Local supervoids and the origin of the WMAP Cold Spot

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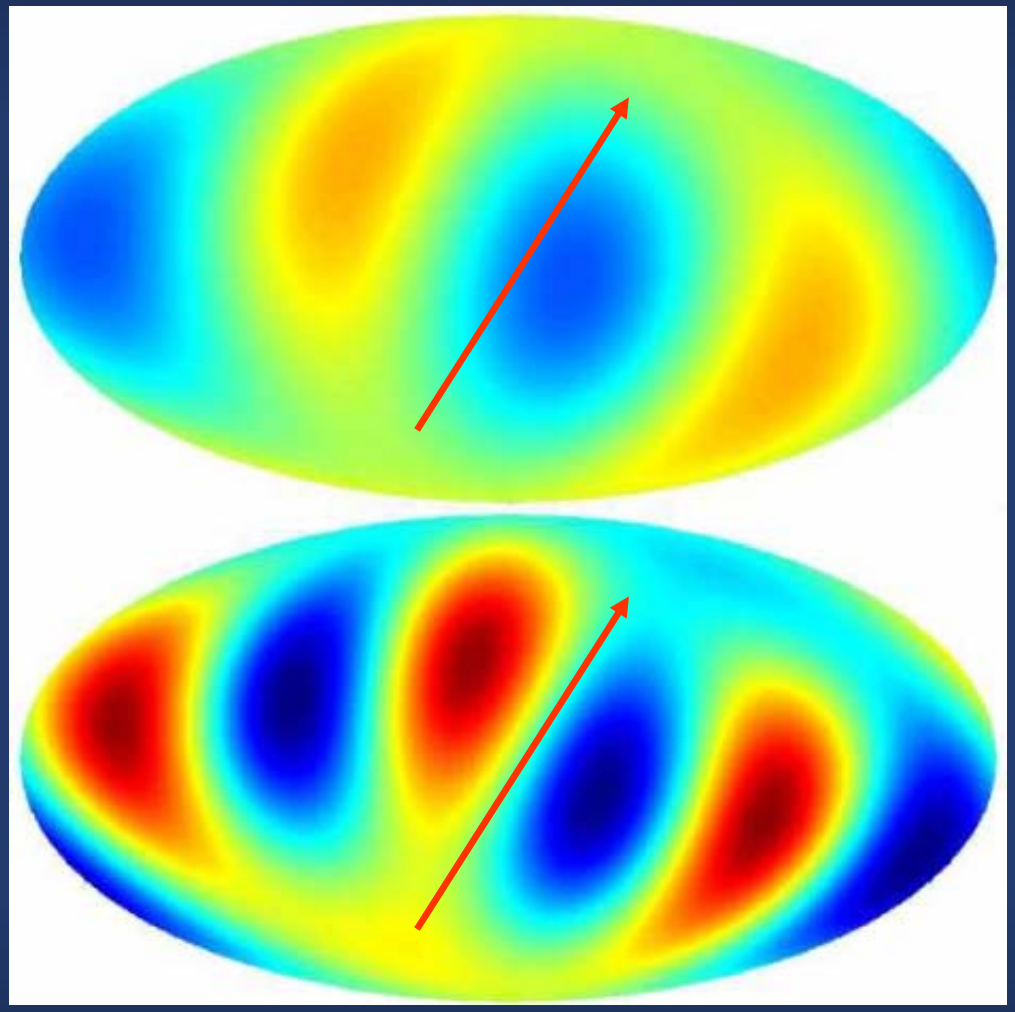
Outline

- CMB large-angle anomalies
- Local supervoids (LSVs)
- The 2nd order ISW effect
- Abundance of LSV's
- Summary & future prospects

CMB large-angle anomalies

- Low-quadrupole (power defficiency outside the galaxy mask)
- Alignment bewteen quadrupole & octopole (Tegmark, et al, ’03)
- Power asymmetry (Eriksen, et al, ’03)
- Correlation with ecliptic plane (Starkman, et al, ’03)
- Cold spot (Vielva, et al, ’03)

Alignment

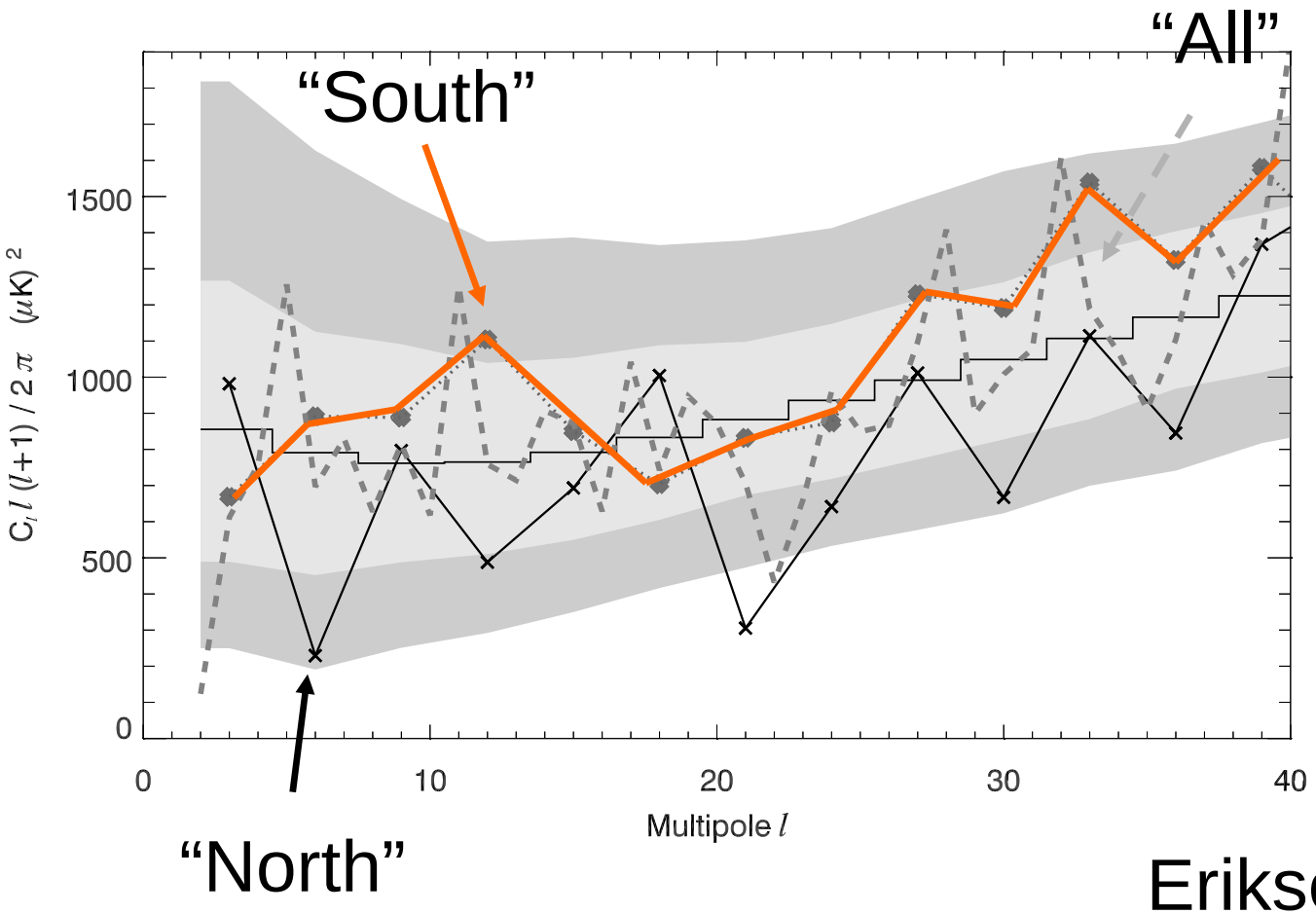


l=2

l=3

WMAP 1st year ILC map (Tegmark, et al, ’03)

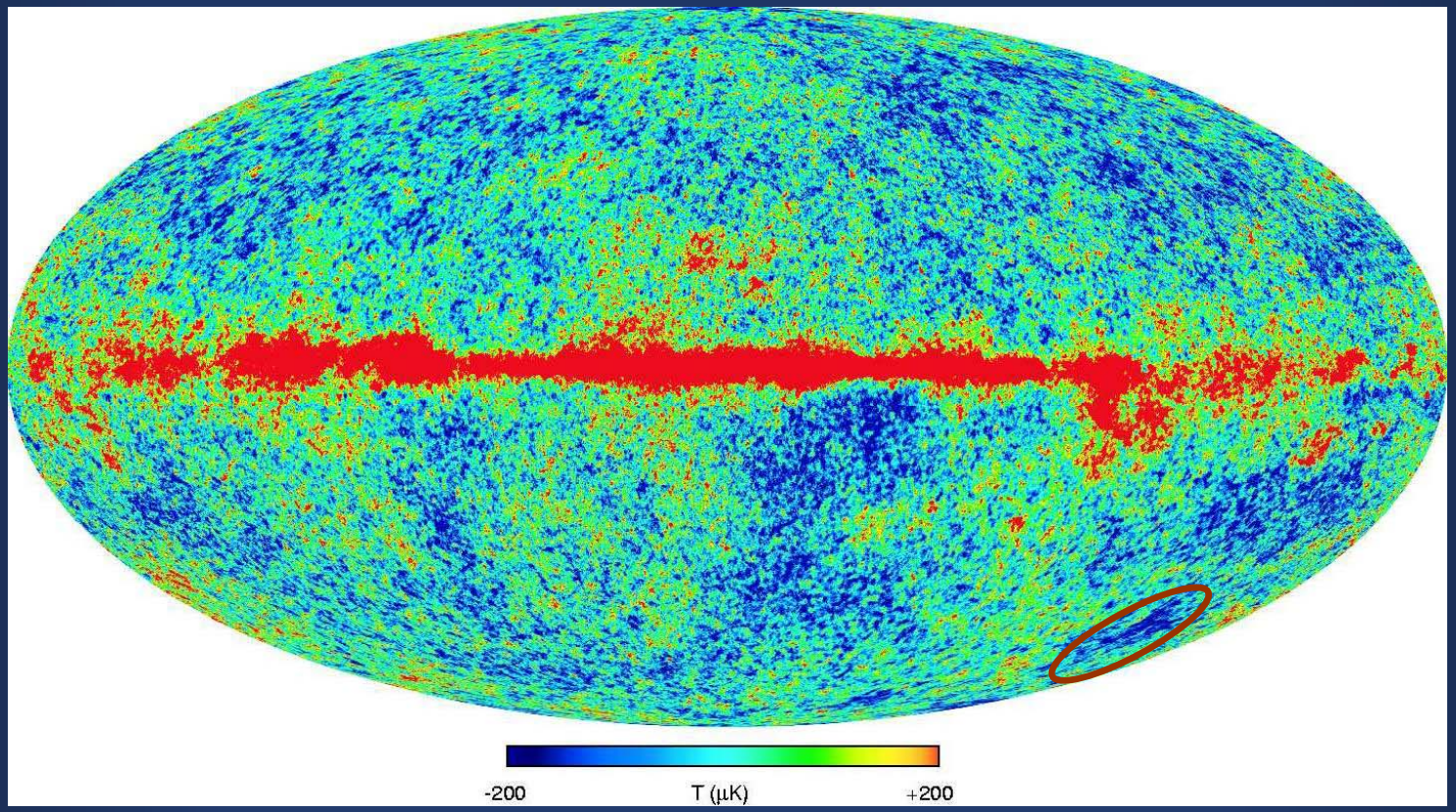
North–South asymmetry



North pole: $(l,b)=(57^o, 10^o)$

Eriksen et al. '03, '04

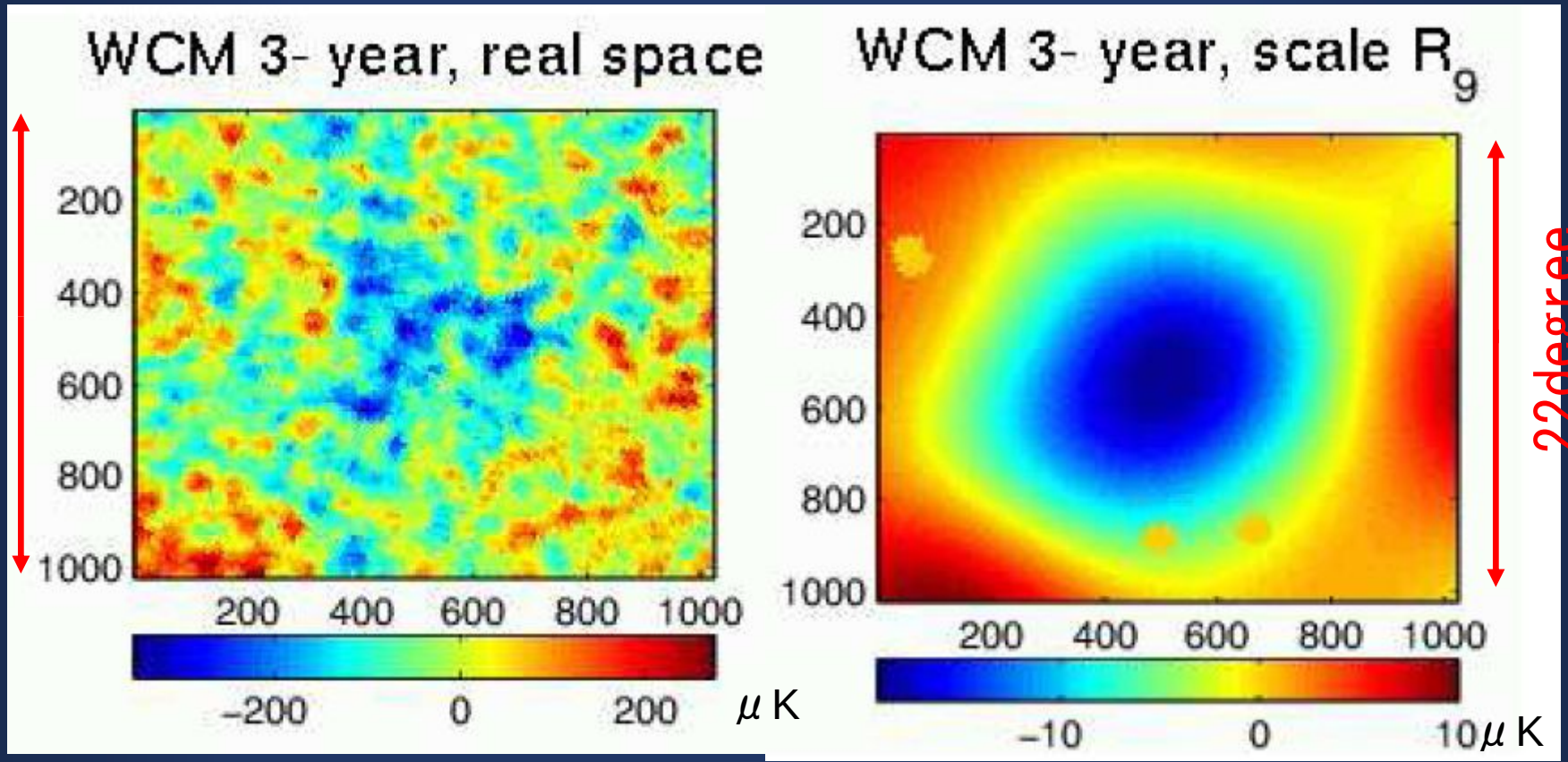
The WMAP Cold Spot



From:spherical wavelet curtsis

Vielva et al.’03

The WMAP Cold Spot



Anomaly at ~5°（～3σ）

(Cruz. et al.'06)

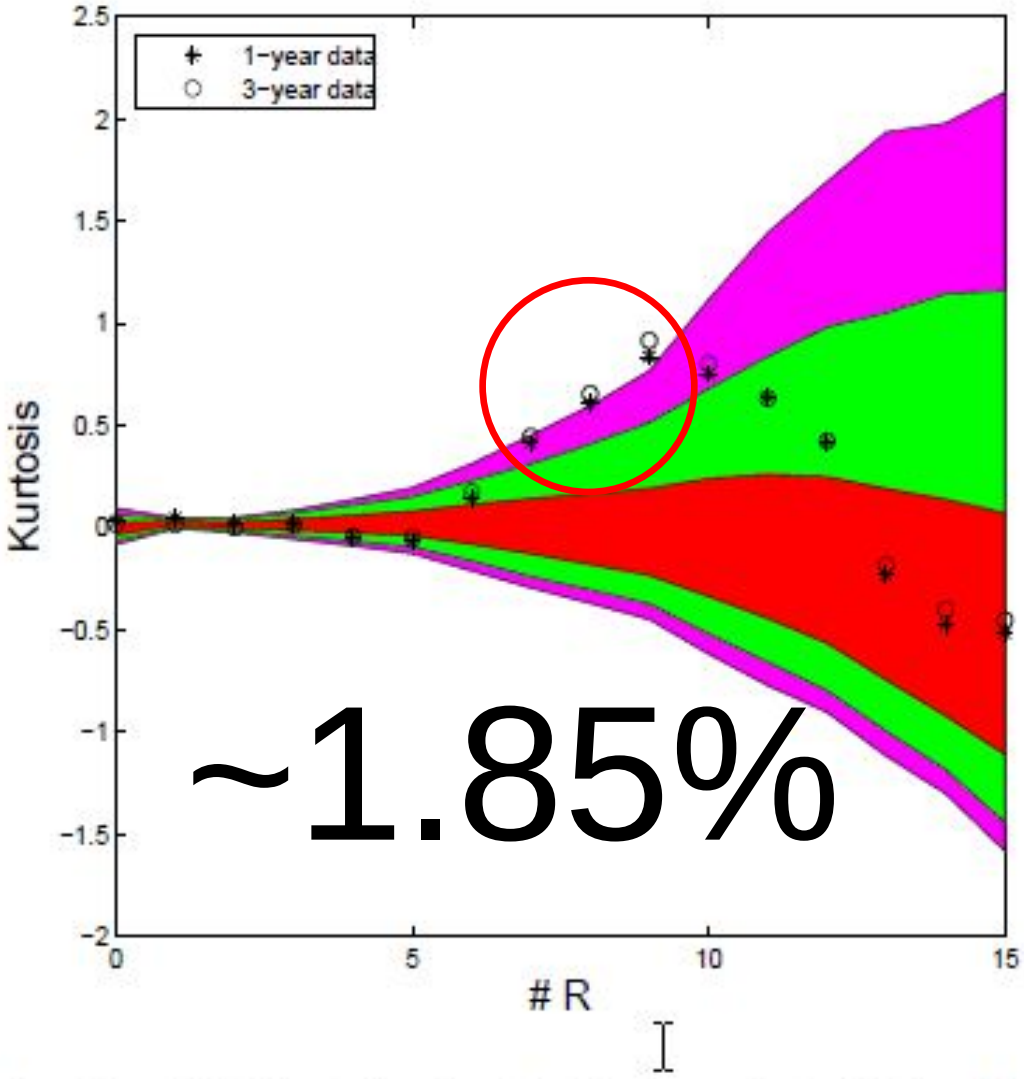
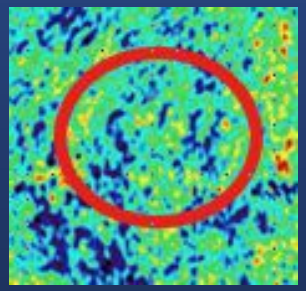


FIG. 2.— WCM kurtosis values for the 1–year (asterisks) and the 3–year data (circles). The acceptance intervals for the 32% (inner), 5% (middle) and 1% (outer) significance levels, given by the 10000 simulations are also plotted.

Ambiguities remain…

- Galactic contamination (S/N)
  - Internal Linear Combination (ILC) maps are not appropriate.
- Statistical significance
  - Do not forget aposteriori significance.



Statistical significance

- Alignment could be
  (Land & Magueijo ’06 Naselsky et al’07)
- Power asymmetry possibly
  (Eriksen et al ’07)
- Cold spot(s) probably
  (Naselsky’07)

Possible mechanisms

- New physics
  - ✧Large curvaton perturbation — Ericksek et al. ’08
  - ✧Elliptic deformation — Campanelli ’06
  - ✧Bianchi VIIh model — Jaff et al. ’05
  - ✧Collapsing texture — Vielva ’07
- Traditional physics
  - ✧1st order effect — Sachs & Wolfe ’67
  - ✧Second order effects — Tomita ’05
  - ✧Local supervoids — Inoue & Silk ’05

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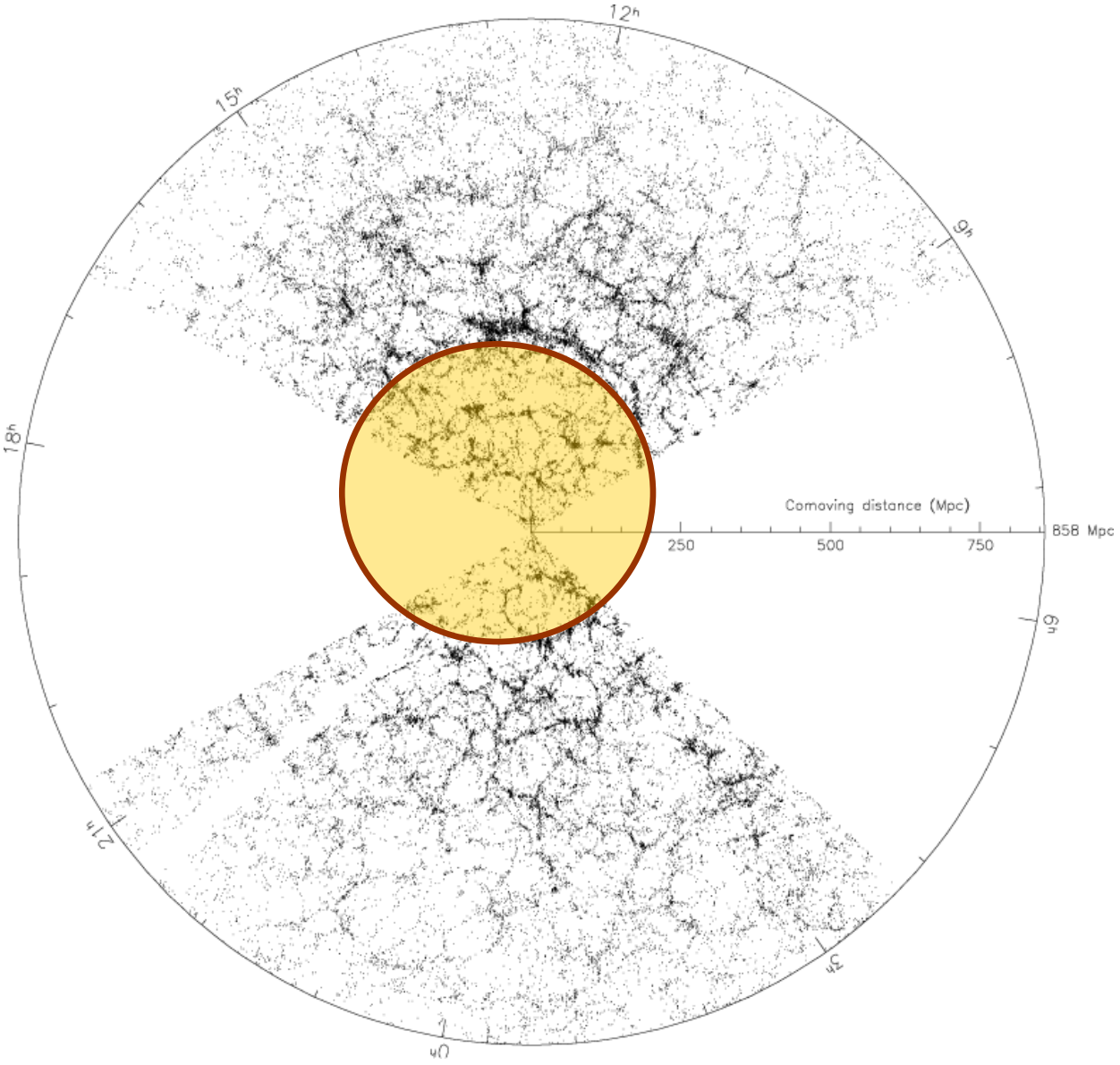
Local supervoids (r>100Mpc)

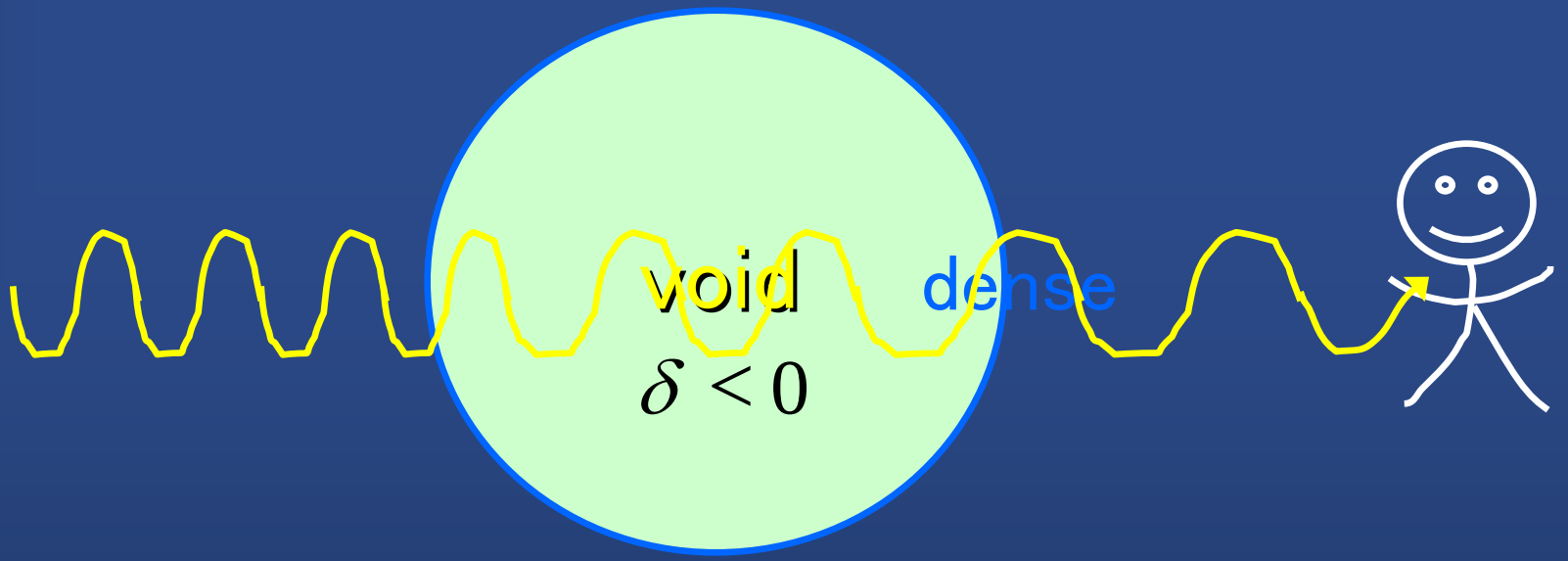
- Volume effects (A large number of samples)
- Non-linear effects (peculiar velocity & non-Gaussianity)
- Implication from observation

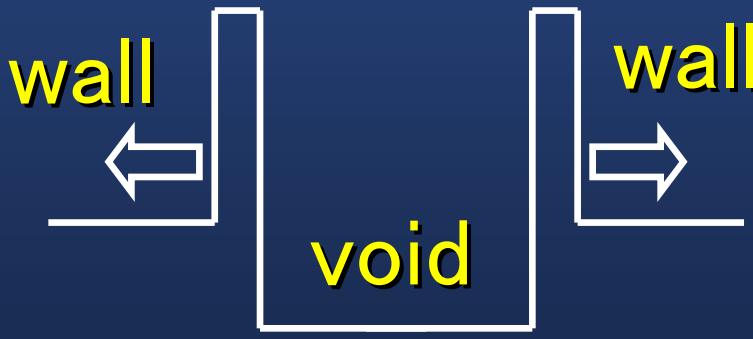
(SDSS,2dF,2MASS & 6dF)

SDSS galaxy map

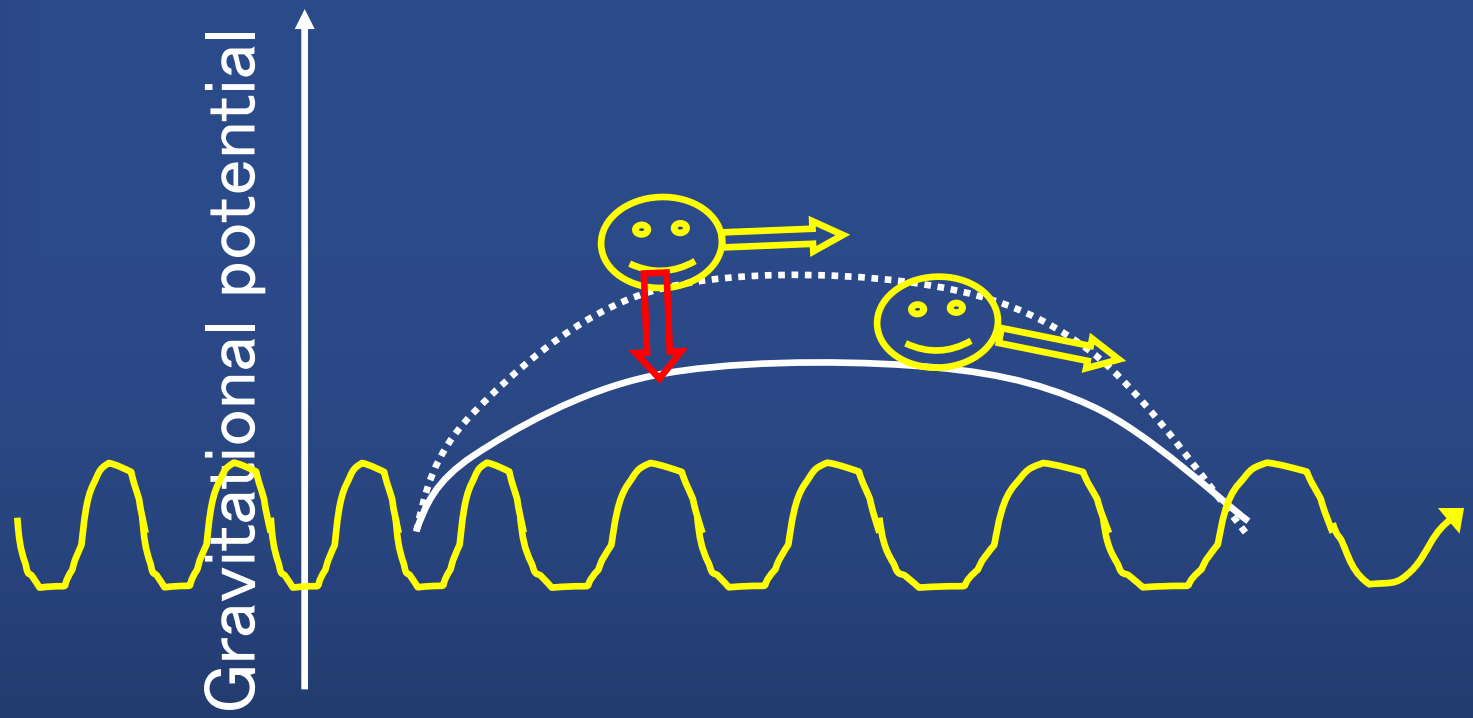


Effects on CMB



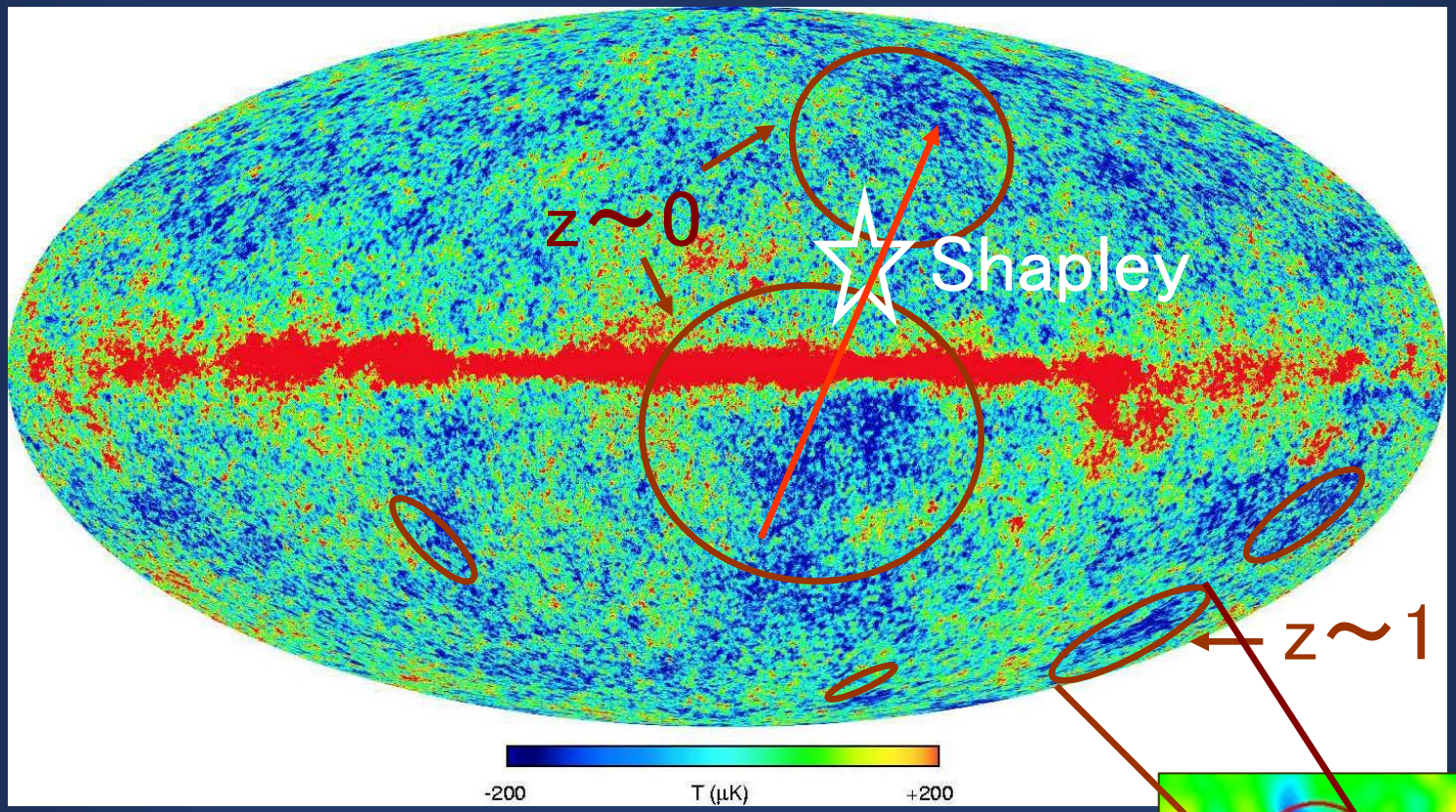


Integrated Sachs-Wolfe（ISW）effect



$$\frac{\Delta T}{T} = 2 \times \int_{\text{Photon path}} \text{Time variability of potential}$$

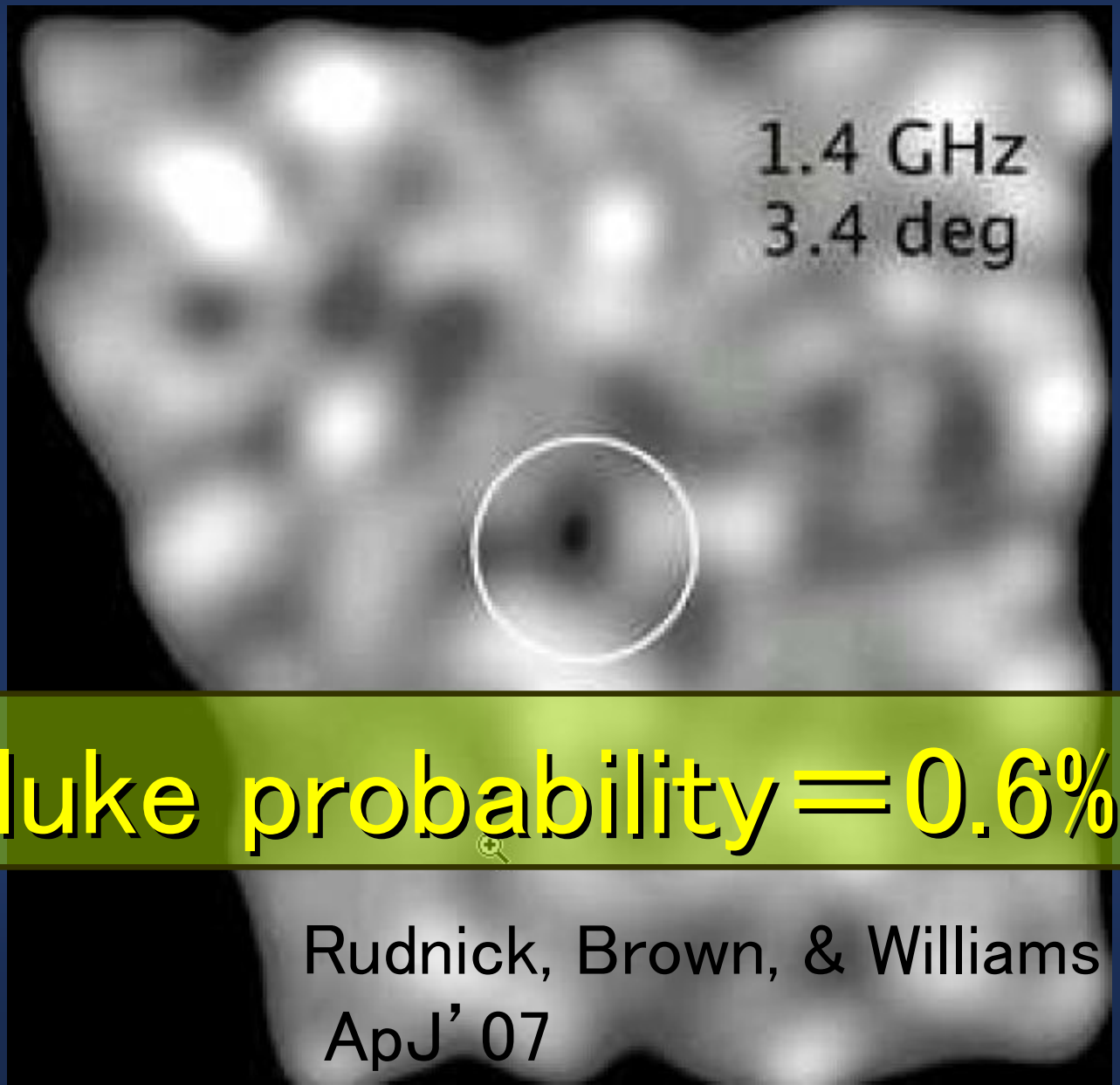
Position and size of Lsv's



Inoue & Silk ApJ '06

"cold spot"

NVSS cold spot ?



Fluke probability＝0.6%

Rudnick, Brown, & Williams
ApJ’07

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Great 'cosmic nothingness' found

Astronomers have found an enormous void in space that measures nearly a billion light-years across.

The result comes from a sky survey by the VLA in New Mexico

LISTEN 'It's hard to picture'

It is empty of both normal matter - such as galaxies and stars - and the mysterious "dark matter" that cannot be seen directly with telescopes.

The "hole" is located in the direction of the Eridanus constellation and has been identified in data from a survey of the sky made at radio wavelengths.

The discovery will be reported in a paper in the Astrophysical Journal.

Previous sky surveys that have traced the large-scale structure of the nearby Universe have long shown, for example, how the clustering of galaxies is strung into vast filaments and sheets that are separated by great gaps.

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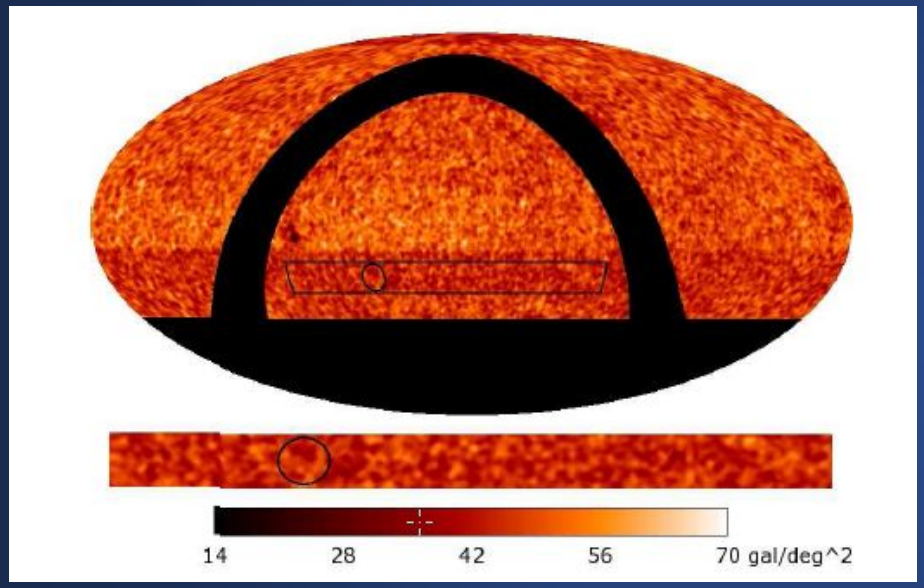
How significant?



- Systematics

(galaxy-galaxy correlation & S/N dependence on the sky)

- Arbitrary choices in size & location

(marginalized over them, leads to a reduction in significance)

Not significant.

Smith & Huterer (astro-ph/08052751)

Another evidence?

Granett et al. (ApJL '08)

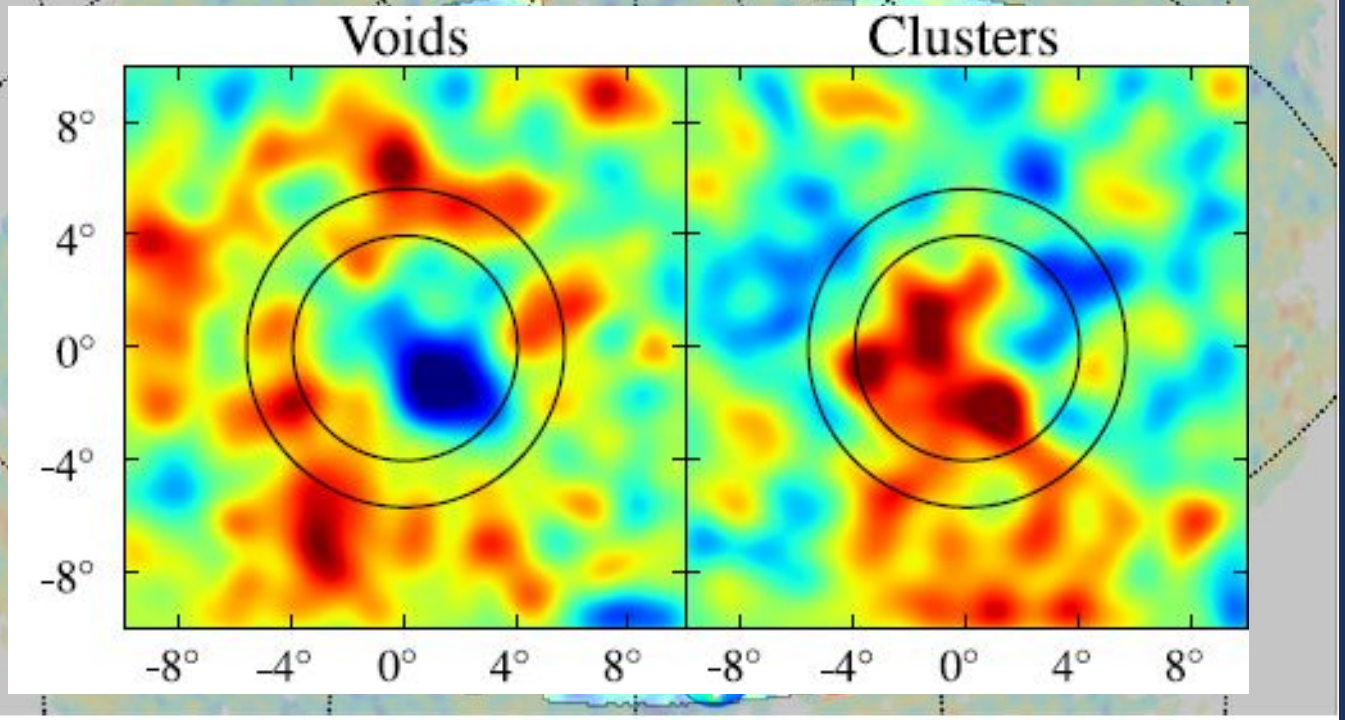


Figure 1: A map of the microwave sky over the SDSS area. The supervoids and superclusters used in our analysis are highlighted and outlined at a radius of 4°, blue for supervoids and red for superclusters. The compensated filter we use in our analysis approximately corrects for the large-angular-scale temperature variations that are visible across the map. The SDSS DR6 coverage footprint is outlined. Holes in the survey, *e.g.* due to bright stars, are displayed in black. Additionally, the WMAP Galactic foreground and point source mask is plotted (white holes). The disk of the Milky Way, which extends

The 2nd order ISW effect

ISW

2nd order ISW

$$\frac{\Delta T}{T} = (c_1\delta - c_2\delta^2)\frac{a^3 r_v^{\ 3}}{H^{-3}}$$

density contrast

(void radius/ Hubble radius)^3

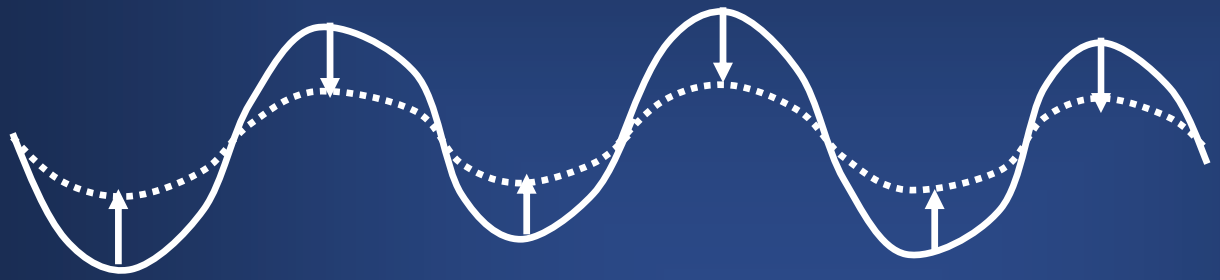
$$\frac{\Delta T}{T} = 10^{-5}$$

$$\delta = -0.3$$

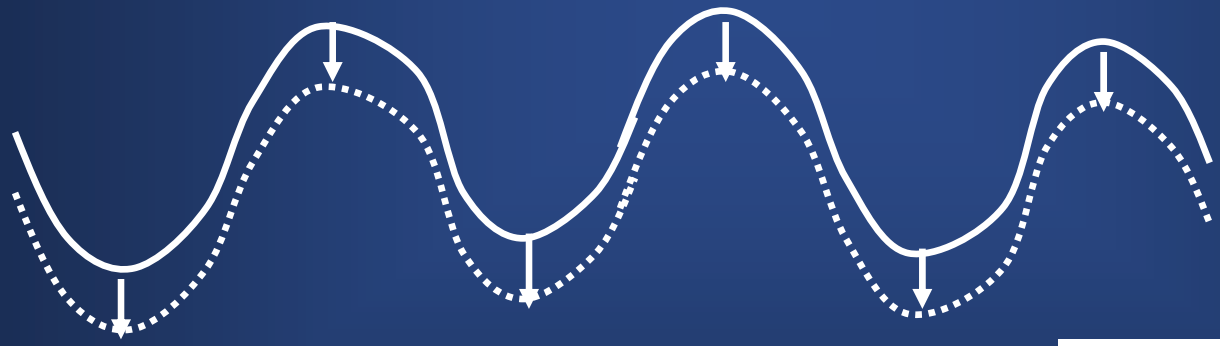
$$r_v \sim 200\,h^{-1}\mathrm{Mpc}$$

Inoue & Silk ApJ' 07, Tomita & Inoue ' 07

The 2nd order ISW effect



1st order



2nd order

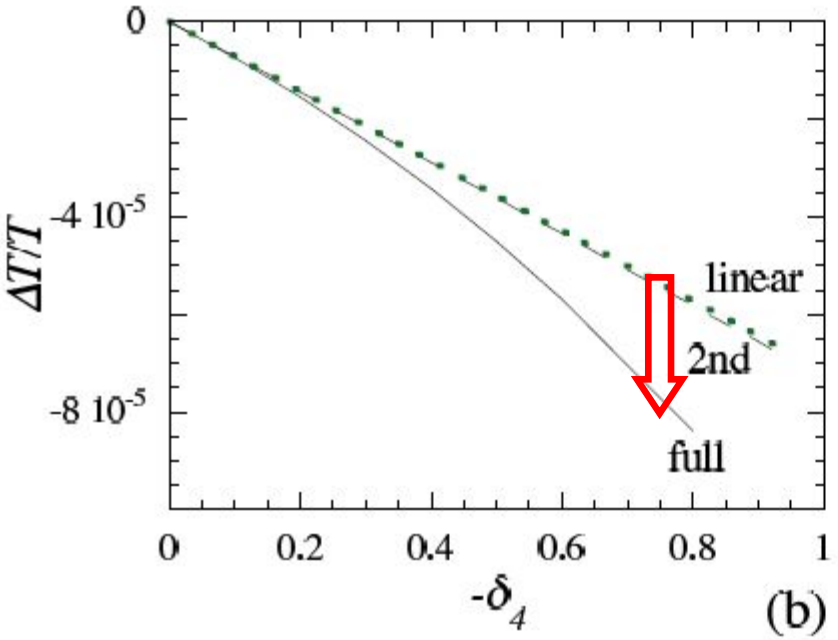
$$\frac{\Delta T}{T} = (c_1\delta - c_2\delta^2)\frac{a^3 r_v^{\ 3}}{H^{-3}}$$

$$\left\langle \frac{\Delta T}{T} \right\rangle^{(2)} < 0$$

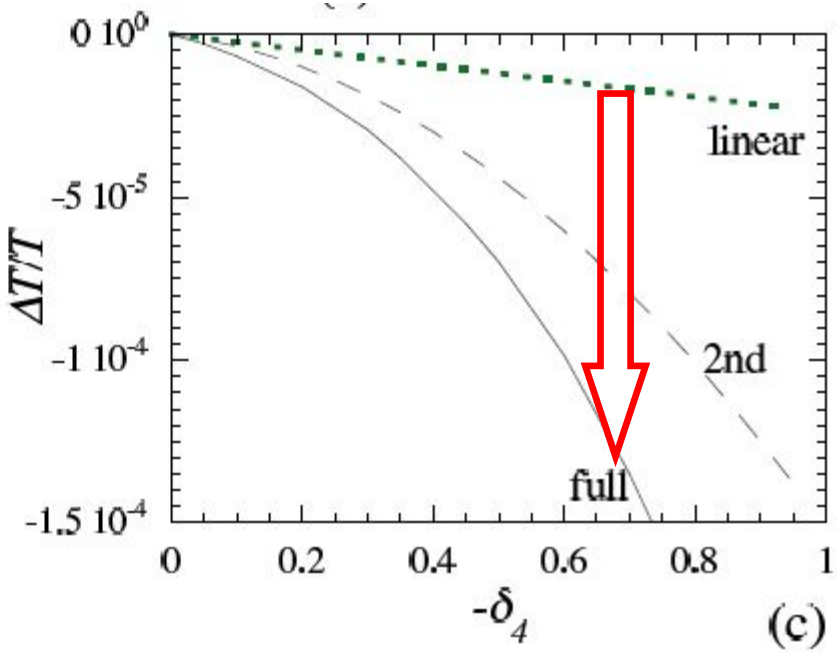
Anisotropy from a non-linear void

(based on LTB solution)

$\Omega_{m0} = 0.24$



$\Omega_{m0} = 0.9$

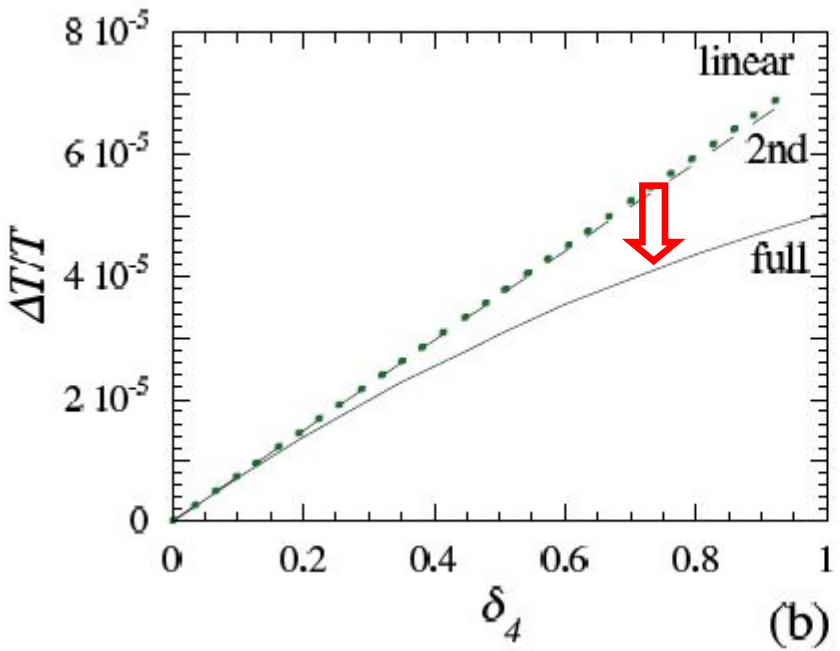


$r_v \sim 200\,h^{-1}\mathrm{Mpc}$

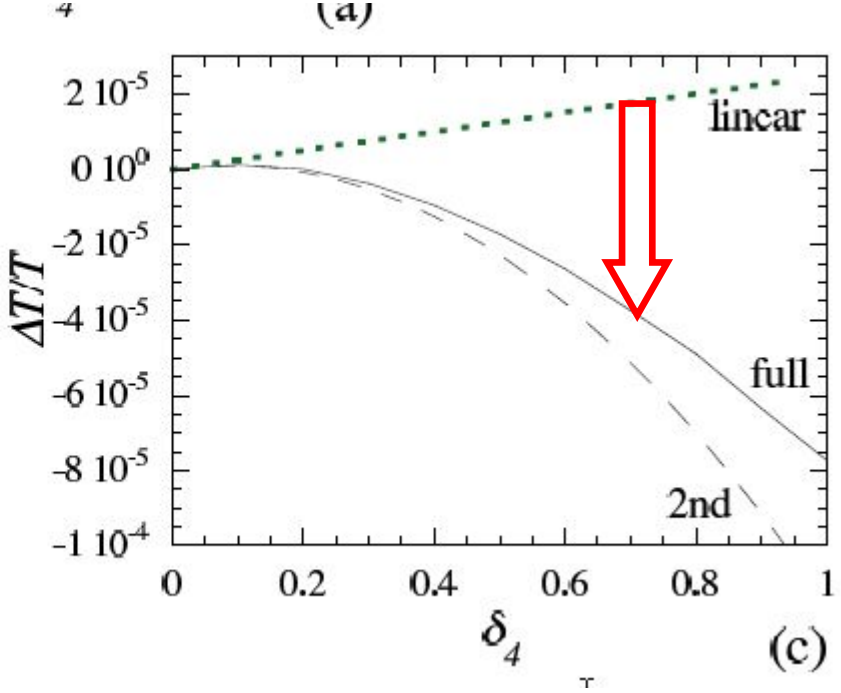
Sakai & Inoue PRD '08

Anisotropy from a non-linear lump

$\Omega_{m0} = 0.24$



$\Omega_{m0} = 0.9$



$r_v \sim 200\,h^{-1}\mathrm{Mpc}$ Sakai & Inoue PRD '08

ISW Effect from Local Superstructures

(Inoue & Silk ApJ'07, Tomita & Inoue '07, Sakai & Inoue '08)

- Linear ISW effect dominant at z<1
- 2nd order ISW effect dominant at z>1
- 2nd order ISW effect lowers temperature

- Asymmetry between hot & cold spots

CMB-LSS anomalies?

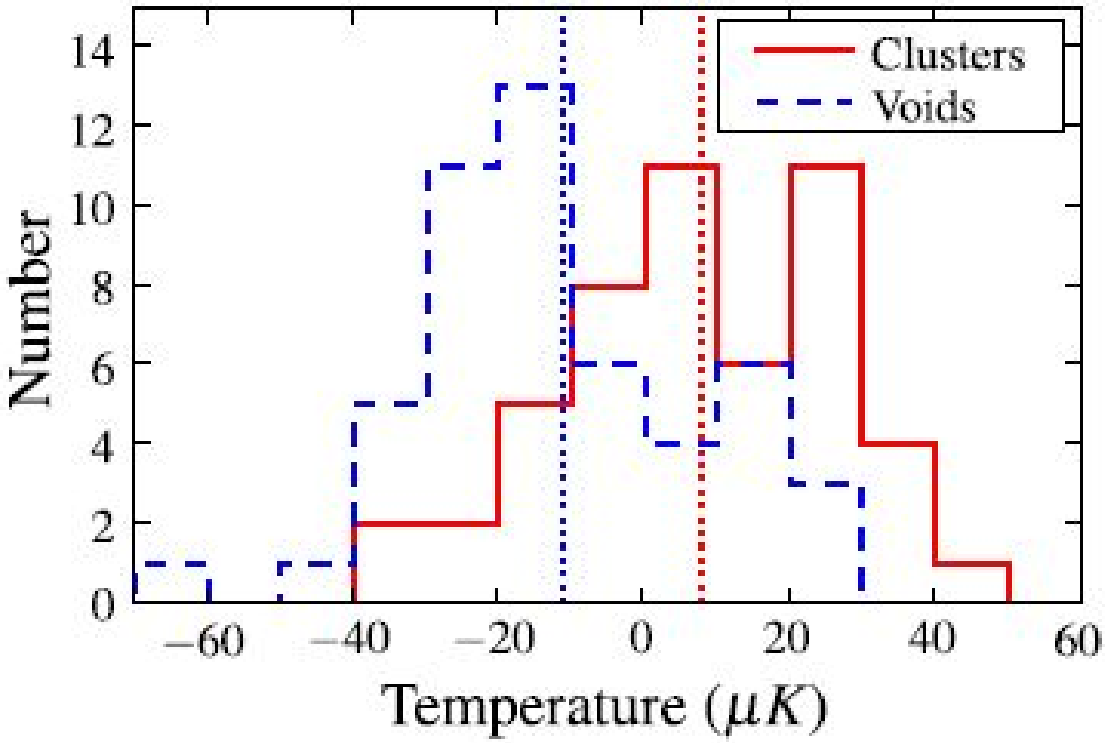


FIG. 2.— Histograms of the signals of the 50 highest-significance supervoids and superclusters used for our detection, measured in our compensated filter. The vertical dotted lines are the means of each distribution, at -11.3±3.1μK(voids) and 7.9±3.1μK(clusters).

source mask is plotted (white holes). The disk of the Milky Way, which extends

Abundance of LSV's

- Non-linearity may play an important role
- Volume effect should be taken into account
- Tale distribution may be not Gaussian (central limit theorem no-longer valid)

Is PS approximation OK?

(Gunn& Gott ’72, PS, ’74 Piran ’97)

- Abundance is small
  - Correction due to void-in-cloud or void-in-void effect is expected to be small.
- Approach to spherically symmetric state
  - Contrary to collapsing cases.
- Neglect spatial correlation & proximity effects from other objects
  - But may be not negligible.

Model parameters:

Comoving radius R、density contrast δ <0、

redshift z

Assumption:

One void to the Cold Spot (~73 μK at 5^o)

Anisotropy ΔT= 8-16 μK、angulr radius θ_v=5-9^o

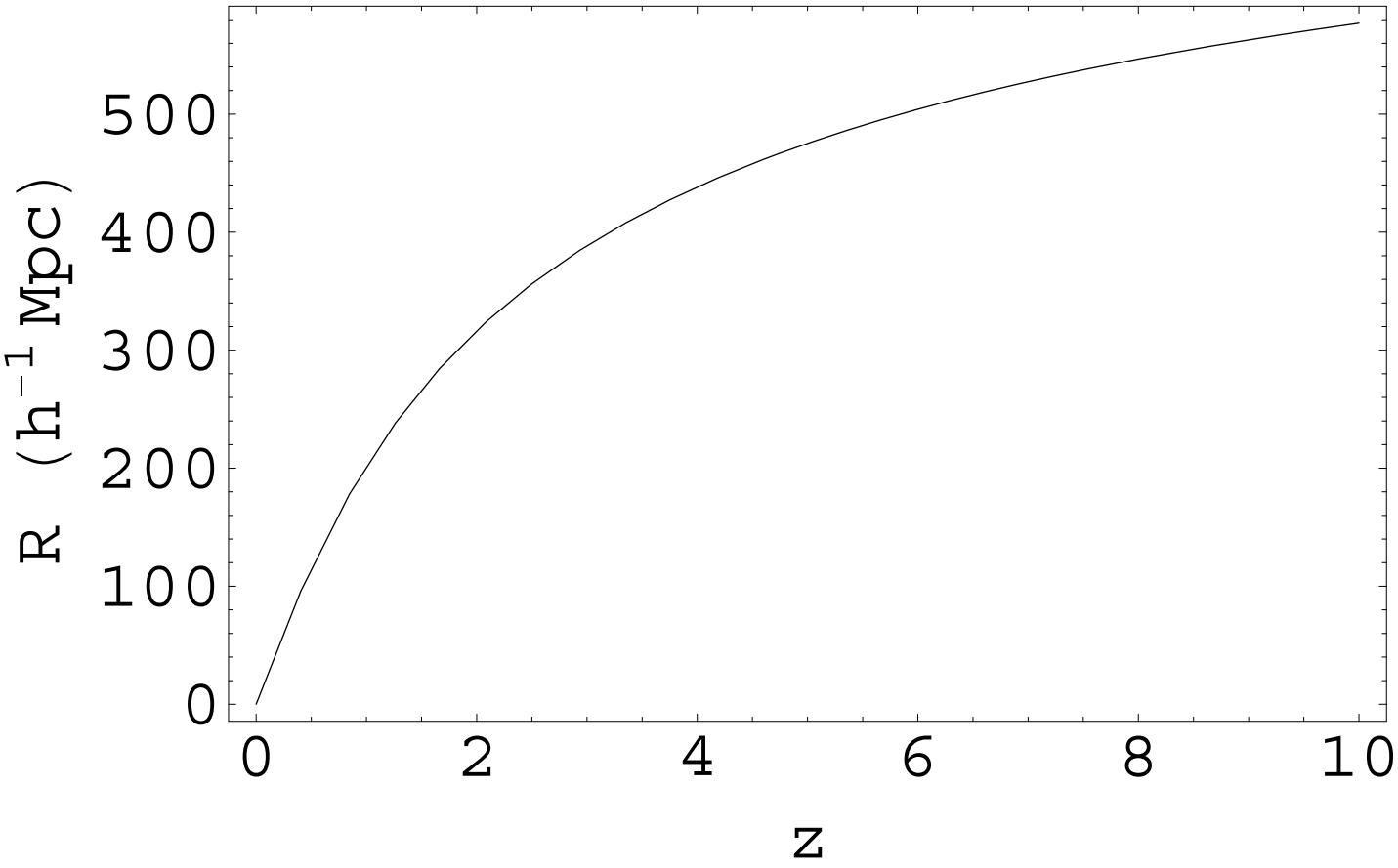
Cosmological parameters

$$\Omega_0 = 0.3,\ \Omega_\Lambda = 0.7,\ h = 0.7,\ \Omega_b = 0.046,\ \sigma_8 = 0.9$$

Mass function: PS approximation, without wall

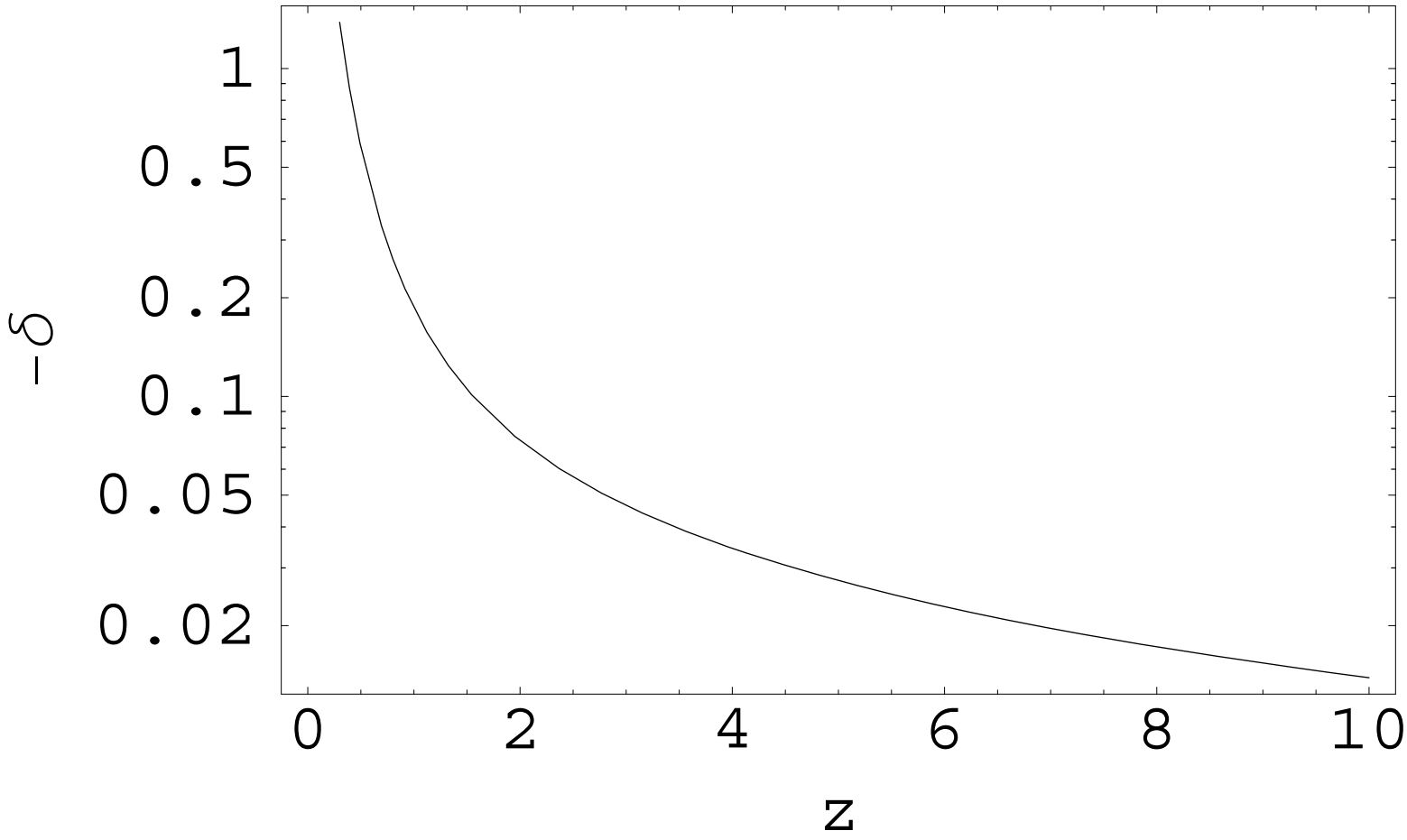
Comoving radius of LSV

$(\theta_v = 5^o, \Delta T = 16\mu K)$



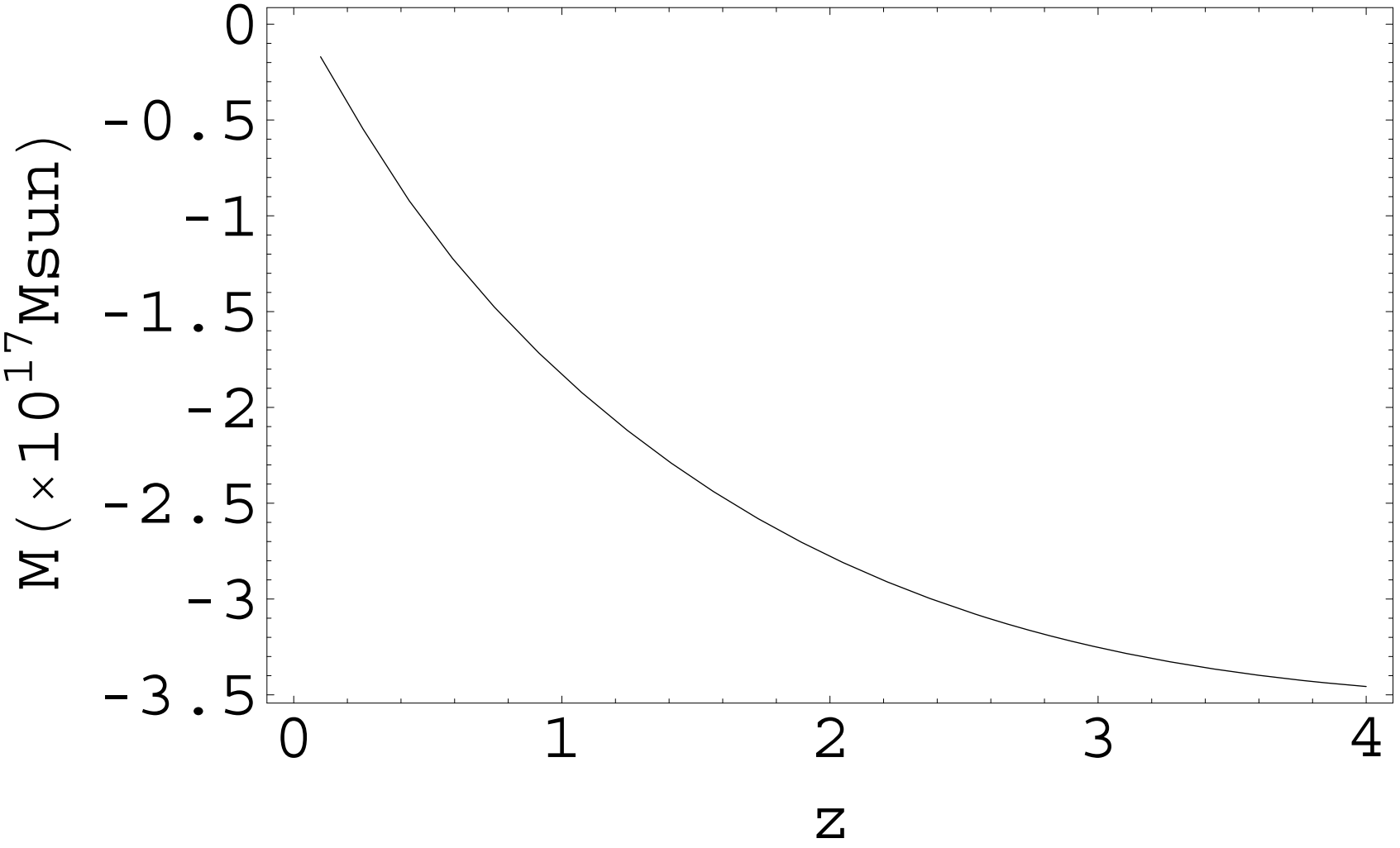
Density contrast

$(\theta_v = 5^o, \Delta T = 16 \mu K)$



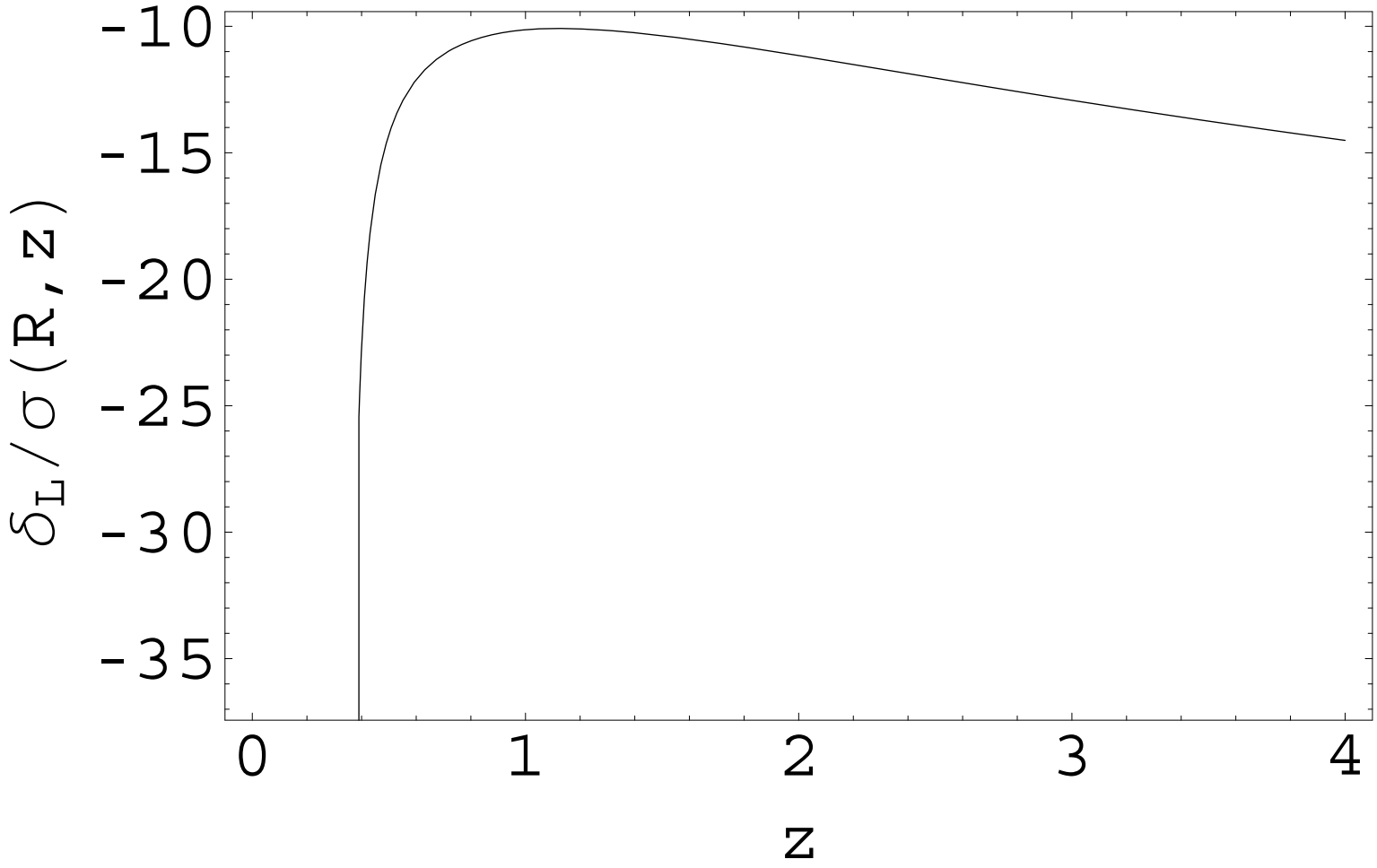
Mass of LSV

$(\theta_v = 5^{\circ}, \Delta T = 16\mu K)$



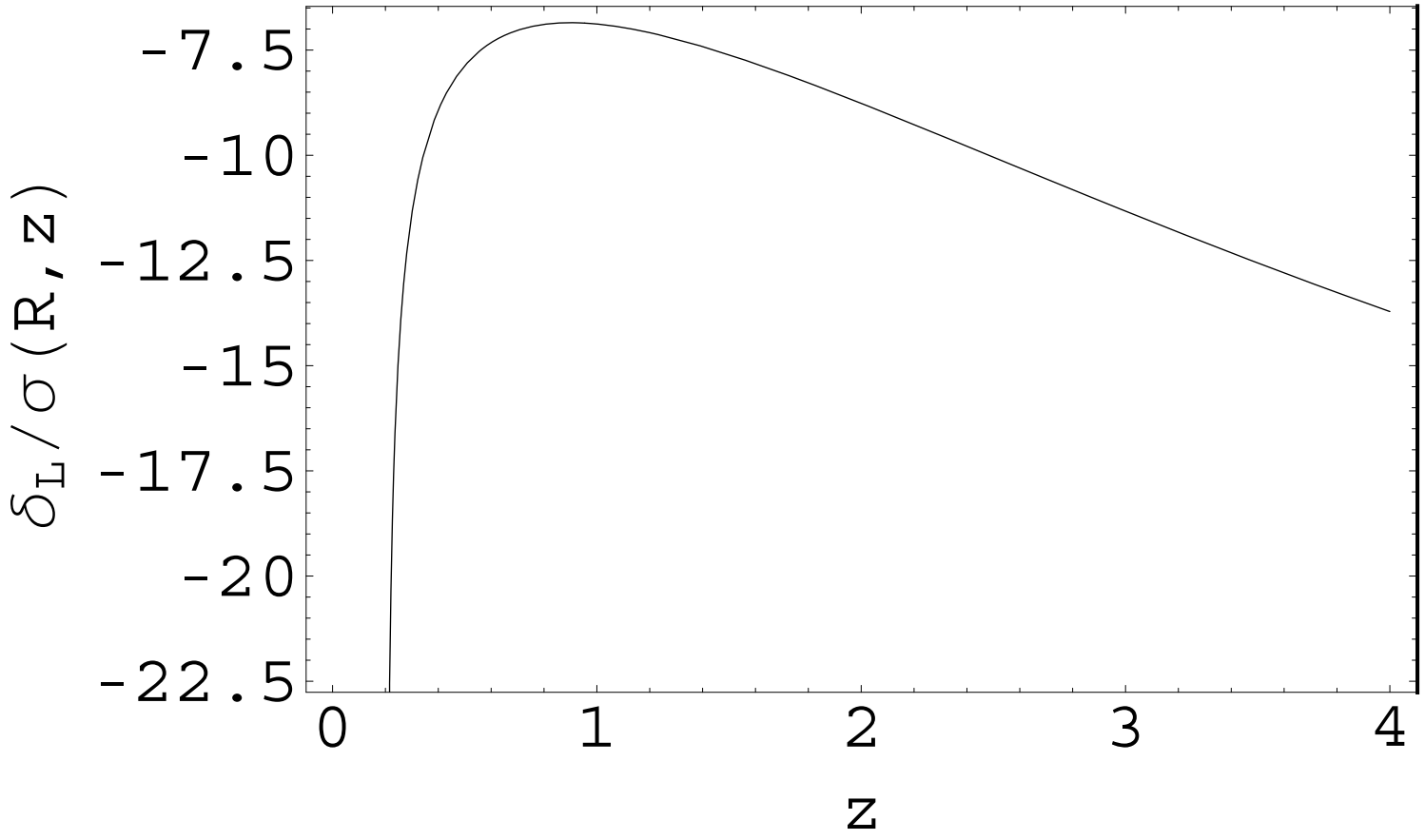
Linear density contrast /1 σ

$(\theta_v = 5^o, \Delta T = 16 \mu K)$



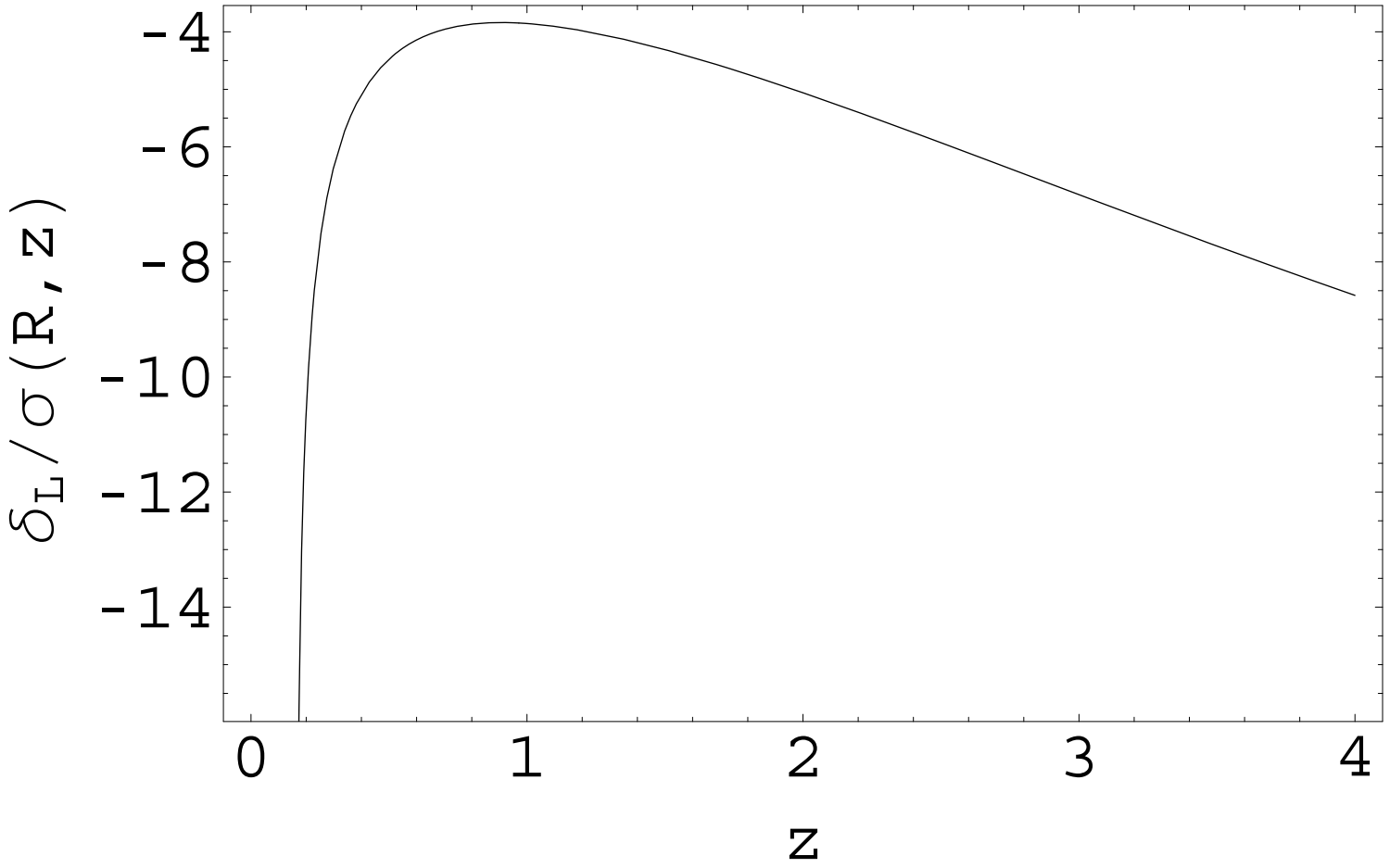
Linear density contrast/1 σ

$(\theta_v = 9^o, \Delta T = 16 \mu K)$



Linear density contrast/1 σ

$(\theta_v = 9^o, \Delta T = 8\mu K)$



Summary & Prospects

- Local supervoids can explain most features of the large-angle anomalies.
- A quasi-linear LSV with radius ~200(h^{-1}Mpc) at z~1 might explain the Cold Spot. But it is very rare (~10σ) if Gaussian.
- Non-linear effects due to superstructures would generate bias toward low temperature.

☆Future observation can test the LSV hypothesis (CFHT, VLT with VMOS ongoing…)