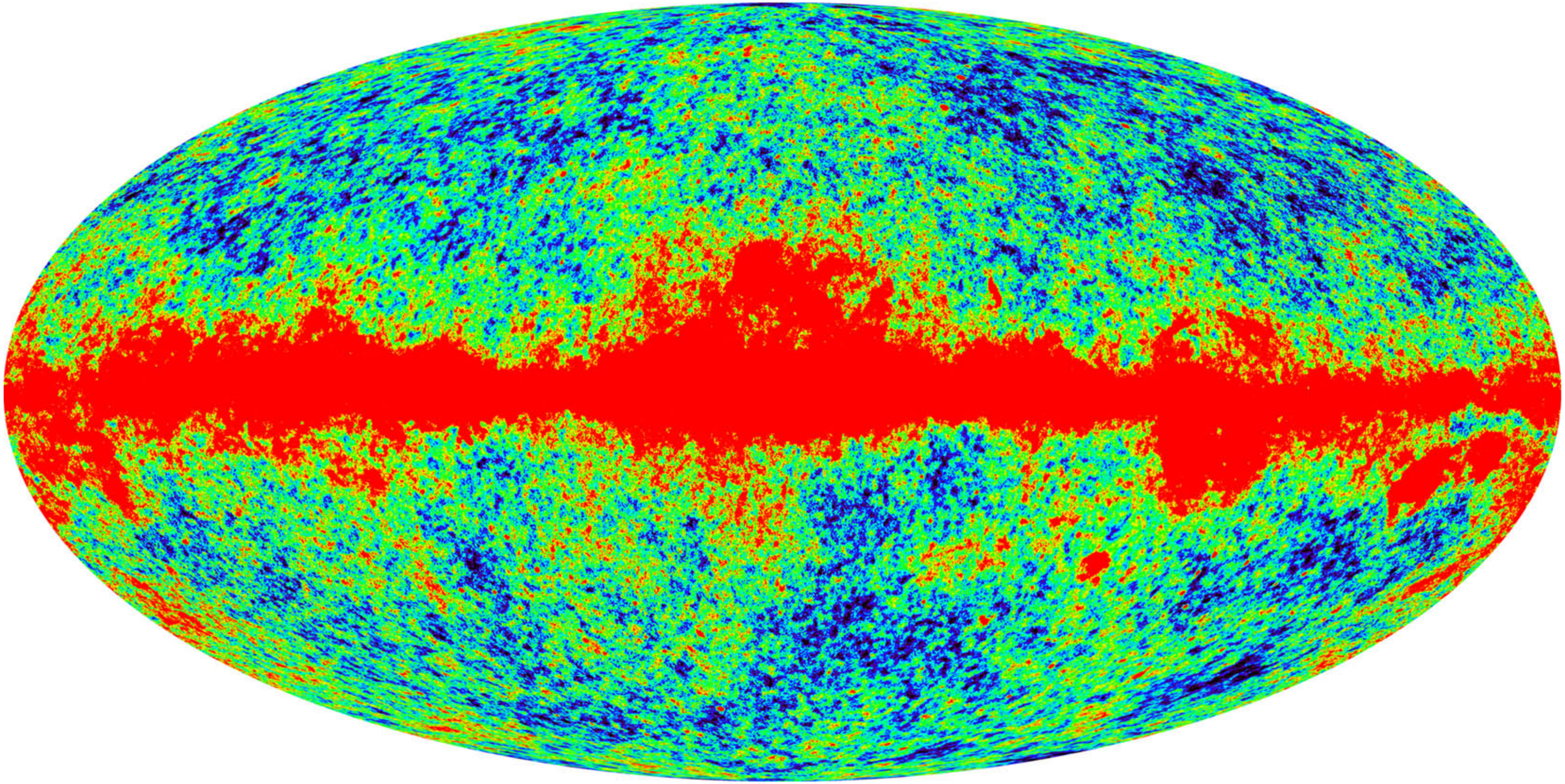
The photon-baryon fluid reacted to the collapse of DM, which took place even before neutrals existed!

Foreground contamination 370,000 years after the Big Bang — photons and baryons took 120,000 years to decouple…



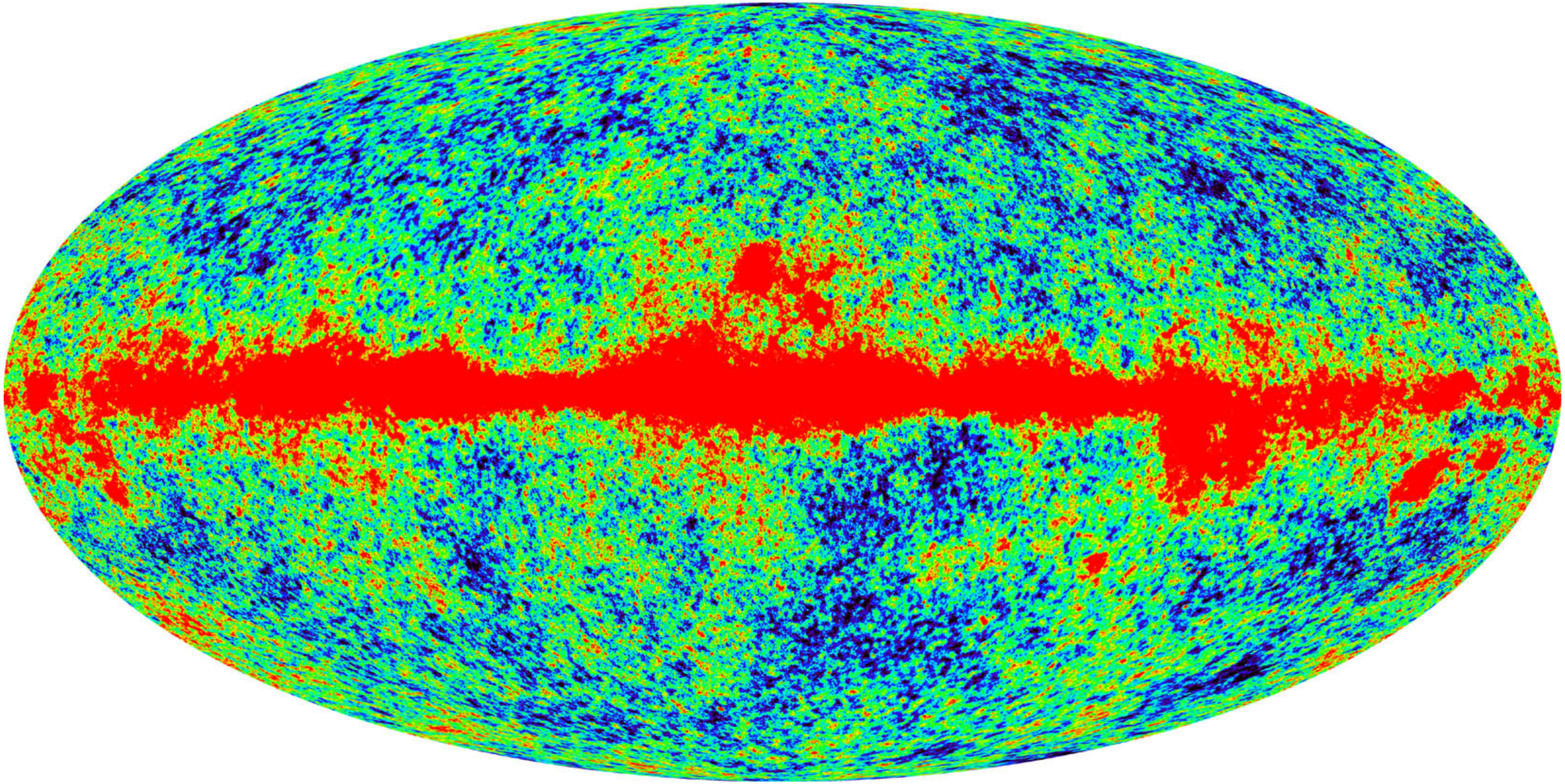
Bland-Hawthorn (Sydney 2012)

Ka - 33GHz



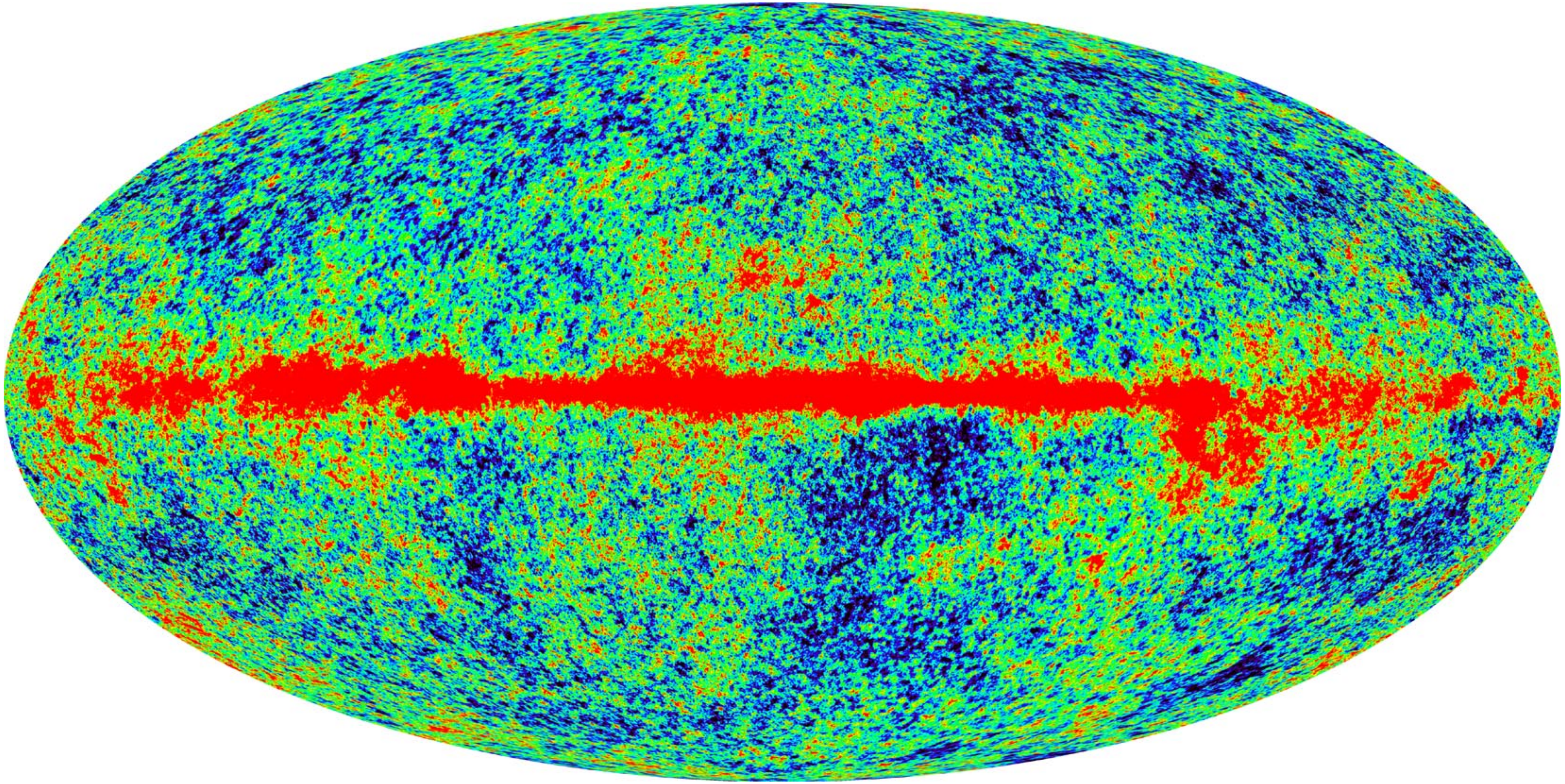
Bland-Hawthorn (Sydney 2012)

Q - 41GHz



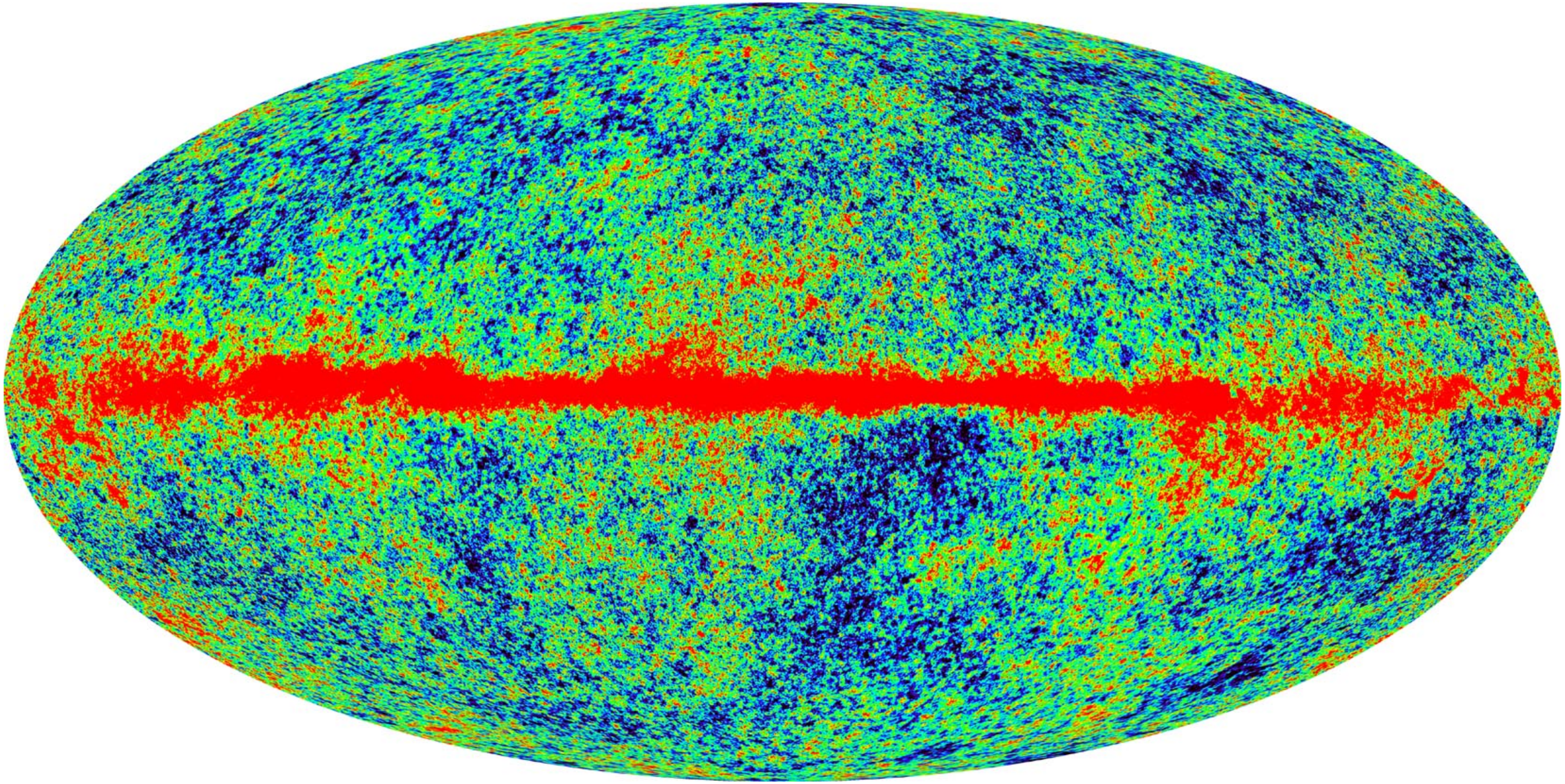
Bland-Hawthorn (Sydney 2012)

V - 61GHz



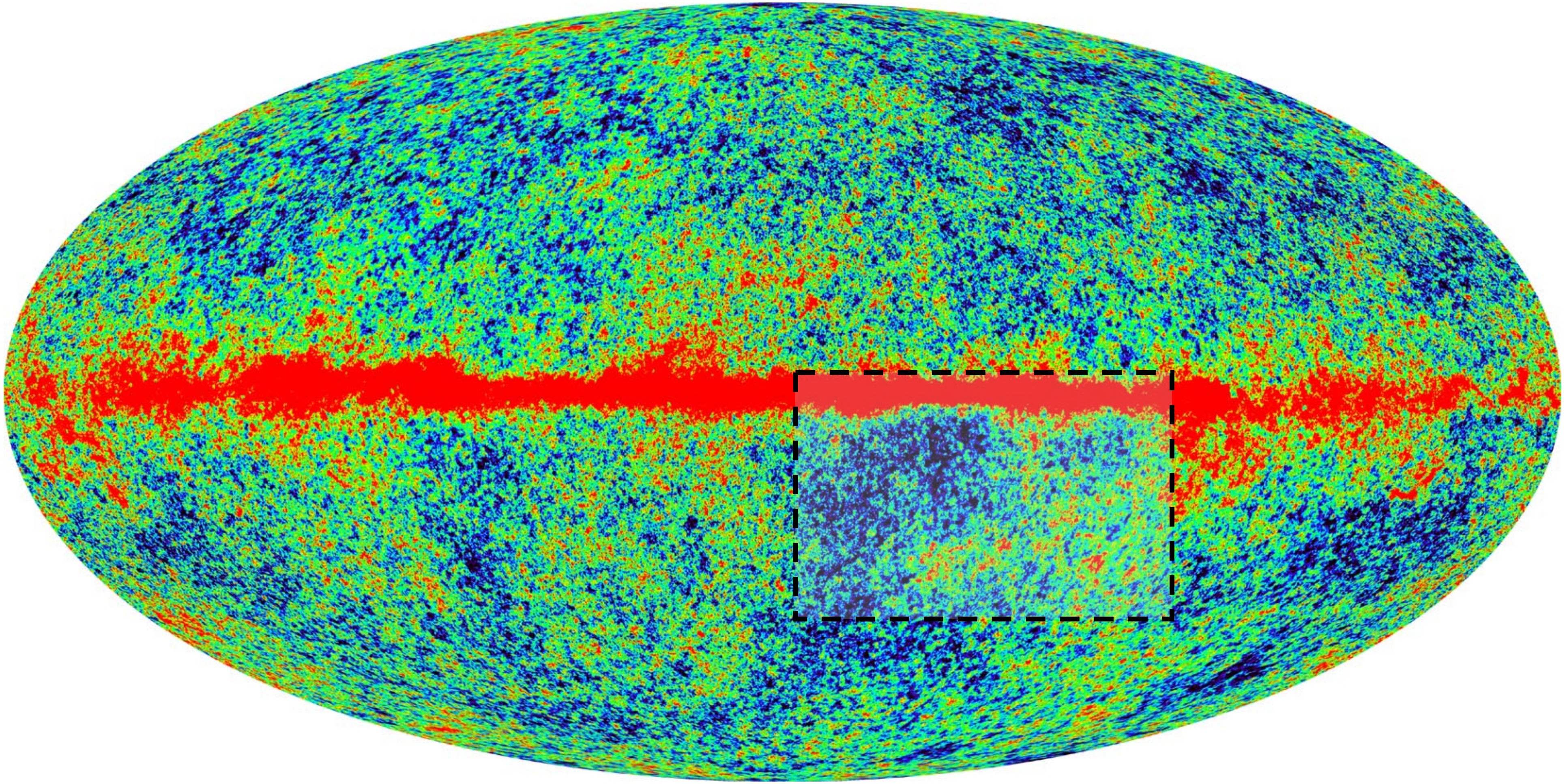
Bland-Hawthorn (Sydney 2012)

W - 94GHz

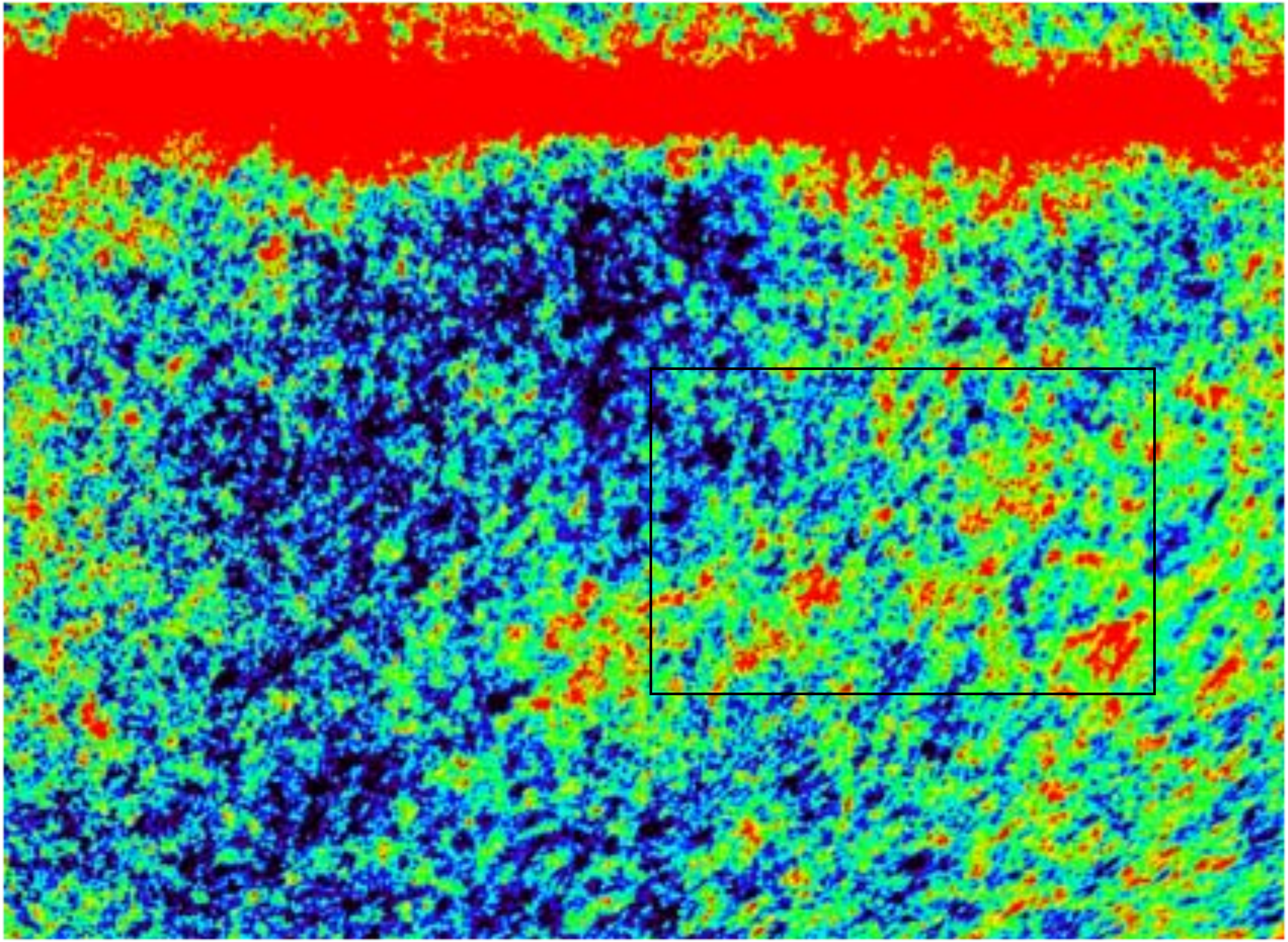


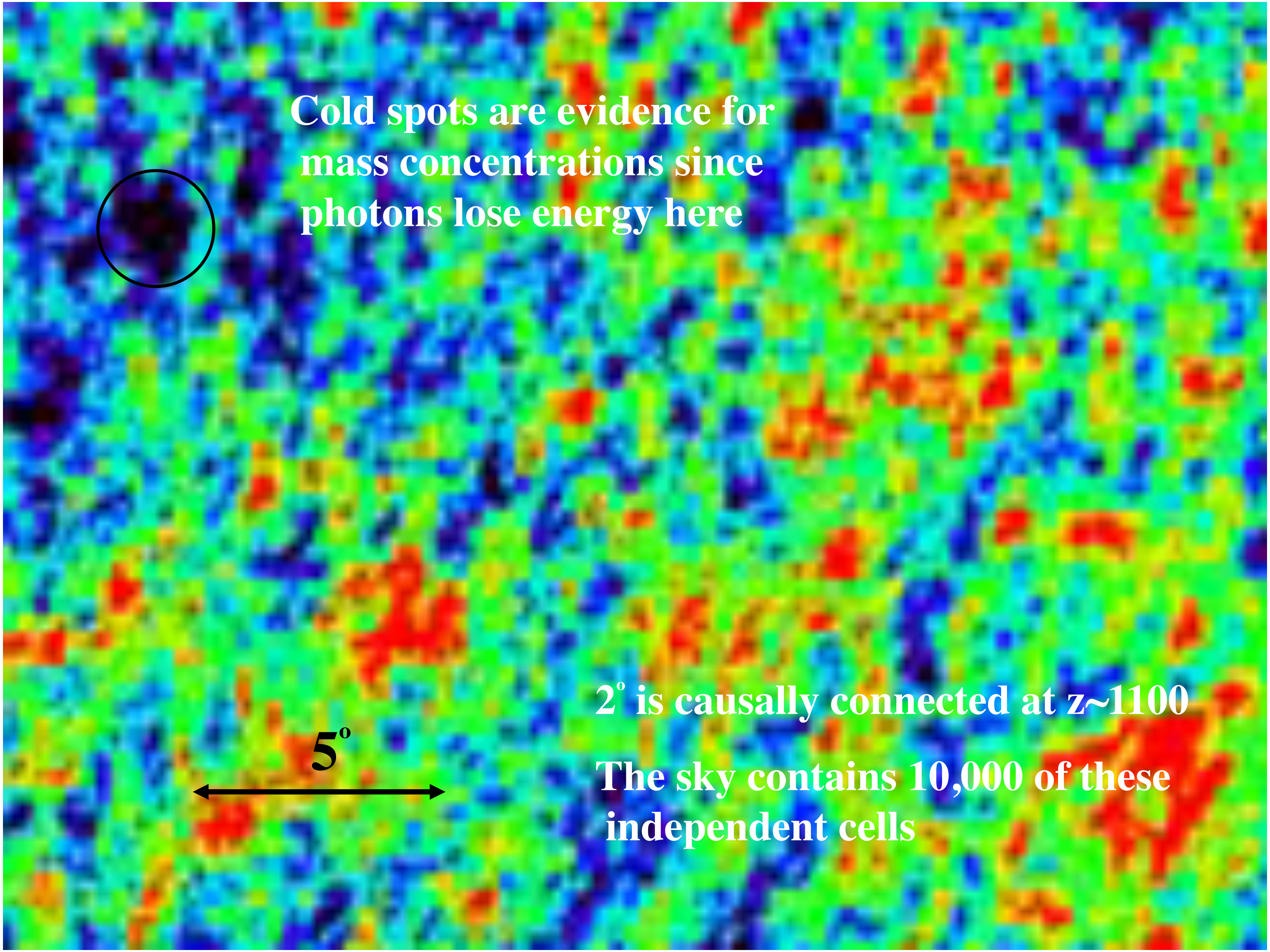
Bland-Hawthorn (Sydney 2012)

W - 94GHz

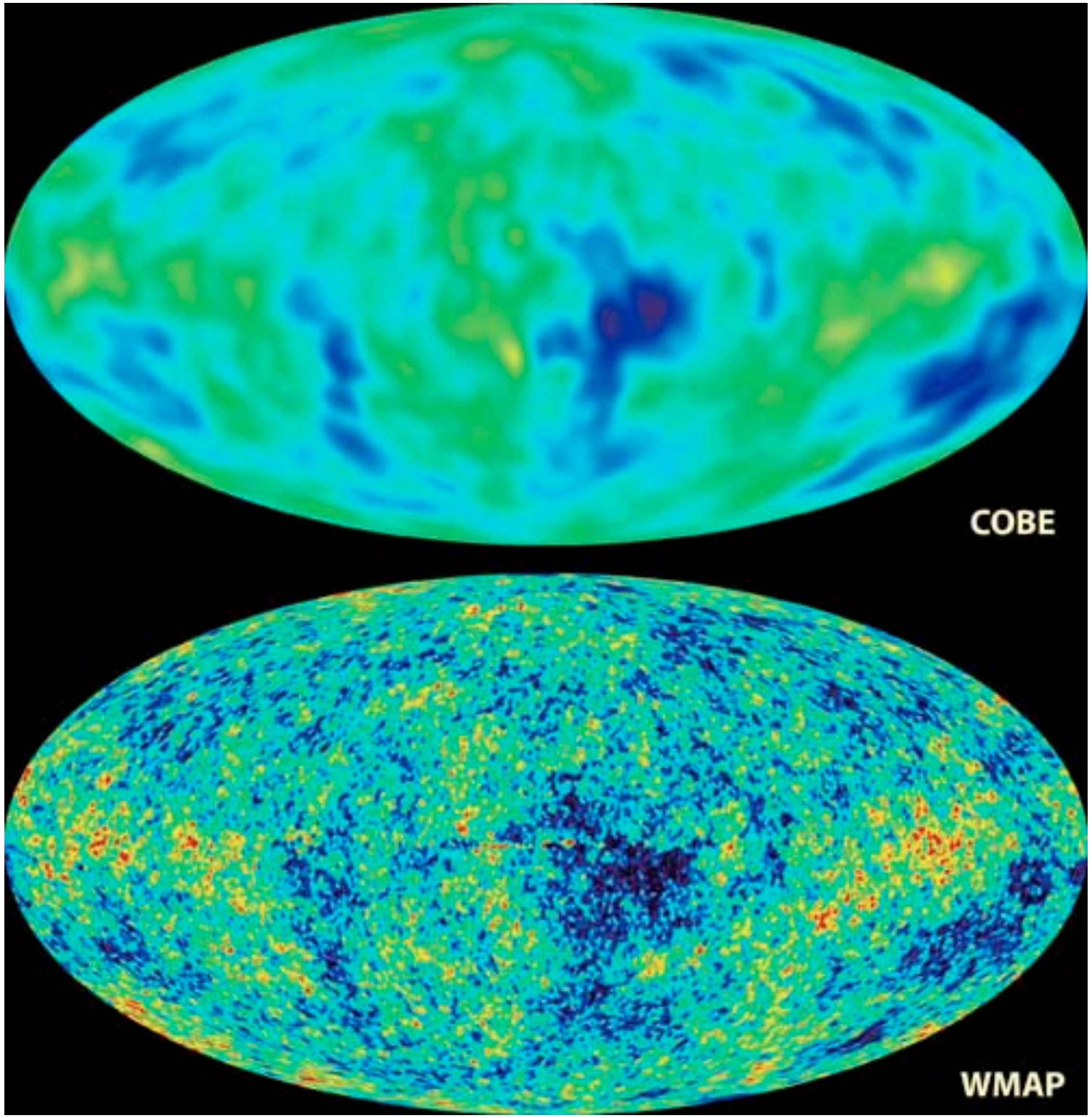


Bland-Hawthorn (Sydney 2012)

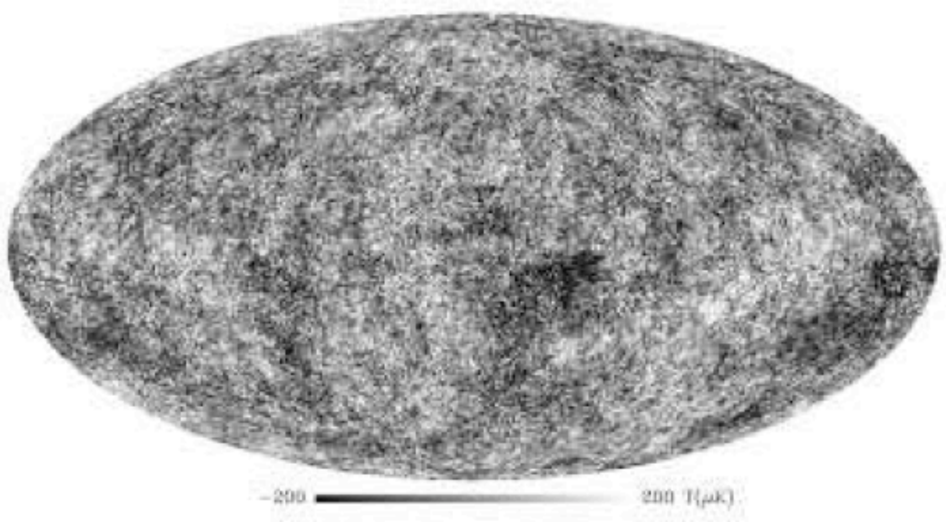


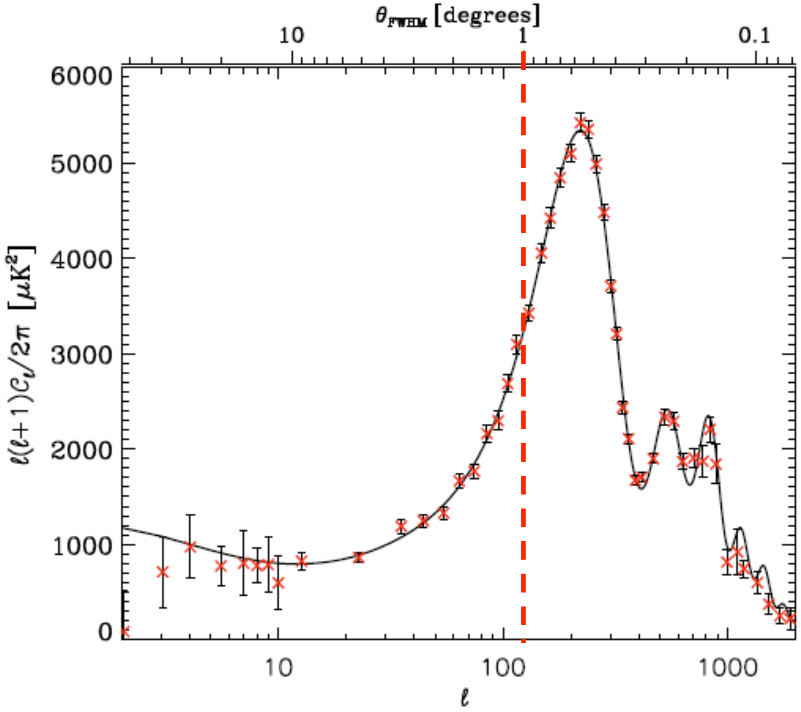

Cold spots are evidence for
mass concentrations since
photons lose energy here
5°
2° is causally connected at z~1100
The sky contains 10,000 of these
independent cells

FOREGROUND CORRECTED MAP



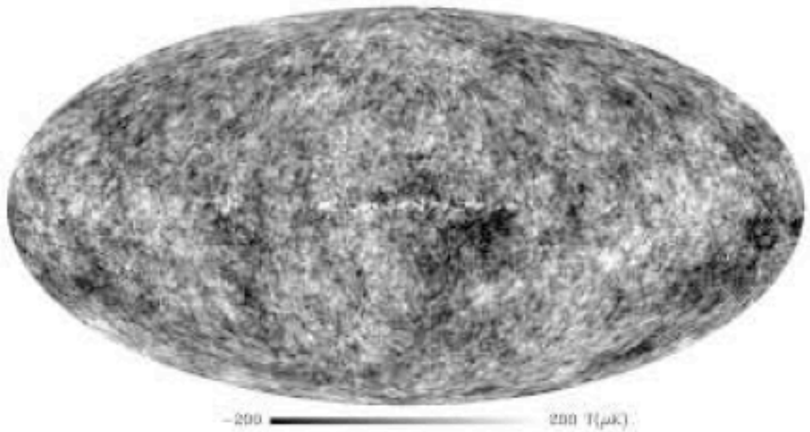
Where is the information?





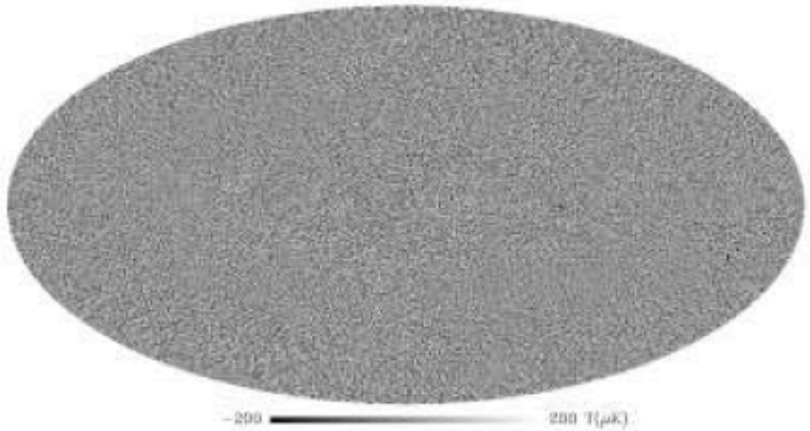
Take the CMB map…

Separate signal above/below 1º…

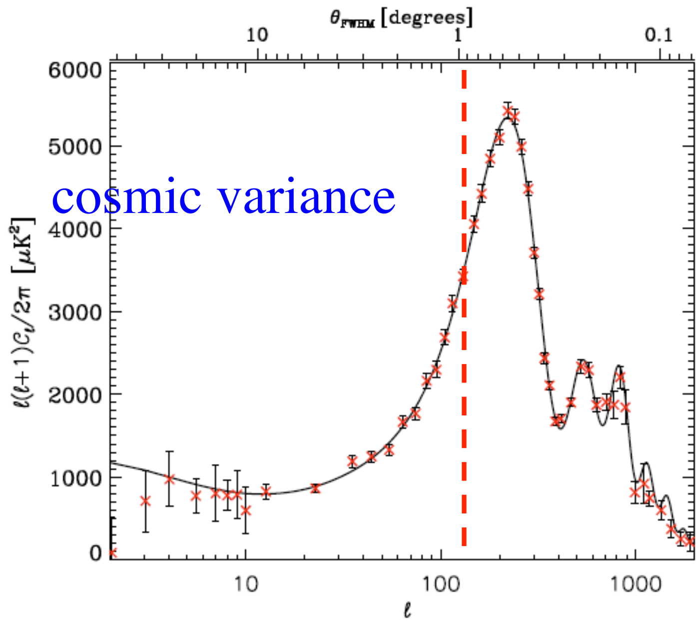


Amazing fact:

We observe direct evidence for perturbations laid down during inflation in the first picosecond!



Foreground contamination 370,000 years after the Big Bang — photons and baryons took 120,000 years to decouple…



§ washes out structure on scales below 8'

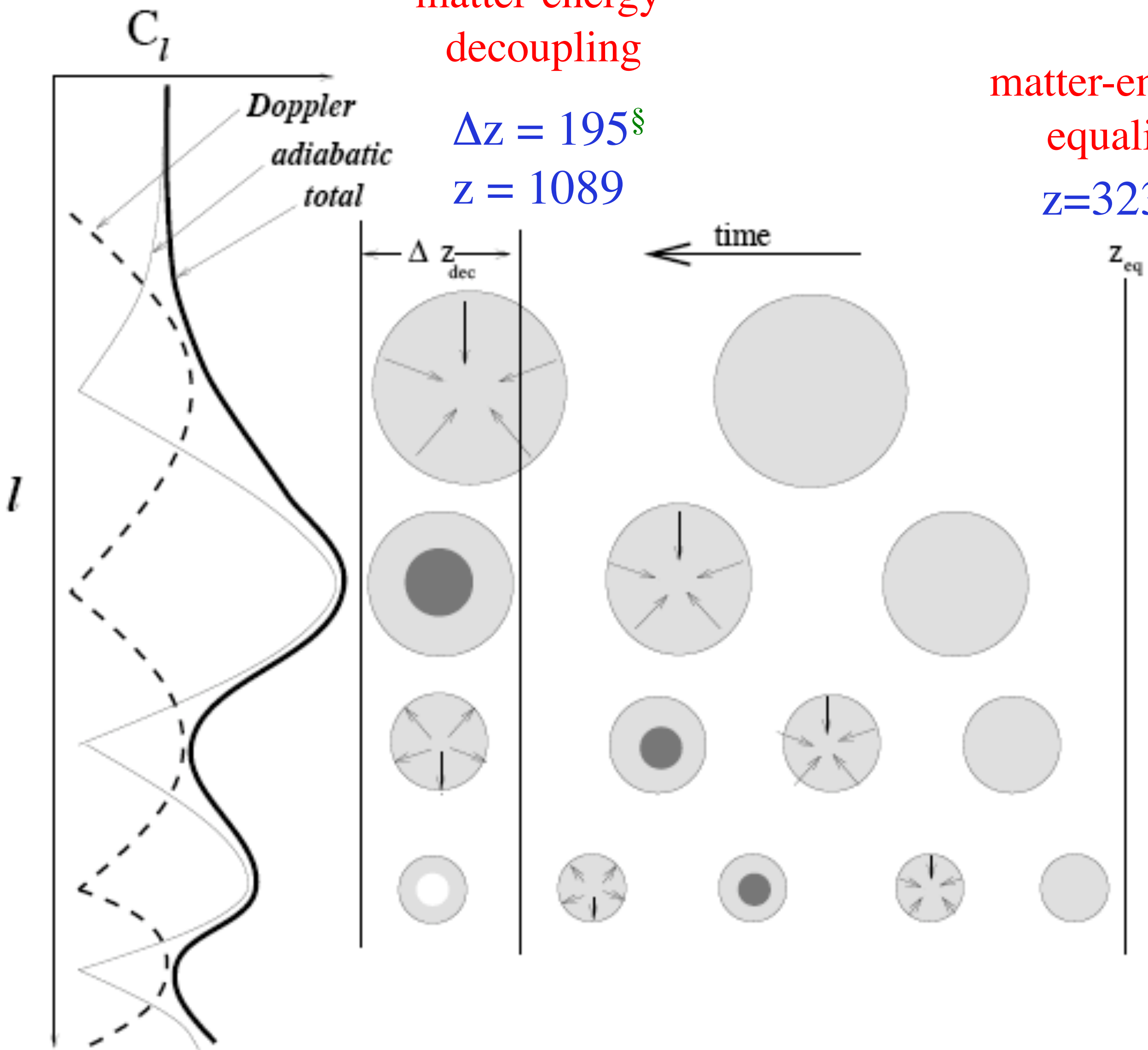
matter-energy decoupling

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

$z = 1089$

matter-energy equality

$z=3233$



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 (Sydney 2012)

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}.

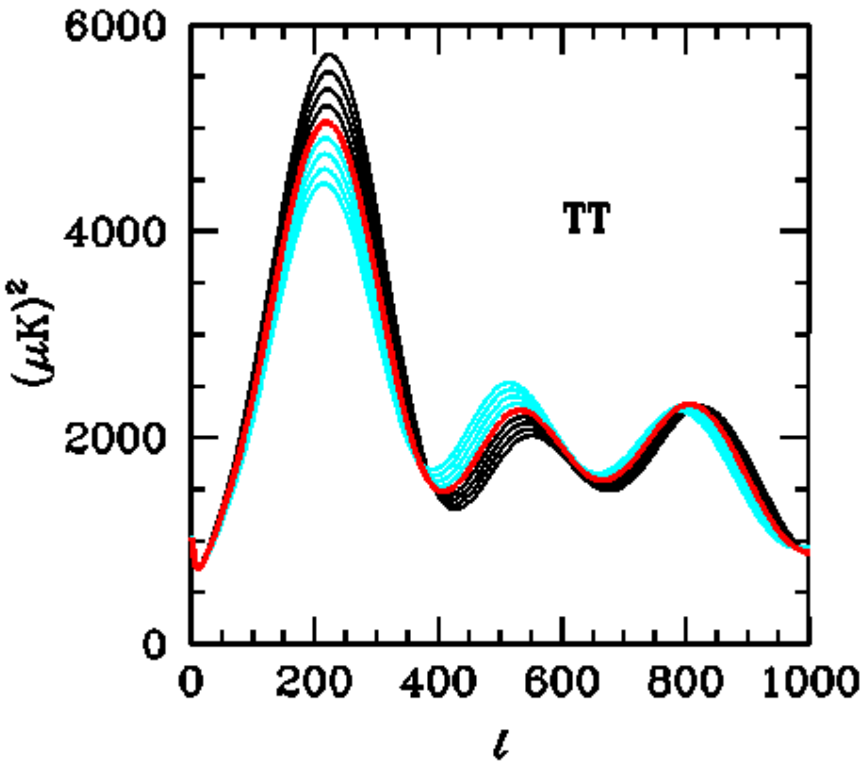
Bland-Hawthorn
(Sydney 2012)

Determining basic parameters

Baryon Density

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

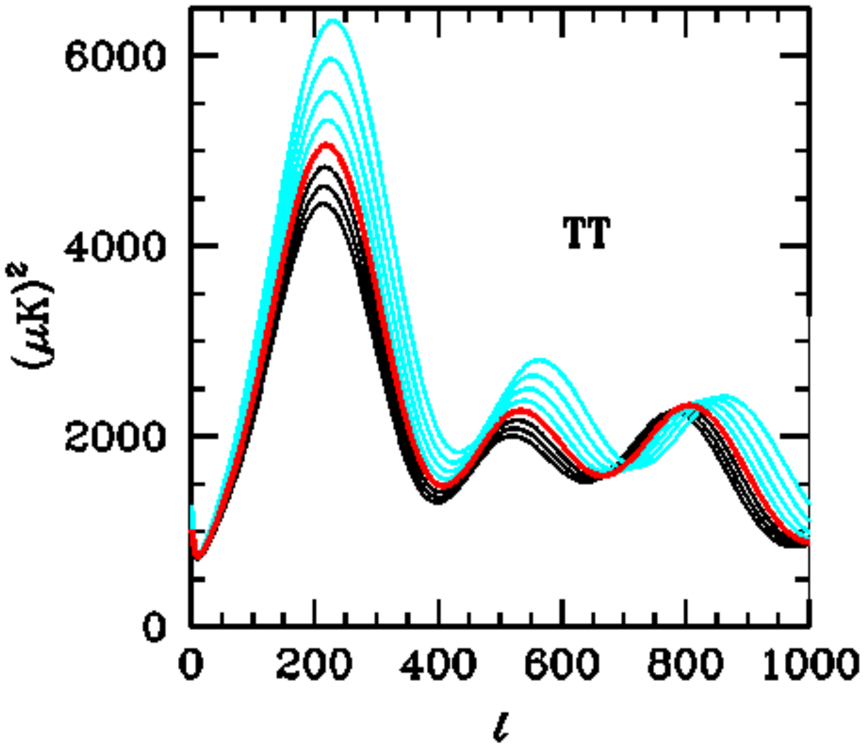
also measured through D/H



Determining basic parameters

Matter Density

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

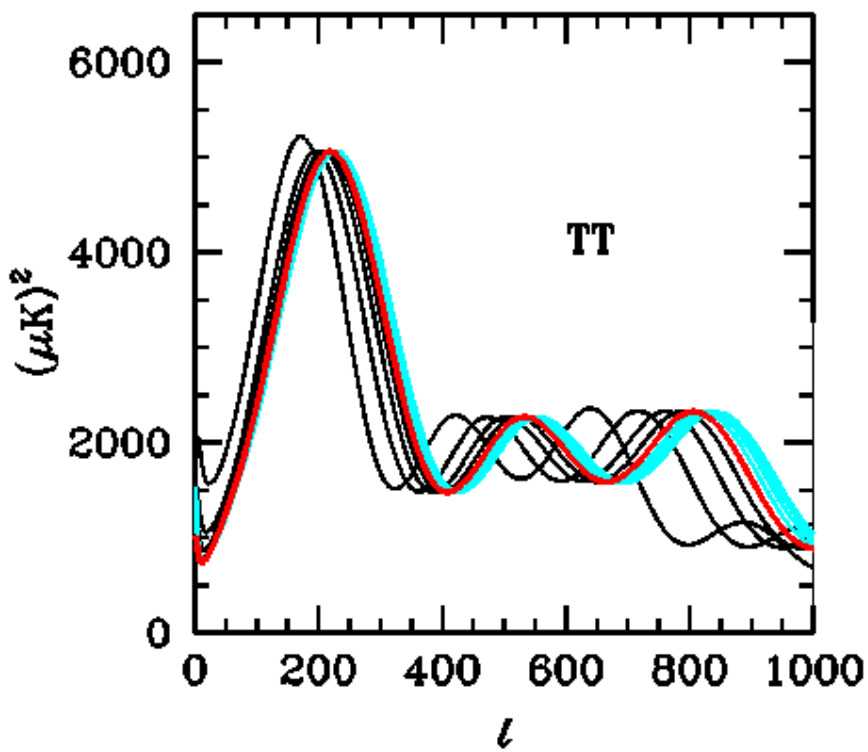


Determining Basic Parameters

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



ɔrn
(Sydney 2012)

Temperature

85% of sky

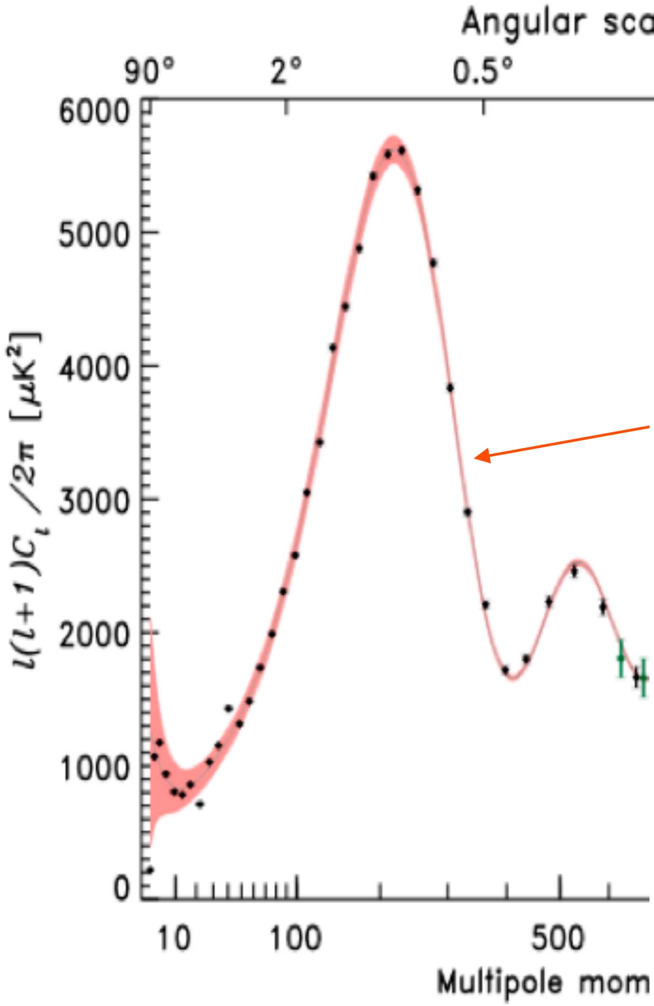


Table 1. Cosmological parameters describing the best-fitting FRW model to the CMB power spectrum and other non-CMB observables (cf. Bennett et al. 2003).

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 (Sydney 2012)

BAO first detected by
Peacock et al 2001 (2dFGRS)

DETECTION OF THE BARYON ACOUSTIC PEAK IN
FUNCTION OF SDSS LUMINOUS

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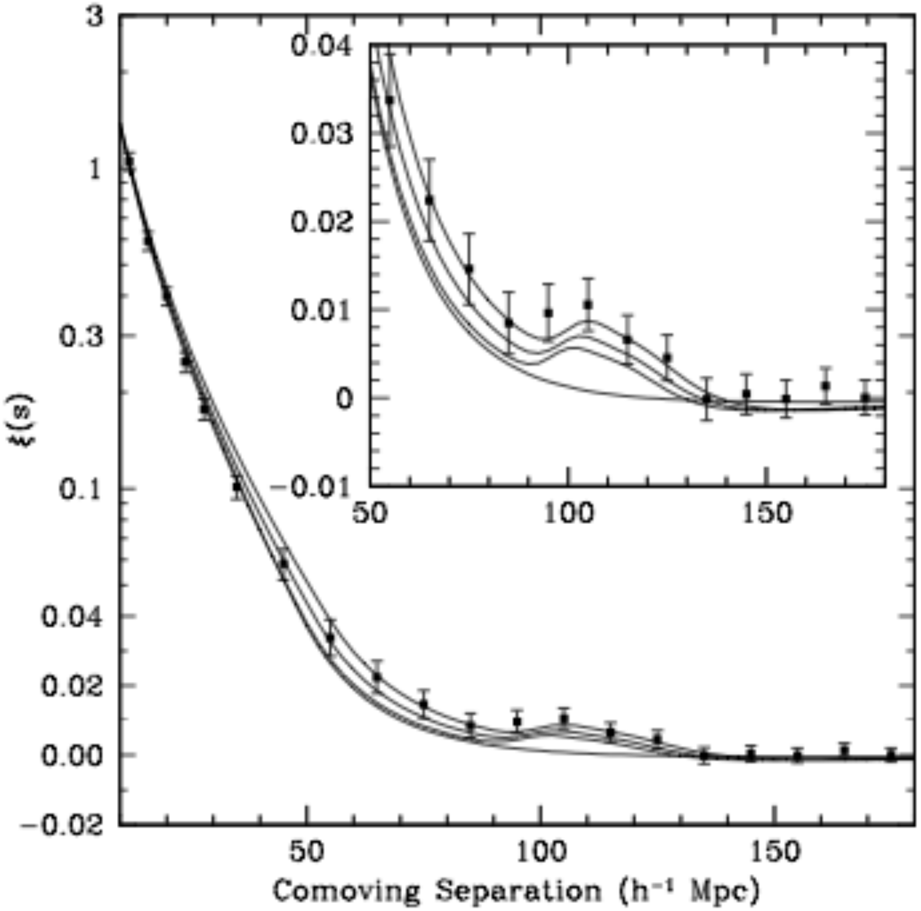
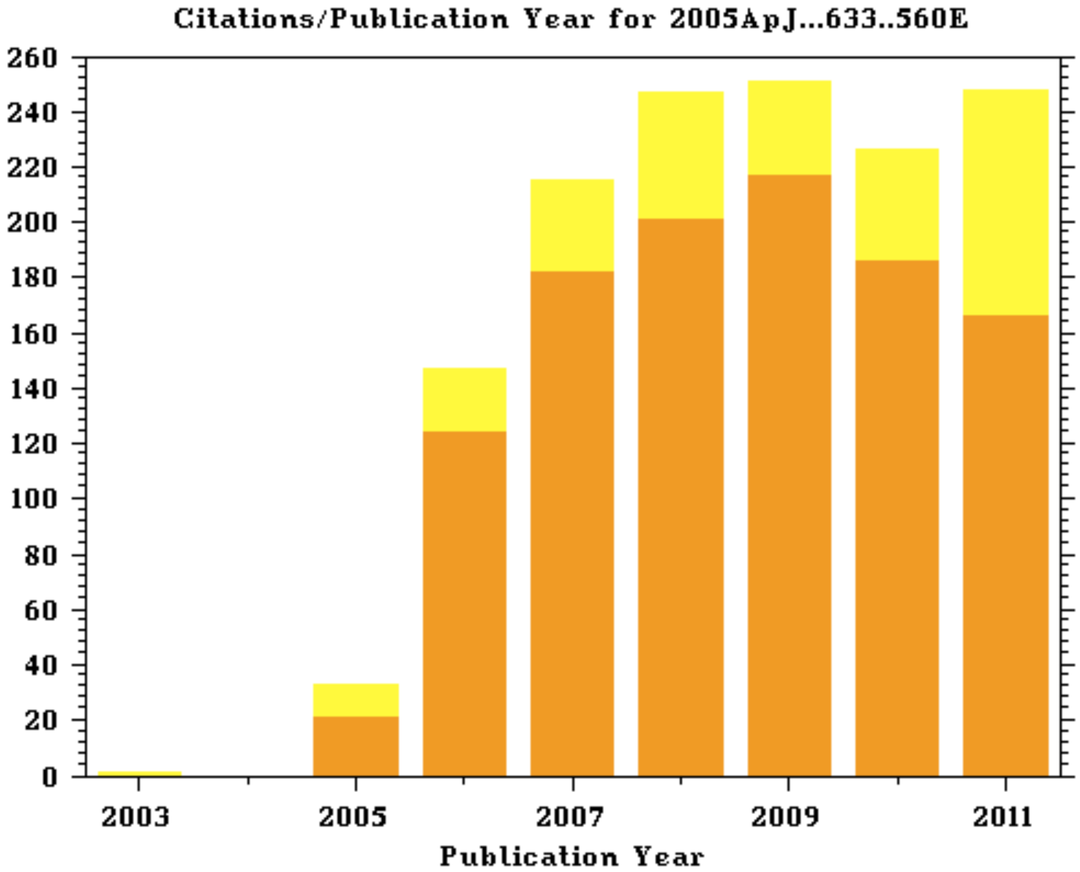
Ryan Scranton,[5] Hee-Jong Seo,[1] Max Tegmark,[6,7] Zheng Zheng,[8] Sc
Jon Brinkmann,[12] Scott Burles,[7] Francisco J. Castander,[13] Andre
Masataka Fukugita,[16] Joshua A. Frieman,[10,17] Karl Glazebro
Gregory Hennessy,[19] Željko Ivezić,[9] Stephen Kent,[10] Gillian R
Robert H. Lupton,[11] Bruce Margon,[21] Timothy A. McKay,
Adrian Pope,[18] Michael W. Richmond,[24] David Sch
Kazuhiro Shimasaku,[27] Christopher Stoughton
Mark SubbaRao,[17,28] Alexander S. Szala
Douglas L. Tucker,[10] Brian Yanny,[10] an
Received 2004 December 31; accepted



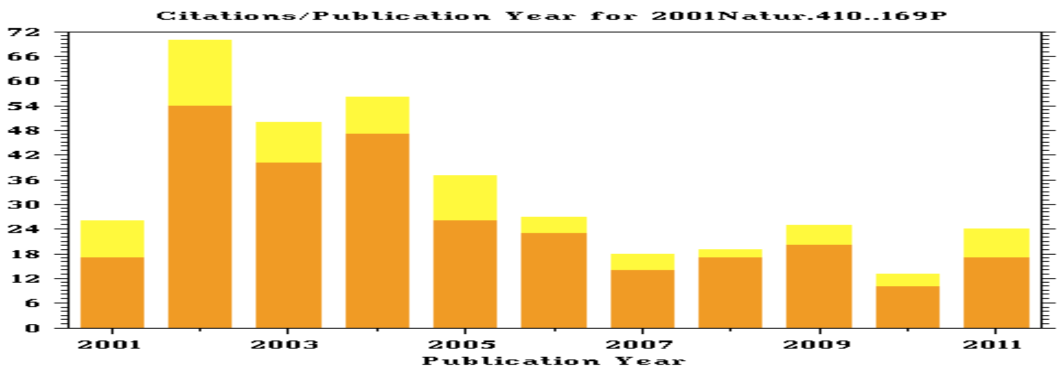
ABSTRACT

We present the large-scale correlation function measured fron 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 detection 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 microwave background anisotropies. The standard cosmological model convincingly passes these new and robust tests of its fundamental properties.

Sloan impact



Eisenstein



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

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

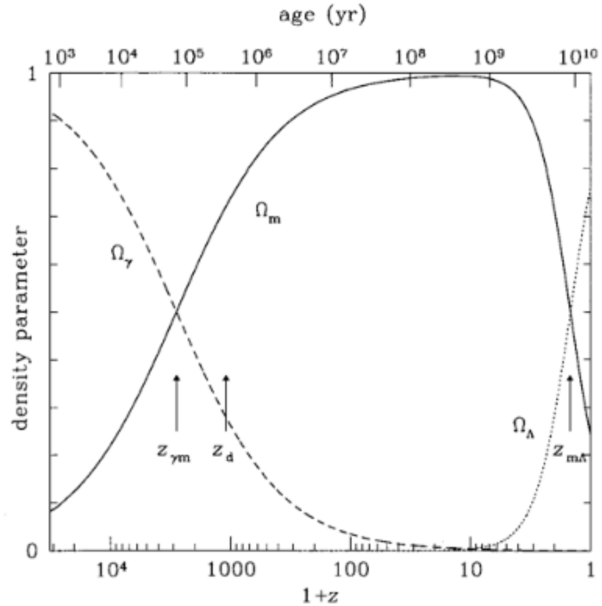
The standard ΛCDM model

- 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?

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 warm matter & energy; dark antimatter?)
- 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 2012-13)

Conclusions

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