FA51 and PRIN-2008 in Ferrara

FA51

Dolgov	PO	
Fiorentini	PO	60%
Masina	RU	
Ricci	RU	40%
Lepidi	dott	
Ejlli	dott	
Dradi	laur	

PRIN-2008

Dolgov	
Fiorentini	
Masina	
Ricci	
Drago	RU
Mantovani	RU
Lepidi	
Bonanno	bors
Mantovani Sarti	dott
Xhixha	dott

Research items:
- CMB
- geo-neutrinos
- neutrinos and cosmology
- physics of compact stars
- physics beyond standard model
- solar models

CMB and Secondaries: the Cold Spot

Isabella Masina
(Ferrara U. and INFN, Italy & CP^3-SDU, Denmark)

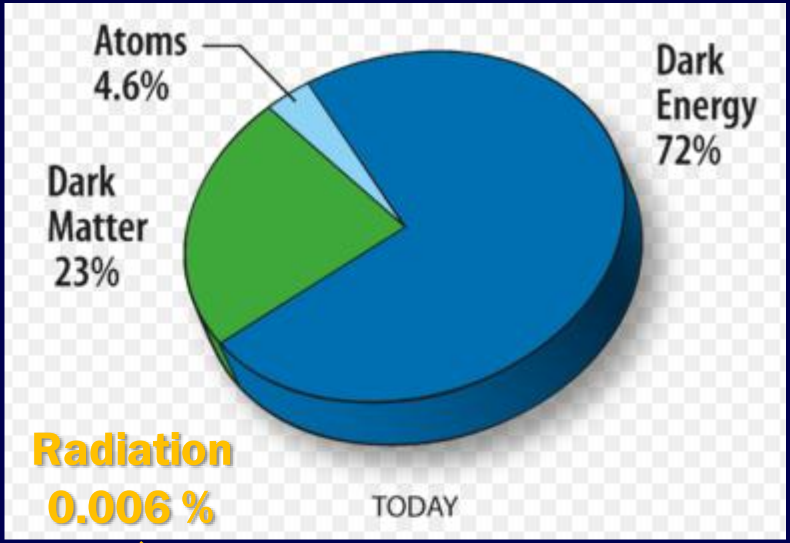
Based on: I.M, A.Notari, JCAP 0902:019,2009. arXiv:0808.1811
JCAP 0907:035,2009. arXiv:0905.1073

INIFA, LNF, 22-23/06/2010

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

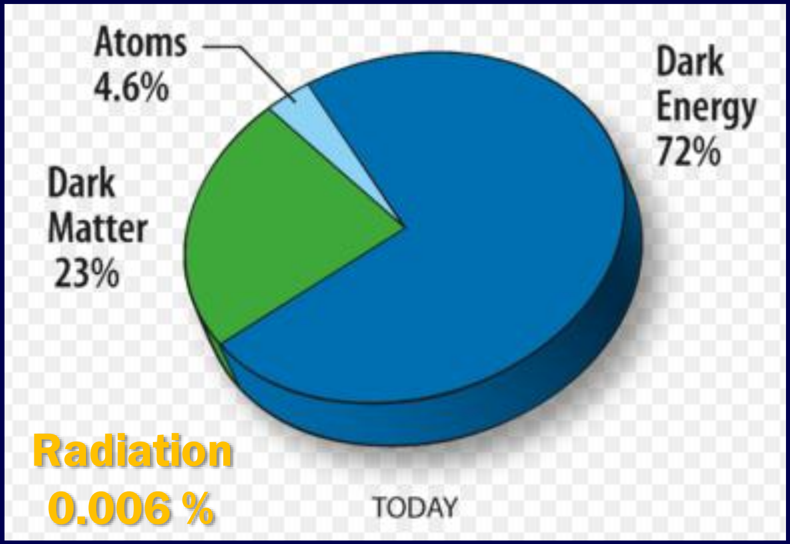


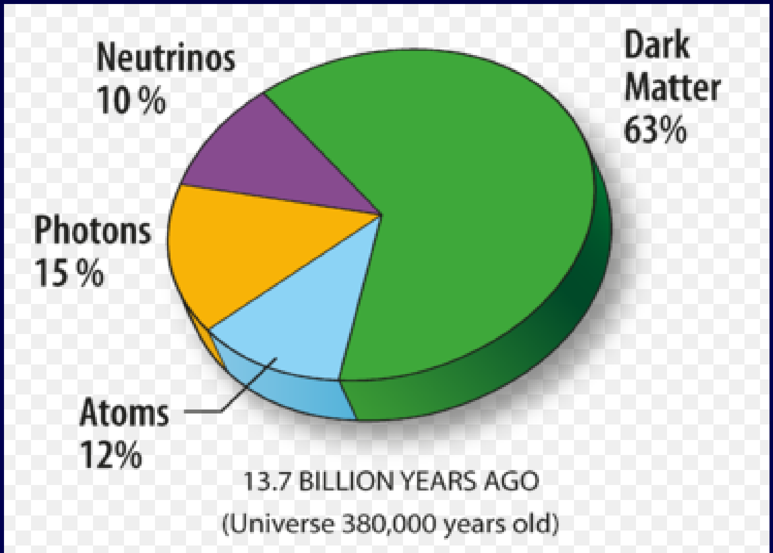
radiation density scales as a^{-4}

WHILE

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

Content of Universe

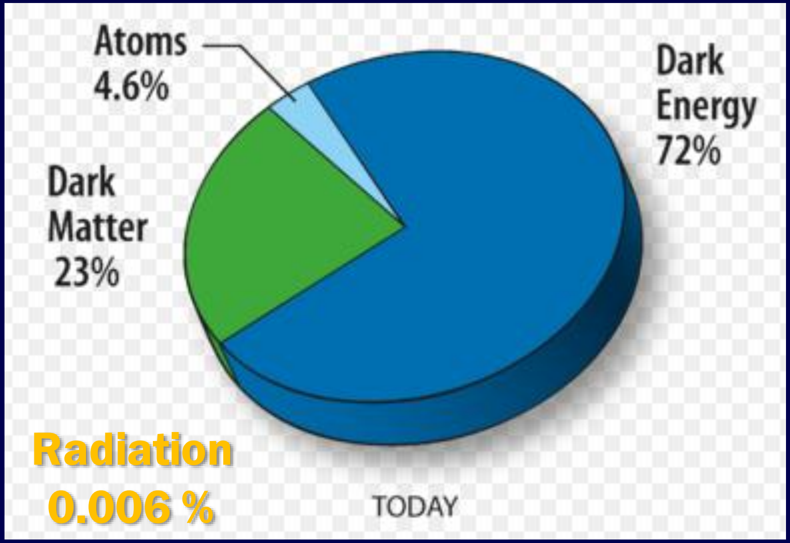


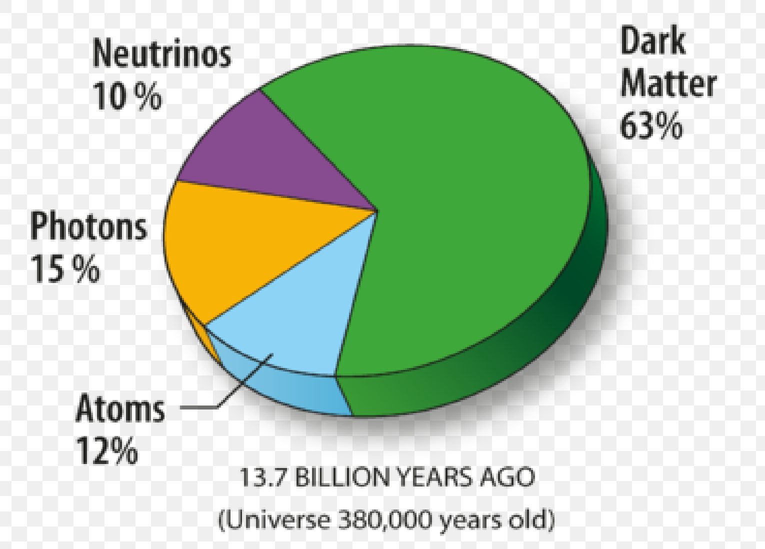


but there has been a time when radiation and matter densities where comparable:

13.7 Gyr ago

Content of Universe





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

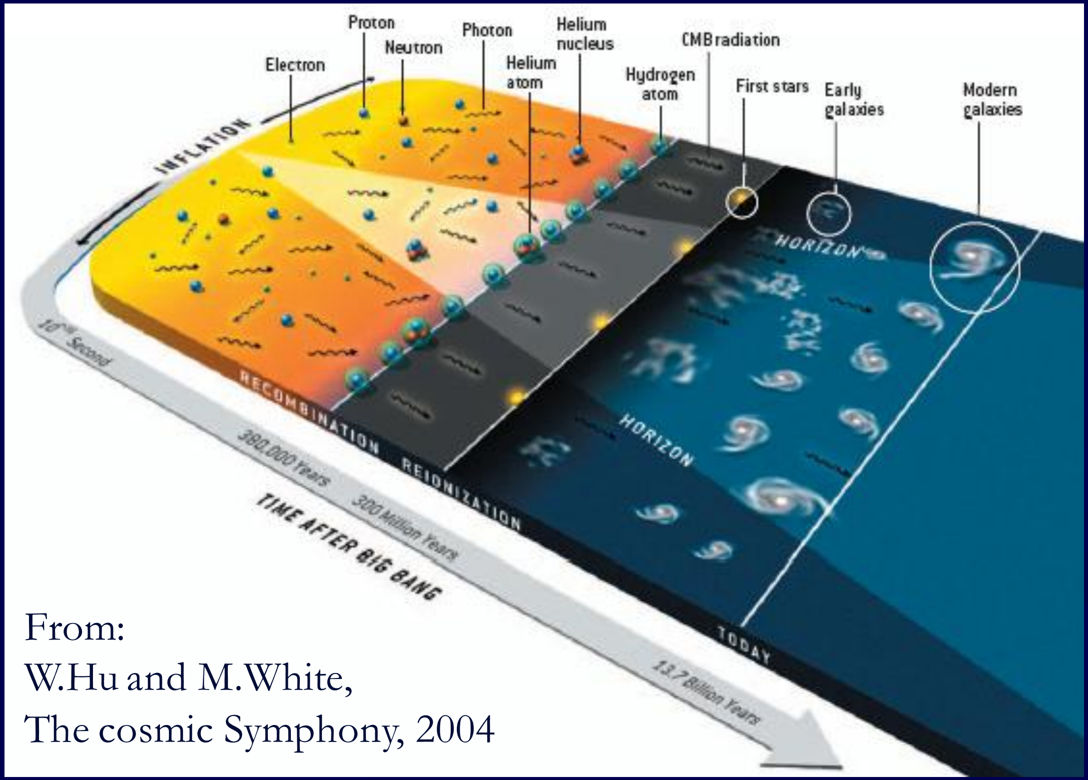
According to BB theory,
the CMB gives a snapshot of the universe at that time

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

Contributions to CMB anisotropy

PRIMARY due to the physics at the LSS and before

→ dominant and linked to fundamental cosmological parameters

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
- ...

Correlation functions

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For a gaussian random field

- 2-point correlation function or POWER SPECTRUM

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

- 3-point correlation function or BISPECTRUM

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

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

Higher statistics correlation functions are fully determined by the power spectrum

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Higher statistics correlation functions are fully determined by the power spectrum

HOWEVER

secondary anisotropies are not random gaussian!

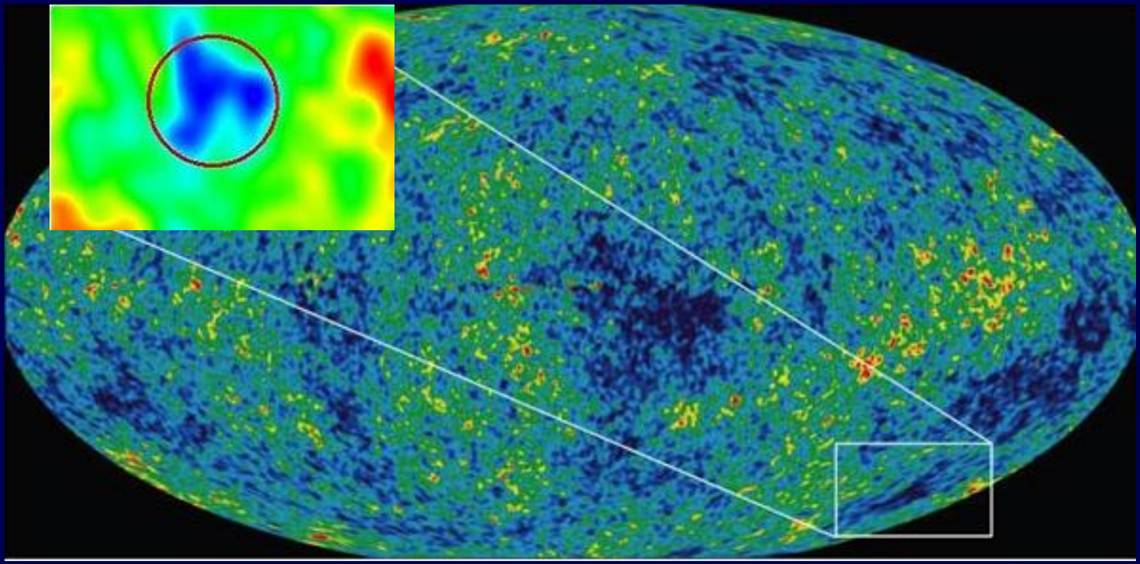
They could be studied by looking at deviations from the predictions above

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: $\Delta T = 190 +\text{-} 80\ \mu K$ [$A = (7+\text{-}3) \times 10^{-5}$]



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

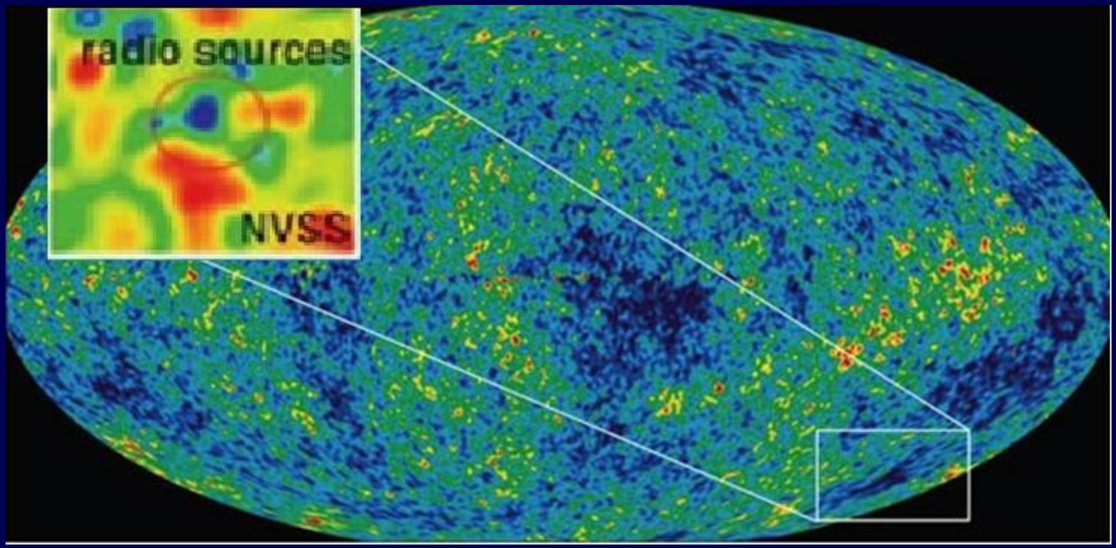
The Cold Spot as a "Void"

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.

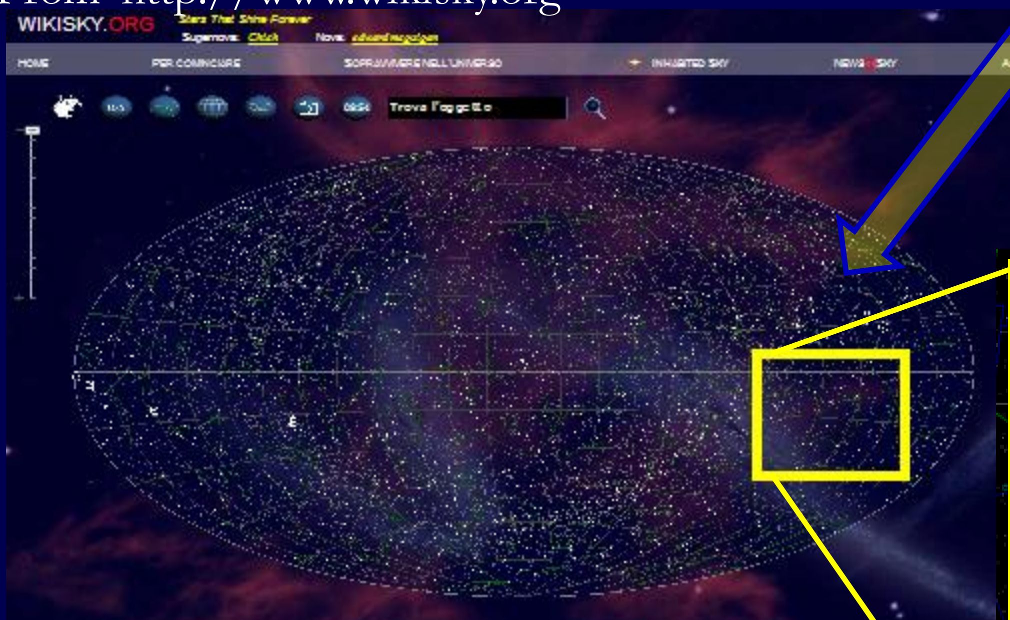
Granett et al. (2009) find no underdense region at $z<1$.

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

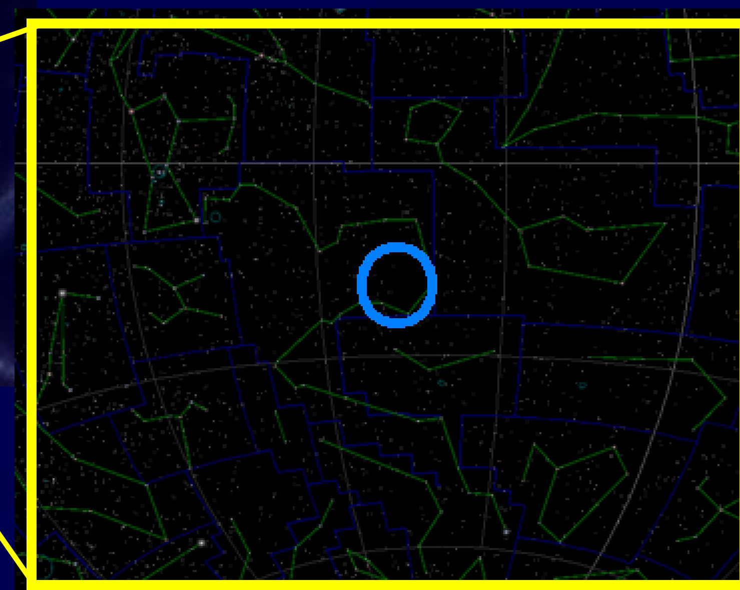
Cold Spot location

galactic coordinates 03h 15m 05s, -19° 35’ 02”

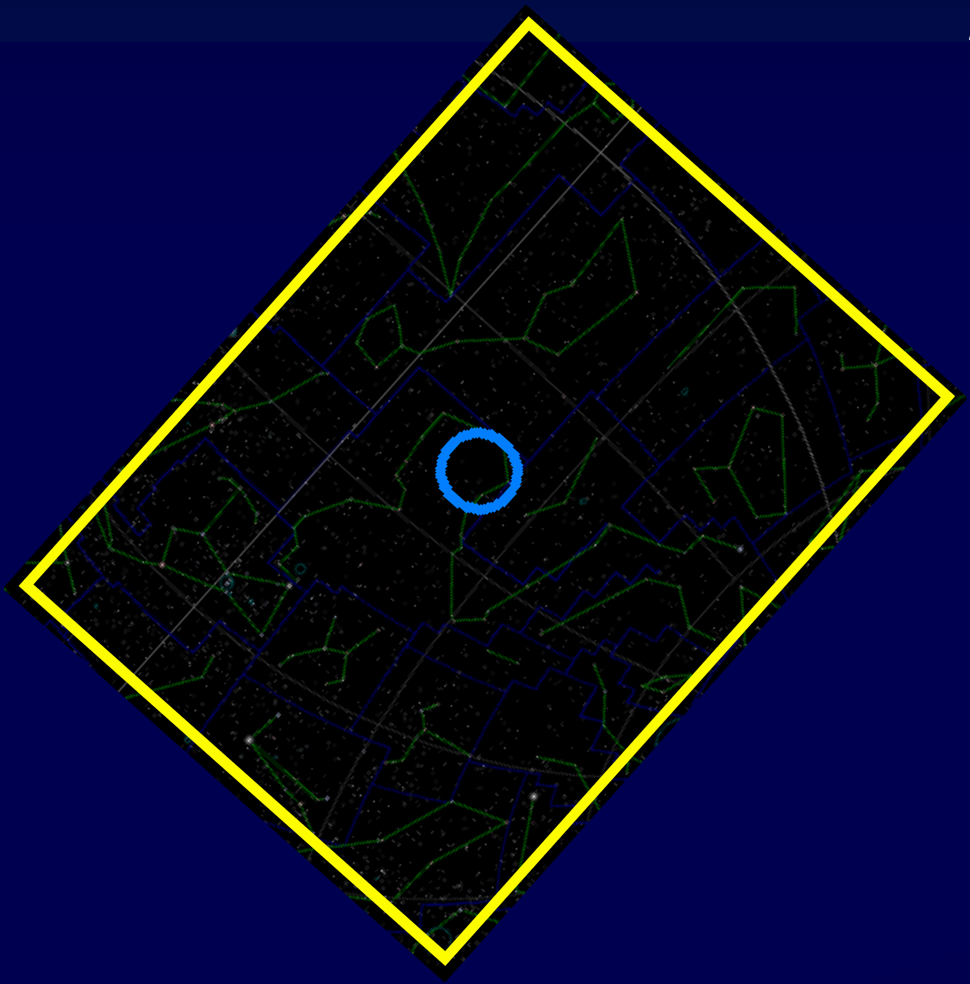
From http://www.wikisky.org



bottom-right of Orion

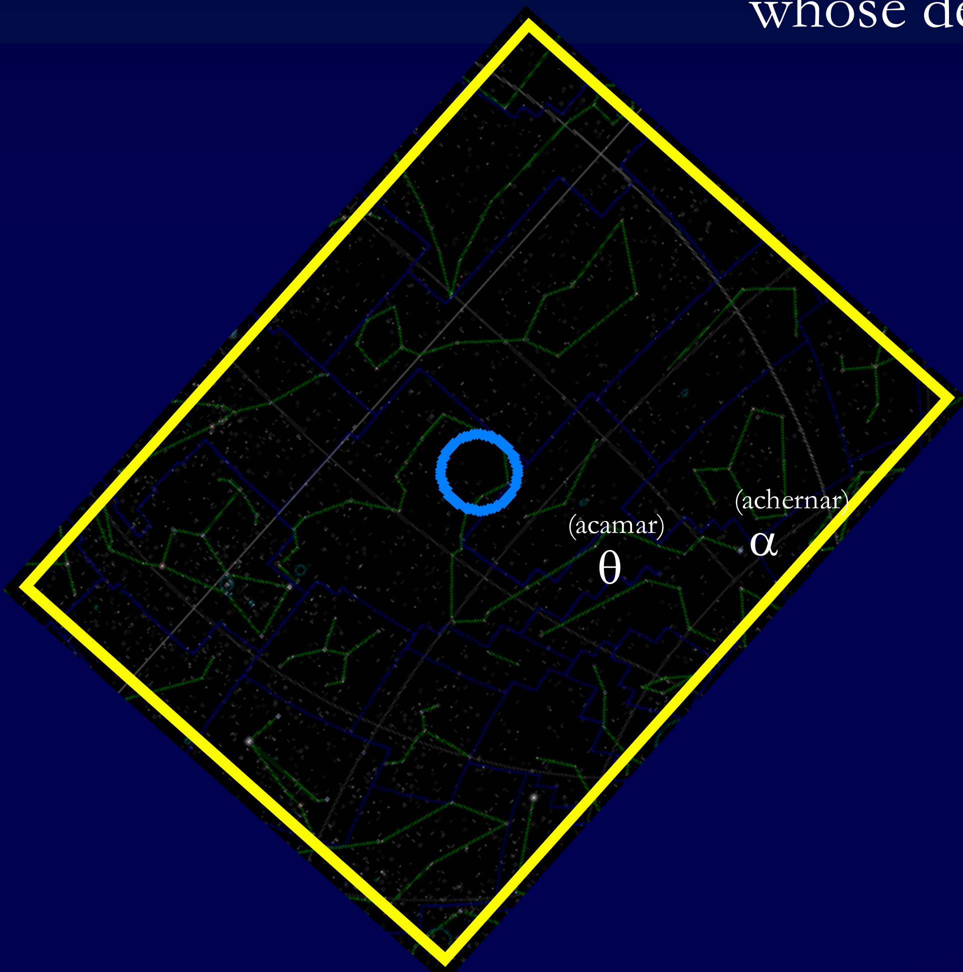


Additional motivation (poetical)

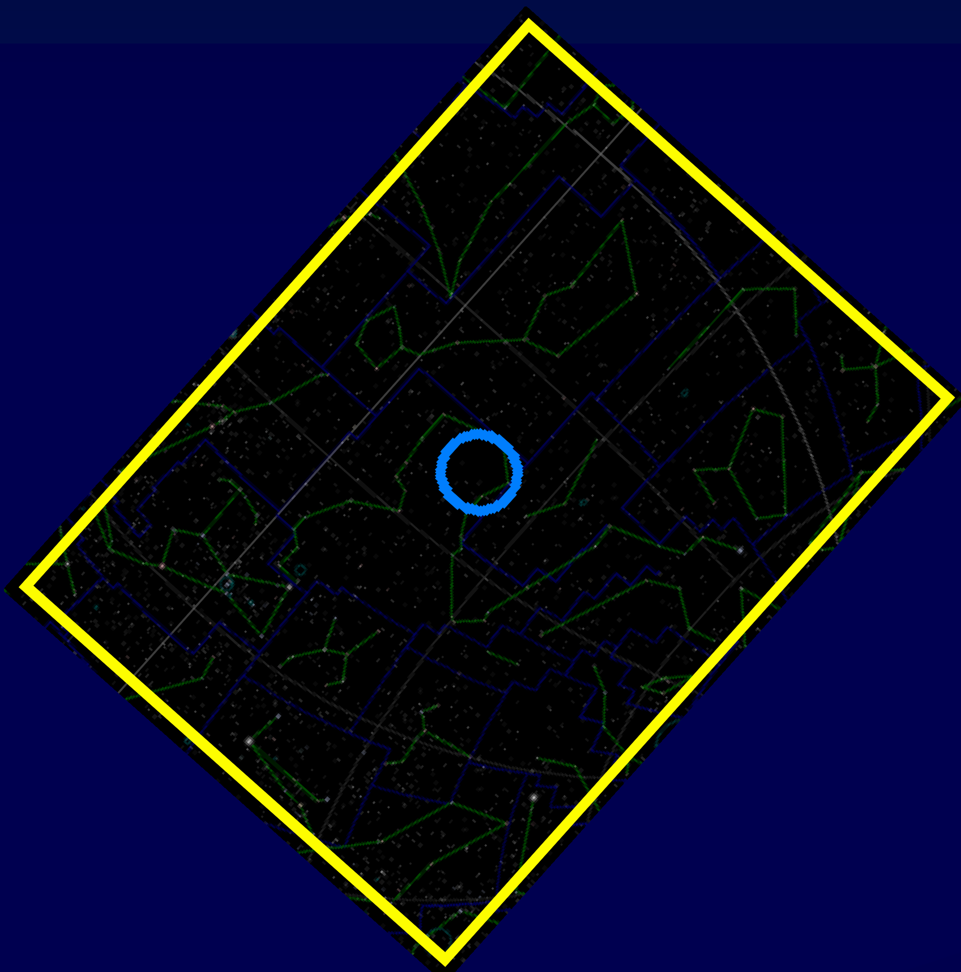


The Cold Spot is in the Eridanus constellation

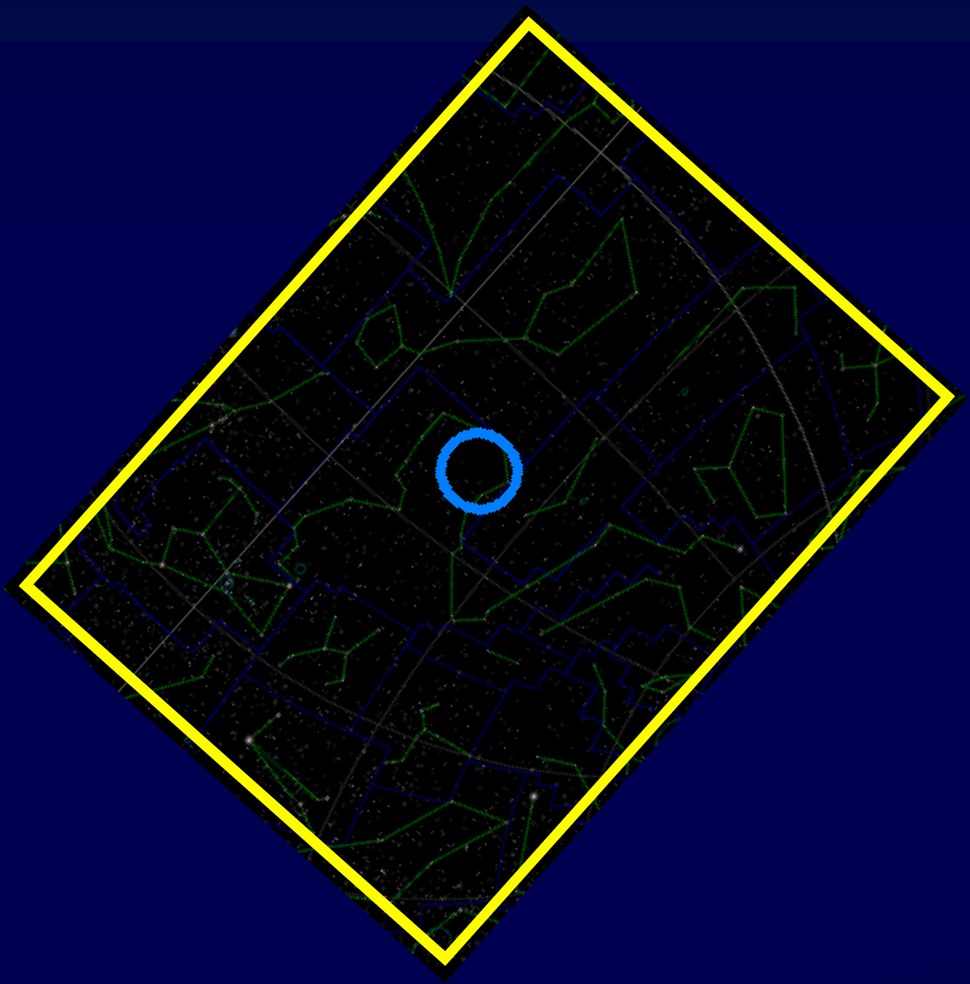
Eridanus is the ancient name for the Po river in Italy, whose delta was about this in 1500 a.C.

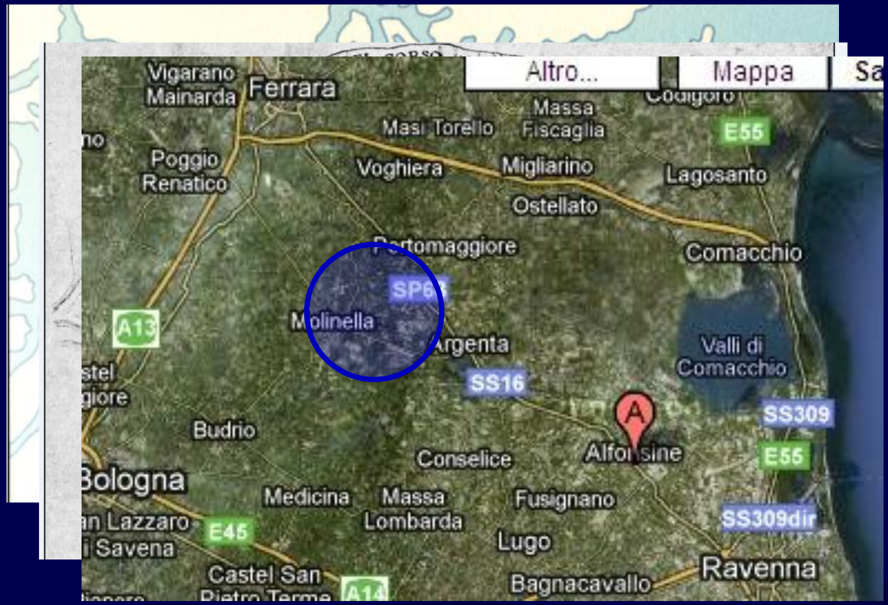


about this at etrusco-roman epoch

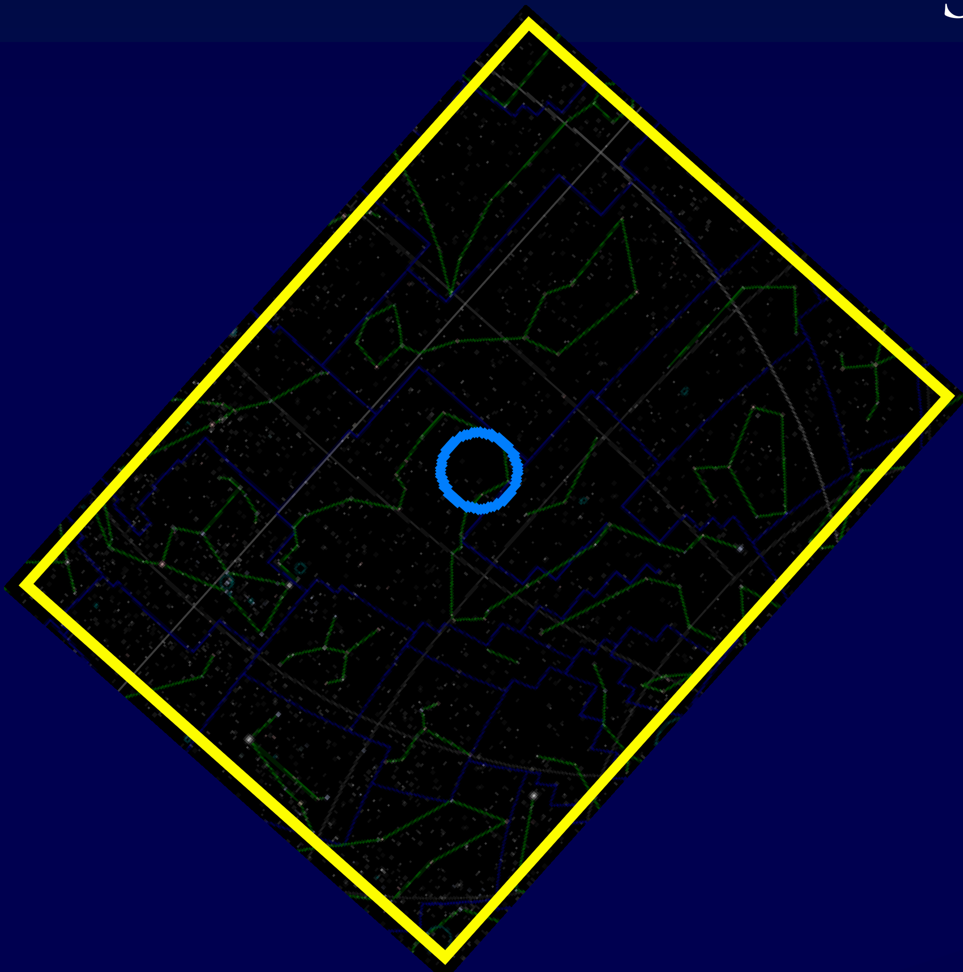


about this now





The Cold Spot is 30 km South-Est of Ferrara



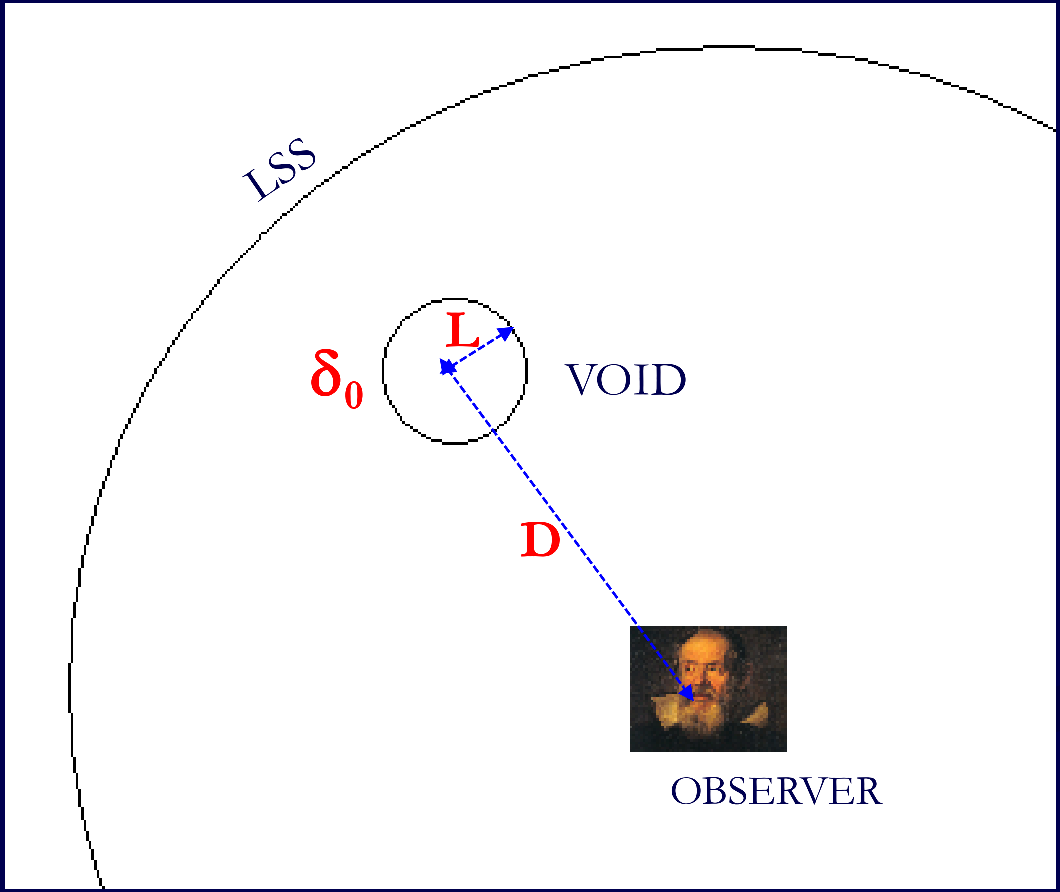
The Cold Spot as a “Void”

[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

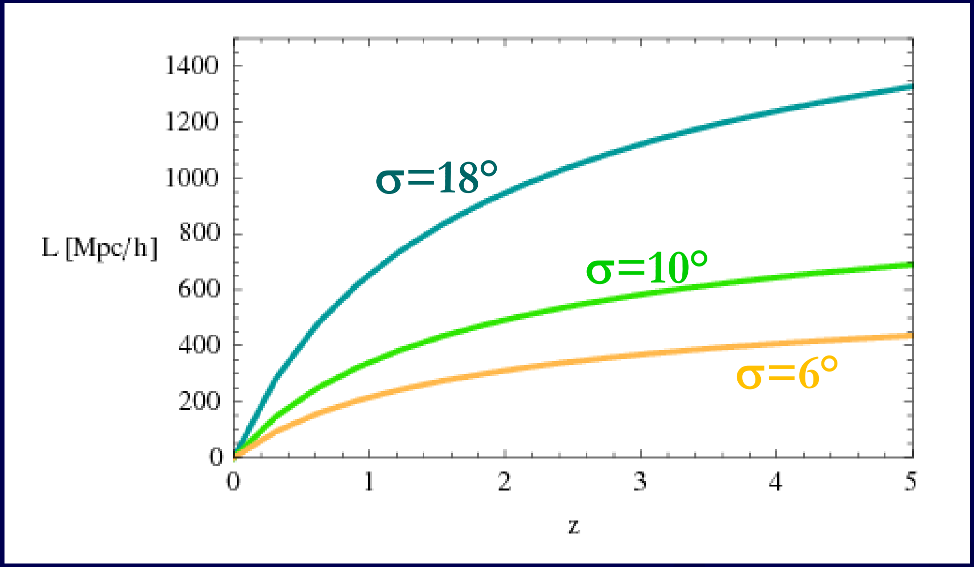
Radius-Redshift relation

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

$\tan \theta_L = L/D$

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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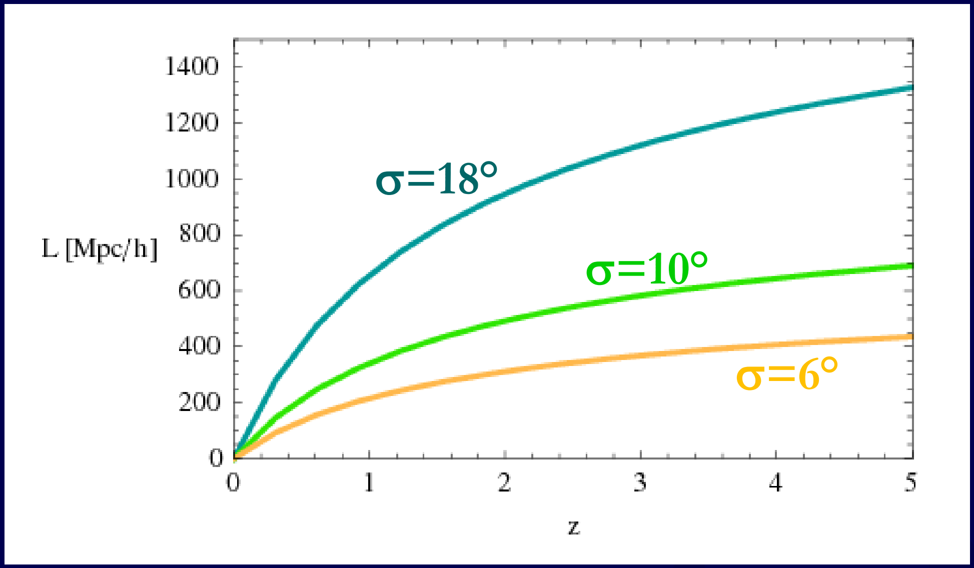


HERE we show that Planck will be able to reject or confirm this hypothesis via the study of secondary effects

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.

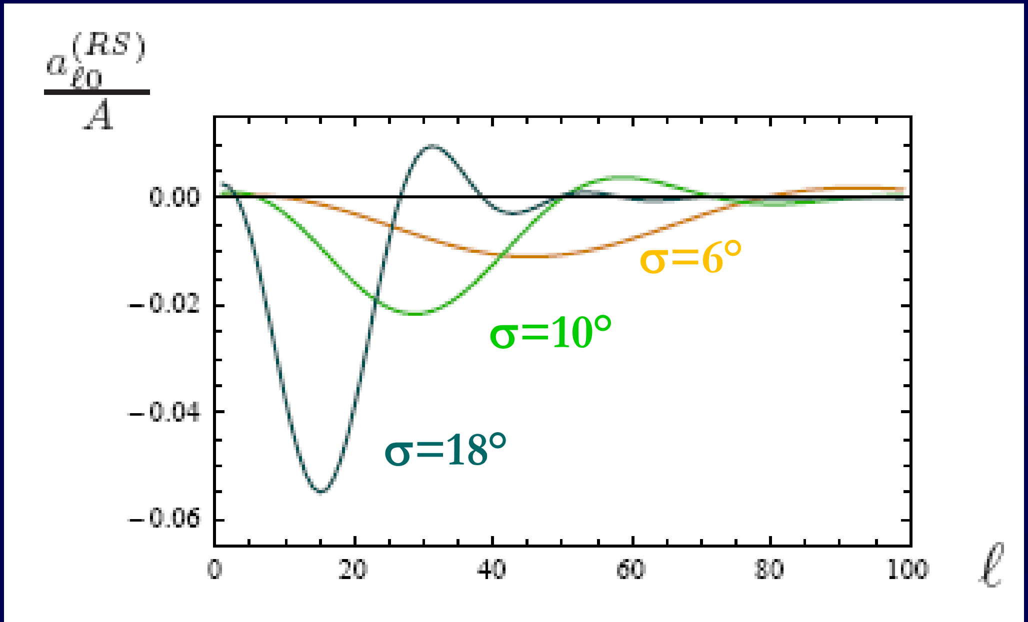
Actually, just the linear level effect is the one usually called "ISW" effect.
It would vanish in a matter dominated flat Universe. It is significant only when a Dark Energy component becomes dominant with respect to matter ($z<1$).

→ 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)

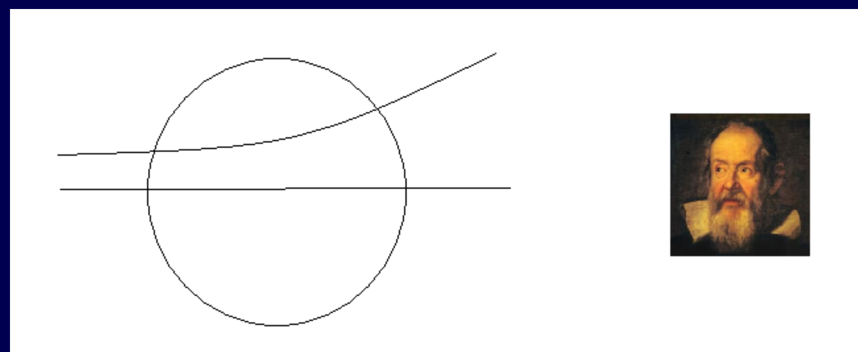
$$A \approx 0.5\ \delta_0^2\ \frac{(LH_0)^3}{\sqrt{1+z}}$$



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

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

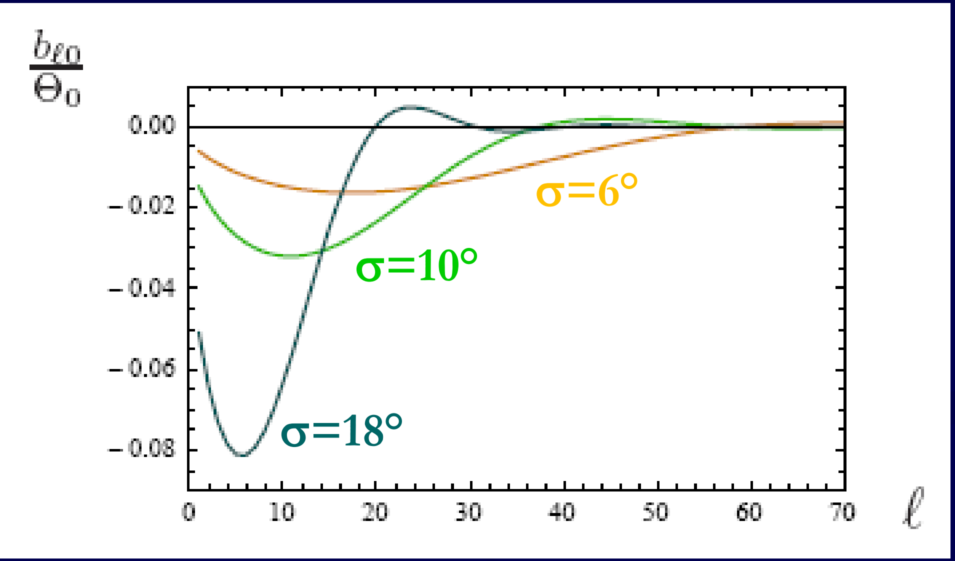
Now define

$$b_{\ell m} \equiv \int d\hat{\mathrm{n}}\ \Theta(\hat{\mathrm{n}})\ Y^{*}_{\ell m}(\hat{\mathrm{n}})$$

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

$$a^{(L)(1)}_{\ell m} = \sum_{\ell',\ell''} G^{-mm0}_{\ell\ \ \ell'\ell''} \frac{\ell'(\ell'+1) - \ell(\ell+1) + \ell''(\ell''+1)}{2} a^{(P)*}_{\ell' -m} b_{\ell'' 0}$$

Diagonal 2-p function

(power spectrum)

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

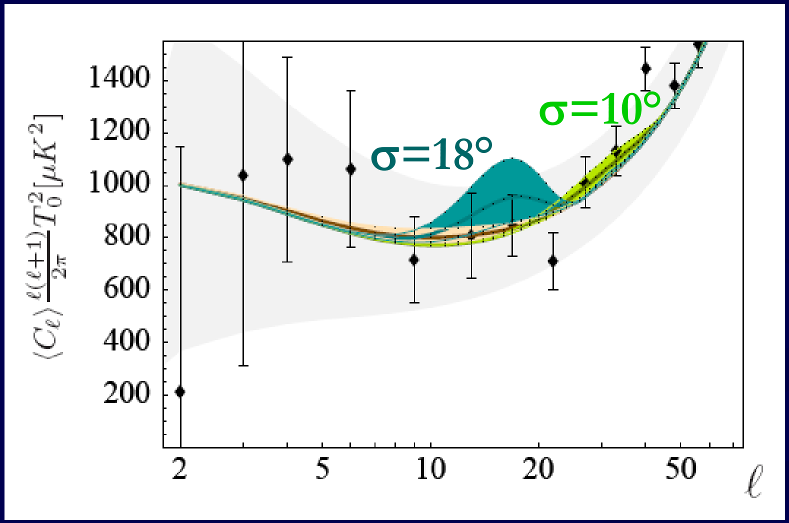
vanishing

(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>~~

negligible

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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

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

cosmic variance of bispectrum

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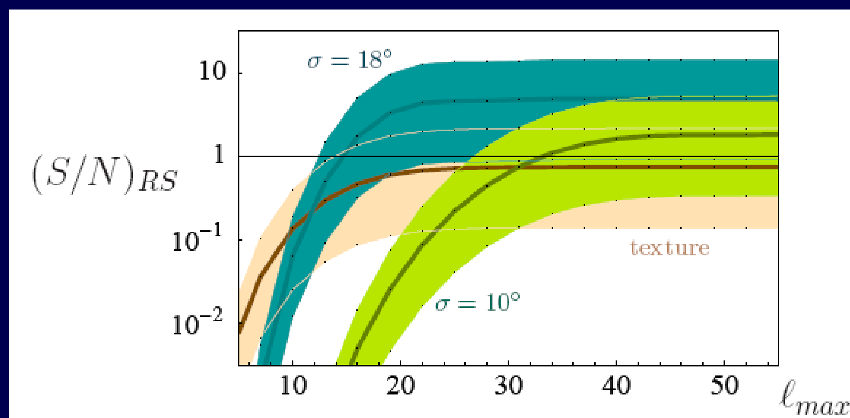
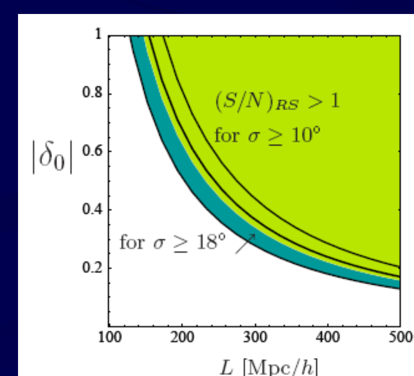
cosmic variance of bispectrum

1. RS^3



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

If no signal found, get constraints on Void parameter space



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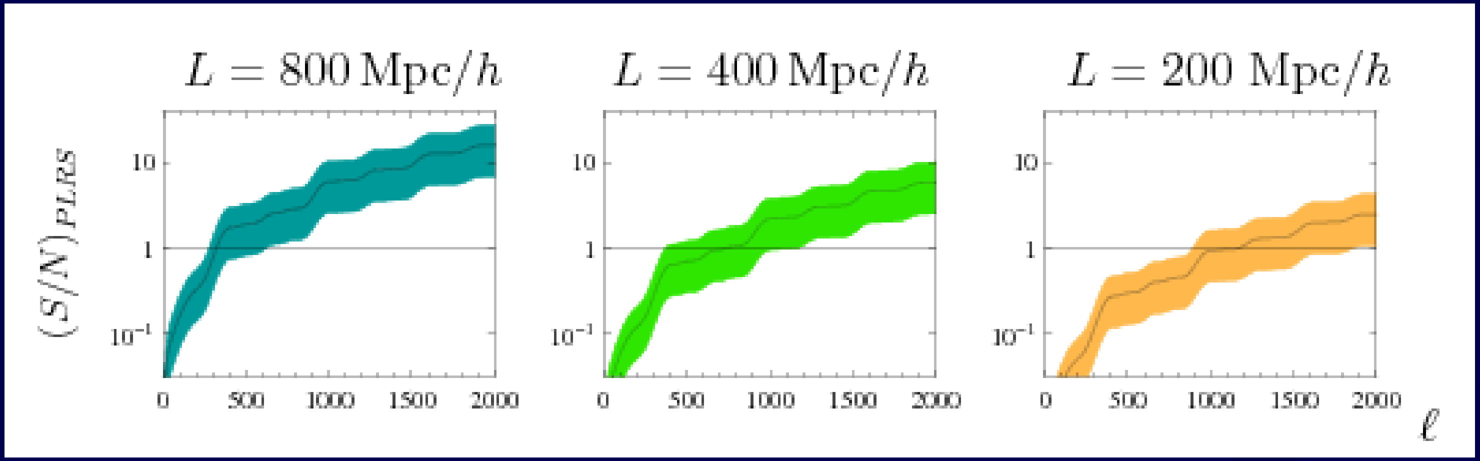
cosmic variance of bispectrum

2. P L RS



Detectable by Planck if Void radius L> 300 Mpc/h

L<300 Mpc/h means z<1, which has 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

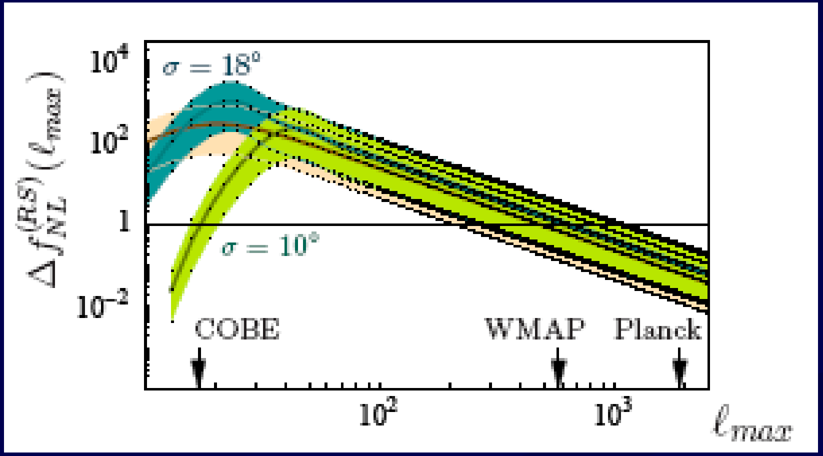
$$\phi(x) = \phi_L(x) + f_{NL}(\phi_L^2(x) - \langle\phi_L^2(x)\rangle)$$

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>

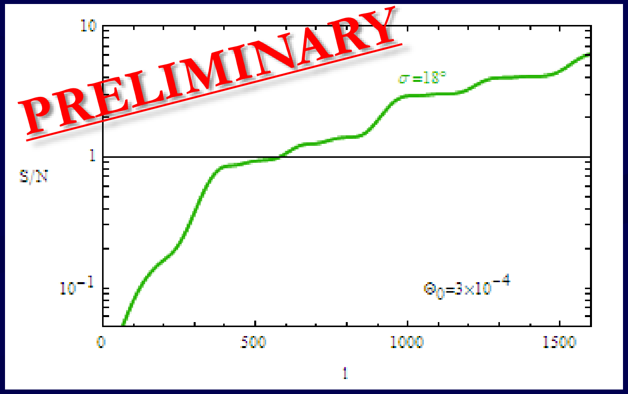
vanishing
(for gaussian and/or isotropous fields)

vanishing
(P&RS uncorrelated)

negligible

PROMISING!
(depends on axis orientation)

Non-Diagonal S/N
exceeds 1 at l>1000



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]