CMB and Secondaries: the Cold Spot

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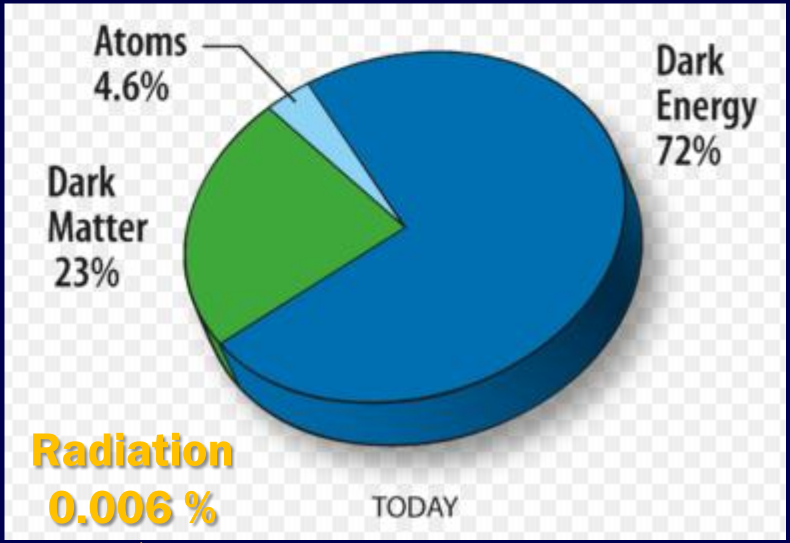
Based on: **I.M, A.Notari, JCAP 0902:019,2009. arXiv:0808.1811**
JCAP 0907:035,2009. arXiv:0905.1073

Plan

- Inflationary BB and CMB
- Unexpected features: the Cold Spot
- The Cold Spot as a Void on the line of sight:
  secondary anisotropies associated to
  the Rees-Sciama & Lensing effects
- Conclusions and perspectives

Content of Universe

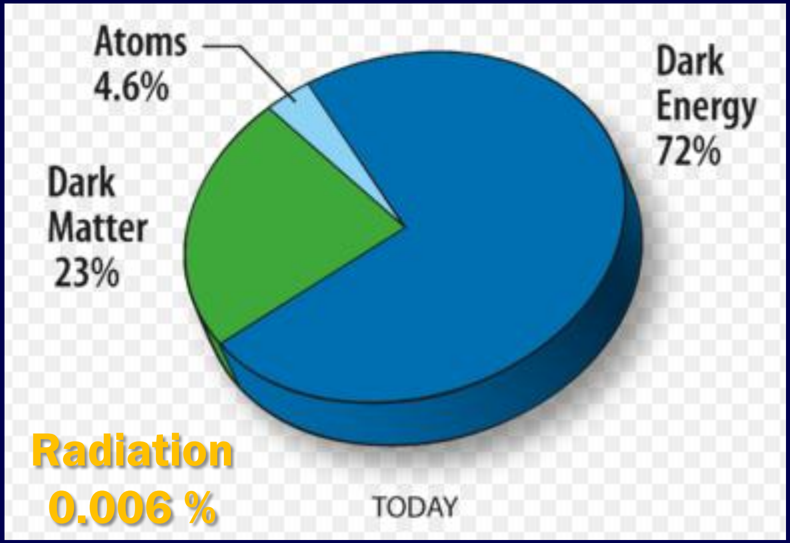


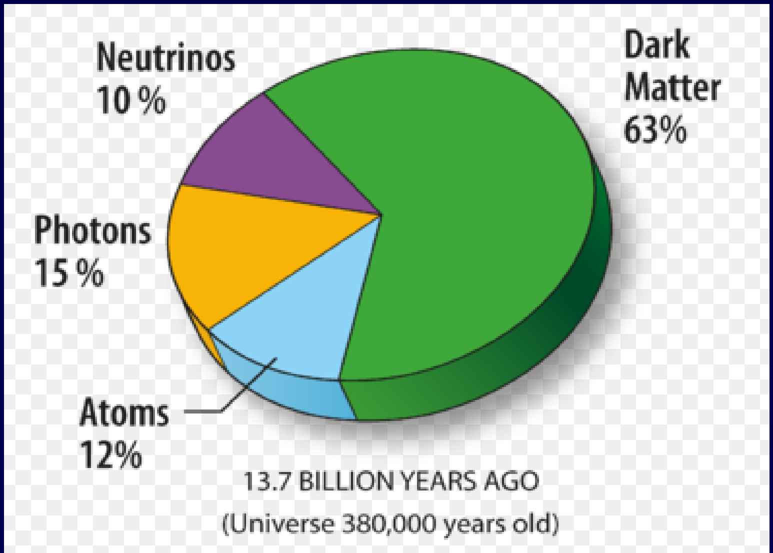
radiation density scales as a^{-4}

WHILE

matter density as a^{-3} & dark energy stays constant

Content of Universe

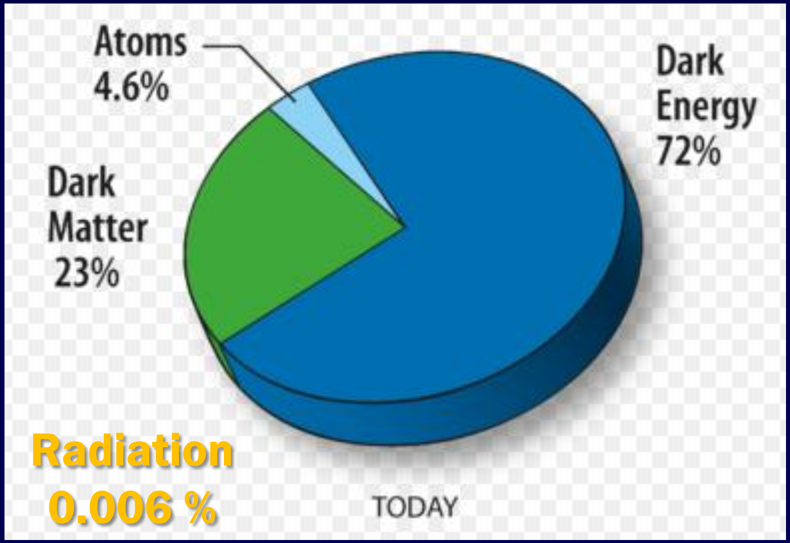


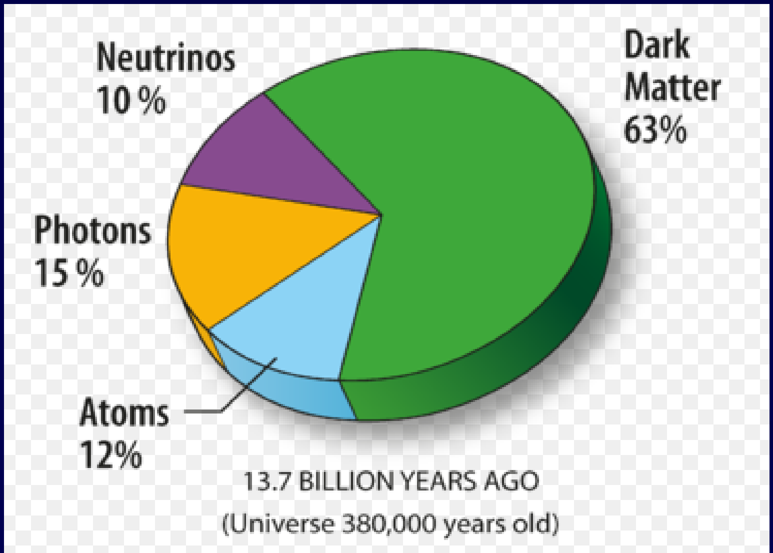


but there has been a time when radiation and matter densities where comparable:

13.7 Gyr ago

Content of Universe





but there has been a time when radiation and matter densities where comparable:

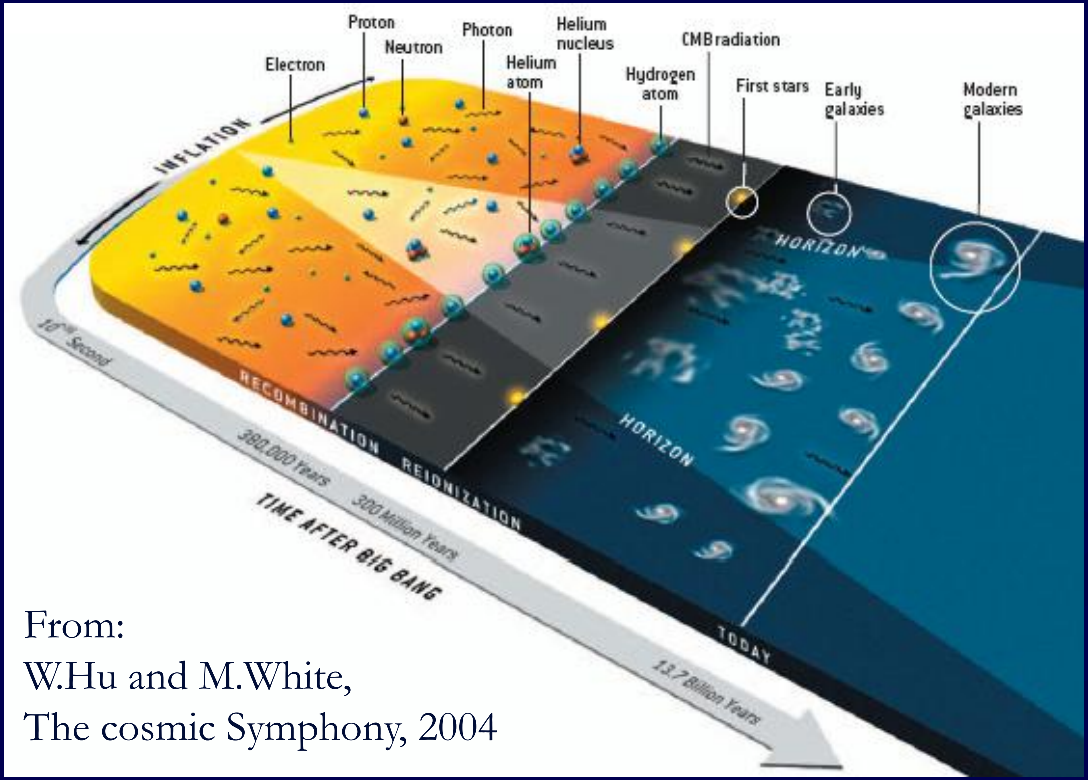
According to BB theory,
the CMB gives a snapshot of the universe at that time

Fiat lux

Because it was just at that time that
T dropped enough to allow e and p to form H atoms,
thus making the universe transparent to radiation
(since then in th eq with matter, including the dark one).

Sistine Chapel – Separation of Light and Darkness

This “last scattering” or “recombination” or “decoupling” period occurred in between 0.38 – 0.48 Myr after BB when the universe was about 1000 times smaller ($z=1100$) and had temperature T about 3000 K (kT about 0.25 eV).



From:
W.Hu and M.White,
The cosmic Symphony, 2004

Anisotropies and Inflationary BB

No model other than the inflationary BB has yet explained the temperature fluctuations or ANISOTROPIES, which are

- about 10^{-5} (rms variation 18μK)
- more pronounced on 1° (twice full moon).

Contributions to CMB anisotropy

PRIMARY due to the physics at the LSS and before

→ dominant and linked to fundamental cosmological parameters

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SECONDARY induced on photons in their travel from the LSS to us

Those associated with a gravitational potential are:

- ❖ Integrated Sachs-Wolfe
- ❖ Rees-Sciama
- ❖ Gravitational lensing

→ generically small but could plague extraction of fundamental parameters.

Spherical harmonics expansion

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

represents a very useful tool to study anisotropies

BECAUSE

theoretical models for inflation generically predict the PRIMARY alm to be nearly Gaussian random fields.

Correlation functions

Brackets stand for a statistical average over an ensemble of possible realizations of the Universe

- 2-point correlation function or
  POWER SPECTRUM
- 3-point correlation function or
  BISPECTRUM
- 4-point correlation function or
  TRISPECTRUM
- ...

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For a gaussian random field

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- 3-point correlation function or BISPECTRUM
- 4-point correlation function or TRISPECTRUM
- ...

$$\langle a^{(P)}_{\ell_1 m_1} a^{(P)*}_{\ell_2 m_2} \rangle = \delta_{\ell_1 \ell_2} \delta_{m_1 m_2} \langle C^{(P)}_{\ell_1} \rangle$$

$$\langle a^{(P)}_{\ell_1 m_1} a^{(P)}_{\ell_2 m_2} a^{(P)}_{\ell_3 m_3} \rangle = 0$$

Higher statistics correlation functions are fully determined by the power spectrum

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- 4-point correlation function or TRISPECTRUM
- ...

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HOWEVER

secondary anisotropies are not random gaussian!

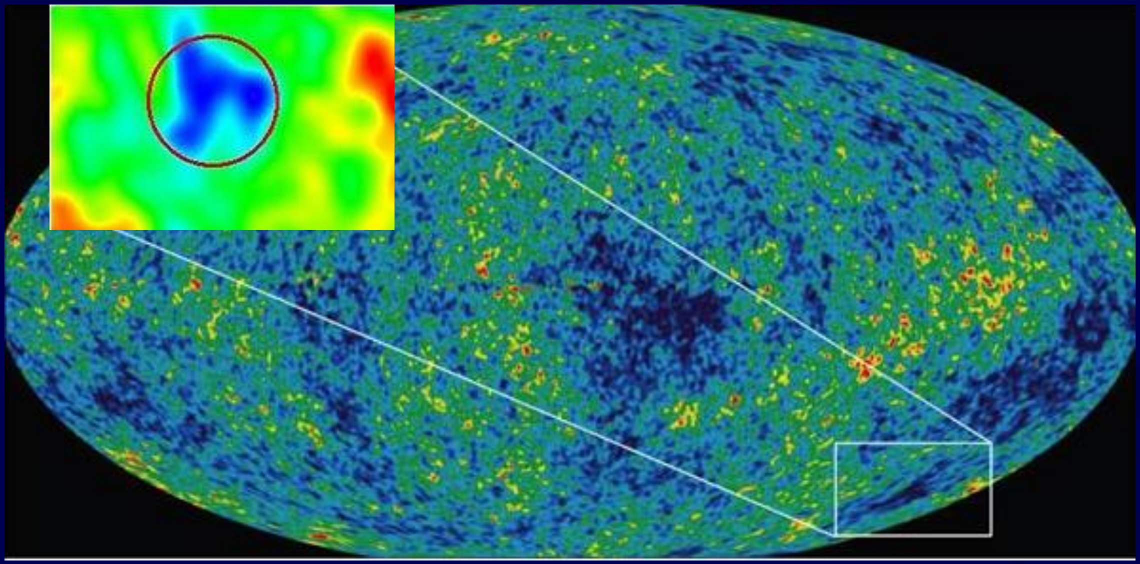
They could be studied by looking at deviations from the predictions above

Let’s apply all this to a concrete case:

The Cold Spot

The Cold Spot

Large circular region on about 10° angular scale which is anomalously cold: $\Delta T = 190 \pm 80\ \mu K$ [A= $(7\pm3)\times10^{-5}$]



Probability of this spot to come from Gaussian fluctuations has been estimated to be < 2% [Cruz et al., astro-ph/0603859]

→ explore other possibilities, e.g. secondaries

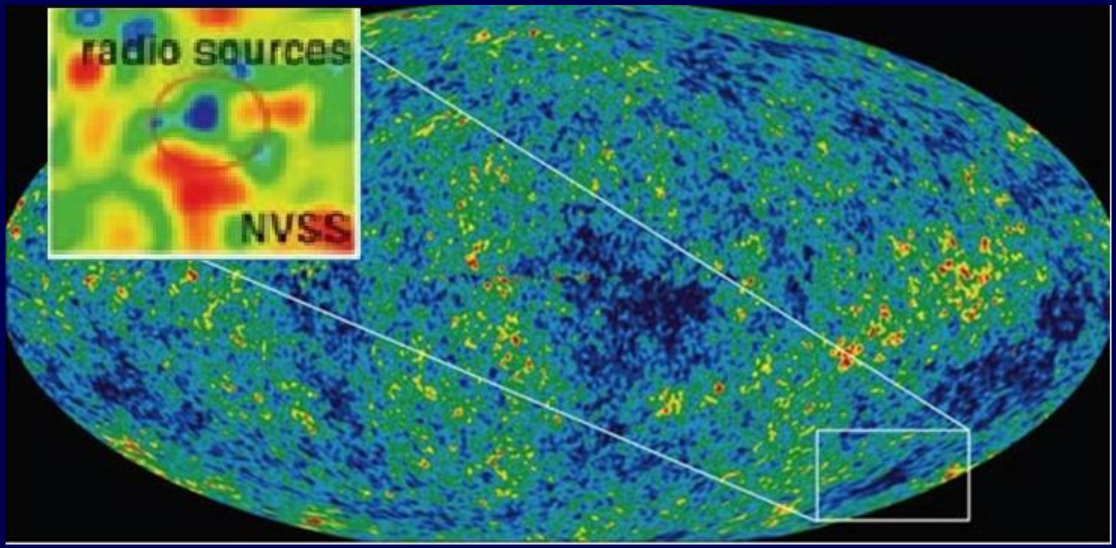
The Cold Spot as a "Void"

K. Tomita, Phys. Rev. D 72, 103506 (2005) [Erratum-ibid. D 73, 029901 (2006)] [astro-ph/0509518].
K. T. Inoue and J. Silk, Astrophys. J. 648, 23 (2006) [astro-ph/0602478]; Astrophys. J. 664, 650 (2007) [astro-ph/0612347].

suggested it could be due to a
large spherical underdense region (of some unknown origin),
on the line of sight between us and the LSS.

Further support ?

McEwen et al. (2006) & Rudnick et al. (2007) claimed that looking at the direction of the Cold Spot in the Extragalactic Radio Sources (NVSS survey), an underdense region is visible at $z \sim 1$



Smith et al. (2008) challenge this claim.

Granett et al. (2009) find no underdense region at z<1.

Bremer et al. (2010) confirm Granett et al.

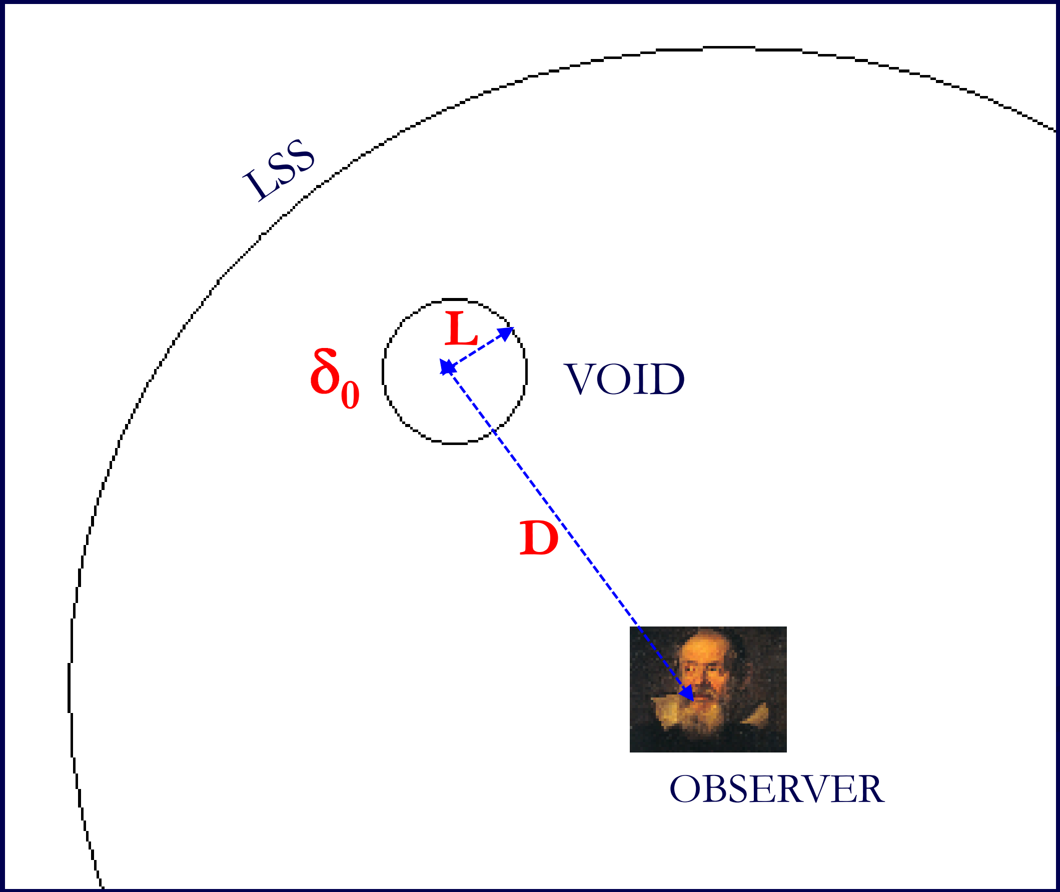
The Cold Spot as a "Void"

[I.M, A.Notari, JCAP 0902:019,2009. arXiv:0808.1811 , JCAP 0907:035,2009.arXiv:0905.1073]

Modelling it through an inhomogeneous LTB metric (requires an overdense compensating shell),

we computed the secondary effects occurring to the CMB photons that travel through the Void:

Rees-Sciama & Lensing



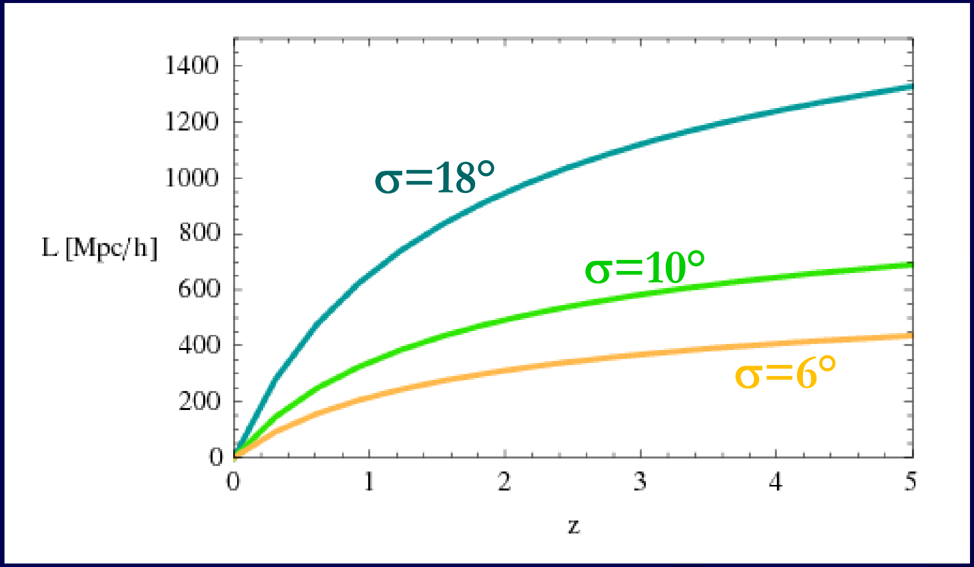
L comoving radius,
D comoving distance,
δ_0 density contrast at centre today

Radius-Redshift relation

$$L = \frac{2\tan\theta_L}{H_0}\left(1 - \frac{1}{\sqrt{1+z}}\right)$$

$\tan\theta_L = L/D$

z >1 means indeed large Void: **L>300 Mpc/h** for cold spot angular size **σ=10°**



Such big underdense region should clearly come from a different mechanism than standard inflation, maybe bubble nucleation due to phase transitions or …

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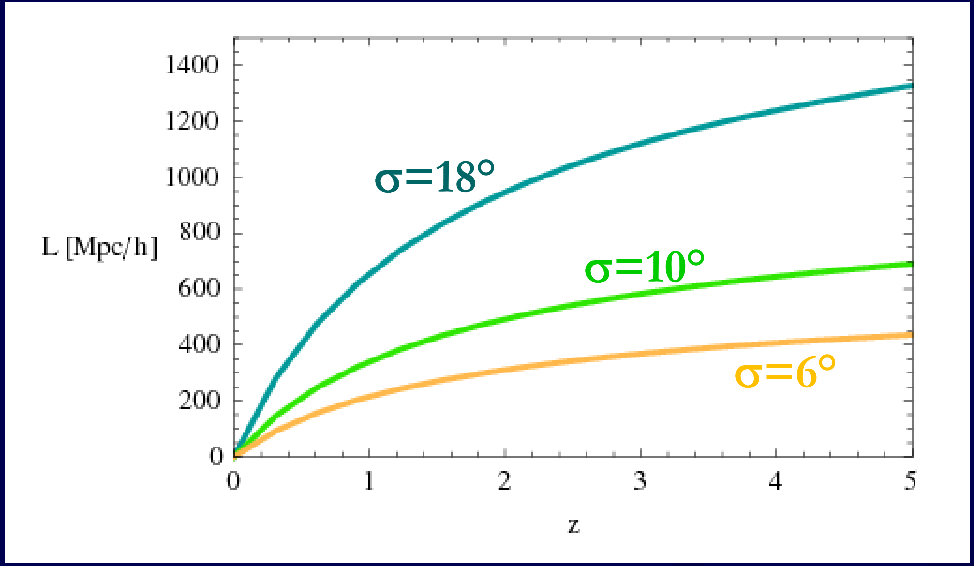

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HERE we show that Planck will be able to reject or confirm this hypothesis via the study of secondary effects

The procedure

1. Find the spherical harmonics decomposition of the i-th (i=RS, L) temperature anisotropy profile (n is the direction of observation)

$$a_{\ell m}^{(i)} \equiv \int d\hat{\mathbf{n}} \, \frac{\Delta T^{(i)}(\hat{\mathbf{n}})}{T} \, Y_{\ell m}^{*}(\hat{\mathbf{n}})$$

2. Add tham all

$$a_{\ell m} = a_{\ell m}^{(P)} + a_{\ell m}^{(RS)} + a_{\ell m}^{(L)}$$

3. Estimate 2 and 3 point correlation functions

4. Look for quantities that would vanish in case of random Gaussian alm

Rees-Sciama

Passing through a Void, photons suffer some blue-shift due to the fact that the gravitational potential ϕ is not exactly constant in time – the so-called Integrted Sachs-Wolfe (1966)

$$\frac{\Delta T}{T}(\vec{n}) = \frac{\Delta T}{T}^{(P)}(\vec{n}) + 2\int_{\tau_{rec}}^{\tau_0} \dot{\phi}\, d\tau$$

line-of-sigh integral over the conformal time from recombination to present time

The RS effect is the ISW part associated to the variation of ϕ due to non-linear effects.

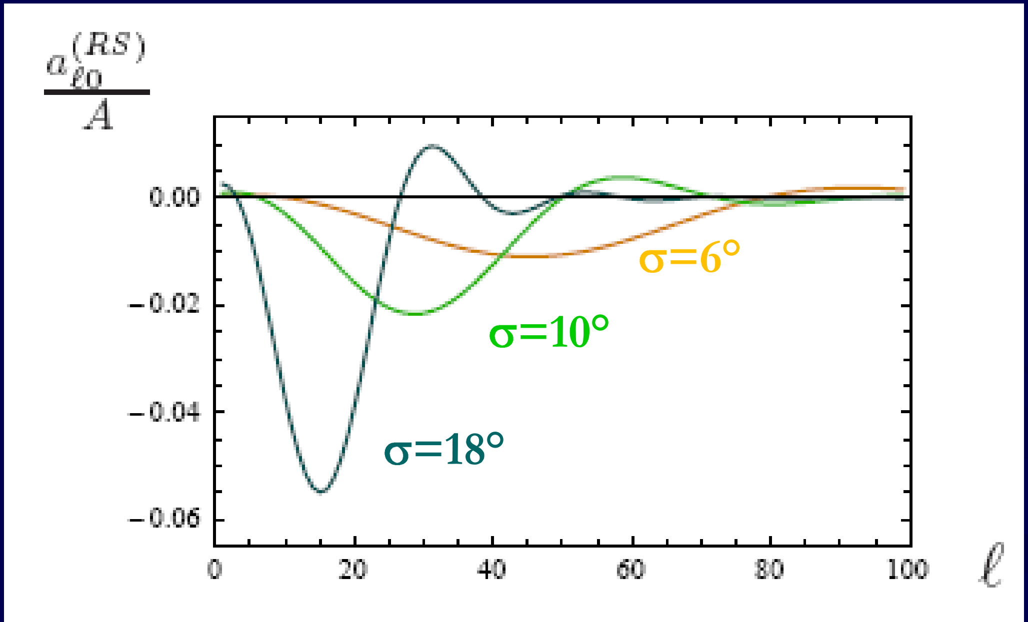
Actually, just the linear level effect is the one usually called "ISW" effect.
It would vanish in a matter dominated flat Universe. It is significant only when a Dark Energy component becomes dominant with respect to matter (z<1).

→ here focus attention on RS effect, which is always present
(we checked that ISW is not bigger than RS)

For RS, due to spherical symmetry, the only non-vanishing alm are those with m=0 (axis z pointing from observer to the center of the Void)

A is the amplitude of T fluctuation at Void centre (fitted experimentally)

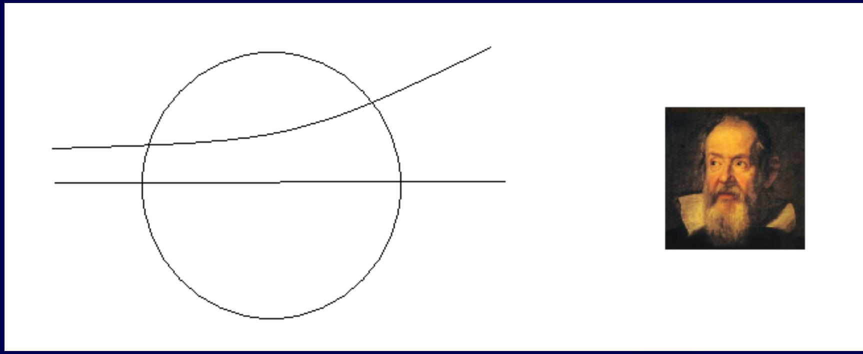
$$A \approx 0.5\ \delta_0^2\ \frac{(LH_0)^3}{\sqrt{1+z}}$$



Lensing

of the primordial perturbations.

See also: Das, Spergel,arXiv: 0809.4704



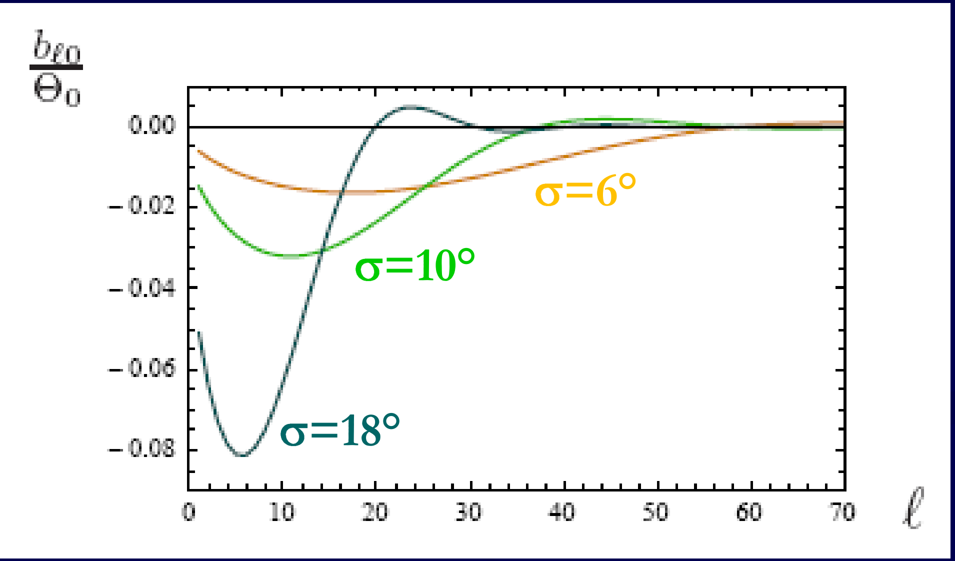
For Lensing we need the so-called Lensing potential, related to the gravitational potential by

$$\nabla_{\perp}\Theta = -2\int_{\tau_{LSS}}^{\tau_O} d\tau \, \frac{\tau_{LSS}-\tau}{\tau_{LSS}} \nabla_{\perp}\Phi$$

Now define $$b_{\ell m} \equiv \int d\hat{\mathrm{n}}\ \Theta(\hat{\mathrm{n}})\ Y^*_{\ell m}(\hat{\mathrm{n}})$$ due to spherical symmetry, the only non-vanishing blm are those with m=0

Θ_0 is the amplitude of the lensing potential at Void centre

$$\Theta_0 \approx \left(\frac{A\ LH_0 \tan^2\theta_L}{1 - \frac{LH_0}{2\tan\theta_L}} \right)^{1/2}$$



At 1st order $$a^{(L)(1)}_{\ell m} = \sum_{\ell', \ell''} G^{-m m 0}_{\ell\ \ell' \ell''} \frac{\ell'(\ell'+1) - \ell(\ell+1) + \ell''(\ell''+1)}{2} a^{(P)*}_{\ell' -m} b_{\ell'' 0}$$

Diagonal 2-p function

(power spectrum)

<a a> = <P P>+<P RS>+<RS RS>+<P L>+<L L>

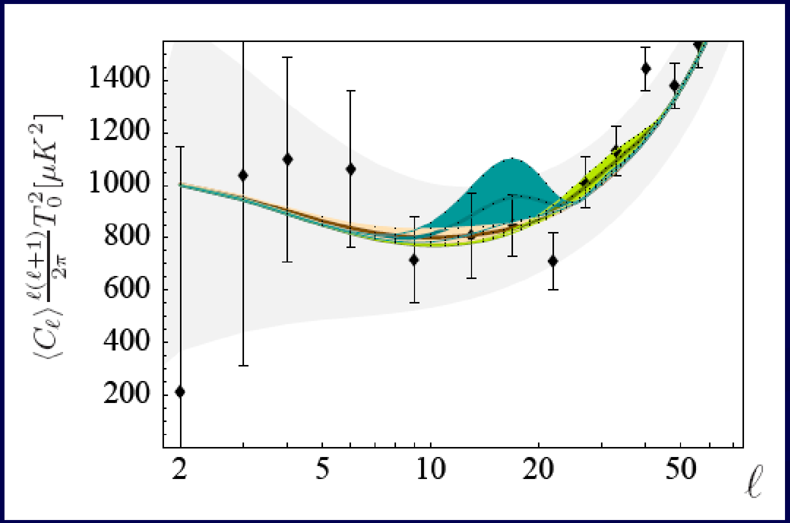
vanishing

(P&RS uncorrelated)

negligible

<P L1>=0 → <L1 L1> and <P L2>

$$\langle C_\ell \rangle = \langle C_\ell^{(P)} \rangle + C_\ell^{(RS)}$$



There is a slight -negligible- increasement in chi-square.

Bispectrum

The basic quantities are the B coefficients

$$B_{\ell_1\ell_2\ell_3} = \sum_{m_1,m_2,m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} a_{\ell_1 m_1}\, a_{\ell_2 m_2}\, a_{\ell_3 m_3}$$

once we calculate the statistical average,

non-trivial

<a a a> = ~~<P P P>~~+~~<P P RS>~~+~~<P P L>~~+~~<P RS RS>~~+~~<P L L>~~

+<RS L L>+~~<RS RS L>~~+<P L RS>+<RS RS RS>+~~<L L L>~~

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+<RS L L>+~~<RS RS L>~~+<P L RS>+<RS RS RS>+~~<L L L>~~

negligible

the only contributions left are

1. RS^3

$$\langle B^{(RS)}_{\ell_1\ell_2\ell_3}\rangle = \sum_{m_1,m_2,m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle a^{(RS)}_{\ell_1 m_1} a^{(RS)}_{\ell_2 m_2} a^{(RS)}_{\ell_3 m_3}\rangle\,,$$

2. P L RS

$$\langle B^{(PLRS)}_{\ell_1\ell_2\ell_3}\rangle = \sum_{m_1,m_2,m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle a^{(P)}_{\ell_1 m_1} a^{(L)}_{l_2 m_2} a^{(RS)}_{l_3 m_3}\rangle + (5 \text{ permutations})\,.$$

For a signal labeled by i, the SIGNAL TO NOISE ratio is

$$(S/N)_i = \frac{1}{\sqrt{F_{ii}^{-1}}} \quad , \qquad F_{ii} = \sum_{2\leq l_1\leq l_2\leq l_3\leq l_{\max}} \frac{(B^{(i)}_{l_1 l_2 l_3})^2}{\sigma^2_{\ell_1 \ell_2 \ell_3}} ,$$

cosmic variance of bispectrum

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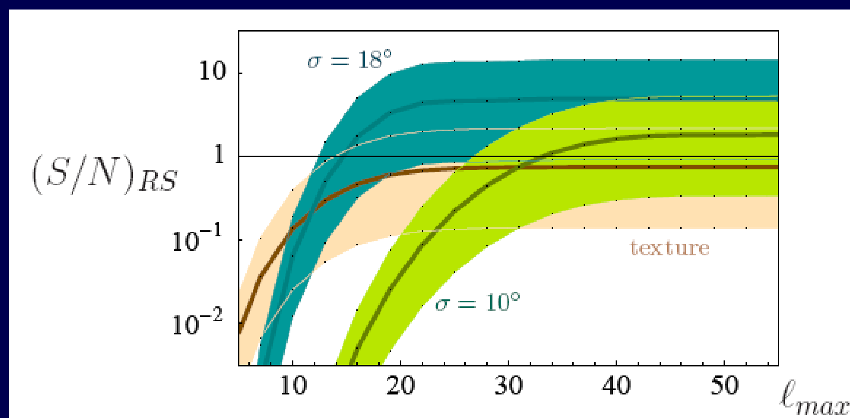
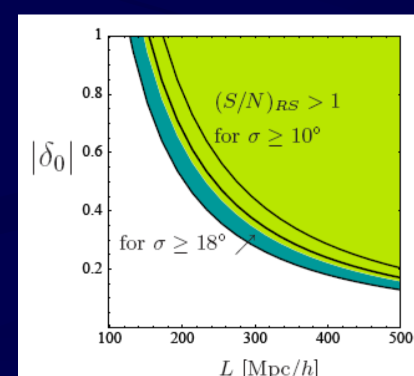
1. RS[3]



exceeds 1 for l >20-40, according to the void size

If no signal found, grt constraints on Void parameter space



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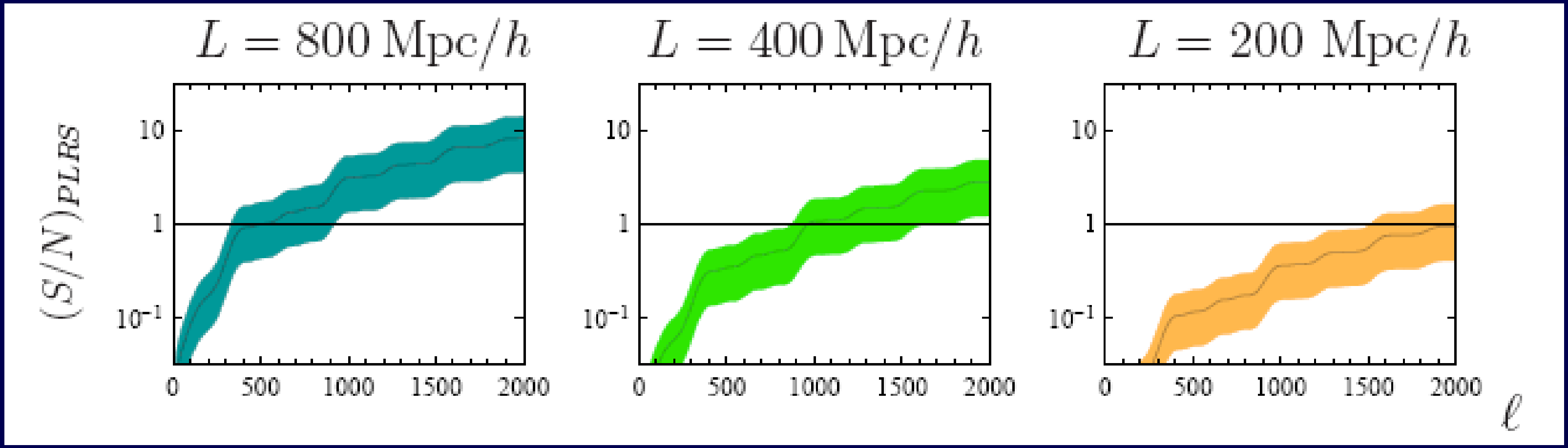
cosmic variance of bispectrum

2. P L RS



Detectable by Planck if Void radius L> 400 Mpc/h

L<300 Mpc/h means z<1, which ha been excluded by galaxy surveys

Signal at low multipoles from RS3 + high multipoles from P L RS

is a UNIQUE SIGNATURE of a Void

→ confirm of reject the Void explanation of the Cold Spot

Contamination of f_{NL}

The primordial non-gaussianity parameter fNL is defined parametrizing the primordial perturbation as

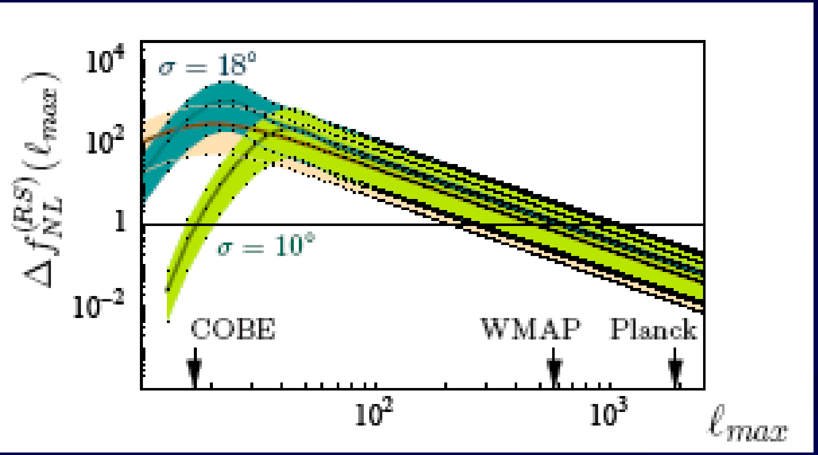
$$\phi(x) = \phi_L(x) + f_{NL}(\phi_L^2(x) - \langle\phi_L^2(x)\rangle)$$

linear gaussian part of the perturbation

Notice that inflationary model generically predict fNL=O(0.1); models exist with O(1) fNL .

The result is
(lensing negligible)

$$\Delta f_{NL}^{(RS)} \approx \begin{cases} 1 & \text{for WMAP} \\ 0.1 & \text{for Planck} \end{cases}$$



Non-diagonal 2-p function

<a a> = ~~<P P>~~+~~<P RS>~~+<P L>+<RS RS>+<L L>

vanishing (for gaussian and/or isotropous fields)

vanishing (P&RS uncorrelated)

negligible

PROMISING!
(depends on axis orientation)

Non-Diagonal S/N
should exceed 1 at l>1000
(preliminary)

Conclusions and perspectives

- ✓ Correct interpretation of new data from Planck requires better understanding of CMB secondaries
- ✓ Cold Spot: Planck could confirm or discard the Void explanation by looking at bispectrum
- ✓ Non-diagonal 2-point function seems also promising
- ✓ Polarization effects also deserve study

[Vielva et al., arXiv:1002.4029]